Sustainable Agriculture Reviews 8

Eric Lichtfouse *Editor*

Agroecology and Strategies for Climate Change

Springer

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Agroecology and Strategies for Climate Change

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ISSN 2210-4410 e-ISSN 2210-4429
ISBN 978-94-007-1904-0 e-ISBN 978-94-007-1905-7
DOI 10.1007/978-94-007-1905-7
Springer Dordrecht Heidelberg London New York

Library of Congress Control Number: 2011935458

Printed on acid-free paper

Springer is part of Springer Science+Business Media (www.springer.com)

Contents

Agroecology, a Tool for the Realization of the Right to Food*

Olivier De Schutter

Abstract The reinvestment in agriculture, triggered by the 2008 food price crisis, is essential to the concrete realization of the right to food. However, in a context of ecological, food and energy crises, the most pressing issue regarding reinvestment is not how much, but how. This manuscript explores how agroecology, understood as the application of the science of ecology to agricultural systems, can result in modes of production that are highly productive, highly sustainable and that contribute to the alleviation of rural poverty and, thus, to the realization of the right to food.

Drawing on an extensive review of the scientific literature published in the last 5 years, the study shows how agroecology can benefit in particular the most vulnerable groups in various countries and environments. Moreover, agroecology delivers advantages that are complementary to better known conventional approaches such as breeding high-yielding varieties. And it strongly contributes to the broader economic development. Appropriate public policies can create an enabling environment for sustainable modes of agricultural production. These policies should prioritize the procurement of public goods in public spending rather than solely providing input subsidies. They should invest in knowledge and in forms of social organization that encourage partnerships, including farmer field schools and farmers' movements innovation networks.

Keywords Agroecology • Climate change • Farmers' movements • Fertiliser price • Food security • Foodstuff price • Nutrition

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*This chapter is a short and revised version of the report I presented, in my official capacity as United Nations Special Rapporteur on the right to food, at the 16th session of the Human Rights Council (UN doc. A/HRC/16/49).

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E. Lichtfouse (ed.), *Agroecology and Strategies for Climate Change*,
Sustainable Agriculture Reviews 8, DOI 10.1007/978-94-007-1905-7_1,

1 Introduction

Agriculture is at crossroads. For almost 30 years, since the early 1980s, neither the private sector nor governments were interested in investing in agriculture. This is now changing. Over the last few years, agri-food companies have seen an increase in direct investment as a means to lower costs and ensure the long-term viability of supplies (Reardon and Berdegué 2002; Reardon et al. 2007, 2009): FDI in agriculture went from an average of US$ 600 million annually in the 1990s to an average of US$ 3 billion in 2005–2007 (UNCTAD 2009). The global food price crisis of 2007–2008 also pushed governments into action. In July 2009, the G8 Summit in L'Aquila produced a Food Security Initiative, promising to mobilize US$20 billion to strengthen global food production and security; and the Global Agriculture and Food Security Program (GAFSP) was established as a multilateral financing mechanism to help implement these pledges. Other initiatives at global and regional levels are underway, such as NEPAD's Comprehensive Africa Agriculture Development Program (CAADP) in Africa. Governments are paying greater attention to agriculture than in the past. The 'urban bias' (Lipton 1977) is still very present, as most governmental elites still depend on the political support from the urban populations for their stability ; but the prejudice against agriculture is slowly being overcome.

However, investments that will allow to increase food production will not allow significant progress in combating hunger and malnutrition if it is not combined with higher incomes and improved livelihoods for the poorest – particularly small-scale farmers in developing countries. And short-term gains will be offset by long-term losses if it leads to further degradation of ecosystems, threatening future ability to maintain current levels of production. The question therefore is not simply *how much*, but also *how*. Pouring money into agriculture will not be sufficient: we have to take steps that facilitate the transition towards a low-carbon, resource-preserving type of agriculture that benefits the poorest farmers.

In this chapter, I explore how agroecology can play a central role in achieving this goal. I argue that it is possible to significantly improve agricultural productivity where it has been lagging behind, and thus to raise production where it needs most to be raised (in poor, food-deficit countries), while at the same time improving the livelihoods of small holder farmers and preserving ecosystems. This would slow the trend towards urbanisation in the countries concerned, which is placing stress on public services of these countries. It would contribute to rural development and preserve the ability for the succeeding generation to meet its own needs. And it would contribute to the growth of other sectors of the economy, by the stimulation of demand for non-agricultural products that would result from higher incomes in the rural areas.

2 A Diagnosis

Most of the attention since the global food price crisis has been to increasing overall production. The crisis has been seen as resulting from a mismatch between supply and demand : as a gap between slower productivity growth and increasing needs.

A widely cited estimate is that, taking into account demographic growth, as well as the changes in the composition of diets and consumption levels associated with increased urbanization and higher household incomes, overall increase in agricultural production should reach 70% by 2050 (Burney et al. 2010).

We should treat this estimate with caution. First, it takes the current demand curves as given. At present, nearly half of the world's cereal production is used to produce animal feed and meat consumption is predicted to increase from 37.4 kg/person/year in 2000 to over 52 kg/person/year by 2050, so that, by mid-century, 50% of total cereal production may have to go to increasing meat production (FAO 2006a). Therefore, the reallocation of cereals used in animal feed to human consumption, an option highly desirable in developed countries where the excess animal protein consumption is a source of public health problems,[1] combined with the development of alternative feeds based on new technology,[2] waste and discards, could go a long way towards meeting the increased needs (Keyzer et al. 2005). The United Nations Environmental Programme (UNEP) estimates that, even accounting for the energy value of the meat produced, the loss of calories that result from feeding cereals to animals instead of using cereals directly as human food represents the annual calorie need for more than 3.5 billion people (UNEP 2009: 27, based on figures from FAO 2006b). In addition, as a result of policies to promote the production and use of agrofuels, the diversion of crops from meeting food needs to meeting energy needs contributes to tightening the pressure on agricultural supplies.

Second, waste in the food system is considerable: for instance, the total amount of fish lost through discards, post-harvest loss and spoilage may be around 40% of landings (Akande and DieiOuadi 2010). Food losses in the field (between planting and harvesting) may be as high as 20–40% of the potential harvest in developing countries due to pests and pathogens, and the average post-harvest losses, resulting from poor storage and conservation, amount at least to 12% and up to 50% for fruits and vegetables (UNEP 2009: 30–31).

Third, even though food availability may have to increase, the focus on increasing production should not obfuscate the fact that hunger today is mostly attributable not to stocks that are too low or to global supplies unable to meet demand, but to poverty : increasing the incomes of the poorest is the best way to combat it. We need to invest in agriculture, not only in order to match growing needs, but also in order to reduce rural poverty by raising the incomes of small-scale farmers. Because poverty remains so heavily concentrated in the rural areas, GDP growth originating in agriculture has been shown to be at least twice as effective in reducing poverty as GDP growth originating outside agriculture (World Bank 2007: 6; Alston et al. 2002). The multiplier effects are significantly higher when growth is triggered by higher incomes for smallholders, stimulating demand for goods and services from

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[1] In developing countries, the consumption of meat is much lower, and meat can be an important source of proteins important for child development (Neumann et al. 2007).

[2] Such as glucose from the degradation of cellulose, a technology that is currently being developed.

local sellers and service-providers: when large estates increase their revenue, most of it is spent on imported inputs and machinery; and much less trickles down to local traders (Hoffmann 2010: 15). Only by supporting small producers can we help break the vicious cycle that leads from rural poverty to the expansion of urban slums, in which poverty breeds more poverty.

Fourth and finally, agriculture must not compromise its ability to satisfy future needs. The loss of biodiversity, unsustainable use of water, and pollution of soils and water are issues which compromise the continuing ability for natural resources to support agriculture. Climate change, which translates in more frequent and extreme weather events such as droughts and floods and less predictable rainfall, is already having a severe impact on the ability of certain regions and communities to feed themselves; and it is destabilizing markets. The change in average temperatures is threatening the ability of entire regions, particularly those living from rainfed agriculture, to maintain actual levels of agricultural production (Stern Review 2007: 67). Less fresh water will be available for agricultural production, and the rise in sea level is already causing the salinization of water in certain coastal areas, making water sources improper for irrigation purposes. By 2080, 600 million additional people could be at risk of hunger, as a direct result of climate change (UNDP 2007: 90). In Sub-Saharan Africa, arid and semi-arid areas are projected to increase by 60–90 million hectares, and it is estimated that in Southern Africa yields from rainfed agriculture could be reduced by up to 50% between 2000 and 2020 (IPCC 2007: Chap. 9). Losses in agricultural production in a number of developing countries, particularly in Sub-Saharan Africa, could be partially compensated by gains in other regions, but the overall result would be a decrease of at least 3% in productive capacity by the 2080s, and up to 16% if the anticipated carbon fertilization effects – the incorporation of carbon dioxide in the process of photosynthesis – fail to materialize (Cline 2007: 96). And losses of production in many developed regions will increase the pressure on the supply side of the global markets.

The current development path of agriculture is worsening this situation. Agriculture currently accounts for at least 13–15% of global man-made greenhouse gas (GHG) emissions. It is especially GHG-intensive in the developed countries, where agriculture is more highly mechanized and relies heavily on synthetic fertilizers. Although some of these emissions are from energy-related carbon dioxide (CO_2) (9% of GHG emissions from agriculture), most are from methane (CH_4), which is emitted by rice paddies, livestock digestion, and manure handling (45%), and nitrous oxide (N_2O), from nitrogen-based fertilizers and manure applications to soils (46%).[3] That represents only the emissions at field level: in rich countries, most of the energy use in the food systems (from 65% to 80%) occurs at other points in the food chain, in the packaging, processing, transport and preparation of food, as well as in production of agricultural inputs and fixed capital equipment. Deforestation for the expansion of crop areas and pastures

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[3] CH_4 and N_2O represent respectively 14.3% and 7.2% of total GHG emissions, and they are particularly potent in trapping heat: CH_4 traps 21 times more heat than CO_2, and N_2O traps 260 times more heat (Kasterine and Vanzetti 2010: 87–111).

produces an additional 19% of global GHG emissions. In addition, the GHG-intensity of agriculture increases faster than its productivity: while agricultural emissions of methane and nitrous oxide grew by 17% in the period 1990–2005, matching increases in global cereal production volume, cereal yields increased by only 6% over the same period (Hoffmann 2010: 5). In other words, agriculture is on a path towards becoming more carbon-intensive. Without a substantial change in policies, the GHG emissions from agriculture could rise by 40% by 2030 (Smith et al. 2007).

Agroecology is increasingly seen as one way to address these considerable challenges. As a way to improve the resilience and sustainability of food systems, it is now supported by an increasingly wide range of experts within the scientific community (IAASTD 2008: Key Finding 7; Wezel et al. 2009a), and by international agencies such as the United Nations Food and Agriculture Organisation (FAO) and Bioversity International (FAO and Bioversity International 2007), and the United Nations Environmental Programme (UNEP 2005). It is also gaining ground in countries as diverse as the United States, Brazil, Germany and France (Wezel et al. 2009b). In the following sections, I explain why agroecology should be further supported, and what it can contribute.

3 Agroecology : A Solution to the Crisis of the Food Systems?

Agroecology has been defined as the ‘application of ecological science to the study, design and management of sustainable agroecosystems’ (Altieri 1995; Gliessman 2007). It seeks to enhance agricultural systems by mimicking or augmenting natural processes, thus enhancing beneficial biological interactions and synergies among the components of agrobiodiversity (Altieri 2002). Common principles of agroecology include recycling nutrients and energy on a farm, rather than augmenting with external inputs; integrating crops and livestock; diversifying species and genetic resources in the agroecosystems over time and space, from the field to landscape levels; and focusing on interactions and productivity across the agricultural system rather than focusing on individual species. Agroecology is highly knowledge-intensive, based on techniques that are not delivered top-down but developed on the basis of farmers’ knowledge and experimentation.[4] Agroecological practices require diversification of the tasks on the farm, linked to the diversity of species (including animals) that are combined.

A wide panoply of techniques have been developed and successfully tested in a range of regions that are based on this perspective (Pretty 2008). *Integrated nutrient management* reconciles the need to fix nitrogen within farm systems with the import of inorganic and organic sources of nutrients and the reduction of nutrient losses

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[4] Modern science combines with local knowledge in agroecological research. In Central America for instance, the coffee groves grown under high-canopy trees were improved by the identification of the optimal shade conditions minimizing the entire pest complex and maximizing the beneficial microflora and fauna while maximizing yield and coffee quality (see Staver et al. 2001).

through erosion control. *Agroforestry* incorporates multifunctional trees into agricultural systems In Tanzania, 350.000 ha of land have been rehabilitated in the Western provinces of Shinyanga and Tabora using agroforestry (Pye-Smith 2010: 15); there are similar large-scale projects developed in other countries including Malawi, Mozambique and Zambia (Garrity et al. 2010: 200; Linyunga et al. 2004). *Water harvesting* in dryland areas allows for the cultivation of formerly abandoned and degraded lands, and improves the water productivity of crops. In West Africa, stone barriers built alongside fields slow down and stop runoff water during the rainy season, allowing an improvement of soil moisture, the replenishment of water tables, and reductions in soil erosion. The water retention capacity is multiplied fivefold to tenfold, the biomass production multiplies by 10–15 times, and livestock can feed on the grass that grows along the stone barriers after the rains (Diop 2001: 152). The *integration of livestock into farming systems*, such as dairy cattle, pigs and poultry, including using zero-grazing cut and carry systems, provides a source of protein to the family as well as a means of fertilizing soils; so does the incorporation of fish, shrimps and other aquatic resources into farm systems, such as into irrigated rice fields and fish ponds. These approaches involve the maintenance or introduction of agricultural biodiversity (the diversity of crops, livestock, agroforestry, fish, pollinators, insects, soil biota and other components that occur in and around production systems) to achieve the desired results in production and sustainability.

Sometimes, apparently minor innovations can provide high returns. In Kenya, researchers and farmers developed the “push-pull” strategy to control parasitic weeds and insects that damage the crops. The strategy consists in “pushing” away pests from corn by interplanting corn with insect-repellent crops like *Desmodium*, while “pulling” them towards small plots of Napier grass, a plant that excretes a sticky gum which both attracts the pest and traps it. The system not only controls the pests but has other benefits as well, because *Desmodium* can be used as fodder for livestock. The push-pull strategy doubles maize yields and milk production while improving soils at the same time. The system has already spread to more than 10,000 households in East Africa by means of town meetings, national radio broadcasts and farmer field schools (Khan et al. 2011). In Japan, farmers found that ducks and fish were as effective as pesticides in rice paddies for controlling insects, while providing additional protein for their families. The ducks eat weeds, weed seeds, insects, and other pests, thus reducing weeding labour, otherwise done by hand by women. Duck droppings provide plant nutrients. Duck swimming activity increases rice growth, leading to stockier stems. The system has been adopted in many rice-growing areas in Bangladesh, China, India, and the Philippines. In Bangladesh, the International Rice Research Institute reports 20% higher crops yields and net incomes on a cash cost basis increases by 80% (Khan et al. 2005).

Such resource-conserving, low-external-input techniques have a huge, yet still largely untapped, potential to address the combined challenges of production, of combating rural poverty and contributing to rural development, and of preserving the ecosystems and mitigating climate change.

3.1 Agroecology as a Response to the Question of Supply

Agroecological techniques have a proven potential to significantly improve yields. In what may be the most systematic study of the potential of such techniques to date, Jules Pretty et al. (2006) compared the impacts of 286 recent sustainable agriculture projects in 57 poor countries covering 37 million hectares (3% of the cultivated area in developing countries). They found that such interventions increased productivity on 12.6 millions farms, with an average crop increase of 79%, while improving the supply of critical environmental services.[5] Disaggregated data from this research showed that average food production per household rose by 1.7 tonnes per year (up by 73%) for 4.42 million small farmers growing cereals and roots on 3.6 million hectares, and that increase in food production was 17 tonnes per year (up 150%) for 146,000 farmers on 542,000 ha cultivating roots (potato, sweet potato, cassava). After UNCTAD and UNEP reanalyzed the database to produce a summary of the impacts in Africa, it was found that the average crop yield increase was even higher for these projects than the global average (79%): 116% increase for all African projects and 128% increase for the projects in East Africa (UNCTAD and UNEP 2008: 16).

The most recent large-scale study points towards the same conclusions. Research commissioned by the UK Government's Foresight Global Food and Farming Futures project reviewed 40 projects in 20 African countries where sustainable intensification has been developed during the 2000s.[6] The projects included crop improvements (particularly improvements through participatory plant breeding on hitherto neglected orphan crops[7]), integrated pest management, soil conservation and agroforestry. By early 2010, these projects had documented benefits for 10.39 million farmers and their families and improvements on approximately 12.75 million hectares. Crop yields more than doubled on average (increasing 2.13-fold) over a period of 3–10 years, resulting in an increase in aggregate food production of 5.79 million tonnes per year, equivalent to 557 kg per farming household (Pretty et al. 2011).

3.2 Agroecology's Ability to Increase the Incomes of Small-Scale Farmers

One advantage of agroecology is its reliance on locally produced inputs. Many African soils are nutrient-poor and heavily degraded, and they need replenishment. But supplying nutrients to the soil can be done not only by applying mineral

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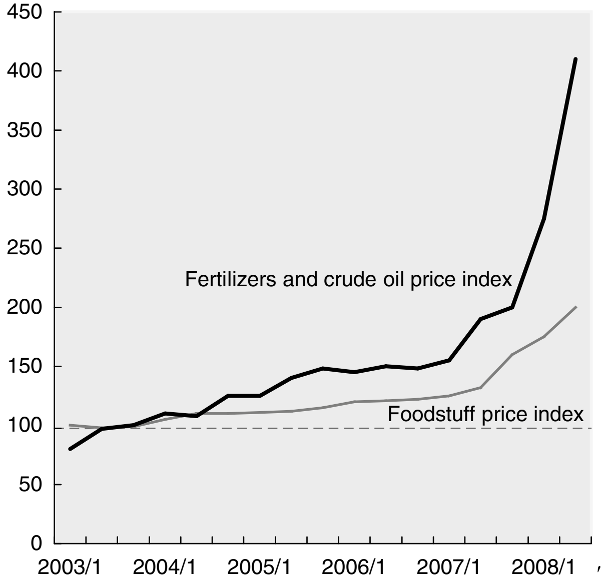
[5] The 79% figure is for the 360 reliable yield comparisons from 198 projects. There was a wide spread in results, with 25% of projects reporting a 100% increase or more.

[6] Not all these projects, it should be added, comply fully with the principles of agroecology.

[7] Such as improvements on cassava, for which NaCRRI developed locally-developed resistant varieties in Uganda, or improvements on Tef in Ethiopia, where the Debre Zeit Agricultural Research Centre developed a new variety, the *Quncho*.

Fig. 1 Comparison between the evolutions of the prices of fossil energy-based fertilizers and food prices, 2003–2008



Sources: Global Challenges for Food and Agriculture: FAO's Long-term Outlook for Global Agriculture, Rome, 2008, available at www.fao.org.

fertilizers, but also by applying livestock manure or by growing green manures. Farmers can also establish what has been called 'a fertilizer factory in the fields' by planting trees that take nitrogen out of the air and 'fix' it in their leaves, which are subsequently incorporated into the soil (World Agroforestry Centre 2009: 10). A tree such as *Faidherbia albida*, a nitrogen-fixing acacia species indigenous to Africa and widespread throughout the continent, performs such a function. Since this tree goes dormant and sheds its foliage during the early rainy season at the time when field crops are being established, it does not compete with them significantly for light, nutrients or water during the growing season; yet it allows significant increases in yields of the maize which it is combined, particularly in conditions of low soil fertility. In Zambia, unfertilized maize yields in the vicinity of Faidherbia trees averaged 4.1 t/ha, compared to 1.3 t/ha nearby but beyond the tree canopy; similar results were observed in Malawi, another country where this tree was used widely (Garrity et al. 2010).

The use of such nitrogen-fixing trees avoids dependence on synthetic fertilizers, the price of which has been increasingly high and volatile over the past few years – exceeding even the increases in the prices of basic food commodities (Fig. 1) – , and shall remain so as a result of peak oil. This means that whatever financial assets the household has can be used on other essentials, such as education or medicine. Agroecology diminishes the dependence of farmers on access to external inputs, and thus on subsidies, the local retailer of fertilizers or pesticides, and the local moneylender. Diversified farming systems produce their own fertilizers, and their own pest control, thus diminishing need of pesticides (Altieri and Nicholls 2004); the availability of adapted seeds, planting materials and livestock breeds also presents multiple advantages, both for the farmer and to ensure the availability of the required diversity of such materials in major crops such as maize, rice, millet, sorghum, potato and cassava (UN Special Rapporteur on the right to food 2009). This is particularly beneficial to small-scale farmers – especially women – with low or no access to credit, and which have no capital, or whom fertilizer distribution systems often do not reach, particularly since the private sector is unlikely to invest into the most remote areas where communication routes are poor and where few economies of scale can be achieved.

A study on agroforestry in Zambia which involved intercropping or rotation between various trees and maize showed that the net benefit of agroforestry practices is 44–58% superior to non-fertilised continuous maize production practice. And while subsidised fertilised maize was the most financially profitable of all the soil fertility management practices, given government's 50% subsidy on fertiliser, the difference in profitability between fertilised maize and agroforestry practices is reduced sharply from 61% to 13% once the subsidy is accounted for in the computation. Even more importantly, agroforestry practices yielded higher returns per unit of investment cost than continuous maize fields with or without fertiliser. Each unit of money invested in agroforestry practices yielded returns ranging between 2.77 and 3.13 (i.e., a gain of between 1.77 and 2.13 per unit of money invested) in contrast with 2.65 obtained through subsidised fertilised maize, and 1.77 through non-subsidised fertilised maize. The return to labour per person-day was consistently higher for agroforestry practices than for continuous maize practice. The study noted that 'in rural areas where road infrastructure is poor and transport costs of fertiliser are high, agroforestry practices are most likely to outperform fertilised maize in both absolute and relative profitability terms' (Ajayi et al. 2009: 279, 283).

3.3 The Contribution of Agroecology Rural Development – and to Other Sectors of the Economy

Agroecology contributes to rural development, because it is relatively labor intensive and is most effectively practiced on relatively small plots of land. The launching period is particularly labor intensive, because of the complexity of the tasks of managing different plants and animals on the farm, and of recycling the waste produced: the higher labor-intensity of agroecology diminishes significantly in the longer term.[8] This relatively higher labor intensivity often has been seen as a liability of sustainable farming. Yet, while labor-saving policies have generally been prioritized by governments, the creation of employment in the rural areas in

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[8] See Ajayi et al. 2009: 279 (research on agroforestry in Zambia does not support 'the popular notion that agroforestry practices are more labour intensive').

developing countries may in fact constitute an advantage, since underemployment is currently massive and demographic growth remains high in many developing countries, and since there is an urgent need to slow down rural-urban migration as the industry and the services sectors appear unable to absorb the excess labor.

Although they can create jobs, agroecological approaches are fully compatible with a gradual mechanization of farming; and the need to produce equipment for conservation agricultural techniques such as no-till and direct seeding could result in more jobs being created in the manufacturing sector. This is true in particular in Africa, which still imports most of its equipment, but which increasingly manufactures simple equipment such as jab planters, animal-drawn planters and knife rollers.[9] Employment could also result from the expansion of agroforestry. In Southern Africa, farmers produce trees as a business, supported by a financing facility established by the World Agroforestry Centre (ICRAF). During its first year, the Malawi Agroforestry Food Security Programme distributed tree seeds, setting up 17 nurseries that raised 2,180,000 seedlings and establishing 345 farmer groups (Pye-Smith 2008: 10).

Growth in agriculture can be especially beneficial to other sectors of the economy if it is broad-based, increasing the incomes of a large number of farming households, rather than if it leads to a further concentration of incomes in the hands of relatively large landowners relying on large-scale, heavily mechanized plantations. There is one line of argument according to which growth in agriculture can benefit other sectors because it will increase demand for inputs and lead to growth in agro-processing activities, respectively upstream and downstream the production process on the farm. However, since most agricultural inputs and machinery are imported, and since crops can be sold abroad as raw commodities, whether such a ‘production’ linkage will occur depends on the organisation of the commodity chain in the country concerned. A more significant linkage – that recent research estimates to be typically four to five times more important than the ‘production’ linkage (Christiaensen et al. 2011) – results from the fact that increased incomes in rural areas will raise demand for locally traded goods or services. This ‘consumption linkage’ – in fact a keynesian argument – is particularly likely where agricultural growth is widely spread across large segments of a very poor population. It presupposes, of course, that the rural population shall buy locally produced goods and locally provided services, and that supply can meet this increase in demand (Delgado et al. 1998). This illustrates that for the full benefits of agro-ecology to materialize – beyond rural development, in order to include multiplier effects in other sectors of the economy – , some degree of diversification of the economy – the strengthening of the industry and the services sectors – must accompany or precede the increase of incomes in rural areas, which allows the growth of a market for manufactured products and services : you don’t accelerate a process that has not been launched.

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[9] In East Africa, this development was facilitated by the exchange of technology from Brazilian manufacturers to their counterparts in Eastern Africa (Sims et al. 2009).

3.4 Agroecology's Contribution to Improving Nutrition

Green Revolution approaches in the past have focused primarily on boosting cereal crops (rice, wheat and maize) in order to avoid famines. However, these crops are mainly a source of carbohydrates. They contain relatively little protein, and few of the other nutrients essential for adequate diets. The shift from diversified cropping systems to simplified cereal-based systems thus contributed to micronutrient malnutrition in many developing countries (Demment et al. 2003): of the over 80,000 plant species available to humans, only three (maize, wheat and rice) supply the bulk of our protein and energy needs (Frison et al. 2006). Nutritionists now increasingly insist on the need for more diverse agro-ecosystems, in order to ensure a more diversified nutrient output of the farming systems (Alloway 2008; DeClerck et al. 2011).

The diversity of species on farms managed following agroecological principles, as well as in urban or peri-urban agriculture, is an important asset in this regard. For example, it has been estimated that indigenous fruits contribute on average about 42% of the natural food-basket that rural households rely on in southern Africa (Campbell et al. 1997). This not only is an important source of vitamins and other micronutrients; it also may be critical for sustenance during lean seasons. And nutritional diversity, allowed by increased diversity in the field, is of particular importance to children and women.

3.5 Agroecology and Climate Change

Agroecology can support agriculture's provision of a number of services to the ecosystems, including by providing a habitat for wild plants, supporting genetic diversity and pollination, and water supply and regulation. It also improves resilience to climate change. Climate change means more extreme weather-related events. The use of agroecological techniques can significantly cushion the negative impacts of such events: resilience is strengthened by the use and promotion of agricultural biodiversity at ecosystem, farm system and farmer field levels, which is materialized by many agroecological approaches (Platform for Agrobiodiversity Research 2010). For instance, following Hurricane Mitch in 1998, farming plots cropped with simple agroecological methods (including rock bunds or dikes, green manure, crop rotation and the incorporation of stubble, ditches, terraces, barriers, mulch, legumes, trees, plowing parallel to the slope, no-burn, live fences, and zero-tillage) were shown to have on average 40% more topsoil, higher field moisture, less erosion and lower economic losses than control plots on conventional farms : they lost 18% less arable land to landslides than conventional plots and had a 49% lower incidence of landslides, and 69% less gully erosion compared to conventional farms (Holt-Giménez 2002).

More frequent and more severe droughts and floods can be expected in the future: agroecological modes of farming are better equipped to support such shocks.

The agroforestry programme developed in Malawi protected farmers from crop failure after droughts, thanks to the improved soil filtration it allowed (Akinnifesi et al. 2010). Indeed, on-farm experiments in Ethiopia, India, and the Netherlands have demonstrated that the physical properties of soils on organic farms improved the drought resistance of crops (Eyhord et al. 2007 ; Edwards 2007). A sixfold difference was also measured in Brazil between infiltration rates under low-tillage agriculture and traditional tillage. This allow rainfall to better recharge groundwater, and it reduces the risks of flooding (Landers 2007). The soil's infiltration capacity is also maintained by the use of mulch cover, which protects the soil surface from temperature changes and minimizes soil evaporation (Kassam et al. 2009). In addition, diversity of species and the diversification of farm activities that agroecological approaches allow are a way to mitigate risks from extreme weather events, as well as from the invasion of new pests, weeds and diseases, that will result from global warming. Several agroecological approaches, such as cultivar mixtures, increase crop heterogeneity and genetic diversity in cultivated fields. This improves crop resistance to biotic and abiotic stresses In the Yunnan Province in China, after disease-susceptible rice varieties were planted in mixtures with resistant varieties, yields improved by 89% and blast (a major disease in rice) was 94% less severe than when they were grown in monoculture, leading farmers to abandon the use of fungicidal sprays (Zhu et al. 2000).

Agroecology also puts agriculture on the path of sustainability, by delinking food production from the reliance on fossil energy (oil and gas). And it contributes to mitigating climate change, both by increasing carbon sinks in soil organic matter and above-ground biomass, and by avoiding carbon dioxide or other greenhouse gas emissions from farms by reducing direct and indirect energy use. The IPCC has estimated the global technical mitigation potential for agriculture at 5.5–6 Gt of CO_2-equivalent per year by 2030 (IPCC 2007: Sect. 8.4.3.). Most of this total (89%) can come from carbon sequestration in soils, storing carbon as soil organic matter (humus); 9% from methane reduction in rice production and livestock/manure management; and 2% from nitrous oxide reduction from better cropland management (Hoffmann 2010: 11; see generally on the mitigation potential of agriculture FAO 2009).

4 Conclusion: Scaling Up Agroecology

The discussion above points to the need for an urgent reorientation of agricultural development towards systems that use fewer external inputs linked to fossil energies, and that use plants, trees and animals in combination, mimicking nature instead of industrial processes at the field level. However, in moving towards more sustainable farming systems, time is the greatest limiting factor: whether or not we will succeed will depend on our ability to learn faster from recent innovations and to disseminate what works more widely.

Governments have a key role to play in this regard. Encouraging a shift towards sustainable agriculture implies transition costs, since farmers must learn new techniques that move away from the current systems, which are both more specialized and less adaptive, and have a lower innovation capacity (Pretty 2008). In order to succeed in implementing such a transition, we should base the spread of agroecology on the farmers themselves, its main beneficiaries, and encourage learning from farmer to farmer, in farmer field schools or through farmers' movements, as in the Campesino-a-Campesino movement in Central America and Cuba (Degrande et al. 2006: 6; Holt-Giménez 2006; Rosset et al. 2011). Farmer field schools have been shown to significantly reduce the amounts of pesticides use, as inputs are being replaced by knowledge: large-scale studies from Indonesia, Vietnam and Bangladesh recorded 35–92% reductions in insecticide use in rice, and 34–66% reductions in pesticide use in combination with 4–14% better yields recorded in cotton production in China, India and Pakistan (Van Den Berg and Jiggins 2007). Farmer field schools are also empowering, helping farmers to organize themselves better, and they stimulate continued learning. The successful dissemination of the push-pull strategy (PPS) in East Africa, promoted by the International Centre for Insect Physiology and Ecology (ICIPE), rests in particular on the demonstration fields managed by model farmers which attract visits of other farmers during field days and on partnerships with national research systems in Tanzania, Uganda, Ethiopia and other countries that made research and development efforts to make the necessary adaptations such as choice of maize cultivars (Amudavi et al. 2009: 226).

An improved dissemination of knowledge by horizontal means transforms the nature of knowledge itself, which becomes the product of a network (Warner and Kirschenmann 2007). It should encourage farmers, particularly small-scale farmers living in the most remote areas and those on the most marginal soil, to identify innovative solutions, working with experts towards a co-construction of knowledge ensuring that advances will benefit them as a matter of priority, rather than only benefiting the better-off producers (Uphoff 2002: 255). This is key for the realization of the right to food. First, it enables public authorities to benefit from the experience and insights of the farmers. Rather than treating smallholder farmers as beneficiaries of aid, they should be seen as experts with knowledge that is complementary to formalized expertise. Second, participation can ensure that policies and programmes are truly responsive to the needs of vulnerable groups, who will question projects that fail to improve their situation. Third, participation empowers the poor – a vital step towards poverty alleviation, because lack of power is a source of poverty, as marginal communities often receive less support than the groups that are better connected to government. Poverty exacerbates this lack of power, creating a vicious circle of further dis-empowerment. Fourth, policies that are co-designed with farmers have a high degree of legitimacy and thus favor better planning of investment and production and better up-take by other farmers (FAO-IIED 2008). Participation of food-insecure groups in the policies that affect them should become a crucial element of all food security policies, from policy design to the assessment of results to the decision on research priorities. Improving the situation of millions of food-insecure peasants indeed cannot be done without them.

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Agroecology and the Food System

A. Wezel and C. David

Abstract On a global scale agriculture and food will face key challenges of properly feeding a population of nine billion individuals in 2050, while preserving the ecosystems from which other services are also expected, such as bioenergy production, biodiversity use and conservation, carbon storage and climate regulation. To develop future sustainable agricultural production and food systems, agronomic, ecological, economic and social challenges have to simultaneously be taken into account. The framework of agroecology applied on the food system could be a useful concept to support this development. Although the scale and dimension of scientific research in agroecology has been enlarged in the last years towards the food system approach, it is still difficult to outline clear concepts, new models and new methods that specify it. In using two contrasted research case studies, we evaluate benefits and challenges using the framework of agroecology applied on the food system.

The first case study illustrates research questions around water quality and management of shallow lakes with fish production, biodiversity of the lakes, agricultural land use on the surrounding land, and local fish products and its marketing strategies. It shows that research was initiated by an ecologist working at the lake scale, but implementing quite quickly a systems approach in integrating the disciplines ecology, agronomy, geography, socio-economy and sociology with a food systems approach. The second case study illustrates research questions around organic wheat production and food chain. It shows the evolution of a research program where research objectives and methodology have been slowly turned from technical questions on nitrogen management of organic wheat, supported by agronomist, applied at field scale, to overall agroecological questions around organic grain producers,

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E. Lichtfouse (ed.), *Agroecology and Strategies for Climate Change*,
Sustainable Agriculture Reviews 8, DOI 10.1007/978-94-007-1905-7_2,

raised by economists, sociologists, agronomists and food technologists, focussing on the wheat-flour food chain, applied at farm and food system scales.

This chapter underlines the importance of the articulation between disciplines such as agronomy, ecology and social science. In using the food system approach, the indispensable interdisciplinary research is carried out automatically by integrating other disciplines such as sociology, socio-economy and geography supporting the disciplines of agronomy and ecology. This chapter also shows that in combining already existing research methods from different disciplines, and applying them to different scales, a concept for agroecological analyses of the food system already exists. In conclusion, we propose necessary prerequisites for agroecological research with the food system approach: ex-ante impact anticipation of expected results when starting research, multi-scale and interdisciplinary research as well as scale related impact assessment of proposed recommendations. In considering these prerequisites, quality of agricultural research will substantially improve in the future, and thus contributing in search for more sustainable food systems.

Keywords Agroecosystem • Food chain • Interdisciplinary research • Multi-scale research • Organic agriculture • Wheat • Pond • Shallow lake • Sustainable agriculture

1 Introduction

World agriculture and food provision will face key challenges of properly feeding a population of nine billion individuals in 2050 where contrasted regional food availability will support important migration. Therefore, there is a crucial need to preserve the environment and natural resources of agricultural land from which other services are also expected: bioenergy production, biodiversity use and conservation, carbon storage and climate regulation. Research on the world's agricultural production and food, to support the objective of sustainable development, has become the subject of many studies and debates (FAO 2003; Agrimonde 2009). The framework of agroecology applied on the food system may significantly support this sustainable development by considering simultaneously agronomic, ecological, economic and social dimension at different scales.

Although agroecology as a scientific discipline exists already since many decades, the food systems approach in agroecology has been developed only recently (Wezel and Soldat 2009; Wezel and Jauneau 2011). Still it is difficult to outline clear concepts, new models and new methods that specify this approach. Besides agroecology as a scientific discipline, other interpretations such as agroecology as a practice or as a movement are present (Wezel et al. 2009).

The scale and dimension of scientific research in agroecology has been enlarged over the past 80 years from (1) the plot, field or animal scale to (2) the farm or agroecosystem scale and finally in the last years to (3) the dimension of the food system (Wezel and Soldat 2009). On the plot/field/animal scale, the aim of agroecological research is to develop new farming practices such as more efficient use of natural resources, improved nutrient cycling, and enhancement of diversity and the health of soils, crops and livestock. For instance, in crop production research focuses on techniques to limit off-farm fertilisers, e.g. mixed crops, intercropping systems to better use crop diversity and N fixation from legumes or to improve pest management by using natural processes, e.g. allopathy or natural enemies for plant protection. In animal production, research investigates for example natural alternatives like plant extracts to antibiotics or adaptation of animal densities and pasture rotation to improve fodder quality and availability. At this scale, research does not really consider interactions and implications of these techniques on the agroecosystem or the environment at a larger scale.

The second major approach is the agroecosystem approach. Here, ongoing research dominates the agroecosystem scale, including exchange with, and impact on the surrounding environment. Agroecological analyses focuses on plant and animal communities, food web interactions, and conservation biology in agricultural landscapes and agroecosystems (Department of Crop Science, Section of Agroecology, at the University of Göttingen 2008). Within the agroecosystem approach the definitions and concepts might vary depending on the delimitation of an agroecosystem. Sometimes, the farm is seen as equivalent to an agroecosystem where the relations between farmers' practices and natural resources are analysed (Conway 1987). For others an agroecosystem is larger, that is, a local or regional landscape where relations between different types of agriculture and the natural resources of the landscape is investigated.

The most recent and broadest approach is the food systems approach. This approach was firstly defined by Francis et al. (2003) as 'the integrative study of the ecology of the entire food systems, encompassing ecological, economic and social dimensions, or more simply the ecology of food systems'. Gliessman (2007) stated that the politics/policy dimension should also be included in this definition, as the different political decisions and policies are an important issue to be considered. This author defined agroecology as 'the science of applying ecological concepts and principles to the design and management of sustainable food systems'. These two definitions are based on former definitions of Altieri (1989, 1995, 2002).

During the beginning of the 2000s, several authors demand that agriculture has to be analysed in a holistic manner. For example Robertson et al. (2004) demand that agricultural research needs long-term, system-level research at multiple scales, and that natural and social science must be better integrated. Gliessman (2007) stated that 'to recognise the influence of social, economic, cultural, and political factors on agriculture, we must eventually shift our focus from sustainability of agroecosystems to the sustainability of our food systems'. Nevertheless, it is still difficult to outline clear concepts, new theoretical models, and new methods that specify and translate these demands, and in particular the expanded definition of agroecology of the food system, into concrete cases. In fact, very few papers are given in the literature where agroecology concepts and theory are applied on the food system, e.g. Francis and Rickerl (2004).

This leads to the objectives of this paper. Two examples of actual research topics will be presented and analysed in how they are placed within or in relation with the food systems approach of agroecology. A particular question will be what distinguishes them from more disciplinary research approaches such as agronomy or ecology, which research concepts are used and how the different research scales are taken into consideration.

In the following, we will present the two case studies, the agroecosystems where they have been carried out, the research objectives and the main research questions, the methods used to analyse them, and the interaction between the different research components and disciplines. A special emphasis will be laid on the historical evolution of the research objectives, which disciplines initiated the projects, and which disciplines joined in thereafter. In a subsequent section their place within the agroecology approach with the food system will be illustrated and discussed.

2 Shallow Lake Agroecosystem: Biodiversity, Agriculture and Fish Production

The research objectives of this case study were, first, to evaluate if shallow lake management practices and agricultural practices in the surroundings favour high biodiversity which can then be used for the promotion of local fish products, and, secondly, if the agricultural and aquaculture practices at the same time can maintain a sufficient level of fish production and preserve un acceptable water quality.

The Dombes region in south-eastern France, the study area, was formed by glacial activity during the quaternary period (Avocat 1975). It is a plateau of about 1,000 km^2 with long, fan-shaped morainic mounds, so-called drumlins. The average altitude is about 280 m. The plateau is flanked by three fluvial valleys about 50–100 m below the plateau. During the late Würm glaciation, substantial amounts of loess were mainly deposited in the depressions between the drumlins (Williams 2006). Post-glacial rain leached much of the loess creating decalcified clayey soils in the depressions which induce water stagnation when soils are wet (Avocat 1975). In the morainic areas, more sandy soils dominate. Annual precipitation varies between 800 and 1,200 mm (Blanchet 1993; Bernard and Lebreton 2007). The history of the Dombes and its shallow lake system started in the thirteenth century (Guichenon 1650 cited in Sceau 1980). The shallow lakes were created in smaller depressions for the production of fish, and to drain surrounding loamy-clayey soils to be able to crop cereals. The fish production activity expanded largely during the medieval period because of the need to find fish at a time in which food prescriptions were very strict. Today, the Dombes region is characterised by about 1,100 shallow lakes with about 12,000 ha, located in an agricultural area with pastures, cropped fields and forests (Bernard and Lebreton 2007). The size of the shallow lakes varies considerably from less than 1 ha up to one which is larger than 100 ha. Average depth of the shallow lakes is about 1 m. The fish farming practiced in the shallow lakes is oriented toward raising mainly carp, but also tench, roach and pike

(Bernard and Lebreton 2007). It is based on an extensive system that alternates fish farming and grain farming on the same unit of land. Shallow lakes are emptied every year for fish harvesting, and then refilled. After 3–4 years, the shallow lakes are left to dry up to be cultivated mainly with oats, maize or sorghum for 1 year; few are not cultivated (Wezel et al. submitted). The water that fills the shallow lakes during the wet phase comes either from a shallow lake situated at a higher elevation or from a system of ditches which lead into the shallow lake and which collect rainwater from the catchment.

The research presently carried out in the Dombes region touches different scales and different disciplines. At the scale of a shallow lake, which is considered here as the plot/field scale mentioned above, different physical-chemical water and sediment parameter are analysed for a selection of shallow lakes to evaluate the trophic status and its changes during a year (ecology). This type of research was started already a few years earlier, before other components were added to have a more holistic approach. For the latter, species richness and diversity of phytoplankton, marcophytes, macro-invertebrates, dragonflies and amphibians are additionally investigated (ecology). Also data on annual fish harvest are collected from managers of the shallow lakes (socio-economy). Land use and biotopes within a 100 m radius around the shallow lakes (field scale) and within the catchment of shallow lakes (agroecosystems scale) are analysed by aerial photograph interpretation and ground surveys (geography, landscape ecology). In addition, farmers are interviewed about their agricultural practices such as fertilisation, nutrient management, pesticide use and water drainage on the fields adjacent to the shallow lakes and in the catchment (field scale; agronomy). Owners or managers of the shallow lakes are questions concerning different fish production and lake management practices (lake/field scale; socio-economy). Finally, an analysis is carried out to investigate the network of stakeholder for processing, selling and marketing of the fish production, and about the creation of a label of geographical denomination of origin for the fish products (food system scale; sociology, socio-economy).

The different analyses carried out are used to evaluate either singular results of the different parameters analysed, but also their complex interactions. Water quality and sediment parameter are analysed to evaluate the trophic status of the shallow lakes itself, but also how these parameters are influenced by land use around and lake management practices. The richness and diversity of the different species groups are evaluated in relation to the trophic status of the shallow lakes, but also in relation to lake management as well as for agricultural practices and biotopes present in the vicinity of lakes. The evaluation of the fish production is the most complex as fish production is evaluated in relation to trophic status of shallow lakes, which is additionally influenced by lake management practices and agricultural land use around the lakes. In addition, the impact of several species groups such as phytoplankton, marcophytes, and macro-invertebrates, are evaluate in relation to fish production because of being a source of feed for fish or being important for nutrient turn-over in the water. Finally, it is evaluated if the existence of a certain biodiversity (the species groups and the biotopes) can be valorised for the marketing of the fish production, or more specifically for a product label, or even as being a quality

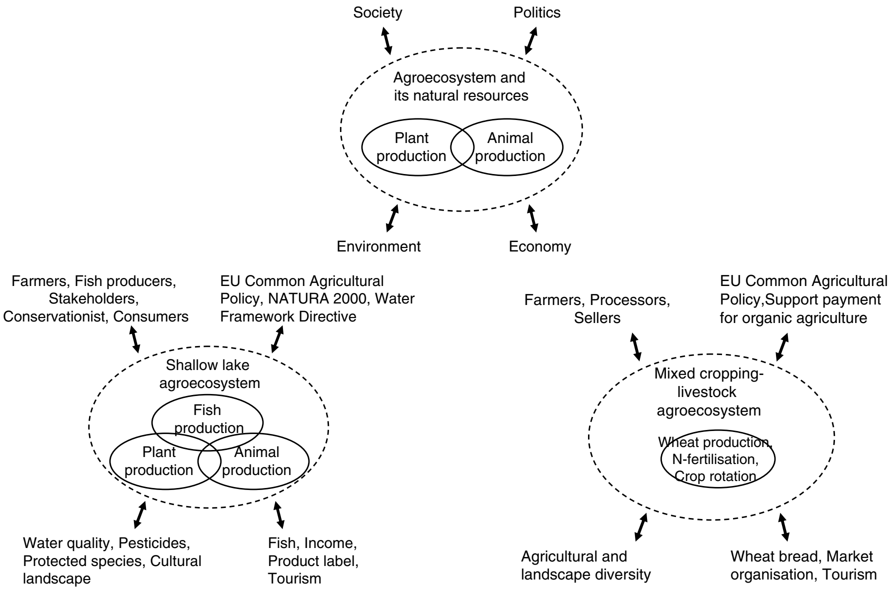

Fig. 1 The general food systems approach of agroecology is illustrated above (From Wezel and Soldat 2009) where agricultural production within an agroecosystem and the interactions and influences from and to the environment, economy, society and politics are taken into account. Below left, the case study of the shallow lake agroecosystem, and below right, the case study of organic cereal farming, are illustrated with the respective key elements

indicator for the Dombes shallow lakes agroecosystem and its different types of management and practices.

2.1 Shallow Lake Agroecosystem and the Agroecology of the Food System Approach

In this section we will show how this first case study can illustrate the theoretical concept of Francis et al. (2003) for the food system approach in agroecology. The agroecosystem of this case study consists of shallow lakes within a matrix of agricultural land forests and (semi-)natural ecosystems (Fig. 1, *below left*). Three types of production exist and interact in different ways: fish production in shallow lakes, cropping of cereals, sun flowers and rape on fields as well as cattle and some sheep production on pastures. These three types of production have different impacts on the environment. The use of fertilisers and pesticides for plant production influences to different degrees the water quality of shallow lakes (Vallod et al. 2008, Wezel et al. submitted), and thus also fish production, but also different natural species in and around the shallow lakes such as dragon flies, phytoplankton or macrophytes. The impact strongly depends on where the different types of land use are located in the agroecosystem, and how they are connected by ditches or drainage systems with the shallow lakes. In addition, it is necessary to know how farmers manage their fields and pastures as well as their borders or the hedgerows in the agroecosystem. This together with the knowledge about how fish producers mange their shallow lakes is necessary to evaluate the impact on ecosystems such as reed, hedgerows, thickets and grassland as well as selected species groups in the shallow lakes vicinity. The management of the farmers and fish producers is influenced to different degrees by regional, national and European regulations such as the EU Common Agricultural Policy, the European Water Framework Directive and NATURA 2000, thus these regulations have to be taken into account if modification of practices are intended. In addition, the role of farmers and fish producer among other stakeholders in the Dombes agroecosystem such as local politicians, mayors, conservationist and different agricultural and fish associations and institutions has to be analysed to anticipate reaction within the social structure of the Dombes region to proposed changes or innovations. Finally, it is essential to identify the different stakeholders of the fish food chain: from producers, collectors, processors, sellers to the consumer. This analysis enable to evaluate how fish could be marketed in increasing or assuring income by using different types of labels such as Geographical Denomination of Origin, or a new local label indicating that with the traditional local fish production the cultural landscape and/or biodiversity is preserved.

This case study illustrates the food system approach with research questions around water quality and management of shallow lakes with fish production, biodiversity of the lakes, agricultural land use on the surrounding agricultural land, and local fish products and its marketing strategies. It shows that research was initiated by ecologist, but implementing quite quickly a systems approach in integrating the disciplines ecology, agronomy, geography, socio-economy and social science with an agroecosystems and food systems approach.

3 Organic Wheat: From Production to Wheat-Flour Food Chain

The research objectives of this case study were, first, to evaluate how nitrogen management of organic wheat can be improved and how the farming system has to be adapted to this, and, secondly, to analyse the organisation of organic grain producers and the wheat-flour food chain.

The study area is located in south-eastern France where two closely located subareas, the Diois and the Plain of Valence, were selected. The Diois is a hilly area located along the Drome River, at the southern feet of the vast karst plateau of the Vercors with an average altitude of 1,100 m. The altitude of the Diois ranges between 420 and 520 m with a mean annual temperature of 10.2°C (David et al. 2005a). In this area, clayey and stony soils dominate, except along the Drome River where cereals are produced on alluvial soils. Annual precipitation varies between 885 and 1,100 mm. The traditional farming system is characterized by a mixed production of livestock with sheep and goats, arable crops and perennial crops such as aromatic plants, walnuts or grapes. Climatic conditions with cold winter and dry summer limit strongly wheat performance.

The Plain of Valence is located at the confluence of the fertile Rhone, Drome and Isere River valleys where loamy and sandy soils dominate. The altitude ranges between 150 and 250 m with a mean annual temperature of 11.4°C (David et al. 2005a). Annual precipitation varies between 850 and 950 mm. The traditional farming system mainly produces grains, sometimes in combination with other productions such as poultry or field vegetables.

In the two districts, where the study areas are located, the development of the organic sector (production and processors) in the last year has been one of the fastest growing in France with 8–10% of the usable agricultural area under organic agriculture (Agence Bio 2008). In particular in the Diois area, an active organic sector around wine, grains and aromatic plants has developed since the beginning of the 1990s.

As the Dombes example, this research project has been carried out at different scales and by integrating different disciplines. The on-farm research program on organic wheat started in 1993, and up to 1998 the objective was to improve the technical and economical performance of organic grain systems with a special emphasis on organic wheat being the most important crop (Von Fragstein et al. 1997). This first phase had been set up on 17 farms, first, to take into account a wider range of growing conditions than is available on on-station experiments, secondly, to benefit from farmers' expert knowledge when research on organic grains systems was still very limited, and, finally, to consider the entire farm system and its socio-economic parameters (Lockeretz and Stopes 1999). Nitrogen and weed management were experimented on more than 40 organic fields from 1993 to 1998 by testing various techniques and equipment (field scale, agronomy) defined by experts to improve yield performance. Different factors limiting organic crop production such as weed and pest infestation, soil compaction or climatic conditions like water stress and hot temperatures could be determined (field scale; agronomy) (David et al. 2005a; Casagrande et al. 2009). From 1998 to 2004, management of N fertilisation had also been studied under controlled on-station conditions, to produce references for N nutrition of organic and low-input wheat from organic N sources (David et al. 2004). This research also allowed developing a decision support system to manage N fertilisation of organic wheat (David et al. 2005b; David and Jeuffroy 2009) to improve grain yield and grain protein content. In addition, it gave an early indication of whether this decision support system is likely to be adopted by farmers (agronomy, sociology). During the second phase of the program, research went beyond the restricted field scale analyses in integrating more farm management aspects. A multivariate analysis of quantitative and qualitative data such as grain yield, protein content, crop management and farming system management from 97 organic farms located in the two districts demonstrated the incidence of the farming systems, e.g. the presence or absence of livestock on the farm, the incidence of crop management, e.g. cultivar, preceding crop, N fertilisation and weed control, but also the incidence of soil and climatic conditions such as water deficit and temperature on grain yield and protein content (field and agroecosystem scale; agronomy). Furthermore, interviews with farmers which were started in the first phase, enlarged in the second phase and which became up to present a key element of the research program, enabled to study more completely the farm management (plot, farm and food system scale; agronomy, economy and sociology). It could be concluded that diversification of farm production and activities, off-farm employment and professional and social networking contributed significantly to farm viability (David et al. 2010). In parallel, the analysis of the wheat-flour food chain allowed to determine the interactions between producers, collectors, processors and consumers (David and Joud 2008). Also, a structured organic food chain supported by cooperatives and bakers improved economic viability of farms.

The present research project now tries to integrate even more many different scientific disciplines such as agronomy, food technology, economy, and sociology, and to work simultaneously at different scales of the field, the farm and the food system to consider a more holistic approach. Thus, the present research objectives are to improve nitrogen supply by undersowing of leguminous species or use of organic fertiliser and soil management for wheat production, but also flour processing to improve baking quality, nutritional value and to avoid mycotoxin contamination. Further research questions are how local and regional processing, marketing, distribution and selling enterprises in the region can be establish or better implemented in the region in considering the increasing requirements from processors on quality and safety of organic wheat as well as the demand from the regional and national organic food market to decrease the variation of offer and quality as well as to limit instability of prices? And last but nor least, how can the organic farmers be better integrated in this food chain network, also considering the different support payment systems on national and European level for organic agriculture?

3.1 Organic Wheat and the Agroecology of the Food System Approach

As for the first case study, we also will illustrate the theoretical concept of Francis et al. (2003) for the food system approach in agroecology with the organic farming case study. The agroecosystems characteristics of the two subareas of this case study strongly influences the farming systems but also the food system (Fig. 1, *below right*). The Diois agroecosystem consists of limited areas with fertile soil in the Drome Valley, where cereals are produced in a long term and diversified crop rotation of 8–11 years, surrounded by large areas with low soil fertility occupied by vineyards, lavender fields, permanent pastures and (semi-)natural ecosystems. The agricultural productivity is limited in this area. In contrast, the high agricultural diversity together with the Drome River and the adjacent mountains make it to a beautiful landscape and give a strong value for tourism for which farmers produce local food, vine and lavender as well as offering accommodation. Conversion to organic production allowed maintaining economic value to low-input agricultural productions like vine, grains and aromatic plants. Moreover, the organic development, promoted by local authorities, supports the “natural” value of this area. The marketing of organic products such as grain, wine and aromatic plants, promoted by cooperatives is associated with identity and origin, supported by traditional varieties and specific products, for instance by the Clairette de Die, a famous sweet sparkling wine produced exclusively in this area.

As the agroecosystem of the Plain of Valence consists of a large fertile plain, yield performance of dominating grain production is much higher, compared to the Diois. Organic grain systems differ only slightly from conventional systems. Cropping systems are based on a balanced proportion of spring crops, mostly irrigated, such as maize and soybean associated in the crop rotation of 4–6 years with winter cereals such as wheat, barley or triticale. The organic grains are collected by conventional cooperatives where a limited organic sector has been developed to answer farmers' requirements. Tourism is very limited in the Plain of Valence area, thus direct selling, provision with local food products or accommodation at farm are rare.

As shown above, the agroecosystems characteristics of the two subareas do not only influence the farming systems but implicate also differences for the food system (Fig. 1, below right). For instance, in the Diois, the wheat-flour-bread chain is essentially based on small niche market for traditional organic bakers or organic retailers looking for specific flavour obtained with ancient varieties, but also providing identity as originating from the area. On the contrary, the wheat-flour food chain in the Plain of Valence is essentially based on standardised quality requirement, e.g. protein content over the conventional threshold of 11.5 g per 100 g and no mycotoxin, applied from mass distribution or enterprises (David and Joud 2008). Nevertheless, on-going research clearly needs to demonstrate the incidence of crop management, in particular N fertilisation, interaction with environmental conditions soil and climate via wheat flour quality to local, regional or national marketing and selling networks. In this relation from the field to the food chain scale, farmers' management goals, their economic situation and their receptivity for innovations, e.g. reduced tillage or undersowing of leguminous species, as well as regional, national and European agricultural policy framework have to be taken into consideration.

This case study illustrates research questions around organic wheat production and food chain in a study area in south-eastern France. It also shows the evolution of a research program since 1993 where research objectives and methodology have been slowly turned from technical questions on nitrogen management of organic wheat, supported by agronomist, applied at field scale, to overall agroecological questions around organic grain producers, raised by economists, sociologists, agronomists and food technologists, focussing on the wheat-flour food chain, applied at farm and food system scales.

4 Agroecology and the Food System Concept

At present, a crucial and highly debated question in relation to agroecology of the food system is if new research concepts are needed or if already adequate concepts and approaches exist which can be used immediately. In our opinion existing concepts and approaches should be valorised, and new one should be developed. We will start with existing concepts, than coming to new potential ones.

In general, the concepts of holism with a systemic approach including different scales and interdisciplinarity exist already, so they can already be the basis for research and analyses for agroecology of the food system. The two case studies presented above show how analyses and evaluations from the field/plot, the farm/agroecosystem, and the food system scale can be used to orient research towards a system approach. Nonetheless, it is essential to emphasize on the up-scaling methods to relate research questions from the field/plot to the food system. The two research examples clearly demonstrate the value of interdisciplinary research combining agronomy, ecology, social sciences, socio-economy, but also food technology. If we really intend to establish sustainable agricultural systems, it is essential to focus research questions around a food product, or more generally around an agricultural commodity, and to analyse the different scales with an interdisciplinary perspective. Two types of research approaches seem possible, a bottom-up and a top-down approach. The bottom-up approach would be for example to analyse the incidence of innovative fertilisation management for crop performance and for farm management, but also to anticipate what type of impact this would have on the agroecosystem and the food quality (Le Bail and Meynard 2003). Which analyses or what type of investigations have to be considered to evaluate their potential impacts? The top-down approach could also be applied. For example if a local or regional food label want to be created for better marketing, specific requirement along the food chain, but also by specific values or 'capitals' from the agroecosystem have to be taken into account. Consequently, the analyses have to be related to the social systems and networks as well as to the agroecosystem itself to know for instance if it is a particular cultural landscape which preserves certain species or certain ecosystems, and thus if this information could be used for the promotion of the product.

In general, different theoretical models have been developed to conceptualise the complex relationships of how agroecosystems exist in the intersection between nature and society (Gliessman 2007). The models presented focus on sustainable agroecosystem and influences from ecological, socio-economic, and technological factors (Hernandéz Xolocotzi 1977, cited in Gliessman 2007), the relation of agroecosystems to certain resources, called 'capitals' such as human, social, natural, and financial capital (Flora 2001), and the interactions among social and ecological components of sustainable agroecosystems (Gliessman 2007). Although some of the factors, capitals, or components are related in different ways to the food system, the food systems approach is not explicitly integrated within the models.

Other possible theoretical approach could be the holon approach of Bland and Bell (2007). Due to the need to tackle the problems of boundaries, e.g. scales, system limits, or actors, and change, e.g. time or evolutions and adaptations, that are evident for all agroecological research questions, they argue that agroecologists need to take into account how intentionalities, e.g. research objectives, seek to create holons, an intentional entity, that persist amid the ever changing contexts, and how boundaries can be recognized based on how intentionalities draw and act upon them.

Nevertheless, this interesting concept remains difficult to be translated into reality. The multi-scale approach is not necessarily used, as a holon can be restricted to the field or the agroecosystem scale, although holons are always part of something larger (Koester 1967, cited in Bland and Bell 2007). This ecology of contexts seems to be very similar to what we see as the agroecology of the food system approach, where the environmental, social, economic and political contexts always have to be taken into account. Bell et al. (2008) state that productivity of variability should be a key principle in agroecology as contextual variability across space and time presents farmers with productive opportunities. This clearly underlines that agroecological research should be carried out simultaneously at different scales if it is intended to be systemic or holistic, also because a multi-dimensional approach touches automatically variability across time, in our examples for instance considerations on long-term impacts such as N fertilisation and N supply of organic wheat performance and flour quality, or investment decisions in perspective of EU agricultural policy regulations to support organic product with guarantee of safety and quality. Although not directly discussing agroecology, Pretty (2008) arguments also clearly that it is necessary to simultaneously consider and analyse natural, social, human, physical and financial capital dimensions to shape concepts for agricultural sustainability, the core topic of agroecology. A practical example on how such different dimension can be evaluated simultaneously is the filter approach of Haigis et al. (1999). In using agroecological, technical, institutional, sociological and economic filters, different technology options for small-scale farmers were interdisciplinary evaluated for their acceptance or rejection. Although this method was not explicitly developed to evaluate a food system, it is one example of an already existing tool which could be further adapted to the food systems approach.

In any case, irrespective to theoretical models or tools that wanted to be used to analyse the food system, it has to be struggled with a high complexity of research questions. If the holistic and system approach really wants to be achieved, we have to think this from the conception of agroecological research in connecting different disciplines from the beginning, different research scales as well as implications of food systems stakeholders. It is also essential to previously fix the boundaries, with the limits of our food system we intend to analyse, and the key disciplines regarding the research questions. For the food system approach of agroecology this would demand that in particular the disciplines agronomy, ecology, geography, socio-economy, sociology and anthropology have to be integrated (Fig. 2). Depending on the research questions, other disciplines such as food technology, as mentioned by organic wheat case study, should be also considered.

5 Future Agroecological Research

Although the basis and the historical origin of agroecology are founded in the two disciplines agronomy and ecology, the present scientific discipline agroecology and its approach to the food system seems to be the most promising research framework

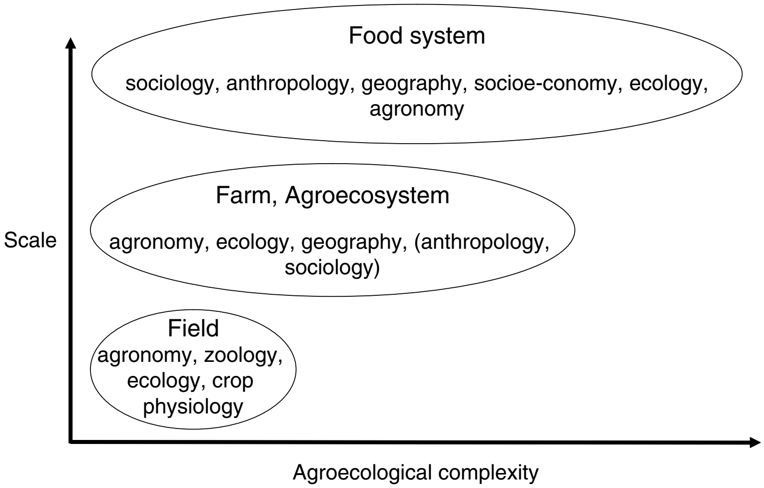

Fig. 2 Agroecological complexity for research with different scale approaches of agroecology. The increasing scales used for the farm/agroecosystem and the food system approach of agroecology demand considering an increasing number of disciplines to deal with increasing complexity of research questions. Agronomy and ecology are the basic disciplines for all scale approaches. The disciplines in brackets are so far only integrated in certain cases at the farm/agroecosystem scale

to respond to actual questions on sustainable agricultural productions systems where ecological, economic and social sustainability aspects are strongly linked. Francis and Rickerl (2004) as well as Robertson et al. (2004) provided already a future vision for the ecology of the food system and a vision for environmental research in US agriculture. Based on this and our own experience, we think that four prerequisites are necessary for carrying out research with the agroecology of the food system approach:

(a) Agroecological research has to be carried out simultaneously at different scales.
(b) Agroecological research has to integrate different scientific disciplines as well as stakeholders from the different food system networks.
(c) Potential environmental, social and economical impacts from the expected research results have to be anticipated during development of a research project and its hypothesis.
(d) Recommendations from agroecological research have to be impact assessment-driven for the different scales.

Without the holistic/systems approach of agroecology and the food system, the different research topics of our case studies would have been treated in a restricted, more disciplinary way, in looking only at parts of the systems – which can be of course also valuable in many cases. But in using the food system approach, the indispensable interdisciplinary research is carried out automatically as shown by the two examples. The two examples also show that in combining already existing research methods from different disciplines, and applying them to different scales, a concept for agroecological analyses of the food system already exists. Nevertheless, our examples also show that they remain to a certain degree incomplete. For example among key social factors in food systems sustainability such as equitability, sustainable diet patterns, control of population growth, and self-sufficiency and bioregionalism, as proposed by Gliessman (2007), only bioregionalism was considered in the Dombes example. We could add more factors to that list which we think as important to be included in food systems analyses such as energy consumption, transport, or food quality, but probably we should also accept that is unrealistic to demand now that every potential parameter or factor has to be included in the analyses. In practice it is evident that it is not that easy to carry out such type of necessary research as it will be seldom financed in its totality, but rather as research projects which analyse only parts of it. In addition, interdisciplinarity is a keyword commonly used everywhere today in the scientific research community, but being really implemented in only rarer cases.

It is also indispensable to integrate the stakeholders from the different food system networks. With this a broader vision of the problems and a better identification of potential solutions are achievable. Consequently, a more client-oriented research will be implemented. Nevertheless, it should not be forgotten that integrating researchers and food system stakeholders in a common process is often a tricky thing as it demands a lot of efforts to find a common language and understanding. It also often slows down the starting phase of the research projects as so many things have to be taken into account, e.g. identification of stakeholders, common workshops or meetings, agreeing on terms and definitions.

Prerequisite three demands that already during the construction of an agroecological research project and the establishment of the research hypothesis, potential environmental, economic or social impacts or problems of the expected results have to be anticipated. For example, the intention to test different levels of liquid manure application to the shallow lakes to increase fish production, as in case study 1, should be first evaluated in respect to an increased nutrient status in the water which might have a negative impact on nearby rivers when shallow lakes are emptied once a year. If negative impacts seem to be possible, then the research approach should be adapted and modified. Anticipating potential impacts at the field scale is of course probably easier than at the agroecosystem scale.

Our fourth prerequisite for agroecology of the food system is that recommendations from agroecological research have to be impact assessment-driven for the different scales. That means that results obtained at a certain scale should be evaluated in respect to their potential impacts at other scales. For example, before recommending a certain amount of N fertilisation for organic wheat, as it proved to increase significantly yields or baking quality, it has to be evaluated if these N inputs might create N leaching and drinking water contamination in the watershed in certain periods of the year, or if the necessary organic fertilisers, or the grains of undersown leguminous species, are not available on the regional market or are too expensive or to energy demanding during production.

We are aware that the four prerequisites for agroecology of the food system approach are not that easy to be completely fulfilled for all research programs. Nevertheless, we are sure that if the food system approach is already taken into account during the design of a research project, and be it only during reflections at an initial stage of the project, it will substantially improve the quality of agricultural research in the future, and thus contributing in search for more sustainable food systems.

In this paper we focused on agroecology and the food system from a scientific research perspective, but as mentioned before, a strong link of agroecology and the food systems has also been established in recent years with a development and movement perspective (e.g. Cruces 1996; Caporal and Costabeber 2000; Altieri 2002; Sevilla Guzmán 2002; Altieri and Nicholls 2008; Brandenburg 2008). The main topics in these and other papers are rural development, built on local social and cultural values, which provides food sovereignty and food security for small farmers in developing countries. Based on local and traditional knowledge, low-input alternative agricultural systems are favoured.

6 Conclusion

From the experience of the two research programs we can state that without the holistic/systems approach of agroecology and the food system, the different research topics would have been treated in a restricted, more disciplinary way, and only at lower scales. In using the food system approach, the indispensable interdisciplinary research is carried out automatically by integrating other disciplines such as sociology, socio-economy and geography to the two basic disciplines agronomy and ecology. These two case studies also show that in combining already existing research methods from different disciplines, and applying them to different scales, a concept for agroecological analyses of the food system already exists. Nevertheless, our case studies also show that they remain to a certain degree incomplete. Other important factors such as such as energy consumption or food quality could have been included, but probably we should also accept that is unrealistic to demand now that every potential parameter or factor has to be included in a food system analysis.

We finally conclude that four prerequisites are necessary for the agroecology of the food system approach: ex-ante impact anticipation of expected results when starting research, multi-scale and interdisciplinary research as well as scale related impact assessment of proposed recommendations. We assume that in considering these four prerequisites, quality of agricultural research will substantially improve in the in the future, and thus contributing in search for more sustainable food systems.

Acknowledgements We highly acknowledge the comments and propositions of Eric Lichtfouse on an earlier draft of this paper.

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Development of a Sustainably-Competitive Agriculture

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Abstract The need for both *Competitiveness* and *Sustainability*, the two primary overarching goals of EU policy, present the agri-food sector with a unique set of formidable challenges and uncertainties. These point to the need for development of new, quality-focused models for agriculture and food production that are sustainably-competitive. The design criteria for the concept are outlined and developed within the context of an agronomic model for multifunctional, grass-based cattle production systems. This model highlights the importance of harnessing the benefits of functional biodiversity within two key epicenters of the system in order to realise both agronomic and environmental – and hence economic – advantage. Whilst much of the knowledge needed to implement the described model already exists, the functionality of biologically complex rumen and pasture processes within the two key system epicenters, represent the two main pillars of an innovation-driven research programme that is needed to provide fundamental new knowledge necessary to underpin practical development of the model.

Optimisation of rumen function is a primary determinant of feed conversion efficiency, animal health and performance, and product quality (milk and meat), and can contribute to minimisation of greenhouse gas (GHG) emissions. These strategic

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E. Lichtfouse (ed.), *Agroecology and Strategies for Climate Change*,
Sustainable Agriculture Reviews 8, DOI 10.1007/978-94-007-1905-7_3,

goals may be achievable through development of low-input, multi-species pastures to provide the optimum level of digestible fibre required by the grazing animal with minimised reliance on external nutrient inputs. In addition to resolving significant animal health and performance issues, such a shift in pasture management strategy is likely to offer a wide range of other important ecological advantages that result from functionally important niche complementarity between sward species in biodiverse grasslands. These advantages include: (i) more efficient utilisation of reduced nutrient availability and improved biomass production throughout the growing season, (ii) consequential reduction in nutrient losses to the environment, (iii) greater resilience of the pasture to environmental variability, including climate variation and weed invasion, (iv) improved soil quality and carbon sequestration potential, and (v) enhanced biodiversity within the farmed landscape.

The development of sustainably-competitive models will require a more systematic approach to research and innovation in the agri-food sector involving in particular, the engagement of all necessary participants in a "value-added" food chain strategy, ranging from governments and national funding agencies to research and business organisations, producers and crucially, marketing, retailer and consumer interests. The fundamental requirement in achieving this aim is a dedicated public good funding system designed to support the transition of agriculture from the predominantly production/output orientation of the former EU Common Agricultural Policy, to development of consumer/society-orientated models that will be necessary for Europe to meet the considerable challenges facing its rural economies and food security. The key to achieving this goal will be the deployment of an appropriate proportion of the Common Agricultural Budget to ensure the development and widespread adoption of the value-adding concept of Sustainably-Competitive Regional Agri-Food Systems.

Keywords Multifunctional agriculture • Ruminant production systems • Functional biodiversity • Feed conversion efficiency • Animal health and welfare • Greenhouse gas emissions • Grassland ecology • Pasture management • Nutrient management • Value-added food production systems • Research policy

1 Introduction

Competitiveness and *Sustainability*, the two primary overarching goals of EU policy, present the agri-food sector with a unique set of formidable challenges and contradictions. The functionality of European agriculture and future viability of rural regions involve a complex multi-dimensional mix of interactions between the domains of food production and processing, land-use and rural economy, environmental management and human health, to which a wide range of scientific, economic, societal and educational policies are all deeply relevant (Tilman et al. 2002). In recent decades, a one-dimensional economic model based on international price competitiveness and increasing globalisation of food markets has largely determined policy and the focus of supports to resolve and find optimum solutions to this complex array of concerns. However, as noted by Boyle (2009), sustainability is vital for the future success of the agricultural sector, and significantly, a healthy environment is now recognized as a necessary output from farming with clear economic value, and immense importance to human ecology and the needs of society.

1.1 Policy Development

International policy developments are predominantly responsible for dictating the direction of European agriculture. A primary determinant in this regard is the outcome of ongoing negotiations under the World Trade Organisation (WTO) regarding free trade in agricultural products. The globalisation of markets has promoted a one-dimensional business model within the agri-food industry, based almost exclusively on maximising price competitiveness. The inevitable outcome is further industrialisation of production, increasing uniformity of farming practices, and greater concentration of production systems in regions of high inherent geo-climatic advantage and low production costs. This inevitably exacerbates sustainability problems arising from the related impacts of greatly increased production intensity in *competitive* regions, and the progressive abandonment of the traditional land management roles of farming in non-competitive areas. The effects of increasing intensity vary according to regional economic imperatives, which become a major determinant of prices, and hence competitiveness in international markets (Bruinsma 2003). The relocation of ever more intensive systems to emerging market economies essentially *exports* many concerns regarding immediate environmental impacts (e.g. see Barrett et al. 1999), whilst ensuring the continuation of a model based on cheap food with little attempt to internalise the full costs of its production.

Increasing food security concerns has become a major consequence, as the lengthening of food chains results in less control over food supply, quality and safety. This leads to a further decoupling of the parallel objectives of *competitiveness* and *sustainability*, as increasing legislation is introduced and inevitably drives a wedge between the perceived best interests of producers and the environment. An immediate concern in this regard is the urgent need to deal with climate change. The pursuit of global free trade in food markets, with its attendant *air miles* consequences, is incompatible with the urgent need for climate change mitigation (UNFCCC 2008; Verburg et al. 2008), and the need for localised adaptation of production systems to meet changing conditions (Howden et al. 2007). Whether the aim for both competitiveness and sustainability in food production is ultimately resolvable within an exclusively price-competitive model is doubtful, especially in the prevailing financial uncertainties.

1.2 The Need for Alternatives

A number of recent strategic initiatives have recognised the need for a radical transformation of agricultural systems to meet wider needs. At EU level, a series of detailed Foresight studies of agri-food futures have been conducted under the auspices of the Standing Committee for Agricultural Research (SCAR). The first major output of these initiatives highlighted the dependency of current production systems on high inputs of declining natural resources, including land, fossil fuels and water, and in the face of increasing global food demands highlighted the unpredictable effects of climate change and the ongoing loss of biodiversity and ecosystem integrity (FEG I 2007). This report identified the vulnerability of current production systems to *climate shock*, *energy crisis* and *food crisis*, and the need for greater *cooperation with nature*. A follow-up report identified and highlighted the deficiencies of increasing reliance on technological solutions subject to the profit motives of commercial organisations operating within globalised international markets. It concluded that the resilience of food supply systems was rapidly deteriorating as a consequence of insufficient innovation in alternative systems development (FEG II 2008).

In seeking to address the needs of global agriculture, the Royal Society in the UK developed a perspective for a *sustainable intensification* of agriculture (Royal Society 2009). This sought to identify strategies for an increase in the global production of food crops to meet the needs of an expanding human population, whilst protecting global ecosystem integrity and remaining natural environments. Focusing on the socio-economic dimensions of agriculture, Friz and Schiefer (2008) outlined a framework for development of sustainable food networks at a more local level. Meanwhile in the US, innovative cooperative structures have become the focus of what is termed *Agriculture of the Middle* (Gray 2009; AOTM 2010). This represents a systematic attempt to develop an alternative strategy for the economic survival of many medium sized farmers that is midway between increasingly *industrialised* scales of food production, and the comparative niche opportunities provided by organic production systems. It also represents a welcome diversification in models for food production strategy that theoretically can do much to enhance the resilience of the wider food supply system. By having a particular regard for the maintenance of production systems that underpin local economies, it clearly has relevance for agriculture-based economies in Europe (MackenWalsh 2010).

In this chapter, we develop the concept of *Sustainably-Competitive Agriculture*, with particular regard to livestock production systems. Through this model, we argue that a holistic integration of scientific knowledge across agronomic and environmental fields can better reconcile the increasing conflicts between industrialised food production, and growing sustainability concerns. We also draw attention to the need for a fundamental change of mind set in terms of policy development and infrastructural supports in order to achieve this ambition.

2 The Concept of Sustainably-Competitive Agriculture

Sustainable-competitiveness (Downey et al. 2008) is a concept that meets multifunctional objectives, and thereby provides the opportunity for a value-adding marketing strategy. Realisation of sustainable competitiveness requires knowledge-based systems, tailored to achieve both economic and environmental sustainability by optimisation of the advantages provided by regional environmental and socio-economic conditions. Implementation of the concept within mainstream European agriculture requires recognition that an important opportunity now exists to achieve a clear marketing advantage by optimising agronomic and ecological performance to secure product safety and quality in response to growing consumer concerns regarding prevailing production systems. Evidence of significant public support for a strategy that correctly internalises the true value of quality food production is provided by the proliferation of the international 'Fair Trade' scheme within the European market. This clearly demonstrates the existence of consumer concern over some of the more extreme consequences of an exclusively cheap food policy. Similar evidence of more discerning EU consumer interests is provided by the success of policy measures focused on preserving local production traditions, such as Protected Designation of Origin (PDO) and Protected Geographical Indication (PGI) (Ilbery and Kneafsey 1998). Further evidence of the opportunity for a value-adding strategy is clearly evident in the increasing popularity of farmer's markets (originally *vente directe* in France) selling local produce directly to a more discerning consumer. The vente directe concept is currently well placed to satisfy this increasing value-added demand (Gilg and Battershill 1998), and by doing so, realise the *virtuous circle* in which producers, consumers, society and the wider environment are all winners (Tudge 2004).

The concept of sustainable competitiveness is compatible with the well-established arguments of economic geographers, who have for some time called for the development of 'alternative systems of food provision' (Watts et al. 2005). Such calls were largely made from the perspective of meeting socio-economic needs in rural areas with traditional farming systems that are increasingly uncompetitive in scale with globalised production systems. They clearly anticipate the socio-economic drivers evident in the development of "*Agriculture of the Middle*" in the US (Gray 2009). However, as the growing global human population faces further food shortage, it is important that at a global level the concept of sustainably-competitive agriculture complements the development of technological innovation in existing production systems. At the global level, the aim must be a *sustainable intensification* of agriculture with minimal use of additional land (Royal Society 2009). The concept of sustainable competitiveness in traditional production regions can help in this regard by ensuring that such regions continue to contribute effectively to the totality of food production, rather than succumbing to the inevitable consequences of global competition and agricultural abandonment. Minor adjustments to existing farming systems, however, cannot realistically achieve the value-adding benefits of sustainably-competitive agriculture, which must harness and apply the benefits of increasing knowledge concerning natural processes in order to achieve multiple goals.

Sustainably-competitive livestock agriculture requires innovative production systems that meet the following design criteria:

- profitable at farm level,
- produce market required food products,
- animal health and welfare needs,
- environmentally sustainable,
- can cope with climate change,
- energy efficient

Whilst there will always be a ready market for "cheap food", the sustainably-competitive model seeks to establish both a technical and a marketing advantage by raising consumer willingness to pay a premium price for a product that is demonstrably superior from multiple (safety, quality, animal health and environmental) perspectives. To a limited extent, such value-adding cooperation is already happening through the development of groupings such as the *Linking Environment and Farming* initiative in the UK (LEAF 2010). Such initiatives are frequently taken by groups of innovative producers, often led by more entrepreneurial individuals from outside the regions involved, who appreciate the potential market for high quality, value-added produce. Such groups receive recognition and support from government agencies, largely because they are seen as an effective means to ensure an integrated approach to the assurance of quality standards (Haskins 2003 – Chap. 8). However, there is as yet an inadequate strategic commitment and assistance for the development of sustainably-competitive farming systems (see Sect. 4). Based on the design requirements listed above, a conceptual model showing the generic components that need to be integrated to develop sustainably-competitive production systems is illustrated in Fig. 1.

This model specifically applies to livestock systems, which present particularly fundamental sustainability issues by competing directly with the growing human population for food crops (Steinfeld et al. 2006). However, analogous models for *sustainable intensification* of crop production systems (Royal Society 2009), would feature basically similar components, e.g. plant genetics/breeding, crop nutrition/husbandry and crop pest/disease control to meet multifunctional (agronomic and environmental) objectives. The components of the indicative model illustrated in Fig. 1 and their relative importance are strongly context dependent, and in some circumstances there may be additional dimensions. In this regard, the development of explicit system models requires the involvement of economists, scientists and stakeholders in a collaborative process of identifying and weighting the relative importance of specified model components (see also Sect. 4).

2.1 Environment and Biodiversity

In any system that is fundamentally reliant on natural processes, sustainability is strongly dependent on the local environment, and a strong emphasis on 'place and

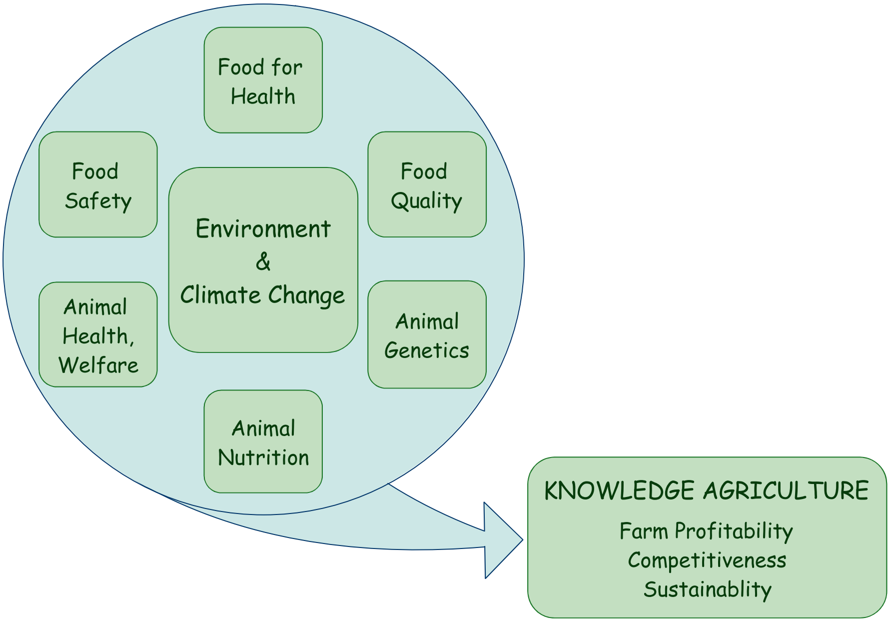

Fig. 1 The architecture of a sustainably-competitive agriculture (Downey et al. 2008)

culture' is needed (Boody and DeVore 2006). Many of the current problems of unsustainability in agricultural systems stem from a failure to recognise this crucial fact. Thus, in designing new systems of food production, particular attention needs to be given to the central importance of, and the advantages provided by the local environment (Fig. 1). For Europe to capitalise fully on its rich heritage of natural and cultural resources, the agricultural sector must also address the daunting challenge of protecting and maintaining environmental quality, which is intimately linked to regional economic viability (Boyle 2009). Purvis et al. (2009a) provide details of a recently developed methodology designed to identify local agri-environmental priorities, and evaluate policy options designed to ameliorate the negative effects of prevailing farm systems. However, much of the knowledge necessary to develop innovative, new farm production systems to achieve such aims already exists. What is lacking is firstly an economic framework that correctly recognises the wider potential of such systems; and secondly, a coherent and *integrative* approach to their development and validation.

To address the growing international concern with climate change, immediate urgency needs to be given to the adoption of more energy efficient agriculture, and in particular to ameliorating the effects of greenhouse gas (GHG) emissions from ruminant livestock production (Johnson and Johnson 1995; US EPA 2006). The protection of biodiversity is also a major environmental concern that brings with it important international obligations (CBD 1993; Brussaard et al. 2010). A significant proportion of habitats within the European landscape is created by farming, and the ongoing process of agricultural intensification across much of Europe has resulted in a significant loss of associated biodiversity (McLaughlin and Mineau 1995; Duelli 1997; Donald et al. 2001; Vickery et al. 2001; Hoffmann and Greef 2003; DeHeer et al. 2005). The most effective approach to addressing biodiversity loss through agricultural policy is a matter of considerable debate. There are two proposed models; an *integrated model* that advocates the enhancement of heterogeneity within farming systems to create a landscape matrix that facilitates population connectivity (Benton et al. 2003; Donald and Evans 2006); and a *land-sparing model* that proposes the separate designation of specified refuge areas for biodiversity protection, in order to avoid compromising the competitiveness of farm systems (Green et al. 2005; Kleijn et al. 2009). Given the deeply embedded land management role of agriculture within the modern European landscape and the relative scarcity of true wilderness areas, the concept of sustainably-competitive agriculture is clearly more compatible with an integrated, heterogeneous landscape strategy. In resolving many of the biodiversity concerns within agro-ecosystems, however, an absolute priority must be given to the functional relevance of biodiversity, and in agricultural research a particular emphasis is required on the role of biodiversity components that improve the efficiency of production processes (Büchs 2003). The resulting systems would then be much more likely to benefit other aspects of biodiversity conservation and nature protection within the farmed landscape.

A lower dependence on the use of concentrate feedstuffs derived from potential human food crops makes pasture-based cattle production systems inherently more environmentally sustainable than feedlot systems (e.g. see Shah 2009). However, the drive to global competitiveness has led to greatly increased intensification of pasture management and consequential environmental damage (Aguir 2005; Bouwman et al 2005; McDowell 2008). The intensification of grassland management, which is especially evident on dairy (Shalloo et al. 2004; O'Neill and Mathews 2001; Dillon et al. 2008) and grass-based beef finishing farms (Crosson et al. 2007), is likely to exacerbate GHG emissions from pasture-based ruminant production (Pinares-Patino et al. 2009). Increasing fertiliser inputs and stocking rates also impact directly on key soil processes. Studies using stable N isotopes have shown that these effects include a marked reduction in the efficiency of atmospheric nitrogen fixation by pasture legumes under conditions of increased inorganic fertiliser use (Purvis et al. 2009b). Additionally, the loss of nutrient inputs from intensified grassland systems to the wider environment is excessive (Ball and Ryden 1984; Ledgard et al. 1999). In Europe, this has contributed significantly to the need for increasing levels of environmental control, notably the Nitrates Directive (91/676/EEC), Water Quality (2000/60/EC), and imminent Soils Framework Directives.

2.2 Animal Genetics, Nutrition, Health and Welfare

Optimum animal health and welfare are also of key importance in the development of sustainably-competitive agricultural systems (Downey et al. 2008). As shown in

Fig. 1, animal nutrition is key to delivering on genetic potential and minimising animal health and welfare problems. A recent expert scientific opinion requested by the European Commission (EFSA 2009), highlighted production diseases as indicators of poor welfare in dairy cows. This report stressed that long term genetic selection for high milk yield is the major factor causing poor welfare, and in particular health problems. The report went on to point out that there is an urgent need to promote changes in the criteria used for genetic selection in the dairy industry, and recommended that a higher weight should be given to fitness and welfare traits when these conflict with selection for milk yield.

Reduced longevity in modern dairy genotypes reflects the impact of production diseases (Drackley 1999; Knaus 2009). Traditionally regarded as encompassing the metabolic disorders of dairy cows (e.g. hypocalcaemia, hypomagnesaemia and ketosis), the term *production disease* is now routinely broadened to include conditions such as retained placenta, displaced abomasum and laminitis. The incidence of such conditions as calving approaches impacts negatively on animal health and subsequent lactation management, as well as reduced fertility and the cow's ability to re-breed. Such production diseases in the transition dairy cow reflect the animal's inability to cope with the metabolic demands of high production, resulting in a likely physiological "trade off" between investment in a current pregnancy, and investment in the possibility of future reproduction (Friggens et al. 2010). Internationally, production diseases continue to be a very substantial cause of economic loss to the dairy industry and a significant animal welfare concern (Mulligan and Doherty 2008). Whilst significant advances have been made in understanding the causes of infertility and poor animal health in the dairy sector, their incidence in many well-managed herds in virtually all major dairying countries remains similar to levels published decades ago.

In Ireland, a comprehensive review published in 2004 on the reproductive performance of dairy herds concluded that the reproductive needs of seasonal milk production systems with a compact breeding season may not be compatible with North American Holstein Friesian genetics, which originated in an industry with all-year-round calving (Mee 2004). To address the inherent weaknesses associated with current grass-based dairy production systems, the Irish dairy industry has two strategic options (Downey and Purvis 2005):

- improve animal nutrition by adoption of more balanced feeding regimes, and/or,
- adopt cattle breeds better suited to the seasonal spring-calving grass-based system.

2.3 *Food Safety and Security*

The progressive lengthening of the food supply chain and the lack of transparency and understanding of its detailed workings are inevitable consequences of increased globalisation in agriculture, and have major implications for food safety, security, and ethics, as well as future energy demands. Arguably this issue is one of the greatest challenges for European agri-food production (Barcos 2001), and is of growing public concern (Safefood 2009). The largest and most economically damaging events affecting European agri-food industries and wider rural economies over recent decades have been widespread outbreaks of animal diseases in cattle (BSE, Foot and Mouth Disease, Blue Tongue), pigs (Classical Swine Fever) and poultry (Avian Influenza). In addition to animal diseases, there have been numerous other food scares, resulting from the discovery of banned substances in animal feedstuffs (e.g. dioxins), and chemical contaminants such as melamine in food products.

Multiple causative factors are responsible for the widespread nature of these food safety problems, including reduced EU import controls. However, the unsustainable lengthening of the food supply chain is an important underlying cause (Downey 2006). As the food supply chain lengthens, the sharing of knowledge, mutual understanding and trust between farmers, food processors, retailers and consumers declines and ultimately ceases. Currently, what is generally referred to as the *food supply chain* is not in fact a chain. Rather, it comprises a series of virtually independent components, each primarily concerned with its own profit maximisation. Despite the introduction of stricter controls on animal feedstuffs and the implementation of new food safety policies and regulations (Ilbery et al. 2000), the absence of reliable transparency and accountability in international markets seriously undermines consumer confidence. As a result, food safety and country of origin now feature among the top concerns of consumers (FSAI 2007; Safefood 2009). This strongly underlines the market potential for value-added products of impeccable production standards, with the highest safety and quality, and demonstrable authenticity.

2.4 Food Quality and Human Nutrition

Consistency is the most critical determinant of food product quality. The plane of animal nutrition is a primary determinant of the consistency and storage stability of dairy products (Downey and Doyle 2007). Dietary factors also affect the quality and nutritional value of meat (Dunshea et al. 2005). Accordingly, in developing new farm production systems, attention needs to be given to employing feeding strategies designed to meet livestock energy requirements, while controlling feed costs. Again, this requires particular attention to optimising the nutritional performance of cattle, otherwise, the composition and processing characteristics of milk and meat may be seriously impaired. In developing such systems, opportunities exist to improve the quality and safety of livestock products through the use of dietary manipulations designed to improve their nutritional value and reduce associated human health hazards, such as pathogen contamination (McGee et al. 2001). Opportunities also exist to enhance human health by raising levels of potentially important health-promoting ingredients in milk and other livestock products through the use of appropriate livestock feeding strategies. For example, milk with enhanced levels of conjugated linoleic acids and vaccenic acid that can protect against some cancers may be produced by pasture-grazing (Coakley et al. 2007), or through other strategic dietary manipulations (Shingfield et al. 2005).

3 An Agronomic Model for Pasture-Based Ruminant Production

Cattle and other domesticated ruminants can convert bulky cellulose-based vegetation into valuable high protein food products without directly competing for human food crops (Oltjen and Beckett 1996). Geo-climatic circumstances in several regions of NW Europe are well suited to capitalising on this ability through pasture-based ruminant production. In such systems, the production process depends on the functionality of two key epicentres, namely rumen function and pasture function. Understanding the role of functional biodiversity within these inter-dependent epicentres is essential in optimising the ecological and agronomic efficiency of the system (Fig. 2).

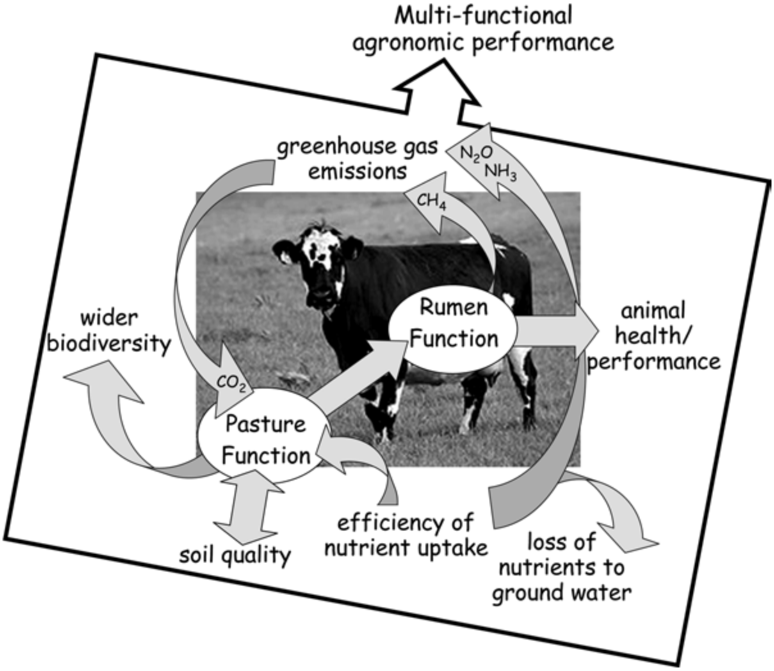

Fig. 2 An agronomic model of sustainably-competitive grass-based cattle production (Modified from Purvis et al 2009b). Multifunctional agronomic performance depends on the effective utilisation of key biodiversity resources within the pasture sward and rumen microbiota to ensure optimum feed conversion efficiency, and the efficient utilisation of fertiliser inputs and animal excreta, with consequential benefits in terms of animal health and welfare and the wider environmental performance of the system

3.1 Optimising Rumen Function

The digestive system of the grazing ruminant is uniquely adapted to metabolise an exclusively plant-based diet (Van Soest 1994). In cattle, such dietary adaptations include a highly complex and controlled gut transit involving selective retention, rumination and maceration of ingested fibre (Mertens 2005; Huhtanen et al. 2006). This facilitates digestion of refractive structural plant polysaccharides by a rich symbiotic rumen micro-biota (Beever 1993; Hobson and Stewart 1997). Fuller understanding of the functionality of ruminant nutrition is essential from the multiple perspectives of feed conversion efficiency, animal health and performance and environmental management (Leng 1993; Bocquier and González-García 2010).

Recent advances have shown that the bovine rumen is especially well adapted to utilise a high fibre diet (Clauss et al. 2010). This includes a unique reticulorumen mechanism for selective retention of larger fibre particles that require further mastication and prolonged microbial digestion to facilitate the breakdown of structural plant polysaccharides, whilst allowing the ongoing passage of suitably digested materials. Current cattle production systems largely fail to recognise the need to efficiently utilise these adaptations, which are intimately dependant on symbiotic relationships with the rumen micro-biota. Consequently, the latter are a poorly understood biodiversity resource within ruminant production, and a fuller knowledge of the functionality of this micro-system could lead to a radical revision of feeding and breeding objectives for both dairy and beef cattle (Knaus 2009; Clauss et al. 2010). The achievement of such an ambition has been greatly facilitated by recent publication of the full cattle genome (Elsik et al. 2009), which suggests that despite recent domestication, extant variation within cattle populations (BHC 2009) provides significant potential for such a targeted breeding strategy. Our understanding of the genetic basis of ruminant digestive adaptations, however, is only beginning to be understood (O'Connor et al. 2010).

Feed conversion efficiency and animal health. The rumen is central to the conversion of fibre-rich feed into milk and meat, and accounts for over 80% of total digestion within the alimentary canal. It is the principal site of fibre digestion and its functionality is the primary determinant of feed conversion efficiency (Beever and Doyle 2007), and key to reducing the incidence of production related diseases (Beever 2006). The predominant health and performance issue is the control of acid production and consequential acidosis in the rumen, which can be most adverse when lactic acid is produced following the ingestion of feedstuffs high in sugar and/or starch content. For optimal efficiency, the rumen contents require gentle and constant mixing, together with strong bouts of cud chewing, which aids long-fibre breakdown. Optimal microbial fermentation of fibre requires a stable pH of at least 6 (Mould et al. 1983). However, conversion of fibre to volatile fatty acids, which supply a very significant proportion of the energy used by the cow (see Box 1), leads to reduction of the rumen pH. If the ingested feed contains a suitable proportion of fibre, repeated rumination events involve both further cud chewing to facilitate physical maceration of larger fibre particles and the secretion and addition of significant amounts of saliva containing bicarbonates and phosphates, which buffer and maintain a suitable rumen pH. In this event, the effects of a transient

Box 1 Nutritional Needs of Cattle

Energy Sugars are not the direct energy fuel of ruminants. Rather, they preferentially utilise volatile fatty acids, which are produced in the rumen as a consequence of the microbial fermentation of plant carbohydrates. The latter include water-soluble carbohydrates, starch, fibre and pectin. Rate of degradation of plant carbohydrates in the rumen varies according to their molecular complexity (sugars and pectins > starches > fibre), with further differentiation of fibre dependant on the degree of lignification, which increases as plant growth progresses from vegetative to reproductive stages.

Protein Cattle acquire amino acids for protein synthesis from two distinct sources, either rumen microbial protein or feed protein. The small intestine is the primary site of protein digestion and amino acid absorption. Optimal microbial protein synthesis requires hexose and energy (ATP) derived from the degradation of plant carbohydrates. Feed protein is the main nitrogen source for microbial protein synthesis. Non-protein nitrogen, either naturally occurring, or added to the diet as a feed ingredient such as urea can also be utilised.

Energy feeds The principal energy sources for ruminants are forages, which supply both sugars and fibre, or cereals, which largely supply starch. Fat can provide an additional form of energy, but makes no contribution to microbial growth. As forages mature, levels of sugar decrease and fibre increases, with a declining proportion of the latter being digestible because of increased lignin content, which contributes less to the nutritional needs of the animal. Early season grass is a good source of sugars but lacks adequate levels of fibre amenable to optimal microbial rumen fermentation.

Protein feeds Grass can be a relatively good source of protein, whilst maize silages and more especially cereal silages, can be more variable in this respect. Alternative feeds include legumes such as lucerne, or clover, the latter normally an important component of mixed grass swards. In regard to feeding protein, it is necessary to balance the rate of availability in the rumen with energy release to optimise microbial growth. The principal protein in grass is the main photosynthesis protein (fraction 1 protein). This has a very rapid rate of solubilisation and degradation in the rumen, and as such, is a less ideal feed protein and may require supplementation from other protein sources to provide more constant, and hence more efficient protein assimilation in the rumen.

fall in rumen pH following initial feed ingestion are likely to be minimal. However, if the ingested substrate lacks the appropriate fibre content and contains relatively large amounts of simpler nutrients, rumination is reduced and sustained periods of sub-optimally low rumen acidity will occur with important and undesirable consequences. Most notably, as the rumen pH level drops the functionality of fibre-digesting bacteria is reduced, and the rumen microbial population shifts towards aggressive utilisers of starch and sugars. Starch in particular is much more rapidly digested producing lactic acid, which is more acidic than volatile fatty acids and so rumen pH declines further. This inevitably impacts negatively on feed conversion efficiency.

Dairy systems. High levels of starch-rich feeds in the diet are a prime cause of rumen acidosis and impaired rumen function in dairy cattle (Krause and Oetzel 2005). In particular, feeding large amounts of cereals in discrete meals at each milking can have a dramatic effect on rumen pH. Sustained acidity below pH 6 leads to sub-acute ruminal acidosis, which may persist resulting in acute ruminal acidosis below pH 5.5 (Bramley et al. 2006; Beauchemin 2007). In severe cases, the rumen wall may become ulcerated, allowing microbial toxins to pass into the systemic circulation, subsequently leading to liver abscesses, or inflamed lamina causing laminitis, a common nutritionally-induced lameness. Compromised foot health has both welfare and economic consequences, whilst compromised liver function impacts negatively on feed intake and feed conversion efficiency. Cows suffering from rumen acidosis tend to have exaggerated hindgut digestion and this can lead to the discharge of manures of inconsistent and frequently highly fluid composition. Low rumen pH levels can also occur in grass fed cows, driven by a relative lack of fibre and high levels of easily digestible sugars in high input ryegrass swards (Wales and Doyle 2003). In Australia, cows grazing lush, “high quality” pastures had rumen pH levels below 6 for more than 75% of the day (Williams et al. 2005).

The growing incidence of production diseases in virtually all major dairying countries has important implications for research in bovine health management. There is a pressing need to develop and refine intelligence gathering for the management of dairy herd health. In particular, systems need to be developed that allow collation of information on herd genetic composition, health and husbandry practice, and integration of these data with centralised databases containing, for example, milk production and fertility statistics. Disease prevention, in its broadest sense is no longer the sole preserve of veterinarians and addressing the challenge of dairy herd health will require the adoption of an interdisciplinary partnership approach, involving the farmer, veterinarian, nutritional advisor and animal breeding consultant (Le Blanc et al. 2006). There is an increasing need to place significant emphasis on dissemination of knowledge, training, motivation and the encouragement of fundamental attitudinal changes to disease prevention within the dairy industry. Whether or not individual farmers implement an optimal disease management strategy is frequently determined by an “intention-behaviour deficit” (Sneihotta et al. 2005). While most farmers would agree on the importance of animal health and welfare, many still fail to act on appropriate advice. There is therefore also a need to engage with social scientists and to use methodologies such as action research and behavioural economics, to ensure farmer understanding of the importance and economic relevance of consumer perceptions regarding animal health and welfare. Only then will the concept of a value-adding approach be truly realisable.

Beef systems. In beef production, greater attention needs to be given to meeting the nutritional needs of pasture-based suckler cows. This could lead to significant improvements in a number of performance indices, including the number of live calves born, and the mean weight of reared calves at weaning. In many situations the breeding window is too long with spring-calving extending to 18 weeks, as recently shown by EBLEX data from the UK. If optimum nutrition can be achieved, and given an average oestrus period of 21 days, a calving period of not more than 9 weeks can be realistically targeted. To achieve improved and consistent rates of weight gain in beef cattle, feed conversion efficiency will need to be improved. As more grain is used for the production of conventional and novel human foods (such as corn sweeteners), and potentially for fuels, less grain will be available for direct feeding to ruminants. Conversely, however, increased industrialised processing of grains is likely to provide significant amounts of co-products suitable for feeding to ruminant livestock (e.g. distillers grains). Including such products in rations for beef cattle could significantly reduce total feed costs/kg weight gain for growing and finishing livestock, as well as providing a productive and environmentally acceptable use for such materials. However, their use will need to be carefully balanced in a feeding regime that ensures optimum dietary fibre.

The needs of high fibre-based bovine nutrition can be met in two ways. Firstly, by provision of additional fibre in carefully balanced rations (Yang and Beauchemin 2005; Humphries et al. 2010). Alternatively, within the context of the pasture-based model depicted in Fig. 2, optimum rumen function may be achievable by the provision of pastures with the required levels of structural digestible fibre for the grazing animal. As well as improving rumen function and animal performance through the provision of greater amounts of digestible fibre, there is evidence that a more varied, species-rich forage would benefit other aspects of animal health and welfare (Villalba et al. 2010).

3.2 Optimising Pasture Function

In addition to improving the diet, health and performance of the grazing animal, optimising pasture function provides an essential means to address and reduce the adverse consequences of intensive grassland husbandry practices. As outlined in Sect. 2, the prevailing emphasis on price competitiveness within a context of apparently in-exhaustible supplies of "cheap" fertilisers, has increasingly driven producers to intensified pasture management. This involves widespread use of short-duration single species grass leys containing perennial ryegrass (*Lolium perenne*), or less persistent Italian ryegrass (*Lolium multiflorum*) cultivars bred for maximum productivity under conditions of high nutrient input. However, in conditions of limited or reduced nutrient input, such cultivars may perform less well than many other potential forage species. Many of the negative effects associated with prevailing, intensive grass production systems may be addressed by adoption of forage species mixes better adapted to, and capable of yielding optimally, under more variable conditions with less intensive inputs. A large body of knowledge derived from both theoretical and empirical studies, indicates that use of low-input, species diverse pastures could also achieve other important ecological benefits.

Advantages of multi-species pastures. Farmers have long known that by adding legumes to their sward they can increase the amount of plant available nitrogen through biological fixation of atmospheric N (Ledgard and Steele 1992). However, studies in both agricultural and semi-natural grasslands suggest that many other forms of ecological niche complementarity between species can lead to multiple advantages in species-rich plant communities (Hooper et al. 2005; Spehn et al. 2005). Some of the more important agronomic benefits to be gained from increased species diversity and niche complementarity in pastures are summarised in Box 2.

Box 2 Beneficial Attributes of Species Diversity and Niche Complementarity in Pastures

Complementarities between plant species can confer considerable ecological advantages in mixed species pastures – for a comprehensive review of the underlying mechanisms at the level of grassland communities see Rees et al. (2001). Many forms of niche differentiation and complementarity have a time dimension; examples include variation in life cycle phenology (Shmida and Ellner 1984), seasonal root activity (Fitter 1987), biomass accumulation (Turkington and Harper 1979a; Fowler and Antonovics 1981), and time-related patterns in inter-specific relationships (Turkington and Harper 1979b; Thórhallsdóttir 1990). In comparison with monocultures, such temporal and spatial variations in growth pattern within mixed species pastures, can confer a number of important agronomic advantages. These include:

- More efficient utilisation of available nutrients throughout the year (Beever and Thorp 1996)
- Enhanced total biomass production (Berendse 1983; Tilman et al. 1996, 2001; Hector et al. 1999; Caldeira et al. 2001)
- An extended growing season (Hooper 1998), with possibly reduced winter-feeding costs
- An increased theoretical (Chesson 2000) and actual resilience to spatial heterogeneity in growing conditions and environmental adversity (Tilman and Downing 1994)
- Decreased susceptibility to sward degradation by weed invasion (Knops et al. 1999; Sheridan et al. 2008).

Other advantages of increased plant (including herb) species diversity in pastures can include:

- Enhanced provision of essential livestock micro- and macro-nutrient requirements (Barry 1998; Tallowin and Jefferson 1999; Sanderson et al. 2003; Sheridan et al. 2003; Harrington et al. 2006)
- Improved micro-nutrient recovery from deeper within the soil profile (Newman Turner 1955; Harrington et al. 2006), and enhanced soil structure, aeration and drainage provided by deep rooting species (Foster 1988; Culleton et al. 2002)

Efficient use of nutrient inputs. Reduction in fertiliser use in grassland farming over the last decade (e.g. Lalor et al. 2010) reflects increasing input costs and regulation of nutrient usage. To deal with these constraints and achieve sustainable competitiveness, a shift will be needed in grassland husbandry away from the use of highly selected ryegrass monocultures that persist and yield optimally only under conditions of high nitrogen input. A major objective for grassland management must be an increased efficiency of nutrient recovery from animal manures, and improved utilisation of inorganic fertiliser inputs. This can be achieved by an improved utilisation of the functional system benefits provided by botanical sward diversity and closely related elements of soil biodiversity such as mycorrhizal fungi (van der Heijden et al. 2006) and soil nematodes (De Deyn et al. 2003), which respond positively to the extensification of grassland management. Such biodiversity components of pasture function are likely to contribute significantly to the efficiency of nutrient retention and supply, and to soil carbon sequestration. Stable isotope tracers and modeling techniques provide a means to study the benefits of low-input, species-rich pasture systems in limiting nutrient losses to soil water and the atmosphere (see Hoekstra et al. 2010). The ecological advantages of low input, mixed species pastures in terms of their more efficient use of plant nutrients (N and P) and reduction of losses to the wider environment is a key component of the model depicted in Fig. 2.

Benefits for farmland biodiversity. The wider impact of grassland farming on the conservation of biodiversity within the farmed landscape was the primary focus of a recently completed study funded by the Irish Environmental Protection Agency (Purvis et al. 2009b). Using pre-existing grass husbandry experiments and extensive surveys on commercial farms, this project documented clearly negative impacts of intensified grassland nutrient inputs on floral and faunal biodiversity at both individual field and landscape scales. A key conclusion of the study was the urgent need to establish dedicated, long-term and large-scale grassland systems research to quantify the specific agronomic and ecological merits of low input, mixed species pastures. However, one of the less expected findings of this study, was that within the wider farmed landscape, dairy farming has important beneficial and ecologically distinct effects on *some* aspects of biodiversity compared with less intensive forms of grass-based livestock farming. In particular, dairy farms were found to support significantly enhanced breeding bird populations compared with drystock farms (McMahon et al. 2010).

Such a finding is a likely consequence of an observed greater availability of invertebrate food (albeit of reduced taxon diversity) that was associated with the relatively higher nutrient levels and stocking rates on dairy pastures, compared with less intensively managed pastures on drystock farms. This observation, however, is also very likely to be related to the fact that all surveyed farms (both dairy and drystock) were typically relatively small, and *both* farm types retained a similar prevalence of permanent field boundaries amounting to over 12 linear km of traditional hedgerows per km^2. Such an extensive network of high quality bird habitat is unusual within European farmland. Accordingly, Irish dairy farming may represent an important dimension of heterogeneity relating to nutrient availability within the farmed landscape. Increased international competition in the dairy sector, however, and the removal of European milk quotas in particular are likely to force the amalgamation of many smaller dairy farms into larger production units. In this event, the increasing scale of intensity associated with dairy farming is likely to result in the loss of essential non-cropped habitats, especially small field boundaries. Only the adoption of a value-adding, sustainably-competitive approach permitting the economic survival of currently small production units, is likely to retain their biodiversity advantages. The wider ecological benefits of grass-based livestock systems, including the effects of low-input, species diverse pasture swards and associated influences on soil quality and landscape heterogeneity on the conservation of wildlife and biodiversity within the wider farmed landscape (Benton et al. 2003), is an important dimension of the multifaceted model elaborated in Fig. 2.

3.3 Reducing Gaseous Emissions

The model outlined in Fig. 2, highlights the urgent need to address climate change, and in particular concerns regarding the output of greenhouse gases (GHGs) from ruminant livestock systems. Manipulation of grass-based forages, particularly with regard to the intensity of nitrogenous fertiliser inputs and the maintenance of optimum fibre content, may have important benefits in reducing the loss of NH_4 and N_20 from animal excreta (Külling et al. 2003; Ambus et al. 2007). Methane production is an inherent consequence of ruminant digestion, currently estimated to be as high as 700 g of methane per kg of edible beef produced when taking full account of the methane costs of the suckler cow. Clearly, this is a situation that needs to be targeted for serious reduction. Shifting rumen fermentation from the production of acetate and butyrate to the production of propionate would provide a sink for hydrogen, and thus simultaneously reduce its conversion to methane and improve feed conversion efficiency. A wide range of dietary modification strategies to limit methanogenesis is currently being investigated (Martin et al. 2009). The use of feed additives has yet to gain commercial success, but even if this could be achieved, such additives would have little practical application in pasture-based systems (Waghorn and Clark 2006). However, improving pasture feed conversion efficiency and raising daily weight gain offers a potentially feasible opportunity to reduce emissions. *In vitro* studies suggest that plants with a range of naturally occurring secondary plant products, including hydrolysable and condensed tannins and saponins (Bhatta et al. 2009; Sirohi et al. 2009), might be beneficially incorporated into a multi-species pasture strategy. The combined influence of pasture husbandry and rumen function on GHG emissions, including rumen methanogenesis and nitrous oxide and ammonia emissions from animal excreta are important components of the model elaborated in Fig. 2.

Optimisation of pasture management to ensure more efficient rumen function and assimilation of energy from a pasture-based diet, and the reduction of methanogenesis in the rumen, may be compatible and mutually achievable goals

(Morgavi et al. 2010); but this remains to be substantiated. However, GHG emissions in pasture-based livestock systems can be mitigated to a significant extent through the carbon sequestration potential of grasslands. This potential is greatly enhanced by avoiding many of the practices associated with intensive pasture management (Davidson et al. 1995; Soussana et al. 2010), such as frequent soil cultivation in short-term ley-pasture farming, and the high intensity of nutrient inputs needed to maintain the productivity of single-species swards. Grass-husbandry based on the use of long-term, low input multi-species pastures can potentially make a significant contribution to the carbon balance of the entire system, and so the influence of pasture composition and grassland husbandry practice on carbon sequestration is a vital focus of the elaborated model (Fig. 2).

Life Cycle Analysis (LCA) provides a means to integrate and quantify the multidimensional performance of production systems (Cederberg and Mattsson 2000; Haas et al. 2001; Thomassen and De Boer 2005). Using LCA, it has been shown that intensification of grassland management reduces the ecological efficiency of grass-based dairy farming (Bassett-Mens et al. 2007), which can be improved by reducing dependency on imported concentrate feeds, and excessive nutrient inputs (Thomassen et al. 2008), which are both inefficient and costly. LCA can effectively be used to evaluate the total, multi-dimensional performance of the model illustrated in Fig. 2. When combined with holistic economic analysis, the development and optimisation of this model could permit governments to deal with climate change by facilitating strategic planning towards a sustainable low-carbon economy, rather than adopting the more expensive and less effective contrivance of purchasing carbon credits (Styles and Jones 2008).

3.4 Authenticity and Traceability

Robust validation systems will be required to justify consumer confidence in value-adding production methods. This includes traceability methods with the ability to track a product through multiple stages of production, processing and distribution (WHO/FAO 2007), and authentication systems capable of verifying that the production process was compliant with product labeling (Dennis 1998). The increasing complexity of globalised food production challenges authentication and traceability methodologies. In particular, the lengthening of food chains increases uncertainty and the sourcing of system inputs at lowest possible cost from global markets, including feedstuffs sourced many miles from where livestock are raised, makes it increasingly challenging to prove the veracity of product labelling (McEntire et al. 2010). Authenticity methods depend on the measurement of markers that derive specifically from the production system used; in livestock systems, these markers originate directly from the feed consumed, or indirectly (via food plants) from the wider environment, including soil and water. The uniqueness and diversity of forage-based inputs confer a clear signature on milk and meat products making it potentially easier to authenticate their origin (Monahan et al. 2010). Among the markers available are: volatile fatty acid and vitamin profiles influenced by forage intake, as well as stable isotope ratios reflecting both the vegetation diet and local environmental factors, including the underlying geology, soil type and climatic conditions under which the animal was reared (Smith et al. 2008; Prache 2009). In grass-based livestock systems, authentication systems can be extended to include reconstruction of an animal's life history prior to slaughter using markers in archival tissues, such as hoof and hair (Schmidt et al. 2005; Harrison et al. 2007).

4 Research Policy Issues

4.1 Innovation-Driven Research

As detailed above, much of the knowledge required to begin the practical development of a sustainably-competitive grass-based cattle production systems already exists. However, the complex biological processes involved in optimising both rumen and pasture functions need to be further elucidated (Bocquier and González-García 2010). These constitute the two main pillars of the innovation-driven research programme required to underpin system development. The overarching *generic* objectives that need to be prioritised in framing research programmes for such systems are outlined in Table 1.

However, the generation of new knowledge in agri-food systems is all too often undertaken by investment in short-term projects that seek to 'unpick' and exploit the functionality of individual components within the wider system. Knowledge derived by this *reductionist* approach has a fractal and probably infinite structure that can rapidly lead to "information overload" (Gallagher and Appenzeller 1999). As objectives, interests and particularly the outputs from different research frontiers become increasingly isolated in an ever-expanding scientific literature[1], a situation has been created where practical integration of research outputs into farm systems development is significantly more difficult (Buhler et al. 2002). The development of sustainably-competitive systems requires a more holistic approach that seeks to *integrate and harness* the use of new understanding and technologies, including where necessary molecular biology and genetic modification. Such integration needs to complement and facilitate the harnessing of the complex processes that characterise natural systems. In contrast to exploitative use of fragmentary knowledge, such an approach would do much to encourage a wider acceptance of new technologies (Arntzen et al. 2003), and ensure that European agriculture benefits from technical innovation.

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[1] For an essay on the limitations of reductionism in the bio-medical sciences, see Ahn et al. (2006), and for an early example of its deficiencies in agriculture that is very relevant to the grass-based ruminant model, see Smil (2001).

Table 1 Generic objectives for the development of sustainably-competitive livestock systems*

Theme	Objectives
Integrated systems	Development of economically and environmentally sustainable production that is customised agronomically and ecologically to achieve optimised product quality and marketing advantage from local conditions.
Environment	Protection of unique natural and cultural heritage that is critical to establishing product quality and marketing advantage, by addressing the major issues relating to energy use, climate change and sustainable resource management.
Biodiversity	Protection and functional utilisation of all aspects of biodiversity, including the genes, species, communities and ecosystems that underpin the fundamental natural processes harnessed within the production system.
Animal performance	Utilisation of the evolutionary adaptations of livestock, and interactions between animal genotype, nutrition and health to achieve optimal feed conversion efficiency, agronomic performance and consistent product quality.
Animal health and welfare	Achievement of integrated health and welfare management through the development of animal husbandry objectives that reduce the incidence of production-related diseases and achieve optimal performance.
Pest and disease resistance	Development of enhanced natural resistance to livestock parasites and disease through application of improved animal husbandry, systems management and the integration of advances in genetic and bio-molecular knowledge.

*as noted in Sect. 2, essentially similar generic objectives are required for the development of sustainably-competitive crop systems

4.2 System-Based Research and Application

In deploying a more focused approach to agri-food research, it is essential that a framework (as illustrated in Fig. 2) be created for credible, *longer-term, systems research programmes*. This needs to clearly articulate common overall goals and purpose, by identifying the disciplines and elaborating the building blocks of knowledge that need to be integrated to achieve the value-added benefits of a sustainably-competitive system. In practice, the integrated research agenda needs to identify and focus on significant knowledge gaps that require more concerted integration between relevant research agencies. It will be essential that all of the latter are involved in developing the necessary systems-based strategy; firstly in drawing up an indicative research and application framework, and secondly, in ensuring the participation of all disciplines, sectoral interests and knowledge fields necessary to implement it. The Rural Economy and Land Use Programme (RELU 2010) developed in the UK, provides one interesting and innovative example of how a multi-agency funding initiative can be developed to pursue an inter-disciplinary research agenda necessary to target the needs of rural land users.

4.3 Organisational Structures

To realise the full economic and environmental benefits of the sustainably-competitive concept, it will be necessary to ensure close organisational and multidisciplinary collaboration in system development at all points along the value chain from the producer to the consumer (Ilbery and Kneafsey 1999; Grunert 2005). European Foresight studies (FEG I 2007; FEG II 2008) have highlighted a growing need for new forms of organisational structures, including public-private partnerships, to realise the necessary level of collaboration. In consequence, a number of countries have, or are putting in place, new institutional arrangements designed to ensure more effective interaction between organisations and interests engaged in the generation, translation and dissemination of knowledge, with the objective of supporting decision making and product and process innovations in agriculture and food production systems.

Of particular concern in this regard, however, is the fact that increasingly inadequate resources are devoted to traditional extension and advisory services, and to knowledge management, translation and transfer processes and the training of the next generation of farmers and other participants in the food chain (FEG II 2008). This will be critical to bringing about a new mindset, and progressive replacement of the exclusively price-competitive approach at all stages along the food chain. Only by ensuring the engagement of all necessary participants (ranging from governments and national funding agencies to research and business organisations, as well as producers and crucially, marketing, retailer and consumer interests) can the concept be developed and translated into practical *Sustainably-Competitive Regional Agri-Food Systems* that can underpin the economic and environmental wellbeing of rural areas. The wider public good benefits to be gained from such a shift in the agri-food agenda would be considerable.

4.4 Public Good Funding

Public good concerns are inherently multi-dimensional, and relate to such crucial strategic areas as policy formation, climate change, energy supply, food safety, animal welfare and wider environmental concerns. Agriculture, like other natural resource based industries, is critically dependent on concerted public good funding as the only realistic means to ensure effective support for longer-term systems development.[2] The concept of sustainably-competitive agriculture is closely compatible with the European model of multifunctional agriculture (OECD 2001). Only dedicated public good funding can ensure the necessary transition from the predominantly production/output bias of the former EU Common Agricultural Policy (CAP), and support the development of more consumer/society-orientated, multifunctional agri-food models

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[2] For an illustrative account of the limitations of the open-innovations, market-lead model in supplying the support necessary for holistic systems development, see Toleubayev et al. (2010).

that meet the considerable challenges facing rural economies and the wider issues of food supply in Europe in the twenty-first century. Key to achieving this goal will be the deployment of an appropriate proportion of the budget for the Common Agricultural Policy to ensure the development and widespread adoption of the value-adding concept of Sustainably-Competitive Regional Agri-Food Systems.

5 Conclusion

The development of a sustainably-competitive agriculture will require a more systematic approach to research and innovation in the agri-food sector. It will be essential that existing agronomic and environmental knowledge is harnessed in the development of ecologically-efficient production systems that fully realise the benefits of functional biodiversity. This will involve in particular, a sustained commitment to the provision of resources to: (i) integrate the extensive reservoir of existing knowledge within relevant, but increasingly compartmentalised disciplines, and (ii) facilitate the effective design and implementation of longer-term, systems-based research programmes. European foresight projects and other initiatives by the European Commission, have highlighted the growing need for new forms of organisational structures, including public-private partnerships designed to ensure more effective interaction between organisations and persons engaged in the generation, translation and dissemination of knowledge and know-how, with the objective of supporting decision making and product and process innovations in agriculture and food production. A fundamental dependency on innovation in the private sector is unlikely to provide the necessary holistic approach. The imperative requirement is a dedicated public good funding system designed to support the transition of agriculture from the predominantly production/output orientation of the former EU Common Agricultural Policy, to development of consumer/society-orientated models that will be necessary for Europe to meet the considerable challenges facing its rural economies and food security. The key to achieving this goal will be the deployment of an appropriate proportion of the Common Agricultural Policy budget towards the development and widespread adoption of the value-adding concept of Sustainably-Competitive Agriculture.

Acknowledgements We gratefully acknowledge the assistance of multiple colleagues who read and commented on earlier drafts of our manuscript, in particular, Dr. Owen Carton, Dr. David Stead, Dr. Olaf Schmidt and Mr. Martin Kavanagh who provided especially constructive inputs.

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Emissions of Ammonia, Nitrous Oxide and Methane During the Management of Solid Manures

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Abstract Organic manures arising from livestock production provide a source of plant nutrients when applied to agricultural land. However, only about 52% of the N excreted by livestock is estimated to be recycled as a plant nutrient. The greatest

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E. Lichtfouse (ed.), *Agroecology and Strategies for Climate Change*,
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losses of N from livestock excreta and manures are as gaseous emissions. These emissions are in the form of ammonia (NH_3), nitrous oxide (N_2O) and methane (CH_4). Ammonia forms particles in the atmosphere which reduce visibility and may also harm human health, and when deposited to land NH_3 causes nutrient enrichment of soil. Nitrous oxide and CH_4 contribute significantly to global warming and N_2O can also cause the breakdown of the protective ozone layer in the upper atmosphere. We established a database of emissions from solid manures. Statistical analysis provided new information, focussing on developing emission factors, emission algorithms and also new understanding of emission patterns from solid manure.

The review found that housing systems with deep litter emit more NH_3 than tied stalls. This is likely to be because the emitting surface area in a tied stall is smaller. Laying hens emit more NH_3 than broilers and reduced-emission housing systems for poultry, including the aviary system, can reduce NH_3 emissions by between 50% and 80%. The greatest N_2O-N emissions from buildings housing livestock were also from deep litter systems, but the amount of N_2O-N was smaller than that of NH_3-N by a factor of 15. Air exchange and temperature increase induced by aerobic decomposition during manure storage may greatly increase NH_3 emission. Emissions of 0.25–0.30 of the total-N have been recorded from pig and cattle manure heaps undergoing aerobic decomposition. Increased density of manure during storage significantly decreased temperatures in manure heaps. Storing solid manures at high density also reduces air exchange which with the low temperature limits the formation and transfer of NH_3 to the surface layers of the heap, reducing emissions. Most N_2O emission estimates from cattle and pig manure have been between 0.001 and 0.009 of total-N. Emission of N_2O from poultry manure tends to be small. Average unabated NH_3 emissions following application of manure were 0.79, 0.63 and 0.40 of total ammoniacal-N (TAN) from cattle, pig and poultry manure respectively. The smaller emission from poultry manure is expected as hydrolysis of uric acid to urea may take many months and is often incomplete even after application, hence limiting the potential for NH_3 emission. Manure incorporation within 4 h after application reduced emission on average by 32%, 92% and 85% for cattle, pig and poultry manure respectively. Reductions following incorporation within 24 h or more after application were 20%, 56% and 50% for cattle, pigs and poultry, respectively. Incorporation by disc or harrow reduced NH_3 emissions less than incorporation by plough. Emissions of N_2O following the application of cattle manure were 0.12 of TAN without incorporation after application and 0.073 TAN with incorporation after application. Conversely, emissions following application of pig and poultry manures were 0.003 and 0.001 TAN respectively without and 0.035 and 0.089 TAN respectively with incorporation after application.

Keywords Ammonia • Methane • Nitrous oxide • Manures

1 Introduction

Traditionally livestock manures, along with deposits of excreta during grazing, clover and green manures, were the only sources of crop nutrients in addition to those already in the soil. Organic manures arising from livestock production (liquid slurries, litter-based farmyard manures (FYM) and poultry manures) applied to agricultural land remain valuable sources of most major plant nutrients and organic matter. Careful recycling to land allows their nutrient value to be used to enhance crop growth and maintain or improve soil fertility, which will usually result in large savings in the use of inorganic fertilizers.

Oenema et al. (2007) estimated that in 2000 total N excretion by livestock in the EU-27 was *c*. 10,400 kt. About 65% of the total N excreted was collected from buildings housing livestock and stored for some time prior to application to agricultural land. Almost 30% of the N excreted in buildings was lost from those buildings or during storage; approximately 19% via emissions of ammonia (NH_3), 7% via emissions of other N gases, and 4% via leaching and run-off. A further 19% of the N excreted in housed livestock systems was estimated to be lost via NH_3 emissions following the application of the manure to land. The results indicate that only *c*. 52% of the N excreted in livestock was potentially recycled as a plant nutrient. Since the greatest losses of N from livestock excreta and manures are as gaseous emissions an improved understanding of these is essential to increasing the proportion of excretal-N that may be effectively recovered by growing crops. Of the gases released from manures, NH_3 is usually emitted in the largest amounts. Ammonia is a reactive gas, and may be removed from the atmosphere by being absorbed by land and water surfaces (dry deposition) (Aneja et al. 2001). Most of the NH_3 is removed from the atmosphere in this way, leading to most of it being deposited close to where it was emitted. However, some NH_3 may reach higher levels in the atmosphere and be transported long distances before being deposited in rainfall or snow (wet deposition) (Aneja et al. 2001). When deposited to land NH_3 causes nutrient enrichment of soil, changing the balance of plant life, in extreme cases leading to the replacement of valuable conservation plant with weeds (Bouwman and Van Vuuren 1999; Heil and Diemont 1983; Pitcairn et al. 1998). Ammonia will react with oxides of sulphur and nitrogen in the atmosphere (Renard et al. 2004), forming particles (aerosols) which reduce visibility (Graedel and Crutzen 1993) and may also harm human health (Brunekreef and Holgate 2002). In aerosol form NH_3 may be transported longer distances before deposition, so NH_3 emissions from one country may be deposited in another.

Although nitrous oxide (N_2O) is usually emitted in only small amounts it contributes significantly to global warming (Bouwman 1990), with each molecule of N_2O having a warming potential of 298 molecules of carbon dioxide (CO_2) (IPCC 2006). Nitrous oxide can also cause the breakdown of the protective ozone layer in the upper atmosphere (Crutzen 1981). Methane (CH_4) is also emitted from manure (Chadwick 2005) and contributes to global warming. Each molecule having a warming potential equal to 25 molecules of CO_2 (IPCC 2006). Only emissions of dinitrogen (N_2), the major component of the atmosphere, are environmentally benign.

The Gothenburg Protocol of the UN Convention on Long-range Transboundary Air Pollution (UNECE 1999) and the EU National Emission Ceiling Directive (EC 2001) require the reporting of national annual emissions of NH_3. Agricultural NH_3 emissions need to be accurately estimated since they commonly account for more than 80% of total NH_3 emissions to the atmosphere (EMEP 2005). The use of a mass-flow approach is recommended (Dämmgen and Webb 2006) in which the fate of N or total ammoniacal nitrogen (TAN; for poultry TAN includes uric acid N) is followed throughout the manure management system in order to take account of the impact of abatement measures on NH_3 emissions at later stages of manure management.

A number of European countries have developed mass-flow models to estimate national NH_3 emissions and the potential for abatement: Switzerland ('DYNAMO', Reidy et al. 2008; 'Agrammon', Kupper et al. 2010); UK ('NARSES', Webb and Misselbrook 2004); Germany ('GAS-EM', Dämmgen et al. 2003); Netherlands ('MAM', Groenwold et al. 2002; 'FarmMin', Van Evert et al. 2003); Denmark ('DAN-AM', Hutchings et al. 2001). Coordination of model development has been undertaken by a core group of emission inventory experts (http://www.eager.ch/Members.htm). Their aim was to achieve a detailed overview of the currently best available inventory techniques, compile and harmonize the available knowledge on emission factors (EFs) for mass flow emission calculation models and initiate a new generation of emission inventories.

These six N-flow models were compared using the same input datasets, e.g. with respect to factors such as the length of the housing period, manure management system, etc., for each model. Output of the models tested proved to be much more variable for solid manure (Reidy et al. 2009) than for slurry (Reidy et al. 2007). In part this is because there are fewer published results of NH_3 emissions from solid manure than for slurry, and hence fewer data on key aspects of emissions. Moreover, the introduction of litter leads to more complex interactions among microbial, biochemical and physical processes compared with the processes taking place in slurry, and this leads to highly variable emissions of NH_3, other N gases and CH_4. While considerable knowledge is available on the processes that occur in solid manure, there is uncertainty over the extent to which these processes operate and how they interact, due to differences in manure management. This is particularly so with respect to quantification of emissions. It is widely recognised that it was important to get a better overview of the existing knowledge of emissions from solid manure and identify research gaps, and to use the findings for a thorough re-editing of some of the models (especially DYNAMO and MAM) for processes other than NH_3 emission. Hence, we considered that a special comparison should be made of emission estimates from litter-based housing systems, storage and spreading of solid manures with the objective of more accurately determining EFs from solid manures.

The approach taken in this paper was not only to review papers published in peer-reviewed journals but also to examine datasets generated by members of the EAGER group as project reports, conference proceedings and other 'grey' literature. Such data were examined and, where possible, amalgamated so that they could be subject to statistical analysis. By this approach we expected to be able to collect all available knowledge and thus draw more robust conclusions on NH_3, N_2O and CH_4 emissions from systems producing solid manure. The data in the 'grey' literature were frequently reported in good detail, often more information was provided than in peer-reviewed papers. This information was often only recently available and, presumably, in the process of being prepared for publication. Information on screening of data prior to analysis and review is given in the sections below.

Our objective in analysing and reviewing these data was to:

1. Describe the major processes driving emissions.
2. Assess whether the empirical data were sufficient to support a recommendation for an emission factor.
3. Where the answer to 2 is no, explain why this is so.
4. Where the answer to 2 is yes, to present a recommendation.

Before reporting the results of research into gaseous emissions arising from solid manures, the basic mechanisms driving the release of NH_3, N_2O and CH_4 from solid manure are described.

2 Emissions of Ammonia, Nitrous Oxide and Methane from Housing Systems with Solid Manure

2.1 Introduction

Solid manure is produced when livestock are provided with litter, usually cereal straw but also other absorbent materials, which makes the resultant manure stackable. The term also refers to stackable manure from poultry, with or without litter. There is a wide range of housing systems for various livestock categories, in which solid manure is stored for widely varying periods of time. Solid manure is therefore any manure that is not slurry and hence otherwise hard to define.

We considered that to provide representative data that could be sensibly analysed, the number of data (n) should be larger than 1 and there should be data from more than one country. For which reason we excluded French data from buildings housing turkeys and Dutch data on suckler cows. In addition, the number of animals per measurement should be greater than 10 for cattle and pigs, and greater than 50 for poultry, otherwise scaling up to practical farm size may not be reliable. This restriction excluded 11 trials with beef from the UK with four animals in a windtunnel ('polytunnel') and four French trials with three fattening pigs. Finally, daily measurements should last for at least 24 h. For example, this restriction excluded two French trials with broilers with measurements of 2 h per day.

Groenestein (2006) summarized the factors affecting emissions of NH_3, N_2O and CH_4 from buildings housing pigs. These factors are given in Table 1. Because this analysis aims to identify the processes giving rise to gaseous emissions, the results

Table 1 Key factors affecting emission of NH_3, N_2O and CH_4 from pig houses

	NH_3	N_2O	CH_4
Animal-related factors			
Age/liveweight	+	+	+
Amount and composition of feed	+	+	+
Water use	–	0	0
Environment-relating factors			
Housing configuration	+/–	+/–	+/–
Air velocity over emitting surface	+	0	0
Temperature of inside air	+	+	+
Temperature of outside air	+	+	+
Factors related to slurry/litter mixture			
C/N ratio	–	+	+
O_2 concentration	+	+/–	–
Surface area	+	0	0
Maturity of litter/slurry mixture	0	+	+
pH[a]	+	6	7
Temperature of the slurry/litter	+	+	+
NH_4^+ concentration	+	+	–
Volatile Solids concentration	0	0	+
Drymatter content	0	0	–

Adapted from Aarnink (1997), Monteny (2000)

[a] Values in columns indicate optima

+ indicates a positive correlation, – indicates a negative correlation and 0 indicates no relevant effect

are also applicable to emissions from buildings housing cattle and poultry. It is clear that all these factors are of importance when explaining differences among measurements and that these factors are mutually dependent. As indicated earlier, differences among emissions from different systems for fattening pigs arise from animal-related factors, such as weight, and environmental factors such as air temperature. Also mentioned are factors related to the characteristics of the emitting substance, in this case solid manure. A particularly important aspect is manure management: type of litter; amount of litter; amount of area covered by litter; depth of the litter bed; removal frequency; frequency of addition of fresh litter etc. (Groenestein et al. 2009).

2.2 System Boundaries

The system for managing solid livestock manure is here considered to start with buildings housing the livestock, continue to manure storage and end with field application. Material enters the livestock buildings as live animals, animal feed, bedding and water for drinking and washing. Gases considered are NH_3, N_2O and CH_4 which leave the system when they escape to the free atmosphere. Manure solids and liquids lost in addition to the gaseous emissions, via uncaptured runoff from housing or storage, are also considered to have left the system, but are not considered here. Manures arising from feedlots are not included in this review.

2.3 Mechanisms Underlying Emissions of Ammonia, Nitrous Oxide and Methane from Manure

The processes driving NH_3, N_2O and CH_4 emissions from solid manure are briefly described here; more comprehensive descriptions can be found in Sommer et al. (2006) and Vavlin et al. (1998). The purpose here is to describe the physical and chemical conditions that determine the emission of each of these three gases. The occurrence of these conditions depends on the design and management of the solid manure management system, as described in subsequent sections.

2.3.1 Carbon and Nitrogen Transformations and Production of Ammonia, Nitrous Oxide and Methane

Carbon (C) and nitrogen (N) enter the solid manure management system in the organic form, as urea and other low molecular weight compounds in urine, or as more complex organic compounds in faeces, bedding and spilt animal feed. In the case of the C and N compounds in urine, decomposition generally occurs quite rapidly, primarily via enzyme-promoted hydrolysis, resulting in the formation of bicarbonate ions (HCO_3^-), carbon dioxide (CO_2) and ammonium (NH_4^+). The decomposition of the more complex organic compounds is a slower process, brought about by microbial degradation and resulting in the formation of microbial biomass, CH_4, H_2O, CO_2 and NH_4^+. The extent to which the different gases are produced depends on aerobicity, pH, C:N ratio, dry matter content and other conditions reported in Table 1.

Nitrous oxide can be produced in two ways. Firstly, the process of microbial nitrification of NH_4^+ to nitrate (NO_3^-) involves the formation of a number of intermediate compounds, including hydroxylamine (NH_4OH) and nitrite (NO_2^-). If the concentration of oxygen is low, a proportion of the NH_4OH is not oxidised to NO_2^- and is instead emitted as N_2O. Secondly, if nitrification proceeds fully to (NO_3^-) and then the oxygen (O_2) concentration falls or the NO_3^- is transported to an area where O_2 concentration is low, micro-organisms will use the NO_3^- as an oxygen source. Complete microbial denitrification results in the release of N_2, with NO_2, NO and N_2O as intermediate products. However, if the conditions are not fully anaerobic, the denitrification may not be complete and nitric oxide (NO) and N_2O can be released.

$$\text{denitrification}\, NO_3^- \rightarrow NO_2^- \rightarrow NO \rightarrow N_2O \rightarrow N_2$$

2.3.2 Emission of Ammonia, Nitrous Oxide and Methane

The solubilities of N_2O and CH_4 in water are moderate (*c*. 60 mL of N_2O/100 mL of water) and relatively small (*c*. 5 mL of CH_4/100 mL of water), respectively, and consequently, these gases are largely expelled from the manure. In contrast, the solubility of NH_3 in water is particularly large and so the emission of this gas depends on a range of conditions. The liquid in manure in animal housing, manure storage or in field-applied manure can be considered a dilute aqueous solution of NH_3. At a number of locations within the manure management system, this solution forms a surface with surrounding air e.g., on the floor of livestock buildings, within the matrix of deep litter in a manure heap. The NH_3 in the layer of air immediately adjacent to the manure solution is in dynamic equilibrium with the NH_3 in the manure solution. The concentration of the NH_3 in this adjacent air layer is determined by the concentration of NH_3 in the surface layers of the solution and its temperature, as described in Henry's Law. The concentration of NH_3 in the solution is itself determined by the concentration of NH_4^+, the temperature and the pH, as described by the dissociation equation for NH_4^+ (Muck and Steenhuis 1982). The concentration of NH_4^+ can decrease over time via emission, uptake and immobilisation by micro-organisms or nitrification, or dilution if water is added. Alternatively, it can increase if new NH_4^+ is added via the hydrolysis of urea or mineralization of N in organic matter, or if water is lost by evaporation. The emission of NH_3 from this layer of air adjacent to the manure surface is dependent on its surface area and the rate at which NH_3 is transported out of the layer. This transport is driven by turbulent diffusion or advection. This turbulent diffusion and/or advection is determined by the extent to which the design and management of animal housing, manure storage or field-applied manure modifies the flow of ambient air.

It is possible that in moving from the bulk of the liquid phase towards the free atmosphere, the gases can undergo further transformation. If N_2O passes through an area of greater anaerobic microbial activity, it may be reduced to N_2. Conversely, if CH_4 passes through an area of aerobic activity, it may be oxidised to CO_2. Finally, if NH_3 passes through an area where the micro-organisms are starved of N, the NH_3 may be assimilated into microbial biomass.

In the following sections, the system for managing solid animal manures covered by this review is defined.

2.4 Data and Data Handling

Data from experiments from various European countries measuring emissions from housing systems with solid manure were studied. None of the systems discussed here had outdoor areas which the stock could access. Table 2 gives the number of available datasets for each livestock category and their country of origin. Apart from those using fattening pigs and cattle very few studies measured emissions of N_2O or CH_4. Details on data handling are discussed in subsequent paragraphs.

Table 2 Experiments on gaseous emissions (NH_3, N_2O, CH_4) from housing of livestock: livestock category; total number of experiments (*n*); countries and the number of animals involved in the experiments

Livestock	Category	*n*	Countries	Number of animals
Cattle	Dairy	10	NL, AT, UK	12–90
	Beef	16	AT, UK	4–99
	Suckler cows	1	NL	49
Pigs	Piglets	3	UK, BE	40–294
	Fattening pigs	35	NL, UK, FR, BE, DE	3–873
	Dry sows	10	NL, UK	366–250
Poultry	Laying hens	44	NL, IT, UK	740–60,000
	Broilers	33	NL, IT, UK, IE, FR	66–48,000
	Turkey	2	FR	3,000–4,200

AT Austria, *BE* Belgium, *DE* Germany, *DK* Denmark, *FR* France, *IE* Ireland, *IT* Italy, *NL* Netherlands, *UK* United Kingdom

Table 3 Variation of system factors between trials with the different housing systems for cattle

System factor	Dairy	Beef
Amount of straw, kg a^{-1}	1,250–3,500	–
Amount of littered surface, %	60–85	100
Type of litter	Long straw, chopped straw	Long straw
Initial live weight, kg	–	200–640
Air temperature inside, °C	3–21	10–18

% of total floor area within buildings

2.5 Ammonia

2.5.1 Cattle

Two dairy systems could be distinguished: tied stalls and deep litter systems. The measurements originated from a limited number of countries (UK and NL for dairy on deep litter, AT for dairy in tied stalls). The four AT datasets from tied stalls were all from the same experimental setting with forced ventilation and 1,000 kg straw per year. The main reported differences for the deep litter systems are listed in Table 3.

The data from buildings housing beef cattle varied between four straw flow systems in the same experimental unit (AT) and a commercial deep litter system (UK). The mean NH_3-N emission is given in Fig. 1. The data suggest greater NH_3-N emission from dairy on deep litter than from beef, which is plausible because dairy cattle are bigger than beef cattle, require more feed and hence excrete more N. Secondly the data suggest that deep litter systems emit more NH_3-N than from tied stalls which is also plausible because the emitting surface area in a tied stall is smaller.

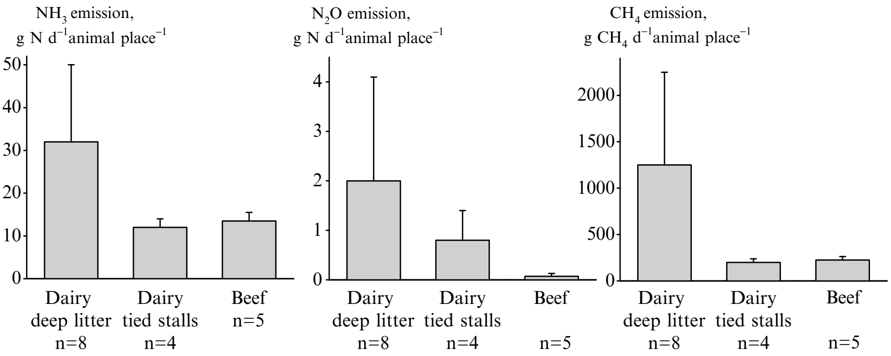

Fig. 1 Mean emission of ammonia-N from cattle housing with solid manure with standard deviation and number of measurements (n). The data suggest that deep litter systems emit more NH_3-N than tied stalls. This is likely to be because the emitting surface area in a tied stall is smaller. Mean nitrous oxide-N emission from Dutch dairy deep litter systems, Austrian tied stalls for dairy and Austrian straw flow systems for beef with standard deviation and number of measurements (n). The greatest N_2O-N emissions were from the deep litter system, but the amount of N_2O-N was smaller than that of NH_3-N by a factor of 15. Mean methane emission from Dutch dairy deep litter systems, Austrian tied stalls for dairy and Austrian straw flow systems for beef with standard deviation and number of measurements (n). The large emission from buildings housing dairy cattle on deep litter may be due to the anaerobic conditions induced by compaction caused by animals walking on the mixture of straw and excreta

Peat as litter may reduce NH_3 emissions from both buildings and stores. The properties of peat are beneficial as peat has a high water-binding capacity, low pH and above all, the ability to chemically bind NH_3. A study by Kemppainen (1987) showed that peat (sphagnum peat) absorbs 0.027 kg kg^{-1} NH_3 per unit mass of DM at 0.70 water content. Karlsson and Jeppsson (1995) found a reduction of 90% of NH_3 emissions during storage with 0.60 peat (weight DM) in straw beds with young cattle compared to only straw in the bedding. However, as peat is a limited natural resource in most areas of Europe, this approach is not considered further in the analysis.

2.5.2 Pigs

The main reported differences observed among the systems in pig housing are listed in Table 4. For piglets and dry sows only a few factors were reported. Ventilation rate was often not reported because houses were mainly naturally ventilated. Mean NH_3 emissions from pig houses and standard deviations are presented in Fig. 2. The above factors were not found to be conclusive in determining the differences in NH_3 emission and no reduced-emission systems could be identified. Although not significant, piglets emit the least and sows the most NH_3 per animal place, which would be expected. The data available do not allow emissions to be expressed as a proportion of N or TAN excreted since N excretion was not reported.

Table 4 Variation of system factors between trials with the different housing systems for pigs

System factor	Fattening pigs	Piglets	Dry sows
Surface area per animal, m^2	0.6–2.6	–	–
Amount of litter,% surface	25–100	100	–
Amount of litter, kg a^{-1} per place	36–395	–	–
Type of litter	Straw, saw dust	Straw, saw dust	straw
Litter management	None; removal of part of slurry; mixing; addition of water	–	–
Initial live weight, kg	18–55	7.7– 12	–
End live weight, kg	90–146	–	–
Air temperature inside, °C	6.3– 22.7	–	–

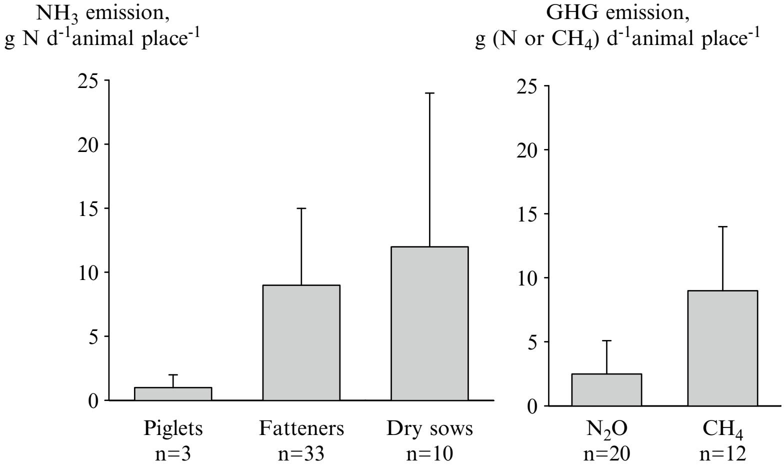

Fig. 2 Mean emission of ammonia-N from pig housing with solid manure with standard deviation and number of measurements (n). Although not significant, piglets emit the least and sows the most NH_3 per animal place, which would be expected given the sizes of the livestock

2.5.3 Poultry

All broiler systems had fully littered floors. Differences were reported due to differences in litter treatment intended to mitigate NH_3 emission. This was the case in four studies, in two of which the litter was belt-dried continuously with an air flow, while in the other two litter was first heated and later in the growing period cooled by means of a cooling/heating system in the concrete floor. All four reduced-emission systems were Dutch.

The differences among systems for laying hens mainly arose because laying hens were housed in basically three different kinds of housing systems:

1. Floor housing: layers live on a fully- or partly-slatted floor with litter and no restriction of movement;

Table 5 Variation of system factors between trials with the different housing systems for broilers and laying hens

System factor	Broiler	Laying hen
Surface area per animal, m^2	0.04–0.15	0.05–0.5
Amount of litter, % surface	100	0–100
Amount of litter, kg a^{-1} per place	0.2–10	–
Type of litter	straw, sawdust, rice husks, wood shavings, wood chips	Wood shavings, sand, sawdust
Litter management	None, drying, cooling	None, removal, drying and removal
End live weight, kg	2–4	–
Air temperature inside, °C	n.m.	16–26
Ventilation rate, $m^3 h^{-1}$ per place	1–12	1–9

2. Aviary housing: floor housing with litter, but with extra living space by levels or tiers, usually wired (tiers with wired floor aviary systems). Underneath the wired floors, belts are installed to collect the droppings. The laying hens are not restricted in movement, even between tiers.
3. Battery cages: laying hens are kept in cages with restriction of movement and without litter. Usually there are several tiers and underneath belts are installed to collect the droppings.

The main reported differences among the systems for broilers and laying hens are summarized in Table 5. It shows that apart from litter management, ventilation rate differed among trials. For laying hens inside temperature was different and for broilers live weight at the end of the production cycle varied from 2 to 4 kg among countries. Inside air temperature was often not measured with broilers, but most countries started with a temperature of 31–32°C and decreased gradually to 18–22°C.

Figure 3 presents the mean and standard deviation of NH_3 emissions from broiler and layer housing. It shows that buildings housing laying hens emit more NH_3 than buildings housing broilers and that reduced-emission systems, including the aviary systems, can reduce NH_3 emissions by between 50% and 80%. Within the floor-housing system and the batteries, traditional and reduced-NH_3 emission systems could be distinguished based mainly on litter management (drying and frequent removal of manure). The aviary system also removed part of the dried litter daily by belt and was therefore also a reduced-emission system. However, litter management appears a major factor, although because of the large variations, differences were not always significant.

While measurements from conventional layer housing systems were available from three countries, measurements from the floor system and the aviary were only reported from the Netherlands and may not be representative of absolute emissions in other countries. Nevertheless, these results provide a useful comparison of NH_3 emissions from three housing systems based on several experiments. We concluded that the relative differences may be applicable to those systems used in other countries.

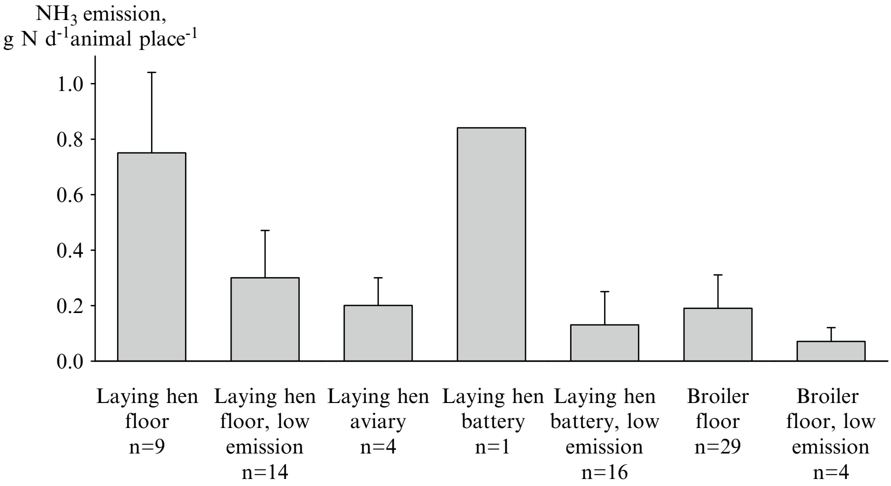

Fig. 3 Mean emission of ammonia-N from poultry houses with standard deviation and number of measurements (n). The data show that laying hens emit more NH_3 than broilers and that reduced-emission systems, including the aviary systems, can reduce NH_3 emissions by between 50% and 80%

2.6 Nitrous Oxide

Data were available for cattle and pigs but none for poultry.

2.6.1 Cattle

Figure 1 gives the N_2O-N emission from five Dutch deep litter trials in two different commercial housing systems, from tied stalls and from beef with a straw-flow system. The UK studies did not measure greenhouse gas emissions. In the tied stall and straw-flow systems, the manure is only stored for a short time in the house and hence there is little opportunity for it to become compacted by the cattle. Consequently the manure is likely to remain aerobic and so few N_2O emissions would be expected. The greatest N_2O-N emissions were from the deep litter system, but the amount of N_2O-N was smaller than that of NH_3-N (Fig. 1) by a factor of 15.

2.6.2 Pigs

Nitrous oxide was only measured in buildings housing fattening pigs in the Netherlands, Germany and Belgium ($n = 20$). The average emission was 2.7 g d^{-1} N_2O-N per animal place (stdev = 2.5) (Fig. 2). This is somewhat more than emitted from cattle manure, despite the much greater TAN excretion of cattle (Fig. 1). This suggests a more aerobic environment in deep litter with pigs. Nevertheless, emissions of N_2O-N were still a factor of 3 less than emissions of NH_3-N.

2.7 Methane

2.7.1 Cattle

Figure 1 shows the CH_4-C emission from the same housing systems from which N_2O-N was measured. Methane emission from dairy cattle was less from the tied stall than the deep litter system because of the short storage time and the straw flow system. The emission from the tied stall system is in the range to be expected from enteric fermentation, suggesting that the manure was a minimal source. The CH_4 from the deep litter system is *c*. six times greater and suggests that the slurry/litter mixture was mainly stored under anaerobic conditions. This is in agreement with the relatively small emission of N_2O-N compared with NH_3-N, and with the N_2O-N from the deep litter systems for pigs. The large CH_4 emission from buildings housing dairy cattle on deep litter could be explained by the anaerobic conditions induced by compaction caused by animals walking on the mixture of straw and excreta. Emissions expressed as CO_2-equivalents for CH_4 from the deep litter bed are much larger than emissions from N_2O expressed as CO_2 equivalent.

2.7.2 Pigs

Emissions of CH_4 were measured in 12 of the 20 buildings housing finishing pigs in which N_2O emissions were measured. The mean emission was 6.5 g d^{-1} CH_4-C per livestock place (stdev = 3.0). Methane is emitted both from the litter bed and from intestinal fermentation from the animals (enteric CH_4-C, according to IPCC 1996, *c*. 3 g d^{-1} per pig). More CH_4 is emitted from the bed than N_2O, but N_2O makes the largest contribution to CO_2 equivalent emissions from this source.

The deep litter system for sows with straw did not produce the large CH_4 emissions reported from buildings housing dairy cattle on the same type of system, despite high densities in the litter bed and presence of anaerobic conditions (Groenestein 2006). Nevertheless, it is likely that CH_4 production in the bedding is substantial. This raises the question why the emissions from the straw-based sow-housing systems are not greater than the emissions from the slurry-based systems. Veeken et al. (2002) measured CH_4 concentrations at various depths in a composting reactor. They found large concentrations of CH_4 in the middle layer and low concentrations in the top layer, because CH_4 is readily oxidised to CO_2 by methanotrophic bacteria in the relatively aerobic top layer (Szanto et al. 2007). Petersen et al. (2005) showed that oxidative conditions prevail in a straw layer on a slurry storage pit, thus reducing overall GHG emissions. Hence it seems likely that CH_4

produced in deeper anaerobic layers of the litter bed in buildings housing pigs is oxidised in the surface layer, due to aeration by the rooting and foraging behaviour of the pigs. Cattle do not aerate the top layer of the bed by rooting and foraging so this effect is absent from the deep litter beds in dairy houses.

3 Gaseous Emission from Storage of Solid Manure

3.1 Introduction

Addition of straw, or other bedding material with a large C:N ratio, to livestock housing will not only increase manure porosity but may also increase the amount of degradable-C and induce immobilization of mineral-N, transforming inorganic- to organic-N (Kirchmann and Witter 1989). During storage of farmyard manure the reverse process may occur and some UK studies (Chadwick 2005; Williams et al. 2003; Sagoo et al. 2006), which carried out a mass balance of total and organic N at the beginning and end of a storage period, indicated net mineralization of up to 0.30 of the initial organic N content of the heap. Using ^{15}N labelling, Thomsen and Olesen (2000) were able to show that gaseous N losses from faecal and straw fractions of farmyard manure (as compared with urine) became progressively more important with duration of storage, indicating that mineralization occurring during the storage period made this previously unavailable organic-N available for gaseous emission. Mineralization was greater in aerobically stored (i.e. actively composted) than anaerobically stored farmyard manure (Thomsen and Olesen 2000). Self-heating will occur in most heaps containing porous manure with access of air to the sides of the heap. In general aerobic decomposition, increasing temperatures up to 70–80°C, will take place in pig faeces and in heaps of cattle manure with daily straw addition rates greater than 2.5 kg straw per head of livestock (Sommer et al. 2006). Further mineralization and immobilization will change the organic N and TAN pools, which will affect emission from the stored manure.

The data provided in this study show that temperatures in manure heaps decrease significantly with increased density of the manure (Fig. 4). Density and water content also affect air transport in the heap (Poulsen and Moldrup 2007), and consequently affect aerobic microbial activity that is the source of heating. Self-heating may be reduced by covering the heap with tarpaulin (Hansen et al. 2007), reducing air transfer to the heap interior. Thus, increasing manure density or effective coverage of the manure reduces the transfer of oxygen to the interior of the heap and thereby reduces heap temperature. A high density may be a consequence of high water content, a low content of bedding material like straw or wood chips, or due to deliberate compaction of the animal manure.

In stored solid manure, the air exchange and temperature increase induced by aerobic decomposition may greatly influence NH_3, N_2O and CH_4 emission, as illustrated in Figs. 5 and 6. Deep litter from pig and cattle housing and pig manure with a large proportion of straw will decompose aerobically, because of the high

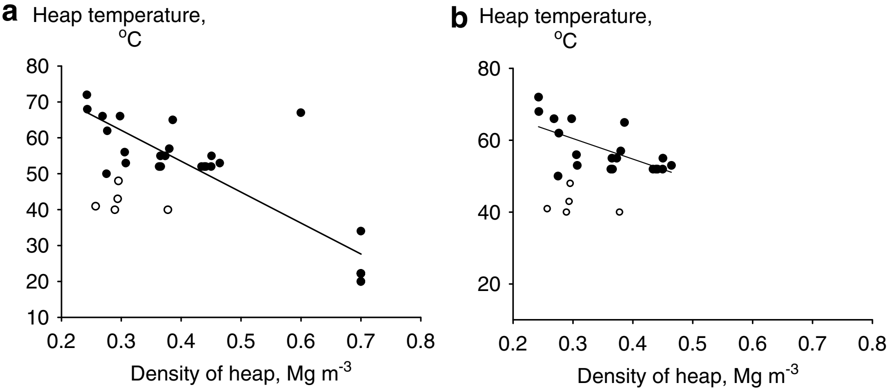

Fig. 4 Temperatures in livestock manure heaps. The open symbols are data from experiments where the heaps were covered with PVC sheets or surrounded by walls. The data show that temperatures in manure heaps decrease significantly with increased density of the manure. (**a**) all data used for the linear regression and (**b**) data from densities > 0.5 Mg m^{-3} have been omitted from the data analysis. (**a**) T(D)=88 – 86*D, $r^2 = 0.75$, (**b**) T(D)=78 – 57*D, $r^2 = 0.41$

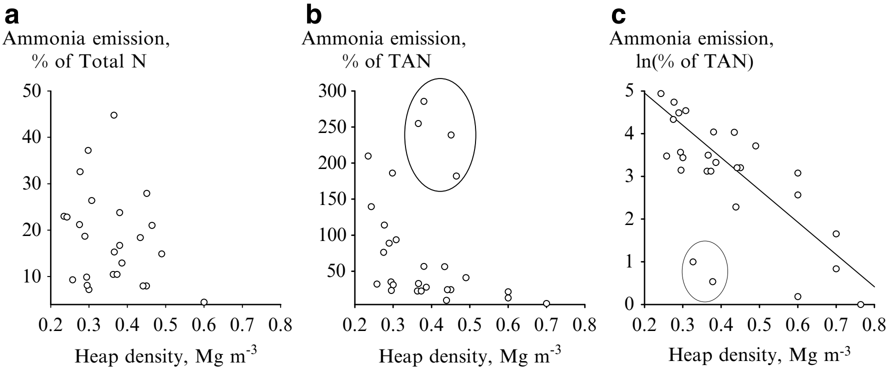

Fig. 5 Ammonia emission from livestock manure heaps related to% total-N content of the manure (**a**),% of total ammoniacal-N (TAN) (**b**) and ln (% of TAN) (**c**). In figure B(**b**), the encircled symbols are data from experiments with high straw amendments or sheeted but still exhibited high temperature. In figure (**c**), the encircled symbols are from experiments where the manure was compressed to some extent or covered efficiently. The data indicate air exchange and temperature increase induced by aerobic decomposition may greatly increase NH_3 emission. Reducing access by air through compacting, covering or otherwise storing manure heaps at high density reduces NH_3 emission during storage. F(D) = 6.5 – 7.6*D, $r^2 = 0.49$

permeability of the organic material and the presence of large amounts of degradable C. In contrast, temperature in high bulk density farmyard manure from cattle will not often increase (Forshell 1993). Manure from open beef feedlots is often so dry that aerobic decomposition will not occur without the addition of water. The gaseous

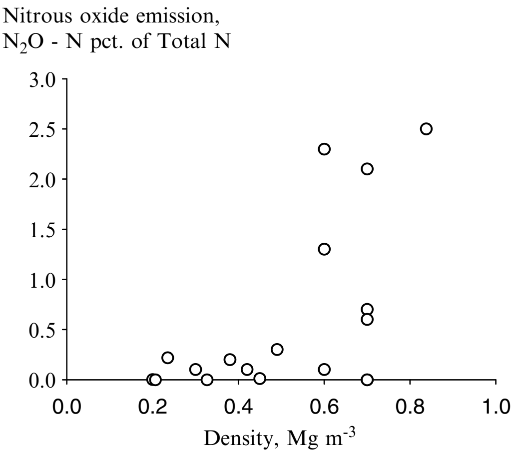

Fig. 6 Emission of nitrous oxide from livestock manure heaps. In one experiment, not included in the figure, the emission was 9.8 N_2O-N% of total-N at a density of 0.82 Mg m^{-3}. Emissions of N_2O increase with increasing manure density

emission from stored solid manure will therefore reflect the variety in manure composition. For example, the addition of water to dry manure heaps will enhance aerobic decomposition, but aerobic decomposition may be decreased if the water content is increased to the extent that air exchange through the heap is reduced (Poulsen and Moldrup 2007).

3.2 Data and Data Handling

The tables and figures presented in this section contain emission estimates from the references given in Table 6. The number of data in the datasets for each pollutant is shown in Tables 7–9.

3.3 Ammonia

Mean NH_3 emissions for different livestock and solid manure types from the data reviewed in this study are given in Table 7 and, although subject to large variation, indicate that emission from pig farmyard manure tends to be greater than from other livestock and solid manure types.

The emission of NH_3 from stored solid manure is controlled by TAN concentration, pH, air flow through the heap and temperature in the heap. Measured TAN proportions in solid manures (10–90% tile) have been reported as between 0.008 and 0.18 of N (cattle) and 0.024 and 0.42 (pigs). Ammonia emission is also affected by the cation exchange capacity (CEC) of the manure and formation of ammonium crystals (Sommer et al. 2006). Data reviewed for this study show that reducing

Table 6 Data presented in figures and tables below are collected from the following reports and articles

	Emission measured			
	NH_3	N_2O	CH_4	Treatment
Sommer and Dahl (1999)	X	X	X	Cattle deep litter; untreated, compacted and mixed
Osada et al. (2001)	x	x	x	Cattle deep litter; untreated
Sagoo et al. (2006)	X	X		Cattle FYM, straw added at increasing rates Pig; FYM
Williams et al. (2003)	x			Cattle FYM. Pig FYM
Nicholson et al. (2002)	X			Poultry manure; wood shavings with and without tarpaulin cover
Mosquera et al. (2005a)	X	X		Cattle FYM
Mosquera et al. (2005b)	X		X	Deep litter
Groot Koerkamp and Kroodsma (2000)	x			Poultry manure; wood shavings
Espagnol et al. (2006)	x	x	x	Pig manure deep litter; heaps turned and unturned
Fukumoto et al. (2003)	x		x	Pig manure; wood shavings
Szanto et al. (2007)	x	x	x	Pig deep litter; rich in straw
Chadwick (2005)	x	x	x	Cattle FYM, covered with tarpaulin and uncovered
Amon et al. (1998)	x	x	x	Cattle FYM – from tied stall
Amon et al. (2001)	x	x	x	Cattle FYM-tied stall; fleece sheet covering
Groot Koerkamp and Kroodsma (2000)	x			Layers manure from belt; some wood shavings
Sommer (2001)	x	x	x	Cattle deep litter; compacted, cut manure, covered with plastic (polyvinyl chloride), untreated

FYM farmyard manure

The greater sources of data are designated X, other sources are designated x

Table 7 Ammonia emission from solid manure heaps

		% of total N			
(Number)		Ave	SD	Max	Min
Cattle (24)	Farmyard manure	15.1	13.9	44.8	0.1
Cattle (13)	Deep litter	7.8	9.2	23.0	ND
Cattle (4)	Farmyard manure tied stall	3.7	3.2	8.0	0.6
Pig (13)	Farmyard manure	30.8	37.8	123.4	0.1
Pig (4)	Deep litter	4.8	2.1	7.0	2.4
Poultry (4)	Manure, belt removed	2.1	1.8	4.5	0.0
Poultry (13)	Litter	8.3	5.9	18.4	0.3

The figures in brackets refer to the number of studies from which the values were derived

ND not detected

Table 8 Nitrous oxide emission from solid livestock manure heaps

		$g\ m^{-2}\ d^{-1}$ N				N_2O-% of initial total-N			
		Ave	SD	Max	Min	Ave	SD	Max	Min
Cattle	FYM	1.3	1.4	4.3	0.1	0.9	0.9	2.3	0.0
Cattle	Deep litter					0.2	0.1	0.3	0.0
Cattle	FYM tied stall					0.5	0.2	0.8	0.3
Pig	FYM	1.9	1.1	2.9	0.7				
Pig	Deep litter					4.6	3.5	9.8	2.5
Poultry	Litter	0.6	0.3	0.8	0.2	0.01		0.0	0.0

SD standard deviation, *FYM* farmyard manure

Table 9 Methane emission from solid manure heaps

		% of total C			
(Number)		Ave	SD	Max	Min
Cattle (6)	Farmyard manure	3.5	3.3	9.7	0.5
Cattle (5)	Deep litter	0.02	0.01	0.03	0.00

SD standard deviation

access by air through compacting, covering or otherwise storing manure heaps at high density reduces NH_3 emission during storage (Fig. 5b). Storing solid manures at high density reduces air exchange and maintains a low temperature which limits the formation and transfer of NH_3 to the surface layers of the heap, and hence emissions may therefore be low. Further, it is seen that covering the manure during storage reduces NH_3 emission to below that estimated by including only density as an explanatory variable (Fig. 5c). The low emission is due to the reduced air influx which reduces both air exchange and the amount of aerobic decomposition that takes place. As shown in Fig. 5b, a high straw content increases NH_3 emissions to more than would be expected from manure density estimates.

As discussed above, mineralization of organic N will slowly replenish the TAN lost due to NH_3 volatilization and to some extent maintain or increase the proportion of TAN in the manure during storage. This means that the gaseous emissions sometimes exceed the original TAN content (e.g. Table 7, Osada et al. 2001). Furthermore, aerobic decomposition causes an increase in pH, which increases the NH_3 fraction relative to NH_4^+. Heaps stacked in one operation will be a source of NH_3 for a few weeks, until the moisture content decreases sufficiently to halt decomposition, all the decomposable N has been emitted as NH_3, oxidized N or N_2, or has been converted into organic-N.

Should active composting be carried out, e.g. by turning of heaps, in order to reduce the mass of manure and/or viability of weeds, NH_3 emissions have been shown to increase (Parkinson et al. 2004). Bishop and Godfrey (1983) and Witter and Lopez-Real (1988) reported that losses of N by NH_3 volatilization were significant at a $pH > 7.0$ and high temperatures (>40°C). Tam and Tiquia (1999) attributed losses of N largely to NH_3 volatilization. Hansen et al. (1989) reported N losses up to 0.33

of the initial N during composting of poultry manure while losses during composting of other animal manure ranged from 0.21 to 0.77 (Martins and Dewes 1992). Amon et al. (2001) found that composting farmyard manure emitted less N_2O and CH_4, but more NH_3, compared with anaerobically-stacked farmyard manure.

Cattle farmyard manure with only a small amount of straw has a high density and C:N ratio and does not decompose aerobically. Consequently, NH_3 emission from cattle FYM is generally less than from heaps of pig farmyard manure, which often will be aerobic and start to decompose aerobically. However, the studies reviewed here provide very little information about the source and characterisation of manures, so the reasons for the differences in emissions between cattle and pig farmyard manure cannot be attributed with certainty.

From manure heaps undergoing aerobic decomposition emissions of 0.25–0.30 of the total-N in stored pig manure and cattle deep litter have been recorded (Petersen et al. 1998; Karlsson and Jeppson 1995). Smaller NH_3 emissions in the range 0.01–0.10 of TAN have also been measured in studies where the low emission was partly due to rain reducing the emission potential of the manure by leaching surface layer TAN (Amon et al. 2001; Chadwick 2005) and partly due to the composition of the manure. Surface concentration of TAN is important as e.g. addition of fresh manure on the heap creates a new outer surface from which emission can occur, thus NH_3 emission will peak soon after each addition of manure to the heap (Muck et al. 1984).

3.4 Nitrous Oxide

Significant N_2O production takes place during storage (Table 8) due to nitrification and subsequent denitrification, as also shown by Yamulki (2006) and Hansen et al. (2007). Nitrification in passively aerated heaps is a consequence of the porous nature of manure in the surface layer, allowing O_2 to diffuse into the manure. Addition of straw litter may also serve as a conduit for O_2 and the oxygenation of the manure (Sommer and Møller 2000). Therefore, NO_2^- and NO_3^- are found in the surface layers of most heaps, and in consequence emissions of N_2O have been measured from dung heaps (Amon et al. 2001; Berges and Crutzen 1996; Groenestein and Van Faassen 1996; Petersen et al. 1998; Chadwick 2005). Nitrous oxide emissions increase with increasing manure density (Fig. 6), which may be due to an increased number and volume of sites with relatively low oxygen content from which N_2O emissions can occur. Groenestein and van Faassen (1996) provided the following explanation: NO and N_2O are intermediate products of anaerobic denitrification and therefore are expected to be emitted when O_2 pressure increases (Burton et al. 1993; Poth and Focht 1985). However, factors that reduce oxygen pressure in the bed can also increase N_2O production. According to Poth and Focht (1985) this is caused by reduction of NO_2^- to NO rather than through the nitrification by an aerobic process, and they defined it as nitrifier denitrification. This is in agreement with Burton and Turner (2003), who found production of N_2O from pig manure without production of NO_3^- and NO_2^-. This occurred during aerobic treatment after the addition of manure, when O_2 consumption tripled within minutes. The laboratory study of

Groenestein and van Faassen (1996) confirmed the findings of Poth and Focht (1985) and Burton et al. (1993).

Hansen et al. (2007) measured N_2O emission of 0.05 of total-N from a heap containing organic solids from separated slurry. This emission was reduced to less than 0.001 of total N by covering the heap, thereby reducing air flow into the heap reducing the temperature significantly. In addition to reducing the temperature, covering also reduced the O_2 content of the manure which reduced nitrification to an insignificant amount. The same effect of covering manure heaps was shown in the study of Chadwick (2005). The use of 5 kg of straw per livestock unit per day in the manure reduced N_2O emission significantly by increasing porosity and thereby reducing anaerobic spots in the heap compared with using 2.5 kg per livestock unit per day (Amon 1999; Sommer and Møller 2000).

Table 8 presents data from the relatively few studies that have examined N_2O emission from manure heaps. The experimental conditions varied greatly, i.e. the heaps included in the study had variable surface:volume ratios, with gradients of O_2 and temperature that varied with time and manure properties (Petersen et al. 1998). The emissions vary considerably but, due to the limited number of studies available, it has not been worthwhile quantifying the effect of the major factors controlling them. This is because there are relatively few data available and the main controlling factors are confounded within the studies. Most emission estimates from heaps with cattle deep litter, straw amended cattle manure or untreated cattle and pig manure have been between 0.001 and 0.009 of total-N (Table 8) as shown in Sommer (2001), Petersen et al. (1998) and Yamulki (2006). From pig deep litter heaps emissions as great as 0.098 of total-N have been measured. Emission of N_2O from poultry manure tends to be small.

3.5 Methane

No relation between manure heap density and CH_4 emission was found in the current study, which could be due to the small number of available data. Although CH_4 emission occurs only under locally anaerobic conditions, the relationship with the aerobicity of the whole stack is not straightforward. Aerobic decomposition in straw-rich loosely-packed heaps of solid manure leads to both high temperatures and anaerobic hotspots, so CH_4 emission occurs, even though the stack is largely aerobic (Hellmann et al. 1997). On the other hand, if an air-tight cover is put over the heap, thereby preventing aerobic microbial activity and the associated increase in temperature, CH_4 emissions will be reduced, even though the stack is largely anaerobic. Efficient covering reduced CH_4 emissions from a heap of a dry matter-rich separated slurry fraction from 0.035 to 0.0017 of the initial C content (Hansen et al. 2007). The balance between aerobic and anaerobic turnover is critical. If the heap is not covered efficiently, or if the compaction is not enough to prevent all air flow into the heap, then CH_4 emissions may be enhanced (Amon 1999; Sommer 2001). Thus loosely-packed pig manure emitted five times more CH_4 than cattle farmyard manure, probably due to a greater gas exchange and higher temperature in the manure (Husted 1994).

Chadwick (2005) reported CH_4 emissions varied from 0.005 to 0.097 of the initial carbon content. The greatest and least emissions were from manure stored in compacted and PVC-covered heaps, respectively (Table 9). Frequent turning can be used to reduce anaerobic zones in the heap. In one study this technique reduced CH_4 emissions to about 0.005 of the initial C content (Amon et al. 2001, 2006).

4 Emissions Following the Application of Solid Manures to Land

4.1 Data and Data Handling

In contrast to the relatively sparse data available for livestock housing and manure storage, the quantity of data available for field-applied solid manure was sufficient to support a more detailed statistical analysis. The relevant characteristics and chemical composition of the manures investigated, the experimental design and the resulting emissions were surveyed. The survey yielded a total of 35 studies including 292 datasets on NH_3, 57 on N_2O and 11 on CH_4 (Table 10), with most of the datasets originating from mid or northern Europe. Two thirds of the manures investigated were stored before application (average duration 175 days), the remainder were applied directly from the livestock building.

Manure composition was in the expected range (up to 20% N in dry matter and up to 80% of total-N as TAN and <1.0% of total-N as nitrate) (Table 11). Differences were likely to depend on housing systems, feeding regimes, litter materials, amounts of litter, duration of storage and conditions during storage.

4.1.1 Experimental Conditions

The studies were carried out between 1990 and 2007, mainly during spring, summer and autumn ($n = 66$, 52 and 106, respectively), while 12 studies spanned all four seasons.

Table 10 Number of datasets on emission of ammonia (NH_3), nitrous oxide (N_2O) and methane (CH_4) following application of solid manures to land, per livestock category

Livestock category	NH_3	N_2O	CH_4
Dairy cattle	49	4	0
Beef cattle	62	29	9
Fattening pigs	85	18	1
Broilers	38	2	0
Laying hens	42	4	1
Suckler cows	13		
Other livestock categories[a]	3		
Total	292	57	11

[a] 1 for turkeys, 2 for a mixture of horse, pig and poultry manure

Table 11 Composition of the investigated manures[a], expressed as: dry matter (d.m.),% of fresh weight; volatile solids (v.s.),% of d.m.; total nitrogen (Ntot)% of d.m., total ammoniacal nitrogen, (TAN),% of total-N; nitrate,% of Ntot; phosphorus, (P),% of d.m.; potash (K),% of d.m.; pH; C;N for dairy cattle, beef cattle, fattening pigs, broilers and laying hens

	d.m.	v.s.	N_{tot}	TAN	Nitrate	P	K	C		
	%	% d.m.	% d.m.	% N_{tot}	% N_{tot}	% d.m.	% d.m.	% d.m.	pH	C/N
Dairy cattle (total number of datasets: n = 53)										
n	36	31	53	36	4	23	19	0	22	8
Average	20	72	2.7	18	0.29	0.6	3.4	–	8.4	14
Median	19	77	2.5	17	0.29	0.5	2.9	–	8.4	14
Minimum	15	41	0.3	1.6	0.17	0.2	0.5	–	7.4	12
Maximum	40	86	20.0	38	0.40	1.0	8.8	–	8.9	16
Standard deviation	5	14	3.6	8.8	0.14	0.2	1.8	–	0.4	1.5
Beef cattle (total number of datasets: n = 69)										
n	47	0	56	69	7	9	9	6	27	6
Average	20	–	2.6	8.2	0.02	0.6	2.7	15	8.2	17
Median	18	–	2.6	7.2	0.01	0.7	2.4	11	8.3	16
Minimum	15	–	0.4	0.0	0.00	0.5	1.8	7	7.7	13
Maximum	42	–	5.9	39	0.08	0.8	4.6	38	9.2	21
Standard deviation	5.6	–	1.3	8.4	0.03	0.1	0.8	12	0.4	3.2
Fattening pigs (total number of datasets: n = 93)										
n	87	4	87	87	7	5	5	7	30	7
Average	25	55	2.9	19	0.02	3.3	2.8	17	8.2	10
Median	22	59	3.0	17	0.03	4.3	2.6	10	8.3	10
Minimum	17	0.0	0.6	0.8	0.00	1.3	2.4	7	6.7	9
Maximum	64	81	6.2	54	0.03	4.6	3.7	37	8.8	12
Standard deviation	7	32	0.9	16	0.01	1.5	0.5	13	0.5	1.3
Broilers (total number of datasets: n = 38)										
n	38	8	38	38	0	16	16	6	29	8
Average	63	71	4.4	30	–	1.7	3.4	30	8.6	13
Median	65	69	4.1	32	–	1.5	3.5	22	8.7	8.5
Minimum	40	67	1.1	9.0	–	1.1	2.4	16	6.5	6.4
Maximum	93	80	6.6	49	–	3.8	3.9	72	8.9	32
Standard deviation	13	4.9	1.4	13.0	–	0.7	0.5	21	0.5	9.0
Laying hens (total number of datasets: n = 44)										
n	36	17	36	36	0	13	13	8	27	8
Average	52	70	4.6	36	–	2.3	3.0	16	7.9	7.7
Median	44	72	4.9	31	–	2.1	2.7	11	8.3	6.1
Minimum	21	61	1.4	2.9	–	1.5	2.2	6.3	6.4	3.4
Maximum	90	80	6.7	78	–	3.6	4.2	33	9.2	19
Standard deviation	22	5.6	1.5	23	–	0.8	0.9	11	0.9	5.1
n for all livestock cat	244	60	270	266	18	66	62	27	135	37

[a] Data were obtained from: Akiyama and Tsuruta (2003); Amon et al. (2001); Asteraki et al. (1998); Bode (1990); Bruins and Hol (1990); Bruins and Huijsmans (1989); Chadwick et al. (2000); Chambers et al. (1997); Hansen (2004); Hol (1992); Karlsson and Salomon (2002); Kosch (2003); Malgeryd (1996, 1998); Mazzotta et al. (2003); Menzi et al. (1997a, b); Misselbrook et al. (2005a, b); Mulder (1992a, b); Mulder and Hol (1993); Mulder and Huijsmans (1994); Regione Emilia-Romagna (2004, 2006, 2007); Rochette et al. (2008); Rodhe and Karlsson (2002); Rodhe et al. (1996); Sagoo et al. (2006, 2007); Sannö et al. (2003); Thorman et al. (2007); Webb et al. (2004, 2006); Williams et al. (2003)

Mean temperatures during measurements ranged between 11°C and 13°C, which can be considered as typical for mid European climates (Flechard et al. 2007). Information on weather conditions was available from 141 datasets. For 67 datasets, dry weather was recorded and for 74 datasets rain events were reported or rainy weather prevailed.

The majority of NH_3 measurements were made using wind tunnels ($n=171$). Micrometeorological methods ($n=47$) and the N balance ($n=10$) approach were also used. Chamber methods ($n=77$) were used for measuring both NH_3 and N_2O: dynamic chambers for NH_3, and closed chambers for N_2O. The average duration of measurements ranged between 96 and 362 h, N_2O measurements were made for longer (between 2 and 12 months).

Application rates were adjusted according to the N requirements of the crops, and thus within the range of usual agricultural practice. Manures were applied onto bare soil, stubbles and grass. Manures from pigs and poultry were mostly applied onto stubbles while manures from cattle were predominantly spread onto grass.

4.1.2 Objectives of the Studies

The objective of most studies was to investigate factors influencing emissions after manure spreading, i.e.: manure incorporation and the time delay before incorporation (33 experiments); the conditions under which manure was stored before application (9 experiments); the type of machine used for incorporation (8 experiments); the amount of litter material (5 experiments); the influence of covering the manure during storage (3 experiments); the influence of rain after application and of turning the manure heaps during storage (2 experiments each); the water content of the manure; the compaction of manure during storage; the application rate and the soil type (1 experiment each), on subsequent emissions.

4.1.3 Data Selection and Statistical Analysis

Thirty datasets reported NH_3 emissions >1.50 of TAN applied. Fifteen of the manures used in these studies had TAN contents <0.10 total-N or TAN contents of the manures were not available. These apparently anomalous emissions were likely due to the difficulty of taking accurate subsamples of farmyard manure (Webb et al. 2004), falsely low TAN contents due to analytical problems or large NH_3 losses during handling or storage of the samples (Misselbrook et al. 2005a). In addition, there could also have been problems achieving an even spatial distribution of solid manure on the plots. We therefore decided to exclude these datasets from the statistical evaluation. The other 15 datasets with >1.50 TAN which exhibited TAN concentrations in the manure reaching at least half of the standard UK book value, which is 10% of total-N (Anon 2000), were retained for the statistical evaluation but the emissions were limited to 1.50 TAN. This was our estimate of the potential maximum emission arising from volatilization of all the TAN in manure at application and emission of any NH_4^+ subsequently mineralized. If these datasets included results on N_2O emissions in addition to NH_3 these results were removed as well. There is consensus that NH_3 emissions mainly originate from the TAN fraction. To our knowledge, there is no study available which would prove that the main part of the emissions are due to the organic N fraction in the manure. Therefore, we had to determine a "threshold" although it might be somewhat arbitrary to do so. Using 1.50 TAN we were not too restrictive. Due to a lack of a more appropriate basis, we decided to keep the procedure as chosen.

All CH_4 emission datasets were used. Even so, the number of data available were few ($n = 11$).

If replicate measurements had been taken with the same manures, i.e. if they were incorporated with different machines or within different time spans, average values were used for data analysis to avoid pseudo-replication. In contrast, datasets with results on N_2O only were not removed from the evaluation, even if they exhibited unusually small TAN contents (e.g. manures with a large litter content) or if emissions were large (e.g. 0.60 TAN). These are all data from peer reviewed papers. We considered this approach reasonable for the evaluation of N_2O emissions, since some of these will have arisen from the nitrification or denitrification of organic-N and not simply from TAN as in the case of NH_3.

The influence of three main factors: incorporation of manure; livestock category; measuring method on NH_3 emissions was tested with factorial analyses of variance. For this analysis, we distinguished only three main livestock categories (cattle, pigs and poultry) and four types of measuring methods, combining the types of system (wind tunnel or other methods) with the duration of measurement (more than 120 h: "long"; up to 120 h: "short"). The other factors could not be included in the analysis due to missing data or insufficient replication; their influence is discussed qualitatively below. To account for the differing number of datasets for each factor combination, analyses were based on type-II sums of squares. The model included main effects and two-way interactions; three-way interactions could not be included because no data were available for some combinations of the three factors. Analyses were done using the package "car" of the R statistical software after checking that residuals met the model assumptions.

The statistical evaluation for N_2O emissions was carried out as for NH_3, except that the analysis of variance included only two factors: incorporation of manure and livestock category (cattle, pigs and poultry). Since only closed chambers were used, the measuring method was not included as factor in the model. Data were log ($x + 0.01$)-transformed to comply with model assumptions.

The results are expressed as the proportion of TAN applied in the manure for NH_3 and N_2O, as it was deemed likely that the majority of the emissions would be generated from the TAN fraction of the manures. In addition, the wide range of manure-N applied would make interpretation of the data difficult if results were expressed in kg N. The database did not provide adequate information on the manure application to express the results as a proportion of C applied. Hence CH_4 emissions were expressed as mg m^{-2} C. Due to the importance of measuring methods with respect to the interpretation of the results of NH_3 emission studies, this topic is discussed in detail below.

4.1.4 Implications of the Measurement Method

Génermont and Cellier (1997) concluded that emission rates measured by enclosures covering small areas (wind tunnels, dynamic chambers) modify environmental conditions (wind speed, temperature, rain) in a way that will tend to lead to an overestimation of NH_3 emissions at the beginning of the measurement period (due to advection) compared with emissions measured over larger areas e.g. by micrometeorological methods. In addition, combined effects of the small surface area sampled and the high spatial variability of the emissions mean that results of enclosure studies have to be interpreted with caution. In general, they are considered as unsuitable for developing absolute values for NH_3 emissions. For determining absolute NH_3 fluxes, micrometeorological methods are the most suitable because they are non intrusive. However, they require larger plots and are difficult to replicate, except for the integrated horizontal flux technique (Shah et al. 2006) and the equilibrium concentration technique, developed at the Swedish Institute of Agricultural and Environmental Engineering (JTI), Sweden (Svensson 1994). However, enclosures covering small areas are appropriate to measure relative emissions in order to compare the relative effect of influencing factors or the effectiveness of different mitigation measures. Pain et al. (1991) assessed the incorporation of pig slurry using both a micrometeorological technique and wind tunnels. In those experiments abatement from incorporation by plough, as estimated using wind tunnels, was *c.* 5% more effective than in the experiment in which NH_3 emissions were measured by the meteorological method. Webb et al. (2004) concluded that wind tunnels were an appropriate method to estimate the abatement efficiency of manure incorporation techniques.

Nitrous oxide emissions may also be measured using micrometeorological methods and by closed chambers. As for NH_3 emissions, micrometeorological methods are considered to be optimal because of minimal disturbance of environmental conditions. However, they are limited to large fields and certain meteorological conditions (Pape et al. 2009). In all the studies reviewed here, N_2O emissions following application were measured using closed chambers. Studies comparing both methods reported good agreement (Christensen et al. 1996; Laville et al. 1999) and we concluded that the results were not systematically biased by the measuring method. However, N_2O emissions following manure application were reported to occur over 30–60 days (Wulf et al. 2002; Rochette et al. 2008). The average duration of measurement for the studies reviewed was 13–18 days, which might lead to an underestimation of emissions.

4.2 Influence of Management, Climate and Soil

Incorporation by ploughing or harrowing after application reduces losses of NH_3 by burying the majority of the manure (Kirchmann and Lundvall 1993; Malgeryd 1998; Rodhe and Karlsson 2002; Sommer and Hutchings 2001; Webb et al. 2004, 2006).

Spreading technique (one- and two-step spreaders, finer scattering) did not influence NH_3 emissions, but greater application rates increased the proportion of N lost as NH_3 (Rodhe et al. 1996). Climatic conditions such as air temperature, saturation deficit of the air, irradiation, wind speed and rainfall may influence emissions. Misselbrook et al. (2005a) did not find a relationship between total NH_3 losses and temperature for solid manure applications. Losses would be expected to increase with increasing temperature. However, crusting of the surface layer of manure at higher temperatures may reduce emissions. For solid manures, rainfall was identified as the parameter with most influence on NH_3 emissions, due to NH_4–N leaching from manure to the soil, where it will be less susceptible to volatilization (Misselbrook et al. 2005a). Sommer and Christensen (1990) found that irrigation with more than 20 mm reduced total NH_3 emission to less than half of the emission from untreated solid pig manure. Rodhe et al. (1996) found a reduction of 30% of NH_3 emissions with 20 mm irrigation directly after spreading of semi-solid manure and less reduction for applied solid manure. On the other hand, regular wetting prevents the manure from drying and might enhance mineralization, prolonging NH_3 release (Misselbrook et al. 2005a) and also potentially increasing emissions of N_2O. Chambers et al. (1997) found emission increased following rain events of 13 mm about 5 days after application and 16 mm about 8 days after manure application. Gordon and Schuepp (1994) reported that rainfall events of approximately 1 mm h^{-1} suppressed NH_3 fluxes on subsequent days after spreading of pig manure. Ammonia losses immediately after field application appeared to be slightly enhanced by watering, although the effects of the total N applied were dominant (Gordon and Schuepp 1994).

Numerous studies have shown that N_2O production increases with temperature (Dobbie et al. 1998; Smith et al. 2003). While no influence of soil type on NH_3 emissions from solid manure has been demonstrated to date, N_2O emissions from agricultural soils were found to be greater from fine- than from coarse-textured soils. This is likely to be driven by the lower redox potentials of fine-textured soils and greater resistance to O_2 diffusion (Rochette et al. 2008). Nitrous oxide production can increase with increasing soil moisture (Dobbie et al. 1998; Smith et al. 2003). Rochette et al. (2008) reported that periods of greater emissions following manure and fertilizer-N application corresponded with the period when soil mineral N contents were greatest and water-filled pore space (WFPS) was greater than 0.5 m^3 m^{-3}. Increasing soil moisture and decreasing temperatures (e.g. over the winter period) are expected to favour the reduction of any N_2O produced to N_2 (Firestone and Davidson 1989).

4.3 Ammonia

4.3.1 Factors Influencing Emissions

Emissions by livestock category, measuring method and incorporation are shown in Fig. 7a–c. Analysis of variance showed that livestock category, measurement method and time of manure incorporation after application significantly influenced NH_3

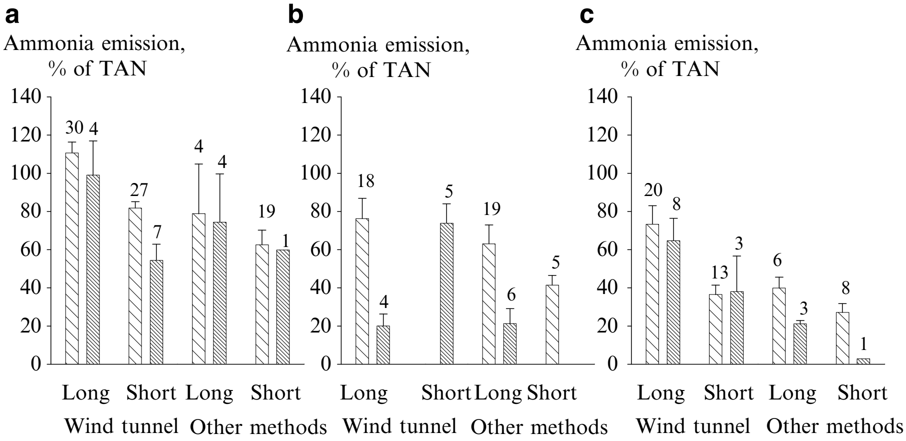

Fig. 7 Ammonia emissions from cattle (**a**), pig (**b**) and poultry (**c**) manure according to the measuring method (wind tunnel and other methods) and the duration of measurement (long: duration of measurement more than 120 h; short: up to 120 h) no incorporation (*light grey* column on the *left*) or incorporation (*dark grey* column on the *right*) after spreading. The columns give the average and the bars the standard error. The numbers over the bars indicate the number of datasets. Consistently greater emissions were reported using wind tunnels, suggesting an overestimation of emissions with this method. Average unabated NH_3 emissions following application of cattle manure were 0.79 TAN, from pig manure 0.63 TAN and from poultry manure 0.40 TAN. Source of the data: see footnote of Table 11

emissions (Table 12). Consistently greater emissions were reported using wind tunnels, suggesting an overestimation of emissions with this method. Short duration of measurement (i.e. less than 120 h) produced smaller emissions, implying that NH_3 emissions may continue for more than 5 days after application. The different measuring methods exhibited mean NH_3 emissions without incorporation after application between 0.62 and 1.11 TAN for cattle manure. Emissions were less for pig manure (0.41–0.76 TAN) and poultry manure (0.36–0.73 TAN) than for cattle manure. It has to be noted however that the number of datasets differ for the livestock categories, measuring methods and incorporation. The incorporation of manure significantly reduced emissions. The reduction due to incorporation was independent of the measuring method but differed among livestock categories. On average, emissions were 17%, 48% and 10% less with incorporation of manure for cattle, pigs and poultry, respectively. However, these figures do not take into account factors influencing emissions that were not included in the statistical analysis. A more precise quantification of the effect of manure incorporation is given below.

We considered an appropriate estimate of unabated NH_3 emissions from cattle manure could be obtained from measurements made over more than 120 h, excluding those made using wind tunnels. This gave an average emission of 0.79 kg kg^{-1} N (related to TAN) (Fig. 7a), albeit from only four datasets. The same approach estimated unabated emissions from pig manure as 0.63 TAN (Fig. 7b). This figure can be considered as relatively robust due to the comparatively large number of datasets

Table 12 Results of the analysis of variance testing the influence of livestock category, measuring method and manure incorporation as well as their two-way interactions on ammonia emissions (% TAN)

	Square	Df	F-value	Significance
Livestock category	56775	2	27.36	$p<0.001$
Measurement method	53140	3	17.07	$p<0.001$
Incorporation	15186	1	14.63	$p<0.001$
Animal: Measurement	15647	6	2.51	$p<0.05$
Animal: Incorp	7085	2	3.42	$p<0.05$
Measurement: Incorp	332	3	0.11	ns
Residuals	204429	197		

Data in the table are type-II sums of squares, degrees of freedom, F ratios and significance levels for each effect in the model

($n=19$). Unabated NH_3 emission following application of poultry manure was 0.40 TAN ($n=6$; Fig. 7c). This smaller emission factor for poultry manure is expected as hydrolysis of uric acid to urea may take many months during storage and is often incomplete even after application, hence limiting the potential for NH_3 emission (Kroodsma et al. 1988).

Other factors potentially influencing NH_3 emissions after spreading which could not be included in the statistical evaluation are the amount and type of litter, storage time of manure before spreading, the interval of incorporation after spreading, rate of application, the machine used for spreading or incorporation and wetting of the manure after application due to rain.

The available datasets did not allow us to determine any influence of litter type on emissions after application since the same material is used for almost all manures (e.g. straw for cattle and pigs, wood shavings for broilers). In the two studies where the influence of different amounts of litter in the manure was investigated, emissions tended to increase with an increasing amount of litter. For manure from fattening pigs, a similar trend was less clear. We did not consider it appropriate to quantify the effect of the amount of litter based on these results.

Emissions tended to be less from cattle, pig and layer (belt removed) manures that had been stored than from fresh manure (Asteraki et al. 1998; Sagoo et al. 2006; Hansen 2004; Karlsson and Salomon 2002; Regione Emilia-Romagna 2007). Hansen (2004) reported that storage reduces the potential for NH_3 volatilization following spreading despite the increase in pH during storage. This is likely to be due to a decrease in the amount of TAN in the manure during storage. Emissions after land spreading of broiler manure, stored in the open air, were less than from manure stored in a heap sheeted with a plastic cover. This was due to more TAN remaining in the sheet-stored manure (Sagoo et al. 2007). For pig farmyard manure, the effect of sheeting was less clear. One experiment (Sagoo et al. 2006) reported NH_3 emission to be less from sheeted manure (0.37 TAN) compared with conventionally stored farmyard manure (0.65 TAN). In a second experiment, the opposite was observed. Webb et al. (2004) investigated whether compaction of manure during storage might lead to enhanced emissions after spreading. Compacted manures contained more

Table 13 Reduction of ammonia emissions after application with incorporation of solid manure from beef cattle, fattening pigs, broilers and laying hens in% of emissions measured without incorporation (in brackets: number of datasets)

	Incorporation after			
	<4 h	4 h	≥24 h	
Livestock category	Emission reduction%			Tool used for incorporation
Dairy cattle	–	63 (2)	38 (2)	Harrow
Beef cattle	–	58 (3)	20 (4)	Plough
Beef cattle	–	–	9 (1)	Harrow
Fattening pigs	92 (4)	64 (9)	63 (8)	Plough
Fattening pigs	–	61 (5)	37 (5)	Disc
Broilers	–	81 (2)	77 (2)	Plough
Broilers	–	53 (2)	24 (2)	Disc
Broilers	–	44 (1)	–	Harrow
Laying hens	97 (1)	–	–	Mouldboard plough
Laying hens	83 (1)	–	–	Chisel plough
Laying hens	82 (1)	–	–	Rotary cultivator
Laying hens	79 (2)	–	–	Harrow

TAN but less total-N. There was no significant effect of the storage method on emissions following spreading cattle farmyard manure in the first experiment while the emissions of NH_3 were greater from the compacted manure in the second one. Losses of NH_3 from pig farmyard manure were unaffected by storage treatment. Turning pig manure heaps twice during storage reduced emissions after surface spreading (Sagoo et al. 2006). Turning has been shown to increase NH_3 emissions from stored cattle farmyard manure (Amon et al. 2001; Parkinson et al. 2004), hence the depletion of TAN during storage might be expected to reduce emissions after spreading.

Increased emissions after wetting were observed for studies with pig and poultry manures. For the latter, wetting increases hydrolysis of uric acid to NH_4^+ which can then volatilize as NH_3. However, reduced emissions due to wetting occurred in one study on manure from cattle and two on laying hens as well.

In most cases, incorporation within 4 h after application reduced emission more than incorporation over longer intervals (i.e. average reduction of 32%, 92% and 85% for incorporation of less than 4 h and 20%, 56% and 50% for incorporation within 24 h or more after application for cattle, pigs and poultry, respectively) (Table 13). Incorporation by disc or harrow reduced NH_3 emissions less than incorporation by plough, although all machines used for incorporation achieved some mitigation. These findings are consistent with other studies (e.g. Webb et al. 2004; Sagoo et al. 2007). Webb et al. (2004) suggested that incorporation of pig farmyard manure can reduce NH_3 emissions by *c*. 90%, 60% and 30% for immediate, within 4 h and within 24 h incorporation, respectively. For incorporation of cattle farmyard manure within 4 h, a reduction of *c*. 50% was achieved (Webb et al. 2004). The results of Sagoo et al. (2007) indicate that rapid soil incorporation reduced emissions by 15–87% compared with surface spreading. In contrast, Nicholson et al. (2002) concluded that the soil incorporation of solid manure from pigs had little effect on NH_3 emissions.

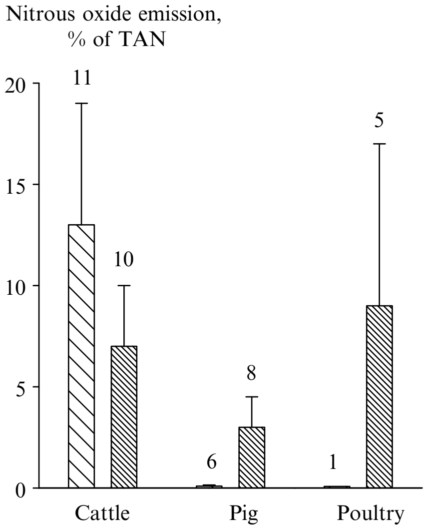

Fig. 8 Nitrous oxide emissions of cattle, pigs and poultry according to incorporation (*light grey* column on the *left*) or no incorporation (*dark grey* column on the *right*) after spreading of manure. The columns give the average and the bars the standard error. The numbers over the bars indicate the number of datasets. Emissions of N_2O following the application of cattle manure were 0.12 of TAN without incorporation after application and 0.073 TAN with incorporation after application. Emissions of N_2O following application of pig and poultry manures were 0.003 and 0.001 TAN respectively without and 0.035 and 0.089 TAN respectively with incorporation after application. However, data variability was large. Source of the data: see footnote of Table 11. *TAN* total ammoniacal nitrogen

4.4 Nitrous Oxide

4.4.1 Emissions Considering Major Influencing Factors

We decided within the Eager group to report TAN based emission factors. Although reporting N_2O emissions as a proportion of total-N is more usual, for this section of the review, we prefer to employ the same emission factors for both NH_3 and N_2O. Emissions of N_2O following the application of cattle manure were 0.12 of TAN without incorporation after application and 0.073 TAN with incorporation after application (Fig. 8). Emissions following application of pig and poultry manures were 0.003 and 0.001 TAN respectively without and 0.035 and 0.089 TAN respectively with incorporation after application. It has to be noted that data variability was large and the results were influenced by a few datasets with emissions of >0.20 TAN from manures with TAN contents much less than average. Chadwick et al. (1999) found N_2O emissions from solid manure of 0.059 TAN. Gregorich et al. (2005) reported data for solid manure from cattle similar to those presented here. In contrast, Loro et al. (1997) observed greater emissions (26.5 kg ha^{-1} N, application rate: 600 kg ha^{-1} N) from solid beef manure.

Table 14 Results of the analysis of variance testing the influence of livestock category, manure incorporation and their interaction on nitrous oxide emissions (% TAN, log-transformed). Data in the table are type-II sums of squares, degrees of freedom, F ratios and significance levels for each effect in the model. *TAN* total ammoniacal nitrogen

	Square	Df	F-value	Significance
Livestock category	31.878	2	3.4759	$p < 0.05$
Incorporation	0.192	1	0.0419	ns
Animal:Incorp	51.742	2	5.6418	$p < 0.01$
Residuals	160.49	35		

Cabrera et al. (1994) reported emissions from poultry manure obtained in a laboratory study between 0.002 and 0.028 of the N applied. This complies with the range found in the present study (0.005–0.014 N_{tot}).

Nitrous oxide emissions decreased in the order cattle > pigs > poultry with statistically significant differences among the livestock categories (Table 14). In general, the effect of incorporation of the manure was not statistically significant. However, interactions between incorporation and livestock categories occurred. Incorporation of cattle manure induced a significant reduction of N_2O emissions while the opposite was observed for pig and poultry manure. The results of Webb et al. (2004) and Thorman et al. (2007) suggest that incorporation does not increase emissions. In contrast, Gregorich et al. (2005) found greater N_2O emissions when manure was ploughed into the soil in autumn than if it was left on the surface.

4.4.2 Interactions Between Ammonia and Nitrous Oxide Emissions

The use of additional straw in animal housing, compaction or sheeting of manure during storage or the rapid incorporation of manure into the soil have been suggested as effective measures to reduce NH_3 emissions after land spreading. However, there are concerns that such measures may increase N2O emissions after manure application by increasing the pool of mineral N in the soil (Bouwman 1996). The results of the datasets collected remain ambiguous on the impact of incorporation of solid manure after application with respect to N_2O emissions.

4.5 Methane

Literature data on CH_4 emissions released from manures following application are scarce. In the studies reported, emissions of CH_4 following application were measured using closed chambers. The duration of measurement was between 1 and 3 weeks. Methane emissions were reported to occur mainly in the first 2 days after application of liquid or solid products obtained from screw press separation of cattle slurry (Fangueiro et al. 2008). It can thus be expected that the duration of measurement of these studies sufficiently reflect total emissions.

Table 15 Ammonia emission factors for solid manure used in national inventories, related to TAN excreted (%). *TAN* total ammoniacal nitrogen

Model	Dairy cattle	Beef cattle	Finishing pigs	Broilers	Layers
Switzerland deep litter	18.3	18.3	15.7	20	50
Switzerland, production of solid and liquid manure	18.3	18.3	–[a]	–	–
Denmark		10.0		36.0	35.7
UK	22.9	22.9	25.0	8.1	19.2
Germany		19.7	28.4	20.0	52.9
Netherlands		16.9		20.0	32.1
Mean		18.9	26.7	28.2	35.0

[a] Systems with production of solid and liquid manure produce negligible amount of solid manure in Switzerland. Therefore, they are not accounted for in the Swiss emission model

In the nine experiments with beef cattle manure, an average CH_4 emission of 8 mg m^{-2} C was measured. While the amount of CH_4 released from poultry manure measured in one study was in a similar range to that for cattle (3 mg m^{-2} C), emissions from pig farmyard manure were considerably greater (239 mg m^{-2} C). Fangueiro et al. (2008) reported CH_4 emissions of 55 mg m^{-2} C from the solid fraction separated cattle slurry measured over 42 days which are comparable with the present datasets.

5 Discussion and Conclusions

5.1 Housing and Storage

Table 15 presents emission factors for NH_3-N emissions from buildings housing livestock used in the different national inventories expressed as the proportion of TAN excreted. As indicated in the present paper, the emission factors vary considerably, not only due to variations in NH_3-N emission, but also due to variations in the proportions of TAN excreted. The dataset analysed here did not provide enough data to calculate emissions based on TAN. From Fig. 2 the mean NH_3-N emission factor for fattening pigs can be calculated as *c*. 10 g d^{-1} per pig.This equates to a mean annual emission factor for fattening pigs of 0.267 N (as indicated by Table 15).

With respect to the strategy we outlined in the introduction, we conclude that the empirical data are not sufficient to support a recommendation for emission factors. When characterising gaseous emissions from the main housing systems, animal category and litter management are major aspects because these define the composition of the emitting substance. As can be seen from the results described above, despite the numerous measurements, the variation is quite large. As far as the data allow, the differences between the main systems were described. However, while the theoretical implications are clear (Table 1), the quantitative impacts on emissions are not sufficiently defined to parameterize systems. For slurry systems, the main parameters like air temperature, air velocity, urea concentration, NH_3 concentration and pH are known and NH_3-N emission can be modelled (Monteny 2000; Aarnink 1997). The microbial ecosystem in solid manure housing systems and the quantitative impact on emissions needs more consideration. One of our intentions in this review was to describe how different approaches to management of solid manures in buildings and during storage might influence subsequent emissions. However, it has not been easy to draw firm conclusions from these studies which, for the most part, were unrelated. Ideally, experiments would make measurements of gaseous emissions from the same batches of manure within buildings, stores and following application to land. In this way the impacts of differences among systems at the earlier stages of manure management on subsequent emissions could be demonstrated unequivocally. However, to carry out such studies in parallel, using replicate buildings and stores, in order to make measurements from different treatments under the same weather conditions, would be very costly. But, if comparisons are made in sequence, using the same facilities, adapted for the different manure management systems, then replication is by time, and temperature, wind speed and other environmental factors may differ and introduce confounding with the treatments, especially during application, making analysis of the results problematic. It would also be useful to incorporate N- and TAN-excretion calculations based on feed intake into measuring protocols. This would enable expression of results in a form which makes results from different studies easier to compare and also make it easier to incorporate the data into N- and TAN-flow models. However one must bear in mind that for an individual batch of manure, the relation between TAN and NH_3 emission is also related to the concentration of TAN. If a lot of litter is used, then even if large amounts of TAN are produced, the concentration of TAN in the manure may be low, resulting in a little NH_3 emission per mass unit of manure.

5.2 Land Application

With respect to our evaluation strategy we conclude it is possible to propose some robust emission factors. The data indicate that NH_3 emissions from cattle, pig and poultry manure are likely to range between 0.80–0.90, 0.50–0.65 and 0.40–0.50 TAN, respectively. It is difficult however to suggest discrete emission factors for subcategories (e.g. dairy cattle, beef cattle, laying hens, broilers). Incorporation was found to be an appropriate measure to abate emissions after spreading of manure. Rapid incorporation was more effective than incorporation after longer intervals. The reduction achieved using a plough for incorporation was greater than from other machines, probably because the working depth was the greatest. The effect of the other potential mitigation measures such as addition of straw in buildings, storage before application and measures during storage such as compaction and the covering with sheeting or wetting of the manure after application were less clear.

Storage before application tended to produce less NH_3 emissions following application.

For N_2O, the variability in the data was large, based on few datasets which reported large emissions. For the statistical evaluation, the data were log transformed (see Sect. 4.1.3). To summarize the results here we used the median which is less influenced by extreme values. Amount of litter in the manure, storage before spreading, storage conditions and incorporation after application did not significantly influence the emissions. We concluded that measures reducing NH_3 emissions such as rapid incorporation do not necessarily lead to increases in N_2O emissions. Median N_2O emissions after spreading of manure were 0.030, 0.003 and 0.006 TAN for cattle, pigs and poultry respectively.

Even though more data were available for gaseous emissions from field-applied manure than for emissions from livestock housing and storage, the database is still limited. We suggest that additional studies focusing on determining absolute NH_3 fluxes from solid manure systems are carried out in order to supply an improved and scientifically sound base, e.g. for modelling purposes. More data for both N_2O and CH_4 emissions are required as well since the database of emissions of these gases from solid manure is much smaller still. These findings make it very difficult to construct mass flow models for solid manure. However, we consider that the development of mass flow models should continue using the limited data available and the output validated against manure analysis data, as was done for the NARSES model (Webb and Misselbrook 2004). Such development identifies gaps in our knowledge and areas of uncertainty that can be given priority for future measurements.

Acknowledgements The authors wish to acknowledge support from: the Federal Office for the Environment (Switzerland), Danish Council for Strategic Research (DSF) under the research program “Strategic Research in Sustainable Energy and Environment” to the project “Clean and environmentally friendly animal waste technologies for fertilizer and energy production (Cleanwaste)”; the Dutch Ministry of agriculture, nature and food quality. We thank Laura Valli of CRPA (Italy) and Melynda Hassouna (INRA) for providing data for the study. We also thank Sabine Guesewell (Swiss College of Agriculture) for the statistical evaluation and Harald Menzi for discussion during preparation of the paper.

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Communication in the Rhizosphere, a Target for Pest Management

Juan Antonio López-Ráez, Harro Bouwmeester, and Maria J. Pozo

Abstract The industrial agriculture has given rise to an excessive use and misuse of agrochemicals causing environmental pollution. Therefore, it is urgent to find alternatives that are more environmentally friendly than chemical fertilizers and pesticides for disease control. The key to achieve successful biological control strategies is the knowledge of the ecological interactions that occur belowground. The rhizosphere constitutes a very dynamic environment harbouring the plant roots and many organisms. Plants communicate and interact with those organisms through the production and release of a large variety of secondary metabolites into the rhizosphere. Thus, they use these metabolites to defend themselves against soil-borne pathogens, which can adversely affect plant growth and fitness, but also to establish mutualistic associations with beneficial soil microorganisms. However, despite the importance of these plant-organism interactions the mechanisms regulating them remain largely unknown.

We review here chemical communication that takes place in the rhizosphere between plants and other soil organisms, and the potential use of this molecular dialogue for developing new biological control strategies against deleterious organisms. We focus on the knowledge of the root parasitic weed germination stimulants – strigolactones – to develop more efficient control methods against this pest.

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E. Lichtfouse (ed.), *Agroecology and Strategies for Climate Change*,
Sustainable Agriculture Reviews 8, DOI 10.1007/978-94-007-1905-7_5,

Finally, we illustrate this with an exciting example: the use of the mutualistic arbuscular mycorrhizal symbiosis for controlling root parasitic weeds by reducing the production of strigolactones in the host plant.

Keywords Rhizosphere • Chemical communication • Signalling • Biological control • Strigolactones • Arbuscular mycorrhizal fungi • Root parasitic plants • Soil-borne pathogens

Abbreviations

AM	arbuscular mycorrhiza
AHL	N-acyl homoserine lactone
PGPF	plant growth promoting fungi
PGPR	plant growth promoting rhizobacteria
QS	Quorum sensing

1 Introduction

Plants are living organisms that continuous and reciprocally communicate with other organisms in their environment. However, unlike animals plants cannot speak, see, listen or run away, and therefore they largely rely on chemicals as signalling molecules to perceive environmental changes and survive. Thus, plants use flower colour and volatiles to attract pollinators, use chemicals to defend themselves against enemies such as pathogens and herbivores, but they also use signalling molecules to establish mutualistic beneficial associations with certain microorganisms such as bacteria and fungi (Fig. 1). Microorganisms can affect plant growth and development, change nutrients dynamics, susceptibility to disease, tolerance to heavy metals, and can help plants in the degradation of xenobiotics (Morgan et al. 2005). As a result, these plant-microorganism interactions have considerable potential for biotechnological exploitation. A nice example of this complex and precisely regulated signalling takes place underground, where plants use the roots to communicate and interact with other organisms in the so-called rhizosphere.

The term rhizosphere derives from the Greek words *rhiza*, which means root, and *sphere*, meaning field of influence (Morgan et al. 2005). The rhizosphere is the narrow soil zone surrounding plant roots that contains a wide range of organisms and is highly influenced by the roots, the root exudates and by local edaphic factors (Bais et al. 2006; Badri et al. 2009). Originally, the root system was thought only to provide anchorage and uptake of nutrients and water. However, it has been shown that roots are chemical factories that mediates numerous underground interactions

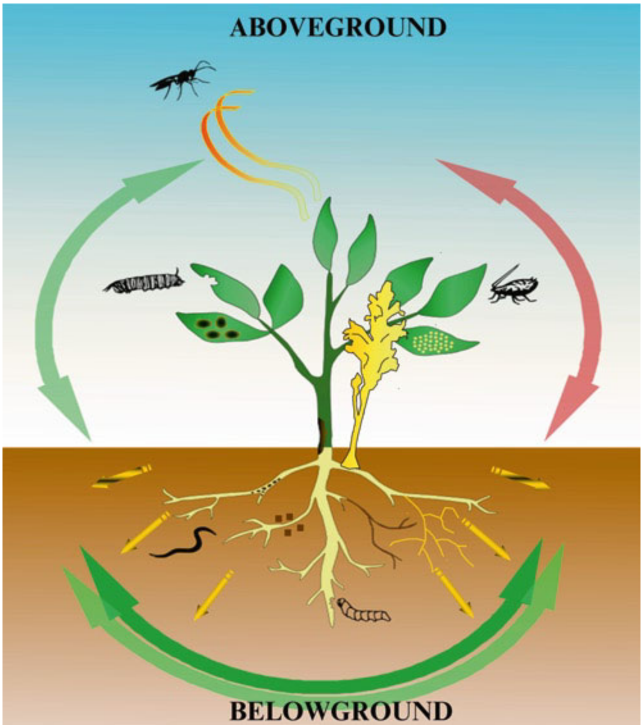

Fig. 1 Plant interactions with other organisms. Positive and negative interactions occurring aboveground and belowground in the rhizosphere. *Yellow arrows* indicate root exudates (Adapted from Pozo and Azcón-Aguilar 2007)

(Badri et al. 2009). Plants produce and exude through the roots a large variety of chemicals including sugars, amino acids, fatty acids, enzymes, plant growth regulators and secondary metabolites into the rhizosphere some of which are used to communicate with their environment (Siegler 1998; Bertin et al. 2003; Bais et al. 2006). Moreover, the release of root exudates together with decaying plant material provides carbon sources for the heterotrophic soil biota. On the other hand, microbial activity in the rhizosphere affects rooting patterns and the supply of available nutrients to plants, thereby modifying the quantity and quality of root exudates (Barea et al. 2005). Of special interest in this rhizosphere communication are the so-called secondary metabolites, which received this name because of their presumed secondary importance in plant growth and survival (Siegler 1998). These metabolites include compounds from different biosynthetic origins and have been shown to be of ecological significance because they are important signals in several mutualistic and pathogenic plant-organism interactions (Estabrook and Yoder 1998; Siegler 1998; Bertin et al. 2003; Bais et al. 2006).

2 Interactions in the Rhizosphere

In the rhizosphere some of the most complex chemical, physical and biological interactions between plant roots and other organisms occur influencing plant fitness. Among these relationships we can find root-root, root-microbe and root-insect interactions. Many of these interactions have a neutral effect on the plant. However, the rhizosphere is also a playground for beneficial microorganisms establishing mutualistic associations with plants, and a battlefield for soil-borne pathogens which establish parasitic interactions (Raaijmakers et al. 2009).

2.1 Parasitic Interactions

As mentioned above, the rhizosphere is not only the playground for mutualistic associations, but also a battlefield where parasitic interactions between plants and soil-borne pathogens take place (Raaijmakers et al. 2009). In most agricultural ecosystems, these negative interactions are economically important as they cause important limitations in the production of marketable yield. It has long been understood that the development of disease symptoms is not solely determined by the pathogen responsible, but is also dependent on the complex interrelationship between host, pathogen and prevailing environmental conditions. Negative interactions with plant roots include pathogenesis by bacteria, true fungi or oomycetes, invertebrate herbivory and parasitism between plants (Agrios 2005; Bais et al. 2006). Among them, fungi and oomycetes, nematodes and parasitic plants are major players in the rhizosphere exerting a serious threat to world agricultural production. Comparatively, fewer bacteria are considered as soil-borne plant pathogens, with some exceptions such as *Ralstonia solanacearum* (causing bacterial wilt of tomato), the enteric phytopathogen *Erwinia carotovora*, responsible of the bacterial soft rot, and *Agrobacterium tumefaciens*, the causal agent of crown gall disease (Hirsch et al. 2003; Genin and Boucher 2004; Badri et al. 2009).

2.1.1 Fungi and Oomycetes

Soil-borne fungal plant pathogens are important determinants in the dynamics of plant populations in natural environments and in agriculture. Fungi and oomycetes are the most important soil-borne microbial plant pathogens, causing economically important losses. They can cause complete destruction of plants and even the total loss of yield (Otten and Gilligan 2006). More than 8,000 species of fungi are known to cause diseases of plants, and most plants are susceptible to several fungal pathogens. The majority of soil-borne fungi are necrotrophic, implying that they do not require a living cell to obtain nutrients. They normally use enzymes and toxins to kill host tissue before hyphal penetration and infection. The most harmful root pathogenic fungi include the genera *Fusarium* spp, *Verticillium* spp and *Rhizoctonia solani*, which affect crops such as barley, wheat, maize, potato and tomato all over the world (Priest and Campbell 2003; Garcia et al. 2006).

The oomycetes include a unique group of biotrophic and hemibiotrophic plant pathogens that gain their nutrients from living cells, and are considered as non-true fungi. Indeed, although they are physiologically and morphologically similar to fungi they belong to different phylogenetical groups. The oomycetes are phylogenetically more closely related to brown algae than to fungi and, in contrast to fungi, they contain cellulose in their cell wall instead of chitin (Raaijmakers et al. 2009). However, despite being only distantly related to fungi, the oomycetes have developed very similar infection strategies. These pathogens establish intimate relations with their hosts by forming an organ called haustorium, which is used to obtain nutrients from the plant, redirecting host metabolism and suppressing host defences. The oomycetes include some of the most destructive plant pathogens worldwide, particularly in the genera *Phytophthora* and *Phytium*, that affect important crops such as potato, tomato, lettuce and soybean (Raaijmakers et al. 2009).

2.1.2 Nematodes

Nematodes are small and complex worm-like eukaryotic invertebrates that rank among the most numerous animals on the planet (Perry and Moens 2006). Most nematodes in soil are free-living and consume bacteria, fungi and other nematodes, but some can also parasitize plant roots being important crop pests in agricultural ecosystems. Some feed on the outside of the root (ectoparasites), some penetrate and move inside the root (endoparasites), and some set up a feeding site in the interior of the root and remain there for reproduction (sedentary endoparasites). Upon infection, nematodes cause important changes in root cells in order to complete their life cycle. Although the parasitism is rarely fatal for the infected plant, there are substantial consequences of the interaction such as stunted growth, chlorosis and poor yields. The most economically important groups of nematodes are the sedentary endoparasites, which include the genera *Meloidogyne* (root-knot nematodes) and *Heterodera* and *Globodera* (cyst nematodes). They are particularly important in tropical and subtropical regions (Bird and Kaloshian 2003; Williamson and Gleason 2003).

Root-knot nematodes are obligate biotrophic pathogens found in all temperate and tropical areas that have evolved strategies for infesting thousands of plant species such as cereals, tomato, potato and tobacco (Caillaud et al. 2008). These root pathogens must locate and penetrate a root, migrate into the vascular cylinder and establish a permanent feeding site, known as giant cells. Unlike root-knot nematodes, cyst nematodes are only able to infect a few plant species, principally soybean and potato, and are more destructive as they migrate and travel intracellularly through the root (Fuller et al. 2008). In both cases, these events are accompanied by extensive signalling between the nematode and the host.

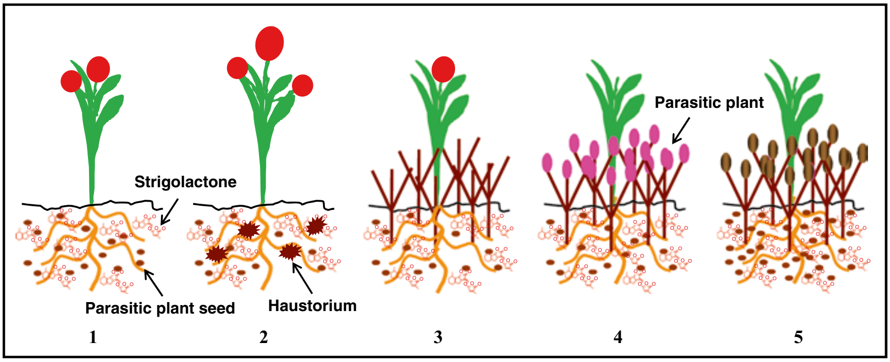

Fig. 2 Life cycle of root parasitic plants. (**a**) Seeds are buried in the soil and perceive the germination stimulants exuded by the roots of the host plant, strigolactones, and germinate. **(b)** The germinated seeds form a haustorium by which they attach to the host root, establishing a xylem-xylem connection. (**c**) The parasitic plant develops, and the shoots emerge from the soil. There is areduction of host growth. (**d**) Parasitic plant flowering and crop yield reduction. (**e**) Production of mature seeds that end up in a new generation of seeds in the soil (Redrawn from Sun et al. 2007)

2.1.3 Root Parasitic Plants

Root parasitic plants of the family Orobancheaceae, including the *Striga*, *Orobanche* and *Phelipanche* genera are some of the most damaging agricultural pests, causing large crop losses. These obligate root parasites attach to the roots of many plant species and acquire nutrients and water from their host through a specialized organ called haustorium (Estabrook and Yoder 1998; Bouwmeester et al. 2003). *Striga* is a hemiparasite, which means that it obtains nutrients from its host but it can also perform its own photosynthesis. It infects important crops such as maize, sorghum, pearl millet, finger millet and upland rice, causing devastating losses in cereal yields in Africa (Gressel et al. 2004). On the other hand, the holoparasitic (lacking chlorophyll and being completely dependent on their host) *Orobanche* and *Phelipanche* spp. affect important agricultural crops in more temperate climates such as southern Europe, Central Asia and the Mediterranean area parasitizing legumes, tobacco, crucifers, sunflower and tomato (Joel et al. 2007).

Although root parasitic plants parasitize different hosts in different parts of the world, their lifecycles are very similar and involve germination in response to a root host stimulus, radicle growth towards the host root, and attachment and penetration through the haustorium (Fig. 2). Upon vascular connection, the parasitic plant obtains nutrients and water from the host plant, negatively affecting plant fitness and crop yield. After emergence from the soil, parasitic plants will flower and produce new ripe seeds that are shattered increasing the seed bank (Fig. 2) (Bouwmeester et al. 2003; López-Ráez et al. 2009). Parasitic weeds are difficult to control because most of their life cycle occurs underground and therefore new control strategies that focus on the initial steps in the host-parasite interaction are required (López-Ráez et al. 2009).

2.2 Mutualistic Beneficial Associations

The rhizosphere generally helps the plant by maintaining the recycling of nutrients, providing resistance to diseases and to improve tolerance to toxic compounds. When plants lack essential mineral elements, such as phosphorous or nitrogen, symbiotic relationships can be beneficial and promote plant growth. Thus, plants biologically interact with other organisms to establish mutualistic associations which rely on a mutual fitness benefit. Mutualism is very ancient, indeed is thought to have driven the evolution of much of the biological diversity present today (Thompson 2005). In addition, mutualism plays a key role in ecology being very important for the correct functioning of the terrestrial ecosystem. Microorganisms that positively affect plant growth and health include the plant growth-promoting rhizobacteria (PGPR) and plant growth-promoting fungi (PGPF), the nitrogen-fixing *Rhizobium* bacteria (rhizobia), and the mycorrhizal fungi (mycorrhiza). The PGPR are non-symbiotic beneficial rhizosphere bacteria that are known to participate in many important ecosystem processes, such as nitrogen fixation, nutrient cycling, seedling growth, phytohormone production, and biological control of plant pathogens (Barea et al. 2005; Raaijmakers et al. 2009). The most commonly genera described as including PGPR are *Pseudomonas* and *Bacillus*. The PGPF include rhizospheric non-symbiotic beneficial fungi from the Deuteromycetes, e.g. *Trichoderma*, *Gliocladium* and non-pathogenic *Fusarium oxysporum* (Raaijmakers et al. 2009). These ubiquitous soil fungi are effective in controlling a broad range of phytopathogenic fungi by competition, antibiosis and mycoparasitism (Raaijmakers et al. 2009).

Other beneficial microorganisms, the endophytes, establish mutualistic symbiosis with plants by colonizing the root tissues and promote plant growth and plant protection (Barea et al. 2005). Although new endophytic microbes which colonize roots and promote plant growth are being found such as the fungus *Piriformospora indica* (Varma et al. 1999), the best studied examples of rhizosphere mutualism are those established with rhizobia bacteria and mycorrhizal fungi.

2.2.1 Rhizobia

Rhizobia are free-living soil bacteria which colonize plant roots (endosymbionts) establishing a mutualistic relationship with most of the plant legume species worldwide (Sprent 2009). The two partners cooperate in a nitrogen-fixing symbiosis of major ecological importance because in many environments nitrogen limits plant growth (Masson-Boivin et al. 2009). Legume-rhizobia symbiosis is a classic example of mutualism, where rhizobia supply ammonia (NH_4^+) or amino acids to the plant and in return receive organic acids (principally malate and succinate) as a carbon and energy source, proteins and sufficient oxygen to facilitate the fixation process (Fig. 3a). Fixed nitrogen is a limiting nutrient in most environments, with the main reserve of nitrogen in the biosphere being the molecular nitrogen in the atmosphere. Molecular nitrogen cannot be directly assimilated by plants, but it

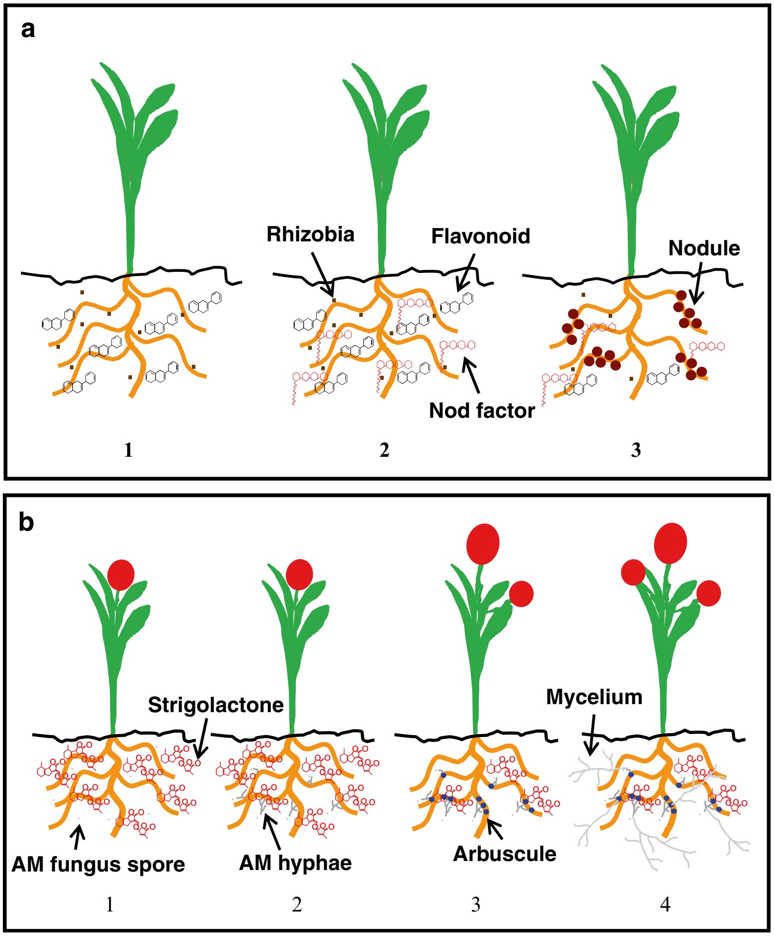

Fig. 3 Scheme of signalling and establishment of plant-microorganism mutualistic associations in the rhizosphere. (**a**) Molecular signalling and nodulation process during rhizobia-legume association; *1* Production of flavonoids by the host plant under low nitrogen conditions. *2* Flavonoids are perceived by the bacteria and induce the production of the bacterial Nod factors. 3 Nod factors are recognized by the host plant and initiate the symbiotic program for nodulation. (**b**) Molecular signalling and mycorrhizal establishment between plants and arbuscular mycorrhizal (AM) fungi; *1* Under phosphate deficient conditions plants release the signalling molecules strigolactones. *2* Strigolactones are perceived by germinating spores of AM fungi and induce hyphal branching and growth towards the host root. *3* AM hyphae produce Myc factors which are perceived by the host plant initiating the symbiotic program. *4* AM fungus colonizes the host root forming arbuscules and develops an external mycelia network. AM symbiosis and nodulation increase plant fitness and crop production

becomes available through the biological nitrogen fixation process that only some prokaryotic cells (diazotrophs), including rhizobia, have developed (Masson-Boivin et al. 2009).

In rhizobial plants, nitrogen fixation takes place in special organs known as nodules. On the roots of host plants, principally in the root hairs, rhizobia colonize intracellularly by triggering the formation of an infection thread structure that elongates, ramifies and penetrates inside the emerging nodule. Then, they become internalized in plant cells via an endocytosis-like process. Once reached the central tissue, known as symbiosome, release the rhizobia in these cells where they multiply and differentiate morphologically into bacteroids. Within the nodules the host plant provides the bacteria with the carbohydrates they need. In return, the bacteroids by the action of the enzyme nitrogenase fix the atmospheric nitrogen from the atmosphere into a plant usable form (NH_4^+). Then, the NH_4^+ is converted into amides or ureides which are translocated to the plant xylem (Masson-Boivin et al. 2009).

2.2.2 Mycorrhiza

Fungi are eukaryotic, filamentous, multicellular and heterotrophic organisms that produce a network of hyphae called mycelium which absorbs nutrients and water from the surrounding substrate. Mycorrhiza is a symbiotic, generally mutualistic symbiosis established between certain soil fungi and the roots of most vascular plants, including agricultural and horticultural crop species (Smith et al. 2006; Smith and Read 2008). Mycorrhizas are commonly grouped into two categories based on their colonization style. They are considered either ectomycorrhiza if they colonize host plant roots extracellularly or endomycorrhiza, if they colonize intracellularly. Ectomycorrhiza are typically formed between the roots of around 10% of plant families, mostly woody plants, and fungi belonging to the Basidiomycota, Ascomycota, and Zygomycota (Bonfante and Genre 2010). Ectomycorrhizas consist of a hyphal sheath, or mantle covering the root tip and a hartig net of hyphae surrounding the plant cells within the root cortex. Endomycorrhiza include the arbuscular mycorrhizal (AM) symbiosis, the ericoid mycorrhiza established with members of the family Ericaceae and the orchid mycorrhiza, a symbiotic relationship between fungi and the roots of plants of the family Orchidaceae (Smith and Read 2008).

Among them, the AM symbiosis is the most common form of mycorrhizal symbiosis and consists of an association established between certain soil fungi of the phylum Glomeromycota – which is widely distributed throughout the world – and over 80% of terrestrial plants, including most agricultural and horticultural crop species (Smith et al. 2006; Parniske 2008). This association is considered to be older than 400 million years and it has been postulated to be a key step in the evolution of terrestrial plants (Smith et al. 2006). AM fungi are obligate biotrophs and therefore they depend entirely on the plant to complete their life cycle (Fig. 3b). They colonize the root cortex forming specialized and tree-like subcellular structures called arbuscules for nutrient exchange (Parniske 2008). Through the symbiosis, the fungus obtains carbohydrates from the host plant for which, in return, the fungus assists the plant in the acquisition of mineral nutrients (mainly phosphorous) and water, hence improving plant fitness (Fig. 3b). AM symbiosis gives rise to the formation of mycorrhizal networks that offer a number of advantages for the acquisition of nutrients such as fungal hyphae extension beyond the area of nutrient depletion and increase of the surface area for the absorption of nutrients. Moreover, some mycorrhizal fungi can access forms of nitrogen and phosphorous that are not available to non-mycorrhizal plants, for example when bound in organic forms (Morgan et al. 2005). Thus, AM symbiosis contributes to global phosphate and carbon cycling and influences primary productivity in terrestrial ecosystems (Fitter 2005). Besides improving the nutritional status, the symbiosis enables the plant to perform better under stressful conditions (Pozo and Azcón-Aguilar 2007; Parniske 2008). Therefore, AM symbiosis plays a crucial role in agriculture and natural ecosystems.

In summary, the rhizosphere is an environment influenced by the plant root exudates where both pathogenic and beneficial interactions between plant and other organisms constitute a major influential force on plant growth and fitness, soil quality and ecosystem dynamics.

3 Molecular Dialogue in the Rhizosphere

All the different interactions reported above are based on molecular communication occurring belowground. Plants produce and release enormous amounts of chemicals into the rhizosphere through their roots in order to communicate and interact with their environment. Root exudates can be divided into two classes of compounds: high-molecular weight such as polysaccharides and proteins, and low-molecular weight compounds including amino acids, organic acids, sugars, phenolics, and other secondary metabolites (Bais et al. 2006). Although the functions of most of the compounds present in root exudates have not been determined so far, it has been determined that several of them are essential to establish plant interactions with other organisms in the rhizosphere. Equally, chemical signals secreted by the rhizospheric organisms are also involved in early steps of host recognition and colonization, and necessary for the establishment of the association. These signalling molecules are important in both negative and positive interactions (Bais et al. 2006).

3.1 Communication Between Plants and Parasites

In plant-plant interactions, plants secrete phytotoxins such as the flavonoids cathechins and benzoflavones, and sorgoleone that reduce the establishment, growth, or survival of susceptible plant neighbours, a phenomenon known as allelopathy, from the Greek words *allele* (mutual) and *pathy* (harm or suffering), to avoid competition with other plant species (Weir et al. 2004). Plants also produce germination stimulants of seeds the root parasitic plants of the genera Orobancheaceae – strigolactones – which are essential for the establishment of a negative association (Bouwmeester et al. 2003) (see Sect. 6).

In addition to plant-plant interactions, plants produce and exudate antimicrobial secondary metabolites such as indole, terpenoids, phenylpropanoids including the flavonoids (e.g. rosmarinic acid) which show potent antimicrobial activity against an array of soil-borne pathogens (Bais et al. 2002). Antimicrobial compounds can be classified in two different classes: phytoanticipins, which occur constitutively in healthy plants acting as chemical barriers to fungal pathogens, and phytoalexins, including terpenoids, glycosteroids and alkaloids, that are induced in response to pathogen attack but not normally present in healthy plants (Badri et al. 2009). It has been described that phenylpropanoid levels, a diverse family of organic compounds derived from the amino acid phenylalanine which provide protection against herbivores and pathogens, were significantly higher in roots that were challenged by non-host bacterial pathogens *Pseudomonas syringae* strains compared to host bacterial strains (Bais et al. 2006). Bacterial pathogens able to infect roots and cause disease were resistant to these compounds, suggesting an important role of phenylpropanoids in defense against non-host pathogens (Bais et al. 2006).

Besides functioning as antimicrobial compounds, some secondary metabolites can act as chemoattractants for certain pathogens. For example, it has been shown that before infection establishment, zoospores of the pathogen oomycete *Phytophthora sojae* are chemically attracted by the isoflavones daidzein and genistein secreted by soybean roots (Hirsch et al. 2003). In a large number of pathogenic bacteria, initiation of the production and secretion of virulence factors is controlled by a phenomenon known as quorum-sensing (QS). QS is a cell-cell communication and density-dependent regulatory mechanism which is mainly induced by the small molecules N-acyl homoserine lactones (AHLs) (Bais et al. 2006). The rhizosphere contains a higher proportion of AHL-producing bacteria than bulk soil, suggesting that they play a role in colonization (Bais et al. 2006). It has been also suggested that plants could be using root-exuded compounds in the rhizosphere to take advantage of this bacterial communication system and influence colonizing communities.

On the other hand, the association between plants and nematodes is also subjected to an extensive signalling between the nematode and its host, although the knowledge of the initial signalling molecules is scarce. It was shown that hatching of juveniles of the cyst nematode *Globobera* is controlled by solanoeclepin A, a molecule secreted by the roots of some Solanaceae species such as potato and tomato (Schenk et al. 1999). More recently, it has been reported that Medicago roots released a volatile (dimethyl sulphide) that attract nematodes (Horiuchi et al. 2005). Reciprocally, nematodes secrete cytokinins that play a role in cell cycle activation and in establishing the feeding in the host root.

3.2 Chemical Signalling Between Plants and Mutualists

A functional mutualistic relationship also implies and requires a signal exchange between both partners that leads to mutual recognition and development of symbiotic structures (Siegler 1998). Moreover, this molecular dialogue must be precisely regulated in order to avoid opportunities for malevolent organisms (Hirsch et al. 2003; Bouwmeester et al. 2007). An important number of plant-derived signalling molecules destined to the establishment of beneficial associations with soil microbe partners belong to the class of the secondary metabolites (Siegler 1998; Steinkellner et al. 2007). We will go into detail on a number of them, the flavonoids and the strigolactones, which are key signalling molecules in the interaction rhizobia-legume and in AM symbiosis, respectively.

3.2.1 Communication in Nodulation

Rhizobia-legume symbiosis is an ecologically important mutualistic association because of its implication in nitrogen fixation. The establishment of this symbiosis requires a high degree of coordination between the two partners, which is based on a finely regulated molecular dialogue that orchestrates the complex symbiotic program (Garg and Geetanjali 2007; Badri et al. 2009) (Fig 3a). The chemical communication between the plant and the bacteria starts, before there is any contact between the partners, with the production of flavonoids and isoflavonoids by the host plant (Badri et al. 2009; Faure et al. 2009). More than 4,000 different flavonoids have been identified in vascular plants, but just a small subset of them are involved in this mutualistic interaction (Bais et al. 2006). Host legume-derived flavonoids and related compounds act as chemo attractants for rhizobial bacteria and as specific inducers of rhizobial nodulation genes (*nod* genes), that encode the biosynthetic machinery for a bacterial signal – the lipochitooligosaccharides – that are released into the rhizosphere (Fig. 3a) (Perret et al. 2000; Reddy et al. 2007). These bacterial-derived signals are known as Nod factors, and are specific for different rhizobial strains. In turn, Nod factors are perceived by the host plant which leads to the induction of root hair deformation and several cellular responses such as ion fluxes. This mutual recognition precedes the intracellular infection by the bacteria through the deformed root hair. The infection triggers cell division in the cortex of the root where a new organ, termed nodule, appears as a result of successive processes (Fig. 3a). Finally, in the nodule nitrogen fixation takes place by the bacteria (see Sect. 2.2.1). Interestingly, this signal-detection machinery for interaction with beneficial rhizobia employs common components that are also implicated in the detrimental association with root-knot nematodes (Weerasinghe et al. 2005).

3.2.2 Signalling During Arbuscular Mycorrhizal Symbiosis

In addition to their involvement in the rhizobia-legume symbiosis, flavonoids play a role also in the AM symbiosis, which is also of ecological importance because it contributes to phosphate and carbon cycling. Flavonoids act as stimulants of AM fungi hyphal growth, differentiation and root colonization (Steinkellner et al. 2007). Besides flavonoids, the strigolactones, a recently described new class of plant hormones regulating plant architecture (Gomez-Roldan et al. 2008; Umehara et al. 2008; Koltai et al. 2010; Ruyter-Spira et al. 2011), have been shown to be crucial for a successful root colonization by the AM fungi (Akiyama et al. 2005). Interestingly, strigolactones are present in the root exudates of a wide range of plants and trigger a response only in AM fungi, not in other beneficial fungal species such as *Trichoderma* and *Piriformospora* (Steinkellner et al. 2007).

AM fungi depend entirely on their plant host to complete their life cycle (Fig. 3b). As for the rhizobia-legume association, AM symbiosis establishment and functioning also require a high degree of coordination between the two partners (Paszkowski 2006; Hause et al. 2007; Requena et al. 2007). The AM fungi-plant host molecular dialogue starts in the rhizosphere with the production of strigolactones by the host plant that induce hyphal branching in germinating spores of AM fungi (Akiyama et al. 2005; Besserer et al. 2006; Parniske 2008). Spores of AM fungi can germinate spontaneously and undergo an initial asymbiotic stage of hyphal germ tube growth, which is limited by the amount of carbon storage in the spore. If a partner is nearby, the hyphal germ tube grows and ramifies intensively through the soil towards the host root (Bouwmeester et al. 2007). It has been suggested that these signalling molecules, later known as strigolactones, may also act as the chemoattractant that directs the growth of the AM hyphae to the roots (Sbrana and Giovannetti 2005). Once the host-derived strigolactones are perceived by the fungus, it engages its catabolic metabolism which results in hyphal branching that will increase the probability to contact the root and establish symbiosis. Similarly to the nodulation process, it has been proposed that a Myc factor analogous to the rhizobial Nod factor and produced by the metabolic active fungus, induces molecular responses in the host root required for a successful AM fungal colonization (Fig. 3b) (Kosuta et al. 2003; Bucher et al. 2009). The chemical nature of the elusive Myc factor, has remained unknown for a long time. However, it has been recently shown to have structural similarities with rhizobial Nod factors (Maillet et al. 2011).

Despite the importance of strigolactones in the initiation of AM symbiosis, it is unknown whether they also play a role in subsequent steps of the symbiosis. Since strigolactones are considered plant hormones and are ubiquitous in plants, it is tempting to speculate about their involvement in other plant-microorganism interactions in the rhizosphere. Indeed, it has been recently shown that strigolactones positively affect nodulation, although their effect was not due to an effect on the bacteria (Soto et al. 2010). Probably, this just represent the tip of the iceberg of biological roles for the strigolactones, showing the biological and ecological importance of these signalling compounds.

Thus, plants form associations – either beneficial or detrimental – with other organisms in the rhizosphere. Interestingly, most of these interactions are facilitated by a molecular dialogue between the host and the symbionts through chemical cues, which are crucial for the establishment of these belowground associations. However, although some of these signalling molecules have been identified there are still many other unknown factors involved.

4 Regulation of Chemical Communication in the Arbuscular Mycorrhizal Symbiosis

As mentioned above, one of the primary roles of AM fungi in the symbiotic relationship with plants is the supply of water and mineral nutrients, mainly phosphorous and nitrogen (Harrison 2005; Karandashov and Bucher 2005; Yoneyama et al. 2007). In many areas of the world the concentration or availability of these essential mineral nutrients in the soil is low, which results in an important negative impact on plant growth and fitness. Phosphorous, which is taken up from the soil as phosphate, is one of the least available of all essential nutrients in soils because of its low mobility, resulting in phosphate depletion in the rhizosphere. Moreover, the majority of the applied phosphorus may be fixed in the soil due to the interaction with other ions and hence be unavailable to plants (Raghothama 2000). Similarly, nitrogen availability may be limited due to its loss through volatilization and leaching (Delgado 2002).

In agreement with the important role of AM fungi in the acquisition of mineral nutrients, it was observed that root exudates produced by plants grown under phosphate limited conditions are more stimulatory to AM fungi than exudates produced under adequate phosphate nutrition (Nagahashi and Douds 2004). Moreover, it was shown that phosphate and nitrogen deficiency have a significant stimulatory effect on the production and exudation of strigolactones by plants (Yoneyama et al. 2007; López-Ráez et al. 2008a). Yoneyama and co-workers have suggested that the response of strigolactones production and exudation to nutrient availability varies between groups of plant species (Yoneyama et al. 2007). Thus, legumes, that can establish symbiosis with rhizobia and acquire nitrogen from root nodules, only respond to phosphate deficiency with enhanced strigolactone production to attract AM fungi, whereas in non-leguminous plant species such as tomato both phosphate and nitrogen starvation enhance the production of strigolactones. The strigolactones have been detected in the root exudates of a wide range of plant species including mono- and dicotyledonous, indicating their broad spectrum of action and importance in nature (Bouwmeester et al. 2007; Yoneyama et al. 2008).

Future research is required to elucidate the mechanisms by which the chemical signalling between plants and AM fungi is regulated to further optimize this beneficial mutualistic association.

5 Strigolactones: Ecological Significance in the Rhizosphere

Strigolactones have been recognized as a new class of plant hormones that inhibits shoot branching and hence controls above ground architecture (Gomez-Roldan et al. 2008; Umehara et al. 2008). More recently, it has been suggested that they also affect root growth and root hair elongation (Koltai et al. 2010; Ruyter-Spira et al. 2011), which shows they are even more important components in the regulation of plant architecture than already postulated. Long before the discovery of their function as plant hormones, the strigolactones were described as germination stimulants for the seeds of root parasitic plants *Striga*, *Orobanche* and *Phelipanche* spp (Cook et al. 1972; Bouwmeester et al. 2003) (see Sect. 2.1.3). They are produced and exuded into the rhizosphere by plants in very low amounts, can stimulate the germination of these parasitic plants in nano- and pico-molar concentrations, and are instable in a watery environment and in alkaline soils (Bouwmeester et al. 2007; Yoneyama et al. 2009; Zwanenburg et al. 2009). Strigolactones are derived from the carotenoids (Matusova et al. 2005; López-Ráez et al. 2008a) and all the strigolactones characterized so far are remarkably similar, showing a similar chemical structure (Fig. 4) (Rani et al. 2008; Yoneyama et al. 2009; Zwanenburg et al. 2009). The structural core of the molecules consists of a tricyclic lactone (the ABC-rings) connected via an enol ether bridge to a butyrolactone group (the D-ring). It has been suggested that the biological activity of the strigolactones resides in the enol ether bridge, which can be rapidly cleavage in an aqueous and/or alkaline environment (Yoneyama et al. 2009; Zwanenburg et al. 2009; Akiyama et al. 2010).

An intriguing question was why plants would produce compounds that have such negative consequences (parasitiation by parasitic plants) for the plants themselves. The answer to this question came only few years ago when Akiyama and co-workers demonstrated that these secondary metabolites are involved in signalling between plants and mutualistic AM fungi (Akiyama et al. 2005). We now know that under nutrient deficient conditions plants increase the production of strigolactones to attract AM fungi and establish a mutualistic relationship, but the parasitic weeds have evolved a mechanism by which they can abuse this ‘cry for help’ plant signal to establish a negative interaction (Bouwmeester et al. 2007) (Fig. 4). The ability to develop AM symbiosis is of great advantage to plants and this, therefore, likely explains why strigolactones are secreted by plants despite the possibility of being abused by root parasitic plants.

Again, a better understanding about how strigolactone signalling is regulated and the possible specificity of different strigolactones seems crucial to further evaluate their importance in the plant-parasitic plant and plant-AM fungus interactions and favor one against another.

6 Control Strategies Against Root Parasitic Plants

As mentioned in Sect. 2.1.3, root parasitic plants are a serious threat to agriculture causing enormous crop losses worldwide. One of the reasons of their devastating effect is that these parasitic weeds are difficult to control because most of their life-cycle occurs underground (Fig. 2). This fact makes the diagnosis of infection difficult and normally only after irreversible damage has already been caused to the crop. To date, a wide number of approaches such as hand weeding, crop rotation, sanitation, fumigation, solarization and improvement of soil fertility are being used to control root parasites without the desirable success (Joel et al. 2007; Rispail et al.

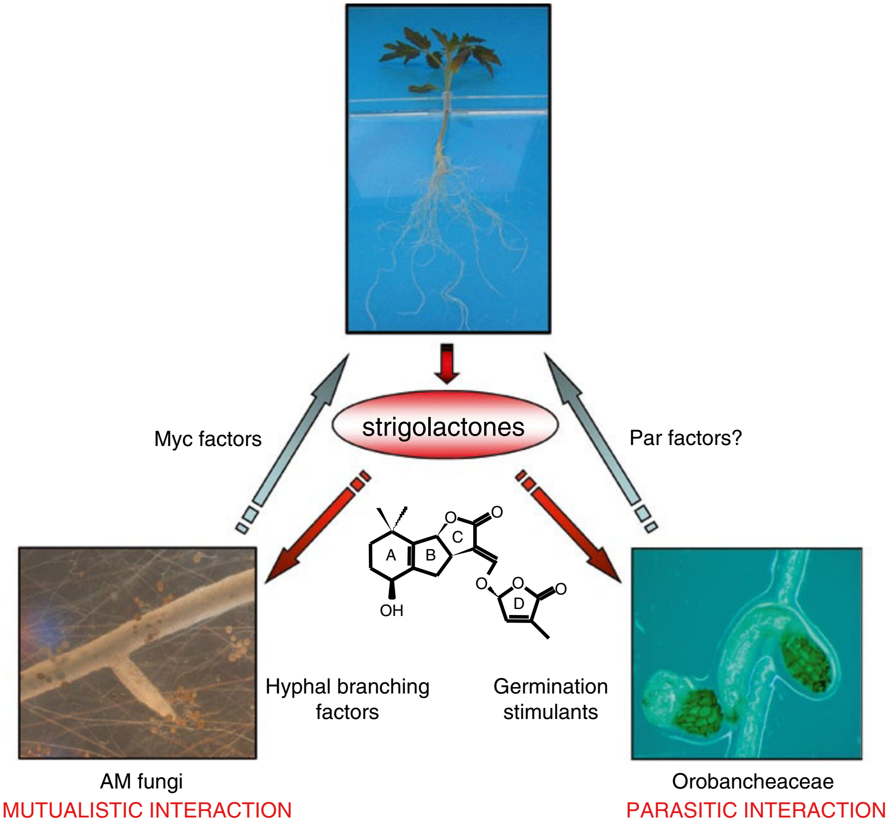

Fig. 4 Underground communication between plants, arbuscular mycorrhizal (AM) fungi and parasitic plants. Plants produce and release strigolactones into the rhizosphere to communicate with AM fungi in order to establish a mutualistic association. As a response, AM fungi release the so-called Myc factors which are recognized by the host plant. However, strigolactones can be abused by root parasitic plants of the family Orobancheaceae as an indicator of host presence, resulting in seed germination and establishment of a parasitic interaction. Similarly to the AM signal (Myc factor), it has been suggested that, in response to the strigolactones, the germinating parasitic seeds would produce Par factors (Modified from Bouwmeester et al. 2007)

2007; Scholes and Press 2008), and the most efficient control method – fumigation – is environmentally hazardous. Therefore, new methods for a more effective control against these agricultural pests are required. Since the root parasites affect their host from the moment they attach and exert the greatest damage prior to emergence (Joel et al. 2007; Scholes and Press 2008), the development of more effective control strategies should focus on the initial steps in the host-parasite interaction. Particularly on the germination of the parasitic weed seed stage, which is trigged by the strigolactones (Sun et al. 2007; López-Ráez et al. 2009). In this sense, two general approaches to control root parasitic plants may be envisaged: through enhanced or reduced seed germination.

6.1 Control Through Enhanced Germination

6.1.1 Trap and Catch Crops

This strategy consists in the use of non-host plant species that produce germination stimulants – strigolactones -, inducing suicidal germination of the parasite' seeds. Once germinated, the seeds cannot survive without a suitable host, hence causing a reduction in the parasite seed bank (Zwanenburg et al. 2009). These trap and catch crops can be resistant in a later stage of the parasite lifecycle – trap crops – or harvested before the seeds of the parasite are shed – catch crops – (Bouwmeester et al. 2003; Sun et al. 2007). The effectiveness of catch and trap crops could be increased by the selection of cultivars overproducing germination stimulants (breeding) or through molecular engineering of such overproduction. The latter can potentially be achieved by overexpression of the rate-limiting enzymes from the strigolactone biosynthetic pathway such as CCD7 or CCD8. In addition to the suicidal germination induced by these catch and trap crops with enhanced production of strigolactones, they could favour arbuscular mycorrhizal colonization in the host plant, with the corresponding benefits on plant growth, fitness and yield.

6.1.2 Synthetic Germination Stimulants

An alternative strategy to controlling root parasitic plant infestation through the induction of suicidal germination is the use of synthetic germination stimulants. In this sense, the application at very low concentrations of the strigolactone analogues GR24, GR7 and Nijmegen-1 to *Striga*-infested soils resulted in reduction in the seed population (Johnson et al. 1976; Wigchert et al. 1999). However, one of the limitations of this approach is that these synthetic germination stimulants are rather unstable in the soil. Therefore, more stable compounds or suitable formulations should be developed in order to overcome these stability problems and increase their effectiveness.

6.2 Control Through Reduced Germination

Another approach to avoid root parasitic weed infection is based on the opposite strategy, aimed at reducing seed germination. However, since strigolactones are also AM hyphal branching factors and are involved in plant architecture, the consequences for the AM fungal community in the soil and possible unwanted side-effects on plant architecture should be carefully evaluated before following this approach.

6.2.1 Soil Fertilization

As mentioned above, plants grown under nutrient deficient conditions, specially regarding phosphate and nitrogen, are more active in producing and exuding strigolactones and, therefore, in inducing germination of root parasitic plant seeds (Yoneyama et al. 2007; López-Ráez et al. 2008a). In many areas of the world, the concentration or availability of these essential mineral nutrients are limited in the soil, fact that has a significant impact on plant growth and health. Therefore, the use of fertilisers not only would improve soil fertility, plant fitness and crop yield, but also would reduce strigolactone production by the host plant and hence reduce the infection by parasitic weeds (Fig. 2). Indeed, the application of phosphate to phosphate-deficient soils significantly reduced the population and infestation of the parasites *Orobanche minor* in red clover and *P. aegyptiaca* in tomato plants (Jain and Foy 1992; Yoneyama et al. 2001). However, since strigolactone production in response to nutrient availability differs between plant species, fertiliser rate and composition should be carefully optimised depending on the crop, soil fertility and possibly the parasitic weed species before using this strategy as a control method.

6.2.2 Chemical Inhibitors

Strigolactones are derived from the carotenoids (Matusova et al. 2005; López-Ráez et al. 2008a). Therefore, herbicides that inhibit carotenoid biosynthesis such as fluridone, norflurazon, clomazone and amitrole could be used in very low concentrations as a tool to reduce strigolactone production and ultimately parasitic seed infection (López-Ráez et al. 2009; Jamil et al. 2010). Indeed, it was observed that application of these inhibitors at concentrations that do not cause chlorophyll bleaching to maize, sorghum, cowpea, rice and tomato strongly reduces strigolactone production and *in vitro* germination of *Striga hermonthica* and *Phelipanche ramosa* seeds by the exudates of the treated plants (Matusova et al. 2005; López-Ráez et al. 2008a; Jamil et al. 2010). These results show that treatments with such herbicides may be an effective and relatively cheap method to reduce parasitic weed infestation in the field either alone or in combination with other control strategies.

6.2.3 Breeding for Low Strigolactone Production Cultivars

The selection of cultivars with low production/exudation of strigolactones could be an attractive strategy to control root parasitic weeds. In this sense, genetic variation for the production of strigolactones has been observed for different crops. We have shown that different cultivars of tomato produce different amounts of strigolactones (López-Ráez et al. 2008b). The tomato mutant *high pigment-2* (*hp-2*^{dg}), which is an important mutant line introgressed into commercial tomato cultivars because of its enhanced levels of carotenoids including lycopene, was less susceptible to *P. aegyptiaca* infection than the corresponding wild-type, which correlated with a reduced production of strigolactones (López-Ráez et al. 2008b). Genetic variation for low germination stimulant production has been also described in sorghum, fact that was used to breed for *Striga* resistant varieties and introduce them into high yielding sorghum cultivars in several African countries (Ejeta 2007). Therefore, selecting programs to breed for cultivars with low strigolactone production is a valid and promising strategy.

6.2.4 Genetic Engineering

Molecular biology techniques targeting one or more of the rate-limiting genes from the strigolactone biosynthetic pathway could be another approach to reduce strigolactone biosynthesis. Indeed, *ccd7* and *ccd8* mutants of several plant species show a reduced production of strigolactones (Gomez-Roldan et al. 2008; Umehara et al. 2008). Moreover, genetic engineering using RNAi technology on *CCD7* and *CCD8* genes induced a significant reduction on strigolactones in tomato, which correlated with a reduction in the germinating activity of *P. ramosa* seeds (Vogel et al. 2010; Kohlen, López-Ráez and Bouwmeester, unpublished). Therefore, molecular engineering may be an important and efficient component of a long-term strategy for parasitic weed control. However, further research is required to completely characterize the biosynthetic pathway of strigolactones in order to select appropriate target genes with temporal or inducible promoters.

6.2.5 Use of Beneficial Microorganisms: Arbuscular Mycorrhizas

The fact that the strigolactones play a dual role in the rhizosphere as signalling molecules for both AM fungi and root parasitic plants (Fig. 4), and that AM symbiosis greatly benefits plant fitness make the strigolactones a suitable candidate to develop environmentally friendly biological control methods against parasitic weeds. Indeed, it was shown that AM fungal inoculation of maize and sorghum led to a reduction in *Striga hermonthica* infection in the field (Lendzemo et al. 2005), and it was proposed that this reduced infection was caused, at least partially, by a reduction in the production of strigolactones in the mycorrhizal plants (Lendzemo et al. 2007; Sun et al. 2008) (Fig. 5). A similar effect was observed in pea, where AM colonization reduced seed germination of *Orobanche* and *Phelipanche* species (Fernández-Aparicio et al. 2010). We have recently shown that AM symbiosis in tomato also leads to a reduction in the germination stimulatory activity of tomato exudates for seeds of the parasite *P. ramosa*, and have analytically demonstrated that this reduction is caused by a reduction in the production of strigolactones (López-Ráez et al. 2011). Moreover, we have also observed that this reduction requires a fully established mycorrhizal association (López-Ráez et al. 2011). The results with maize, sorghum, pea (although not analytically supported) and tomato suggest that the reduction in strigolactone exudation induced by AM symbiosis is conserved across the plant kingdom. As AM fungi colonize roots of most agricultural and horticultural species and are widely distributed around the globe, this environmentally friendly biocontrol strategy can potentially be used in the majority of economically important crops that suffer from these root parasites worldwide. Thus, mycorrhizal

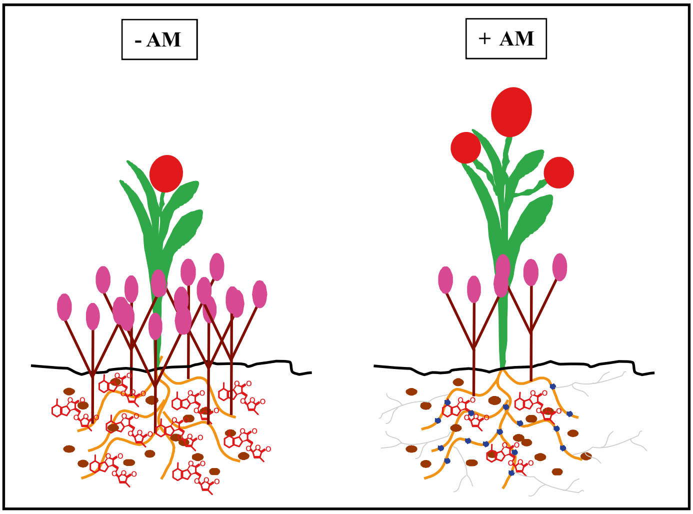

Fig. 5 Effect of arbuscular mycorrhizal (*AM*) symbiosis on root parasitic plant control. Under low phosphorous conditions plants produce an increased amount of strigolactones. These signalling molecules act as germination stimulants of root parasitic plant seeds (*left*). Upon mycorrhizal colonization, plants reduce the production of strigolactones thus reducing parasitic plant infection, and consequently diminishing the deleterious effect of these weeds on plant fitness and yield (*right*)

management through agroforestry, reduced soil disturbance, crop rotation or mycorrhizal inoculation would improve mycorrhizal benefits in agro-ecosystems. In addition, these crops would take advantage of all the other well-known benefits of the AM symbiosis such as positive effect on plant fitness and boost of plant defence mechanisms (Fig. 5). Altogether makes AM symbiosis a suitable and promising tool for the biological control of parasitic weeds.

So far, none of the reported approaches applied alone has led to an optimal solution against root parasitic weeds. Therefore, an integrated approach using several strategies, including the control of seed germination, should lead to an efficient and long-term management of this pest in agriculture.

7 Conclusion

Chemicals fertilizers and pesticides are used to prevent, mitigate or control plant diseases. However, the environmental pollution caused by excessive use and misuse of agrochemicals has led to public concerns about the use of these chemicals in agriculture. Therefore, there is a need to find more environmentally friendly alternatives for disease control. The key to achieve successful biological control is the knowledge on plant interactions in an ecological context. We emphasize here the importance of the chemical communication that occurs in the rhizosphere between plants and other organisms, and the potential use of this molecular dialogue as a target to control soil-borne pathogens and pests. An interesting example is the use of the mutualistic AM symbiosis for controlling root parasitic plant infection by reducing the production of strigolactones by the host plant. This example illustrates the suitability of approaches based on the knowledge of the biological system to target. Further research will expand our knowledge on what is going on underground, and the information generated will help us decipher the regulation of chemical communication in the rhizosphere and may result in the development of new biocontrol strategies against soil pests.

Acknowledgements Our research is supported by grants PERG-02-2007-224751 from the Marie Curie program from the European Commission, AGL2009-07691 from the National R&D Plan of the MINCIN, and The Netherlands Organisation for Scientific Research (NWO; VICI-grant to HB). HB is also (co) financed by the Centre for BioSystems Genomics (CBSG), a part of the Netherlands Genomics Initiative/Netherlands Organisation for Scientific Research. JAL-R is supported by a postdoctoral contract (JAE-Doc) from the Spanish Research Council (CSIC).

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A Novel Land-Energy Use Indicator for Energy Crops

E.G. Koukios and V. Sardo

Abstract The growth of the bioenergy field raises a myriad of problems, including the selection of the most appropriate crops and cropping systems, the trade-off between land to be allocated for bioenergy and for food production, the appraisal of the agro-energy systems sustainability in their economic, social and ecological aspects. A correct approach to such multifarious problems requires unbiased and transparent procedures, based on accepted common protocols and metrics, permitting to objectively compare and rank all the possible solutions. This chapter focuses on the evaluation of resource inputs to energy crops, in one attempt to contribute to clarify the existing confusion in terms and appraisal methods and to offer a tool for supporting the correct evaluation of contrasting crops and farming systems. Currently, energy use is analyzed mainly in terms of difference between output and input, of ratio between output and input, of annual energy input per unit of surface, and of energy input per specific crop yield. Here the criticism to all such "uni-dimensional" indicators is illustrated, and a novel indicator, combining land and energy use in crop systems and potentially including more aspects - is proposed. This novel, bi-dimensional "Land and Energy Use Indicator" (LEUI) and its advantages vis-à-vis uni-dimensional indicators are demonstrated with specific examples in the comparison of four energy crops. By evidencing the difference with other indicators, it is also demonstrated how this indicator avoids misleading conclusions in the comparison of organic and non-organic farming systems. It is suggested that its adoption can reduce the room for intended or unintended misinformation.

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E. Lichtfouse (ed.), *Agroecology and Strategies for Climate Change*,
Sustainable Agriculture Reviews 8, DOI 10.1007/978-94-007-1905-7_6,

1 Introduction

The growing concern for the environmental and social problems linked to bioenergy and biofuel crops has triggered the sprouting of researches, theories, simulation models and guidelines aimed at optimizing the choices and supporting the strive for sustainability, which has resulted in a considerable advancement of knowledge and in a better awareness by operators. According to Reijnders (2006) "*The sustainable use of biomass is defined as a type of use that can be continued indefinitely, without an increase in negative impact due to pollution, while maintaining natural resources and beneficial functions of living nature relevant to humankind over millions of years, i.e., the common lifespan of a mammalian species*." The list of factors affecting the sustainability of bioenergy applications is a long one, including a group preserving the stock of vital natural resources, such as soil, soil organic matter, nutrients, consumption of fossil fuels, and water; and another group of factors maintaining key natural cycles and ecosystem services, such as the mobilization of elements, impact on climate, land use, biodiversity, economy and social acceptance (Reijnders 2006).

Due to such a quantity of intervening factors many shadows remain even in basically important issues: one example is given by the passionate debate between those maintaining that the mineral energy required to produce one unit of bioethanol or biodiesel exceeds the amount of useful energy produced and is even "a crime against humanity", because it reduces available food (e.g., Pimentel 2001, 2003; Pimentel and Patzek 2005; Pimentel et al. 2007; Ziegler 2007) and those insisting on the need for producing bioenergy to improve the environment and reduce greenhouse gas emissions (e.g. Graboski 2002; Shapouri et al. 2002; Schmer et al. 2008; USDE 2009; Aljama 2010). One further issue for debate is the extent to which organic agriculture principles should be accepted for sustainable biomass production, in the light of its supporters' claims of top sustainability (International Network for Sustainable Energy–Europe 2006; Muller and Davis 2009), categorically denied by others (Trewavas 2004; Wu and Sardo 2010).

Reasons for such discrepancies in views include the inconsistency in procedures and metrics used by the diverse researchers, as pointed out by Bertilsson et al. (2008), and frequently also strongly biased approaches, even in high profile institutions, such as the Food and Agriculture Organization of the United Nations (FAO), and the British Ministry of Agriculture, Fisheries and Food (MAFF) and Department for Environment, Food and Rural Affairs (DEFRA), as demonstrated below in Sect. 4.2 of this paper.

As advocated in a brochure issued by the Royal Society (2008), *"[a]dditional sustainability metrics need to be agreed to guide developments in the supply chain, including energy efficiency, amount of fossil energy used, cost per unit of energy and environmental impacts such as local air and water pollution"*. Any attempt aimed at supplying "*additional sustainability metrics*", contributing to improve the procedure for an objective evaluation of alternative options and reducing the risk of misrepresentations seems therefore of some interest.

2 An Overview of Energy Efficiency Metrics

With the ongoing diffusion of biomass crops "*competition may arise between different land use systems for food, feed, biomass production, and nature protection and landscape conservation, as well as between the production of different biofuel feedstocks*" and therefore "*the choice of the best suited energy crop is crucial for the development of strategies that allow for the highest land use efficiency, substitution of fossil energies and the reduction of GHG emissions*" (Boehmel et al. 2008).

In a 2009 ATTRA publication Holly Hill wondered: "*One issue that affects reliable comparison is how to account for the potential yield differences between systems. Should energy consumption be measured per unit of land area, per unit of economic activity or per unit of produce?*" (Hill 2009). In this section, some metrics commonly used to give an answer to such questions are briefly commented upon; an excellent, thorough overview can be found in Appendix A of Spitzley and Keolian (2004).

Indicators based on the difference between energy output and energy input basically include Net Energy Gain (NEG), Net Energy Value (NEV), and Primary Net Energy Yield (PNEY); they are useful in the evaluation of energy crops, but have not much sense when applied to food crops. Even less useful are the Net Energy Ratio (NER) or the Energy Use Efficiency (EUE), namely the ratio of the total system energy output to total energy input (e.g., MAFF 2000; FAO 2002; Boehmel et al. 2008): a convincing criticism of this type of indicators can be found in Farrel et al. (2006).

Expressing energy use in terms of annual energy input per unit of surface (EI, in MJ/ha.year; e.g., MAFF 2000; FAO 2002; Lillywhite et al. 2007; Gomiero et al. 2008) is practically meaningless, because extremely low values of input, even approaching zero, can be easily achieved by neglecting or even omitting the agricultural practices, to the extent that a false impression of superb achievements can be conveyed in those cases when the only energy input -other than solar energy- is the one required to pick the scanty fruits spontaneously offered by undomesticated plants.

In the same way, expressing energy use in terms of energy input per unit of crop yield (EI, in MJ/t) can have the effect of deceiving the readers, as was the case with MAFF (2000) and later, on a larger scale, with Azeez and Hewlett (2008) with the unfortunate endorsement by FAO (Ziesemer 2007) and DEFRA (2008), as illustrated below (see Sect. 4.2). An indicator based simply on energy input per unit of yield can in fact be used to suggest positive results, namely that a lower specific energy is required, whenever some saving in energy is obtained at the cost of a reduction in production, as shown in the examples in Tables 1 and 3 below.

As Thorup-Kristensen et al. comment: "*Even though the amount of energy produced per kJ of energy used may be better in the organic systems, the higher productivity of the conventional systems means that conventional systems tend to have a higher net energy production per hectare. The significance of the area used for crop production is another open question when comparing different production systems.*

Table 1 Comparing different indicators in three agricultural systems

	System A	System B	System C
Yield (t/ha*y)	10	5	1
Land Input (ha*y/t)	0.1	0.2	1
Energy Input (MJ/ha*y)	10,000	5,000	500
Energy Input (MJ/t)	1,000	1,000	500
LEUI (Land and Energy Use Indicator)	100	200	500

While the organic systems may have the highest productivity per amount of invested energy, they have a lower production per area. What is most important here investment of energy or area? Our area for crop production is not unlimited, and the extra land we need for organic food production could be used for other purposes" (Thorup-Kristensen et al. 2008*). The same concept is illustrated by Bertilsson et al. (*2008*): "Energy use per unit yield expresses system efficiency, but the term is insufficient to evaluate the energy characteristics of agricultural systems [omissis]. Lower yields in the organic systems, and consequently lower energy production per unit area, mean that more land is required to produce the same amount of energy. This greater land requirement in organic production must be considered in energy balances"*

3 Introducing a Novel Indicator

To solve this dilemma, land or energy, a "bi-dimensional" indicator is proposed for the comparison of different cropping systems, under the name of "Land and Energy Use Indicator", LEUI, encompassing land and energy specific inputs, which can be applied to food and biomass crops. It is defined as the product of the land surface required to annually produce a metric tonne of yield (ha*year/t) times the energy required to produce a metric tonne (MJ/t), and can be formalized as

$$LEUI = ha * \frac{y}{t} * \frac{MJ}{t}$$

As LEUI expresses the combined land and energy burden required by crop systems, the best crop system is the one with the lowest LEUI value. For instance (Table 1) if we compare three systems A, B and C, yielding 10, 5 and 1 t/ha of biomass, respectively, with a specific energy input EI (in MJ/t) of 10000/10 = 1000 in system A, 5000/5 = 1000 in system B, and 500/1 = 500 in system C, we find that the indicator EI (MJ/t) does not permit to appreciate any difference between systems A and B, and even denounces a better performance (i.e., a lower EI) in system C, failing to take into due account the reduction in crop productivity, and thus we shall absurdly conclude that the performance of system C is largely superior. Similarly, if the specific energy input is referred to the surface area (in MJ/ha*y), system C appears far better than the others. In conclusion, system C seems largely preferable under both

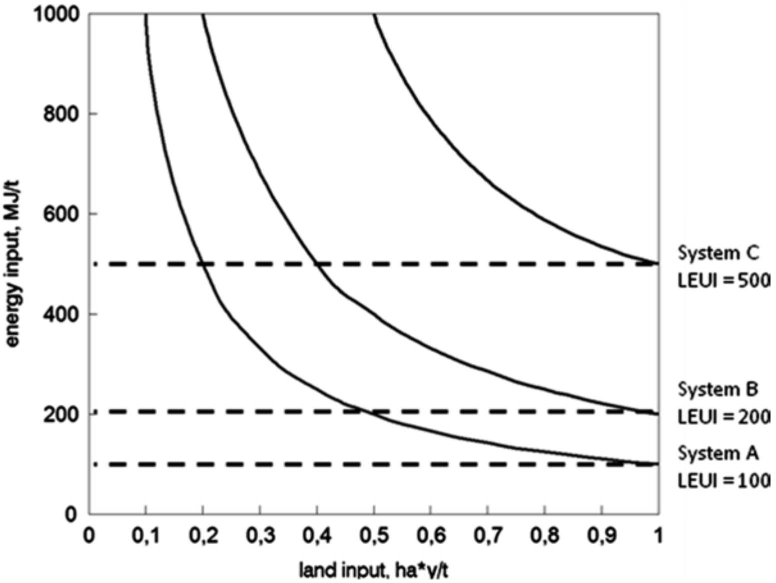

Fig. 1 Graphical representation of the three systems' "iso-burden" curves LEUI = Land and Energy Use Indicator, corresponding to the areas between the abscissa and the dashed lines of the three systems

criteria because it uses "*less energy per unit area and per unit of output*", according to DEFRA's flawed criteria (Shepherd et al. 2003), echoing MAFF's (2000) misrepresentation. However, if the yearly land input (ha*y/t) as well as the energy input (MJ/t) are simultaneously taken into account through the proposed LEUI, in the case of system A we obtain the value of 100, whereas in system B the value is 200 and in system C rises to 500, which denounces the worse global performance in B and C because of their higher combined resources use. The principle is graphically illustrated in Fig. 1, reporting for the three ideal systems the land and energy "iso-burden" curves –they could also be named "iso-productivity" or "indifference" curves- along which constant LEUI values are located.

Assuming that land and energy inputs can be freely inter-changed -which is true within some limits: e.g., by applying more fertilizer or water the same yield can be obtained with less land, and vice versa- the diagram shows for every system how one input will change in response to the other's changes when moving along the curves. This permits to find the trade-offs between land and energy input best fitting any specific conditions. For instance, in system A 100 MJ/t rather than 1,000 MJ/t of energy will be sufficient if the used land moves from 0.1 to 1.0 ha*y/t (LEUI value remaining unvaried); conversely, in system C 1,000 MJ/t will be required rather than 500 to reduce the land input from 1 to 0.5 ha*y/t.

The areas included between the abscissa and the dashed lines at the lower limit of the single systems convey a visual representation of the environmental burden, in terms of specific land and energy use, imposed by the particular system and expressed by LEUI; of course a larger area denounces more inputs and therefore indicates a less favorable solution.

The proposed indicator could be useful for ranking different energy crops, for identifying the most suitable land/energy input combinations under a constant LEUI, or comparing different farming technologies implying different LEUI values.

The principle of LEUI can be also extended to formulate multi-dimensional, complex indicators, which can assist in the rationally based quest for the most sustainable solutions, e.g. by considering also the other factors listed by Reijnders (2006), such as the greenhouse gas emissions, the impact on biodiversity, the water consumption etc., and permitting to attribute diverse weights to the various dimensions (e.g. Matute and Gupta 2007; Gómez-Limón and Sanchez-Fernandez 2010). In the proposed bi-dimensional LEUI different weights can be attributed to land and energy inputs.

4 Application to Specific Cases

In order to demonstrate the practical use of LEUI, we will apply it in two specific cases, one referring to the ranking of different energy crops, and one comparing organic to non-organic farming technologies. In these examples the same weight has been assigned to the inputs “energy” and “land”.

4.1 Comparing Different Energy Crops

Data from a paper by Boehmel et al. (2008) were elaborated in order to jointly appreciate land and energy aspects. Out of the six crops analyzed in the paper only four, namely willow, miscanthus, switchgrass and energy maize, were considered for comparison because data referring to two crop rotation systems were not easy to handle due to the presence of co-products.

The experimental plan of the research was rather complex and included three levels of nitrogen fertilization for each crop: here only the treatment labeled “N1” with intermediate amounts of nitrogen was selected.

Some simple data manipulation was necessary to obtain the value of dry matter yield (DMY) and specific Energy Input (MJ/t) of the four crops, since they were both implicitly reported. DMY, necessary to express land input, was obtained by dividing the Primary Energy Yield (PEY) from their table 6 by the lower heating values in Table 3, while the energy input was obtained by subtracting the Primary Net Energy Yield (PNEY) from the PEY.

The elaboration permitted to rank the four crops according to the values of five indicators, i.e., annual land and energy input per metric tonne, PNEY, Energy Use Efficiency – namely output/input ratio (EUE), and LEUI, as shown in Table 2.

Table 2 Ranking energy crops according to different indicators (From Boehmel et al. 2008)[a]

Crop	Land input (ha*y/t)	Energy input (MJ/t)	PNEY (GJ/ha)	EUE	LEUI
Willow	0.0747 (*3*)	224(*1*)	243 (*3*)	78 (*1*)	16.7(*1*)
Miscanthus	0.0670(*2*)	537(*3*)	255 (*2*)	32 (*3*)	36.0(*3*)
Switchgrass	0.0924 (*4*)	463(*2*)	193 (*4*)	38 (*2*)	42.8(*4*)
Energy maize	0.0546 (*1*)	656(*4*)	342 (*1*)	29 (*4*)	35.8(*2*)

PNEY Primary Net Energy Yield, *EUE* Energy Use Efficiency, *LEUI* Land and Energy Use Indicator

[a] Within brackets the crop ranking according to the indicators

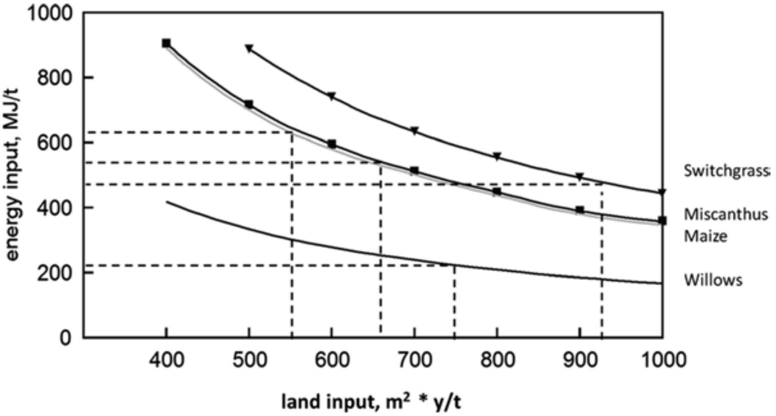

Fig. 2 Iso-burden curves for the four crops of Table 2

Striking dissimilarities in the ranking according to the various indicators are evident, particularly in the case of energy maize, and LEUI-based rankings result in some way intermediate, thanks to the very nature of this indicator. It is therefore reasonable to assume that LEUI-based assessments can assist for more balanced decision processes.

In Fig. 2 the possibility is shown of finding a trade-off between land and energy input for the four crops, moving along the iso-burden curves, thus maintaining constant values of LEUI. The dashed lines correspond to the land and energy input data reported in Table 2; again, the surface of the rectangles formed by the dashed lines and the coordinates defines the LEUI values, which in this example are highest for switchgrass and lowest for willow.

4.2 Comparing Organic and Non-organic Farming Systems

While the need for producing biomass in sustainable ways is evident (e.g. Schlegel and Kaphengst 2007; Ceotto 2008; van Dam et al. 2008; ISCC 2009), organic farming enthusiasts claim that only the adoption of their “philosophy” permits to achieve the highest sustainability (e.g. Kotschi and Műller-Sämann 2004; Azeez 2009), and go so far as to suggest that for agricultural products economic support should be confined to "*solid and liquid biomass*" complying with the rules of organic farming and certified by IFOAM, the International Federation of Organic Movements (INFORSE 2006). On the other hand, it is contended that such claims are unfounded at least with reference to greenhouse gas emissions (e.g. Tuomisto et al. 2009), carbon sequestration and soil fertility improvement (Bergström et al. 2008) and, above all, energy balance and land productivity, as we shall try to demonstrate.

In an MAFF report aimed at modeling energy use in agriculture, energy inputs to a number of conventionally and organically grown crops were compared, in terms of MJ/ha and MJ/t, with the organic systems resulting more energy efficient than the conventional: "*[o]rganically grown crops have a lower energy input per unit area than conventional crops, largely because of lower fertiliser and pesticide inputs"* (MAFF 2000). Organic crops fared better also in terms of energy input per unit output (MJ/t).

The report gave evidence to the higher "Energy Ratio" (e.g. the energy output/input ratio) in organic production, which is a rather useless, deceiving indicator, since an extremely high energy ratio can be easily achieved by simply reducing inputs, just picking naturally produced yields. In the case of pre-agriculture hunter-gatherers, energy ratios approached infinity – neglecting solar energy – but at the same time the land surface requirement in the wild was enormous. Bertilsson et al. (2008) aptly write: "*the calculation of output/input ratio is a poor measure for system comparisons as it only expresses the efficiency and not the total or net energy production"*. The higher land input typically required by organic farming was not given the due relevance in the MAFF report and as a consequence the real effects on the overall performance of the systems were not highlighted. In conclusion, the false impression was conveyed to the reader that organic systems are "more efficient".

In 2006 Williams and co-workers released a comprehensive report on environmental burdens depending on agricultural and horticultural activities, where land and energy inputs were defined for a number of commodities, with the aim of modelling and comparing the burdens involved in their production (Williams et al. 2006). The burdens in the case of non-organic and organic production systems were compared. Unlike MAFF (2000), the authors correctly emphasized the considerably higher land input in organic farming: "*Land use was always higher in organic systems (with lower yields and overheads for fertility building and cover crops), ranging from 65% more for milk and meat to 160% for potatoes and 200% more for bread wheat*".

The list of land and energy inputs resulting from the elaboration of their data revised in 2009 (available at www.agrilca.org) for selected agricultural products is reported in Table 3.

In almost all the cases organic systems required "*less energy per unit area and per unit of output*", thus confirming earlier MAFF (2000) and DEFRA (Shepherd et al. 2003) claims, but also required more land per tonne of crop yield.

Table 3 Elaboration from data by Williams et al. (2006)

Crop	Technology	Land input (ha*y/t)	Energy input (MJ/ha)	Energy input (MJ/t)	LEUI (Land and Energy Use Indicator)
Bread wheat	Non organic	0.12	21,825	2,620	314
	Organic	0.42	5,140	2,160	907
Oilseed rape	Non organic	0.28	18,850	5,280	1,478
	Organic	0.91	5,775	5,250	4,777
Potatoes main crop	Non organic	0.02	73,500	1,470	29
	Organic	0.04	37,500	1,500	60
Potatoes 1st earlies	Non organic	0.04	35,000	1,400	56
	Organic	0.09	13,887	1,250	112
Potatoes 2nd earlies	Non organic	0.02	39,500	790	16
	Organic	0.04	18,750	750	30
Feed wheat	Non organic	0.11	21,180	2,330	256
	Organic	0.29	7,176	2,080	603
Winter barley	Non organic	0.14	17,422	2,440	342
	Organic	0.35	6,664	2,330	815
Spring barley	Non organic	0.16	14,250	2,280	365
	Organic	0.42	6,331	2,660	1,117
Field beans	Non organic	0.28	9,353	2,520	706
	Organic	0.30	8,125	2,440	732
Soya beans	Non organic	0.44	9,982	3,670	1,615
	Organic	0.45	7,193	3,240	1,458
Maize – grain	Non organic	0.13	16,918	2,200	286
	Organic	0.34	6,703	2,280	775
Maize – silage	Non organic	0.08	21,375	1,710	137
	Organic	0.18	9,063	1,630	293

In 2007 an FAO report was released (Ziesemer 2007), copying data published only later by Azeez and Hewlett (2008); the figures of MAFF (2000) and Williams et al. (2006) were selectively picked to support the author's claim that *"[b]ecause of its reduced energy inputs, organic agriculture is the ideal production method for biofuels"* (p. 20) and the conclusion that *"[t]ypically, organic agriculture uses 30 to 50 percent less energy in production than comparable non-organic agriculture*" (p. 23). Possible energy savings were illustrated for the auspicious event that all agriculture in the UK would become organic, but the parallel larger land input required by organic farming was not mentioned.

Azeez and Hewlett for the Soil Association (2008) were quick to side this approach –actually their own brainchild, to which the FAO had been a loudspeaker-claiming that the figures by MAFF (2000) and Williams et al. (2006) demonstrated that "*UK organic farming uses around 26% less energy per tonne of output on average"*. Along the same reasoning as Ziesemer (2007), they revealed that if the entire agricultural production in the UK went organic, the total savings in energy could be 27.51%, but unfortunately they too forgot to mention that UK agricultural land should simultaneously increase over twofold.

In 2008 DEFRA issued a report titled "*The Contribution That Organic Farming Makes in Supplying Public Goods*", where a table based on data from MAFF (2000) and Williams et al. (2006) illustrated, once again, the possible percentage-wise savings, in terms of energy use per tonne, when moving from non-organic to organic systems. Their comment was: "*Not surprisingly, there are many reliable life cycle assessments from the UK and abroad that have found organic farming to be more energy efficient that it's* [sic] *non-organic counterpart*" and "*The research shows organic production to be significantly more energy efficient per tonne of food produced in eleven out of the fifteen sectors examined*". Once again, the authors were oblivious of the larger land inputs required by organic farming.

The simple inspection of Table 3 shows indeed that energy inputs in terms of MJ/ha and MJ/t are lower with organic technology, but at the same time the combination of energy and land inputs through the adoption of LEUI highlights the combined impact of the two environmental burdens, remarkably lower in the case of non-organic farming, thus evidencing the high risk of adopting the less sustainable organic systems.

The same exercise was done on other papers comparing organic and non-organic farming (e.g., Reganold et al. 2001; Jørgensen et al. 2005; Gündoğmus 2006; Pimentel 2006; Kaltsas et al. 2007; Guzmán and Alonso 2008), always with identical results: although the use of EI (MJ/t) and EI (MJ/ha) as well as the Energy Use Efficiency or Energy Productivity indicators alone may suggest that better results are achieved with organic farming, the use of LEUI, after adjusting – when necessary – the energy input data for human labour and organic manure (Wu et al. 2011) shows that the opposite is in fact true.

5 Conclusion

The use of LEUI permits to fill a major gap in the quest for a rationally based tradeoff in the decision making process in the agricultural activity, i.e. the one between land requirements and energy inputs.

Although its adoption can lead to rather counter-intuitive results when comparing various alternative energy crops and cropping systems, its indications are more objective, comprehensive and soundly based than those resulting from uni-dimensional indicators.

When used to assess the comparative value of organic vs. non-organic farming systems, LEUI makes apparent the vast superiority of the latter in terms of land and energy efficiency, evidencing how organic farming is not a solution in the quest for sustainability.

Overall, it is clear that the adoption of bi-dimensional LEUI permits the correction of the incomplete description given by the use of uni-dimensional indicators, and thus gives more balanced information reducing the room for intended or unintended misinformation.

In conclusion, LEUI seems to deserve a place as a decision support tool in the toolkit of the biomass policy and decision makers.

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Conventional, Organic and Conservation Agriculture: Production and Environmental Impact

Jens B. Aune

Abstract Agriculture production has to increase by 70% within 2050 in order to keep pace with population growth and changing diets. However, this production increase will have to be achieved in a way that preserves the environment and reduces the vulnerability of agriculture to climate change. Agriculture will furthermore need to minimize the emissions of greenhouse gases, pesticides and plant nutrients like nitrogen and phosphorous to the environment. Organic agriculture, conventional agriculture and conservation agriculture can be considered as different approaches for dealing with these production and environmental challenges. This chapter discusses the production and environmental implications of these three different approaches for agricultural development. Conventional agriculture is characterised by ploughing and limited recycling of organic materials. Organic agriculture uses no pesticides and mineral fertiliser whereas conservation agriculture is characterized by zero tillage, use of mulch and crop rotations.

The studies reviewed show that conventional agriculture and conservation agriculture have similar yield levels, but the yield levels in organic agriculture is in the order of 30–50% lower than in these two systems. One important reason for lower productivity in organic agriculture is limited supply of plant nutrients as organic sources of plant nutrients only supply 30–35% of the nitrogen taken up by crops. Conservation agriculture is furthermore more efficient in building soil organic matter than organic agriculture and conventional agriculture. Conservation agriculture has been found to sequester between 0.1 and 1 tC ha^{-1} $year^{-1}$. Building soil organic matter content can be considered as a cornerstone in adaption to climate as this will increase soil water holding capacity and reduce soil temperature. System studies

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E. Lichtfouse (ed.), *Agroecology and Strategies for Climate Change*,
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have shown that nitrogen and greenhouse gas emission are less in conservation agriculture as compared to conventional and organic agriculture. The non-use of pesticides is the major environmental advantages of organic agriculture.

It appears from this review that conservation agriculture is the approach that can best deliver on the production and environmental objectives of agriculture.

Keywords Conventional agriculture • Organic agriculture • Conservation agriculture • Productivity • Greenhouse gas emissions • Environmental impacts • Adaptation to climate change

1 Introduction

The main role of agriculture is to produce food for a growing population. However, this production has to be achieved in an environmentally friendly way that minimizes the external effects of agriculture related to the emission of green house gases, the release of nitrogen and phosphorous to the environment and the use and accumulation of harmful pesticides in nature. Agriculture will also need to adapt to climate change including more extreme weather events. In principle, there are three pathways for agricultural development: conventional agriculture (CO), organic agriculture (OA) and conservation agriculture (CA). These pathways have different approaches for addressing the above issues. This paper will assess how the different pathways perform in relation to fulfilling the objectives of producing sufficient food and preserving the environment. The differences between the pathways are summarised in Table 1.

Conventional agriculture (CO) is characterized in high income countries and in most parts of Asia and America by ploughing, nutrient supply through organic and mineral fertiliser, limited use crop rotations and the use of synthetic chemicals to control weeds, pest and diseases. Integrated Pest Management (IPM) is used to a limited extent. Conventional agriculture in Sub-Saharan Africa is a subsistence oriented type of agriculture characterized by ploughing or hoe cultivation and very low use of external input like mineral fertiliser and pesticides. Yields are often very low and nutrient recycling is limited (Fig. 1).

Organic agriculture (OA) is characterized by no use of mineral fertilisers and synthetic pesticides. Soil fertility is instead maintained through the use of organic

Table 1 Key differences between the different forms of agriculture

	Conventional agriculture	Organic agriculture	Conservation agriculture
Ploughing	Yes	Yes	No
Residues retained	No	Limited	Yes
Crop rotations	Limited	Yes	Yes
Use of mineral fertilizer	Yes	No	Yes
Use of pesticides	Yes	No	Yes

Fig. 1 Conventional agriculture with ploughing causing wind erosion (Photo by CFU Zambia)

fertiliser and biological nitrogen fixation. Pests and diseases are controlled by use of resistant varieties, crop rotation and natural enemies. This is a more regulated type of agriculture as the production is certified. Organic agriculture is based on the principles of health, environment, fairness and care (IFOAM 2009) and has a very strong ideological underpinning.

Conservation agriculture (CA) can be characterized as direct sowing without any tillage, complete soil cover and crop rotations (Hobbs et al. 2000). Conservation agriculture therefore has an opposite approach to tillage, residue management and crop rotation than conventional agriculture. Mineral fertilisers are permitted in conservation agriculture. No certification system has been developed for conservation agriculture. Conservation agriculture is a system that tries to mimic a natural ecosystem by minimizing soil disturbance (Fig. 2).

Certified organic agriculture was by the end of 2007 practiced on 32 million hectares (IFOAM 2009) whereas the area of conservation agriculture (no tillage systems) is above 100 million hectares (Derpch and Friedrich 2009). Conservation agriculture is widely practiced in South America and in the USA.

This objective of this review paper is to assess how the different agricultural pathways affect food production and the environment in temperate as well as in tropical areas. Limited data are available to assess the environmental consequences of the pathways in the tropics. Results from temperate areas are therefore used to analyse the environmental consequences of the different pathways.

Fig. 2 Conservation agriculture with ripping and retention of crop residues as mulching (Photo by CFU Zambia)

2 Agricultural Pathways and Productivity

Currently there are more than one billion people that suffer from hunger and the number is on the increase (Fan 2010). World production of food will have to increase by 70% from 2009 to 2050 in order to provide sufficient food for the population (FAO 2009). Most of this production increase will have to take place in low-income countries as most of the population growth will occur here. A vital criterion for assessing the different pathways will therefore be how they contribute to increased agricultural productivity.

Assessing productivity of conventional, organic and conservation agriculture is a complicated issue. Productivity of these systems cannot be assessed just by studying productivity at the plot level, but must also be based on analyzing the pathways in a system perspective. Productivity analysis will therefore be based on yield extrapolation from historic yield levels, trends in yield levels in countries with different degrees of intensity in agricultural production, productivity without mineral fertiliser, trends in long-term trials and nutrient balances. General development trends such as population growth, growth in income, changes in diet and urbanization will in addition influence the need for growth in agricultural production.

2.1 Assessment of Yields

There are different views on how the different pathways can contribute to global food production. Kirchmann et al. 2008a, argue that yields in organic agriculture is 25–50% lower than conventional agriculture depending on availability of manure. This result is based on official yield data in organic and conventional farms in Sweden and Finland and on analyzing experiments comparing organic agriculture and conventional agriculture. A 21-year rotation in Switzerland comparing organic and conventional farming showed that yields of the organically grown crops were 20% lower than the yields of the conventionally grown crops (Mäder et al. 2002). Long-term trials in Norway comparing conventional agriculture (ploughing), conservation tillage and organic farming showed that yield levels of cereals were similar in conventional and conservation tillage, but yield levels were 55–60% lower in organic farming (Korsaeth 2008). A survey of farmers in south-Asia rice-wheat system showed that yields were equal or higher in fields of zero tillage farmers compared to in conventional tillage farmers (Erenstein et al. 2008). Yields can be similar in organic agriculture as in conventional agriculture, but that depends on sufficient access to organic manure. It is very difficult to produce sufficient manure on the farm unless farmers have access to large pasture areas. Access to manure is therefore a key limitation in organic agriculture.

However, comparison of yields under organic and conventional agriculture has also showed that it is possible to produce enough food with organic agriculture and that nitrogen fixation can provide adequate nitrogen supply (Badgley et al. 2007). The paper has, however, been criticized by Connor (2008) and Kirchmann et al. (2008b) on the grounds that the comparisons undertaken between conventional agriculture and organic agriculture are not valid because the assessment for developing countries were made between plots that did not receive any fertiliser (conventional agriculture) with plots that received organic fertiliser (organic agriculture). This gives misleading results as fertilisers are generally applied in conventional agriculture. The study by Badgley et al. (2007) also failed to recognize the increasing competition for organic fertiliser as organic agriculture expands. Furthermore, the study underestimated the amount of land that has to be sacrificed for growing N-fixing crops in order to provide sufficient nitrogen.

At the global level, it has been calculated that the type of agriculture that existed around the year 1900 could provide food for about three billion people (Smil 2001). This agriculture was similar to organic agriculture as its external input was very low. However, based on the per capita food supply and including the changed food consumption habits of 1995, this 1900-type of agriculture can presently only supply food for about 2.4 billion people. This way of estimating future agricultural productivity may both underestimate and overestimate agriculture productivity. Underestimation may occur due to technological and biological advances in organic agriculture that have come about during the last century. On the other hand, overestimation can result because of nutrient depletion that often takes place in agricultural systems that do not receive any mineral fertiliser like in Sub-Saharan Africa (Smaling et al. 1997).

Conservation agriculture has yield levels equivalent to or higher than conventional agriculture (Giller et al. 2009; Mazvimavi and Twomlow 2009). In South America conservation agriculture has increased yield in all countries where it has been practiced on a large scale (Vlek and Tamene 2009). Grain production increased in Argentina from 28 million tons in 1988 to 74 million tons in 2000 due to the change to conservation agriculture (Derpch 2005).

Doubts have been raised whether conservation agriculture is a feasible approach for small scale farmers in the tropics despite the success in South America (Giller et al. 2009; Gowing and Palmer 2008) because of delayed yield response, problems related to weed control, access to mulch and difficulties in input supply. This critique illustrates that conservation agriculture might not be applicable under all conditions and introduction of conservation agriculture is dependent on factors such as success to input, credit, farmers knowledge level and livestock system.

The studies reviewed show that conventional agriculture and conservation agriculture have similar yield levels, but the yield levels in organic agriculture are in the order of 30–50% lower than in these two systems.

2.2 Nutrient Supply and Productivity

Plant nutrients supply is a key difference between the agricultural pathways. FAO calculated that by the mid 1990s mineral fertiliser supplied between 44 and 51% of nitrogen taken up by crops and this share may increase to 84% in the years to come (Smil 2001; Fresco 2003). Organic fertiliser, organic recycling and irrigation water supply about 30–35% of the global crop nitrogen supply in agriculture while the remaining part is released from soil organic matter.

Nutrient mining must be considered as one of the primary causes of low productivity in Africa (Sanchez et al. 1997). Net losses of nutrient for N, P, and K have been found to be respectively 22, 2.5 and 15 kg ha^{-1} year^{-1} (Smaling et al. 1997). These losses occur mainly as a result of nutrient export via harvested products and soil erosion and these losses must be replenished through nutrient inputs. Sub-Saharan Africa only uses 2% of the mineral fertiliser that is used globally (Bellarby et al. 2008).

The importance of fertiliser can be assessed by studying how yields and fertiliser use have developed over the years in different regions of the world. In Sub-Saharan Africa and South Asia, cereal yields were below 1 Mg ha^{-1} in 1960. Yields in 2005 in Sub-Saharan Africa were still below 1 Mg ha^{-1} whereas yields in South Asia were about 2.5 Mg ha^{-1} in 2005 (FAOstat, Morris et al. 2007). Fertiliser use in this period has remained below 10 kg nutrients ha^{-1} in sub-Saharan Africa whereas in South Asia fertiliser use has increased to about 100 kg nutrients ha^{-1}. In East and South East–Asia cereal yields increased from 1.6 Mg ha^{-1} in 1960 to 3.7 Mg ha^{-1} in 2005. The corresponding fertiliser increase in this period was from 0.01 to about 0.1 Mg nutrients ha^{-1}. Fertiliser use has been assessed to have contributed 50% of the yield increase in Asia (Morris et al. 2007).

A review of low external input technologies used in OA (intercropping, alley cropping, cover crops, green manures, compost, animal manure and improved fallows) showed that these technologies have limited potential to increase crop yields on a broad scale (Graves et al. 2004). These technologies may effectively increase yields at a low population density, but with increasing pressure on the land, their utility decreases as land is needed just to produce these organic fertilisers. The labour requirements of these technologies are also generally high and experience shows that farmers may abandon these methods if income opportunities are higher in other areas. Another problem with relying only on organic sources of fertiliser is that they cannot supply sufficient amounts of nutrients for increasing crop productivity (Vanlauwe and Giller 2006). If the soil is low in plant nutrients, the organic fertiliser produced in this soil will also be low in nutrient content making nutrient recycling more difficult as a strategy to maintain yields. Furthermore, the composition of plant nutrients in organic fertiliser does not often match the requirements of the crops. Nitrogen fixation can be high under tropical conditions on good soils, but most of the nitrogen is not recycled when the grains of the legumes are harvested (Vanlauwe and Giller 2006).

The cost of fertiliser represents a constraint for fertiliser use in developing countries, particularly in dryland areas. However, recent studies in sorghum and pearl millet show that even small rates of mineral fertiliser applied in the planting pit in the order of 0.3–2 g fertiliser per pit (micro-dosing) can be a very effective and profitable way of increasing crop yield, especially on marginal land where soil quality is low (Aune and Bationo 2008; Tabo et al. 2005). This method of fertilization is feasible also for small scale farmers in dryland cultivation. Farmers should first make use of all the organic fertiliser available and use mineral fertiliser as a supplement depending on the cost and availability. Such an integrated approach also reduces the risks of using mineral fertilisers (Graves et al. 2004). In areas where access to market is poor and the price of fertiliser is high, farmers will have to rely on organic fertilisers.

A treat to future use of mineral fertiliser is the availability of rock phosphate (Cordell et al. 2009). However, there are different views on the availability of rock phosphate. Cordell et al. 2009 argue that current phosphate reserves may be deleted in 50–100 years while Gilbert (2009) claims that reserves of phosphates are expected to last about 125 years based on current growth in use of phosphorus fertiliser. In addition to the reserves that are economically exploitable, there exist reserves that are three times as high as the economically exploitable reserves (US Geological Survey 2009). These reserves may become exploitable as technology advances. However, it is important to utilize the phosphate resources as efficiently as possible in order to minimize the energy cost of producing fertiliser and to reduce the release of phosphorus into waterways. Increased recycling of phosphorus is one option that deserves increased attention. However, the global urbanization process makes recycling of plant nutrients difficult because the distance between producers and consumers is growing as more than 50% of the population now lives in cities. Plant nutrients end up in the sewage making recycling costly. Use of treated sewage should be stimulated, but use of sewage is only a partial solution as recycling of sewage only represents about 20% the total phosphorus required in agriculture (Cordell and White 2008).

In conclusion it can be stated that global food production is very dependent on mineral fertilisers and organic method only supply 30–35% of nitrogen taken up by crops.

3 Agricultural Pathways and the Environment

Agriculture influences the environment through the emission of greenhouse gases (GHG), release of nitrogen, eutrophication of lakes, biodiversity loss, contamination by pesticides and through deforestation. The three pathways for agricultural development have different strengths and weaknesses in relation to these environmental challenges, but none of the three pathways can provide solutions to all these environmental challenges.

3.1 Adaptability to Climate Change

Building soil organic matter can be considered a cornerstone in adapting agriculture to climate change as organic matter has key functions related to soil water storage, increasing infiltration of water, reducing soil erosion and regulating soil temperature (Buerkert et al. 2000). This makes agricultural systems less vulnerable to drought, extreme temperatures and flooding. A comparison of conventional, organic and conservation agriculture in the USA showed that the accumulation of soil carbon was three times higher in conservation agriculture as compared to organic agriculture (Robertson et al. 2000). Long-term experiments (15 years) from Norway showed that there was a significant reduction in soil organic carbon in organic arable agriculture whereas there was no significant change in conservation agriculture (Riley et al. 2008). Conservation agriculture is more efficient than the other pathways in building soil organic carbon because of higher biomass production that leaves behind carbon in roots and straw, reduced soil temperatures due to mulching and reduced carbon losses due to decreased soil respiration as a result of zero tillage. Conservation agriculture has been found to sequester 0.1–1 MgC ha^{-1} $year^{-1}$ (Lal 2004).

Temperatures in drylands like in the Sahel are already close to maximum for plant growth, particularly at the beginning of the growing season. An experiment with different levels of shading showed that temperatures have a pronounced effect on millet production in the Sahel (Vandenbeldt and Williams 1992). Temperatures in the Sahel are expected to increase more than in other areas because average temperatures will increase more over land than over the oceans (IPCC 2007). A further increase in temperatures may be a real challenge for Sahelian agriculture. Mulching, as practiced in conservation agriculture, is particularly effective in controlling the rise in temperatures. More storage of water in the soil as achieved through CA will also have a cooling effect.

The first rains are often used for ploughing in conventional and organic agriculture while in conservation agriculture it is possible to use the first rains for direct sowing or using planting basins that have been established in the dry season. Earlier sowing makes it possible for the crops to escape drought and in some cases also pests and diseases.

Establishment of a permanent soil cover through retention of crop residues on the soil surface is a challenge for development of conservation agriculture in low–income countries because crop residues are used for so many other purposes like fodder, fuel and building material. If farmers are to retain increased amounts of crop residues they must be provided with alternative sources of fodder, fuel and building material.

It appears from the studies reviewed that conservation agriculture is more efficient in building soil organic matter than organic agriculture and conventional agriculture.

3.2 Effect on Green House Gas (GHG) Emissions

Agricultural soils can both act as a source and a sink of greenhouse gas. Soil acts as a sink by sequestering carbon in soil and vegetation while emissions of greenhouse gas from agriculture occur in the form of N_2O (nitrous oxide), CH_4 (methane) and CO_2. The emissions of CH_4 and N_2O account for about 10–12% of the total emissions of greenhouse gas in CO_2 equivalents (Smith et al. 2007). Methane contributes 54% of the emissions from agriculture and the rest is N_2O.

According the IPCC report 2007, deforestation account for about 17% of global greenhouse gas emissions and expansion of agricultural land is the main cause for deforestation (Baker et al. 2007). Higher yields in conventional and conservation agriculture reduce the need to expand the cultivation area into forest and pasture land. Since yields in OA are 25–50% lower than in conventional agriculture (Kirchmann et al. 2008a), the land requirements are 50–100% higher. In reality the land requirements are likely to be higher, because the best land is already taken for agricultural production. A large study from England and Wales reported that land requirements increased between 60% and 200% for the different crops when changing from conventional to organic agriculture (Williams et al. 2006). Agricultural land requirements in India would be twice as high if the intensification of agriculture through the green revolution had not taken place (Waggoner 1997).

The effect of the different pathways can therefore not be studied by looking at greenhouse gas emission per hectare and per ton of product produced, but the land requirements of the different pathways are of equal importance.

Fertiliser can contribute to both increased and reduced greenhouse gas emissions. Increased emissions are related to the release of CO_2 and N_2O from the production and use of mineral fertilisers and reduced emissions can occur if farmers choose to increase productivity of existing land rather than clearing forests. The greenhouse gas emissions from the production of mineral fertilisers in the form of

CO_2 and N_2O account for about 0.8% of the world's total emissions of greenhouse gas (Bellarby et al. 2008) whereas soil N_2O from mineral fertiliser represents about 1.2% of the world's emissions of greenhouse gas (Brentrup 2009). The production and use of mineral fertiliser therefore represents about 2% of the total emissions of greenhouse gas. Improved new technologies in the production of fertiliser can reduce the N_2O emission from the production of fertiliser by about 70–90% by using a de-N_2O catalyst (Yara 2007). This technology is now gradually being introduced in existing and new fertiliser plants.

The effect of the different pathways for agricultural development on the emission of greenhouse gas has only been measured in temperate agricultural systems. The global warming potential of conventional, organic and no-tillage agriculture was compared in an 8-year study including all the greenhouse gas on different plots in the mid-west United States (Robertson et al. 2000). None of the three systems were able to mitigate climate change, but no-tillage had lower CO_2 emissions than the other systems. The no-tillage-system, organic system and conventional tillage system had emissions corresponding to 14, 41 and 114 g CO_2 m^{-2} $year^{-1}$ (CO_2 equivalents) respectively. Plantation of poplar was able to sequester 105 g CO_2 m^{-2} $year^{-1}$.

Greenhouse gas emissions from organic and non-organic farming have been studied in England and Wales (Williams et al. 2006). The results showed that emissions were generally slightly lower for organically produced crops, but emissions from livestock production were clearly higher in organic production. For wheat, oilseed rape and potatoes, the emissions were respectively 2%, 4% and 8% higher in non-organic whereas for poultry, eggs and milk the emissions were 46%, 26% and 16% higher in organic.

Conservation agriculture appears to have lower emission than organic and conservation agriculture because of the lower land-use requirements and the ability of conservation agriculture to build soil organic carbon.

3.3 Effect of Release of Nitrogen to the Environment

Nitrogen release to the environment is another serious environmental problem that is connected to the different agricultural pathways and is dependent on such factors as total nitrogen input, crop rotation, use of catch crops and the tillage system. Analysis of nitrogen efficiency in 20 long-term experiments showed that there are no clear differences between organic and mineral fertiliser when the same amount of nutrient is applied (Edmeades 2003). A literature review of nitrogen efficiency of fertiliser nitrogen and organic nitrogen confirmed that there is no clear difference between the two sources (Crews and Peoples 2004). These studies indicate that nitrogen losses to the environment will be in the same order if the same amounts of organic or mineral fertiliser N are used.

The above mentioned studies have, however, not considered how conservation agriculture influences the loss of nitrogen to the environment. Results from a 17-year experiment in Norway where arable systems of conventional agriculture, conservation agriculture (reduced tillage and catch crops) and organic agriculture systems were compared shows that the organic arable systems have nearly three times as much nitrogen loss to the environment per energy unit food produced as a conservation agriculture system (Korsaeth 2008). Arable conservation agriculture performed better due to higher yield and less leaching of nitrogen. Conventional arable agriculture also has 50% more nitrogen emissions per kg food energy produced than conservation agriculture. Danish results showed that nitrogen leaching from organic arable farms was similar to conventional arable farms (Knutsen et al. 2006). Results from the UK studying nitrogen loss from organic and conventional farms also showed higher nitrogen losses (leaching) per kg grain in organic compared to conventional systems (Stopes et al. 2002). When comparing conventional and organic dairy systems in the Norwegian long-term experiment, there were no differences in nitrogen loss per produced unit of energy suitable for human consumption (Korsaeth 2008). These results indicate that promoting organic agriculture for the purpose of reducing the amount of nitrogen load to the environment appears not to be an appropriate approach. Both conventional and organic agriculture can have high nitrogen loss to the environment. The lower nitrogen use efficiency in organic and conventional systems compared to conservation agriculture systems in the Norwegian experiments is also an indication of higher loss of nitrogen to the environment. This loss of nitrogen will contribute to global warming (N_2O emissions) and increasing the N load to the environment.

The loss of nitrogen to the environmental also differ between animal-based and crop- based systems. This effect is more important than whether the agricultural system is conventional or organic. Animal based systems will have a higher loss of nitrogen to the environment per kg of food produced because of nitrogen loss in fodder production, in the conversion of fodder to animal products and in loss from manure (Korsaeth 2008). In crop systems up to 50% of the nitrogen is taken up by plants. In milk production about 40% of the nitrogen is transferred to milk whereas for beef production only 5% of the nitrogen is transferred to meat (Smil 2002). In a study of different farming systems in Norway including conventional arable production, conservation agriculture, and organic and non-organic livestock systems, the livestock system had more than double the loss of nitrogen to the environment per kg metabolisable energy compared to the crop production systems (Korsaeth 2008). A high proportion of meat in the diet will therefore increase the nitrogen load to the environment.

The results show that conservation agriculture has less loss of nitrogen to the environment as compared to conventional agriculture and organic agriculture. However, the losses will also depend on whether the production system is focused on producing crop or livestock products.

3.4 Effects on Soil Quality

Important soil quality parameters such as soil organic matter, nutrient content and top-soil depth will also be affected by the choice of agricultural pathway.

Fig. 3 Burning of crop residues as often practiced in conventional agriculture decreases the carbon input to the soil (Photo by CFU Zambia)

The conventional agricultural pathway as practiced in Asia through the green revolution during the last 50 years has negatively affected soil quality. The characteristics of the green revolution were high use of mineral fertiliser, mono-cropping, use of improved varieties, excessive irrigation and tillage. This reduced soil quality through depletion of organic matter, accelerated soil erosion, degradation of soil structure, waterlogging and increased soil salinity (Singh 2000). However, a low input agriculture will also have negative consequences on soil quality. As shown in Sect. 3.1 of this paper, conservation agriculture is more efficient than the other pathways in maintaining or improving soil organic carbon content. A study on soil organic matter dynamics in Zimbabwe after forest clearing showed that the soil carbon was nearly twice as high (15 Mg ha^{-1} higher) under commercial agriculture than in smallholder agriculture on clay soils (Zingore et al. 2005). The reason for this difference was a high input of organic carbon of about 10–12 Mg straw ha^{-1} under commercial agriculture whereas the carbon input under small scale farming was very low. In a long-term experiment in Zambia conservation agriculture plots had higher earth worms population, improved aggregate stability and increased total carbon compared to ploughed plots (Thierfelder and Wall 2010) (Fig. 3).

A challenge in conservation agriculture is to produce sufficient mulch. Conservation agriculture without increased residue retention is not sustainable (Wall 2009). The importance of residue retention increases with increasing aridity and temperatures (Buerkert et al. 2000). Research has shown that 1 Mg residue ha^{-1} is the minimum required to control soil erosion, while if the aim is improving soil quality the amount of crop residues retained should be in the order of 3 Mg ha^{-1} (Wall 2009). However, this amount of residue is difficult to produce particularly under dryland conditions where crop residue yields often are as low as 1 Mg ha^{-1}. The challenge is therefore to increase crop yields while at the same time retain the crop residues in the field. Fertilisers will have a key role in order to produce sufficient mulch in CA systems. Retention of crop residues in the field is however difficult, because the residues are used for other purposes such as fodder, fuel and building material. In addition, free grazing of the animals is frequently practiced. Developing conservation agriculture is therefore not only an agronomic challenge, but calls for an integrated approach involving changes in land-use, livestock management, energy and input supply and farmers' institutions.

The nutrient budget is often negative in organic agriculture because the nutrient outputs from the system will be higher than the inputs. In Sub-Saharan agriculture low in-input agricultural systems were shown to have a negative nutrient balance (Smaling et al. 1997).

Soil erosion rates will often be higher in conventional and organic agriculture because ploughing is often practiced. Ploughing causes high erosion rates in all agricultural areas with carbon emissions and eutrofication of lakes as end results. Conservation agriculture is an effective way of controlling soil erosion as the no-till system can reduce soil erosion rates up to 90% (Vlek and Tamene 2009). The erosion rates are low in conservation agriculture because an undisturbed soil will be more resistant to the erosive forces of rain and wind and because the mulch protects the soil.

Conservation agriculture is efficient in improving soil quality because soil organic carbon content is increased and erosion controlled. Farming systems using the plough exposes the soil to soil erosion.

3.5 Environmental Effects of Pesticide Use

One of the major advantages of organic agriculture is the elimination of the use of pesticides and organically produced food has been found to contain less residues of pesticides (Baker et al. 2002). Use of pesticides is often high in conventional agriculture in order to control pest, diseases and weeds. Conservation agriculture also uses pesticides, particularly to control weeds. The weed problems may increase under conservation agriculture because ploughing is not used. However, the environmental risks of using glyphosate which is the most commonly used herbicide in conservation agriculture is limited because it is broken down by micro-organisms in soil (Borggaard and Gimsing 2008). However, glyphosate resistant weeds have started to appear particularly in fields where glyphosate is frequently used in crops that have transgenic glyphosate –resistance (GRC) to tolerate spraying of glyphosate (Glyphosate Ready Crops) (Powles 2008). The combination of glyphosate resistant crops like soybean and maize and extensive use of glyphosate is particularly found in conservation agriculture is USA and South America. It is a danger that conservation agriculture in these areas has become so reliant on the use of one herbicide. However, the problems of glyphosate resistant crops can be overcome by using a wider mix of herbicides and by giving more emphasis to controlling weeds by cultivation methods. Integrated approaches to control pests are increasingly introduced in conventional agriculture and conservation agriculture. Use of pesticides is particularly worrying in low-income countries because there is much less restriction on pesticide use. A recent development is the use of the label "IPM foods" that signifies low use of pesticides (Baker et al. 2002). This is food produced using Integrated Pest Management, but use of mineral fertilisers is allowed.

The non-use of pesticides is the major environmental advantage of organic agriculture. A risk in conservation agriculture is its dependence on the use of glyphophate which have led to development of weeds resistance to glyphosate when the herbicide is used frequently in crops with glyphosate resistance.

4 Conclusion

The main objectives of agriculture are to secure the production of sufficient and nutritious food while at the same time protecting the environment. Conventional agriculture, today's dominant agricultural form of agriculture, is efficient in producing food, but the environmental costs are high.

There are clear differences in the pressure that the different agricultural forms of agriculture exert on the environment. Conventional and conservation agriculture have higher yields resulting in less pressure on forest resources. The long-term productivity of organic agriculture is questionable because the nutrient balance is often negative.

The strength of conservation agriculture is to build soil organic carbon and reduce soil erosion thereby making crop production more prepared to climate change. Conservation agriculture has also lower greenhouse gas emissions and less release of nitrogen to the environment than the other forms of agriculture. Organic agriculture is better than conventional agriculture in terms of reducing greenhouse gas emissions per hectare, but requires more land than the other forms of agriculture. When comparing greenhouse gas emission per kg food produced, there a less clear difference between organic and conventional agriculture. A problem with the type of conservation agriculture practiced in the USA and South America is that it has become so dependent on using glyphosate for weed control.

Conservation agriculture is the agricultural form of agriculture that can best reconcile the interests of achieving sufficient production and preserving the environment. However, conservation agriculture will need to take many forms depending on the variations in agro-ecological and socio-economical conditions across the globe. There is therefore a need for continued research on conservation agriculture.

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Improving Water Use Efficiency for Sustainable Agriculture

Amir Raza, J.K. Friedel, and G. Bodner

Abstract Fresh water resources are becoming scarce and polluted while their demands for agriculture, domestic, industrial, environmental and recreational uses are on a continuous rise around the globe. Traditional ways to increase yield by extending the area under cultivation, using high intensity of external inputs and breeding for yield potential in high input agro-ecosystems offer limited possibilities under limiting resource availability. Improved agricultural systems should ensure high yields via an efficient and sustainable use of natural resources such as water. This prospect has evoked calls for a "blue revolution" based on the core idea of obtaining more crop per drop of water. This chapter presents approaches to improve water use efficiency by better crop, soil and irrigation management, and analyses underlying physiological and hydrological mechanisms. We found that most management measures contribute to better water use efficiency by improving water availability to the crop while reducing unproductive water losses. The main effect of crop, soil and irrigation management is an increase of the transpiration component in relation to runoff, soil evaporation and drainage. Also the effect of deficit irrigation methods is achieved partially by reducing stomatal conductance that results in higher transpiration efficiency. Redistribution of water from soil evaporation to plant transpiration is the key for better water use efficiency of residue management and most measures in crop rotation design. Improved water use efficiency by better

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E. Lichtfouse (ed.), *Agroecology and Strategies for Climate Change*,
Sustainable Agriculture Reviews 8, DOI 10.1007/978-94-007-1905-7_8,

agronomy is achieved most effectively by an integral set of measures that are evaluated over the whole crop rotation. Processes underlying most improvements of water use efficiency in agronomy suggest that research should target plant water uptake capacity. We conclude that an integral system approach and an interdisciplinary focus on possibilities for root system management are most promising for a better water use and sustainable productivity in agriculture.

Keywords Agronomy • Water use efficiency • Drought tolerance • Water balance • Soil and crop management • Root water uptake

1 Introduction

World population is projected to reach 9.4 billion by 2050 and 10 billion by 2100 (Fischer and Heilig 1997). Highest increase (3.5 billion) is expected to occur in developing countries of South Asia and sub-Saharan Africa. Agriculture is confronted with the challenge of feeding the rapidly growing population under a scenario of decreasing land and water resources worldwide (Bossio and Geheb 2008). Global estimates of food-insecure populations comprise 825 million (Lobell et al. 2008) to 850 million (Borlaug 2007), mainly in South and Southeast Asia and sub-Saharan Africa. Contrary to United Nations' Millennium Development Goals of cutting hunger by half by 2015, the number of food-insecure populations in the world is likely to grow (WWAP 2009).

Since the 1990s yields have not increased at the pace registered since the 1950s, while world population continues to rise (Araus et al. 2008). The "yield-gap" (Röckström 2001) is expected to further aggravate due to climatic change impacts such as extending soil degradation and higher frequency of droughts (IPCC 2007; Bates et al. 2008; Trondalen 2008).

Globally, agriculture accounts for 80–90% of all freshwater used by humans, and most of that is in crop production (Wallace 2000; Shiklomanov 2003; Morison et al. 2008). Still, water is the main abiotic stress limiting crop production in several regions of the world (Araus et al. 2002; Ali and Talukder 2008). In 2030, 47% of the world population will be living in areas of high water stress (WWAP 2009). Even where water for irrigation is currently plentiful, there are increasing concerns about future availability (Falkenmark 1997). The competition from industrial and urban uses is increasing with demographic pressure and rapid industrialization (Gleick 2003; Kondratyev et al. 2003; Johnson et al. 2001). The scarcity of fresh water is also exacerbated by non-point and point source pollutions (Tilman et al. 2006), particularly salinization of groundwater aquifers (UNEP 1996). Global water pollution is on rise as every day two million tons of sewage and industrial and agricultural waste are discharged into the world's water (WWAP 2003). Seventy percent of untreated industrial wastes in developing countries are disposed into water where they contaminate the existing water supplies (UN-Water 2009). Mean nitrate levels have risen globally by an estimated 36% in global water ways since 1990, with the

Table 1 Options for improving irrigation efficiency at a field level (Adapted from Wallace and Batchelor 1997)

Improvement category	Options
Agronomic	1. Crop management to enhance precipitation capture or reduce water evaporation e.g., crop residues, conservation till, and plant spacing 2. Improved varieties 3. Advanced cropping strategies that maximize cropped area during periods of lower water demands and/or periods when rainfall may have greater likelihood of occurrence
Engineering	1. Irrigation systems that reduce application losses, improve distribution uniformity, or both 2. Cropping systems that can enhance rainfall capture e.g., crop residues, deep chiseling or paratilling, furrow diking, and dammer-diker pitting
Management	1. Demand-based irrigation scheduling 2. Slight to moderate deficit irrigation to promote deeper soil water extraction 3. Avoiding root zone salinity yield thresholds 4. Preventive equipment maintenance to reduce unexpected equipment failures
Institutional	1. User participation in an irrigation district or scheme operation and maintenance 2. Water pricing and legal incentives to reduce water use and penalties for inefficient use 3. Training and educational opportunities for learning newer, advanced techniques

most dramatic increase seen in Eastern Mediterranean and Africa, where nitrate concentration has more than doubled (GEMS 2004).

Traditional approaches of yield maximization were based on (i) increase in area under cultivation, (ii) high intensity of external inputs (fertilizer, irrigation) and (iii) breeding for high yield potential in high input agroecosystems ("green revolution varieties") (Richards 2004; Waines and Ehdaie 2007).With decreasing land and water resources, for the future these ways offer limited possibilities to satisfy the increasing food demand. Improved agricultural production systems are required that ensure high yield via an efficient and sustainable use of available natural resources. This prospect has been evoked calls for a "blue revolution" (e.g. Lynch 2007; Finkel 2009) based on the core idea of obtaining "more crop per drop" (UNIS 2000).

Improvements in agricultural water use can be achieved at several points along the production chain, such as (1) the irrigation system (2) the proportion of water attributed to plants use, and (3) the conversion of crop water consumption into yield (Hsiao et al. 2007). Gravity driven irrigation systems can have efficiencies as low as 40%, being a main limiting factor for a productive water management (Howell 2001). Better water use efficiency in field crop production can be achieved by adequate soil and crop management measures. Wallace and Batchelor (1997) resumed four options for enhancing water use efficiency in irrigated agriculture (Table 1) and pointed out that focusing on only one category will likely be unsuccessful.

The present review focuses on agronomic approaches to improve water use efficiency. We will first discuss definitions and concepts of water use efficiency at different scales. In this context we will also present some critical remarks that have been raised in relation to water use efficiency as a key strategy to improve agricultural water use. Some methodological problems related to measuring water use efficiency will be outlined. The analysis will follow an agronomic concept of water use efficiency proposed by Gregory (2004) (see Eq. 2 in Sect. 1.1). Based on this concept we will use the term transpiration efficiency for the strict dry matter-to-transpiration ratio, while water use efficiency integrates other fluxes such as soil evaporation. Based on the recommendations of practical measures for improved water use efficiency by Food and Agriculture Organization (FAO 1997), the review will discuss related scientific findings reported in literature. Our analysis will cover agronomic options of crop, soil and irrigation management, while engineering and breeding aspects are beyond the scope of this article. The particular scope of this review is to provide a mechanistic understanding and interpretation of agronomic approaches for better water use efficiency by relating practical measures to the underlying processes of stress physiology and soil hydrology. This should support a more targeted search for promising roads and instrument for a better agricultural water use.

1.1 Definitions, Concept and Critical Remarks on Water Use Efficiency

Water use efficiency can be defined for different spatial and temporal scales and according to the respective research focus (Passioura 2002, 2006). Table 2 gives an overview of common definitions and scales where water use efficiency (WUE) is studied.

Different integrative water use efficiency terms are often used interchangeably in literature, e.g. transpiration efficiency, biomass water-use efficiency (WUE_b; e.g. Tambussi et al. 2007) and biomass water productivity (WUE_b; e.g. Steduto et al. 2007). Subscripts can be used to clearly indicate the relation of the numerator to either biomass or yield.

Up scaling of water use efficiency from instantaneous leaf gas exchange to a time integrated biomass or yield related parameter is complex and requires consideration of relevant processes and environmental influences at the distinct scales (Steduto et al. 2007). While intrinsic water use efficiency is largely controlled by stomatal resistance, boundary layer effects can substantially affect the ratio of carbon to water vapour fluxes at the leaf and canopy level when plant-atmosphere coupling is imperfect (Jones 2004a; Passioura 2006).

At the whole plant level, transpiration efficiency of vegetative biomass under given environmental conditions is a rather conservative measure (Steduto et al. 2007) and mainly a function of the photosynthetic pathway. When targeting yield, the

Table 2 Definitions of water use efficiency

Term	Definition	Scale	Reference
Gas exchange WUE measures			
Intrinsic WUE	$WUE_{\mathrm{int}} = \frac{A}{g_s}$	Stomata	Jones (2004a)
Instantaneous WUE	$WUE_{inst} = \frac{A}{T}$	Leaf	Polley (2002)
Integrative WUE measures			
Transpiration efficiency	$TE = \frac{M}{T}$	Biomass	Gregory (2004)
Water productivity	$WP = \frac{Yield}{T}$	Yield	Pereira et al. (2002)
Irrigation WUE	$WUE_I = \frac{Yield}{Irrigation}$	Yield	Howell (2001)

WUE water use efficiency, *TE* transpiration efficiency, *WP* water productivity, *A* assimilation, g_s stomatal conductance, *T* transpiration, *M* biomass

distinct energy cost of yield components must be taken into consideration (cereals < legumes < oil crops), suggesting the use of glucose equivalents for better comparison (Jones 2004a).

The dominant role of environment for the biomass-water relation is expressed in the classical equation of De Wit (1958),

$$\frac{M}{T} = \frac{k}{ET_0} \tag{1}$$

where transpiration efficiency (M/T) is a linear function of a plant-specific coefficient *k* normalized for the environment using e.g. reference evapotranspiration (ET_0).

From an agronomic point of view, Gregory (2004) proposed the following relation:

$$WUE = \frac{M}{T} \frac{1}{1 + \frac{E_s + R + D}{T}} \tag{2}$$

where total water use efficiency is separated into transpiration efficiency (M/T) and a water balance based term for the magnitude of plant water use (T) compared to unproductive losses (E_s) being soil evaporation, R being runoff and D being deep drainage.

Passioura (1977) proposed a framework of factors determining yield formation in water limiting environments which since then has been applied extensively in plant breeding.

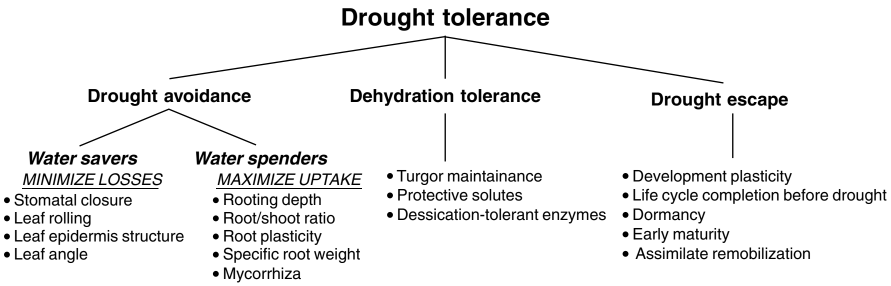

Fig. 1 Mechanism of drought tolerance. Plants tolerate drought by using different mechanisms including drought avoidance, dehydration tolerance and drought escape. These mechanisms are governed by physiological processes and help plants to sustain growth and reproduction under drought conditions (after Levitt 1972 and Jones 2004a)

$$Yield = WU * WUE * HI \tag{3}$$

where WU is plant water uptake, WUE is water use efficiency and HI is harvest index.

An extended model of overall water use efficiency across several scales was proposed by Hsiao et al. (2007) to allow a stepwise analysis of all relevant efficiencies along the whole production chain. This conceptual model covers the efficiency of the irrigation system, the efficiency of crop water use at the field scale and the efficiency of assimilation and yield formation with a given amount of water. In rain-fed agriculture Hsiao et al. (2007) introduced two soil management related terms, being infiltration and rhizostorage efficiency. These terms again point to the water balance concept as given in Eq. 2.

Equations 1–3 reveal the two relevant sides for a mechanistic analysis of agronomic options to improve water use efficiency, being (i) physiological processes of biomass production and drought tolerance of plants, and (ii) hydrological and soil physical mechanisms of water dynamics.

Knowledge on relevant drought tolerance mechanisms is of high importance to improve crop production in water limiting environments (see Farooq et al. 2009). Figure 1 gives an overview of plant responses to drought in natural ecosystems following Levitt (1972).

Most adaptations that have evolved in plant communities of dry ecosystems are at the cost of reduced plant growth while ensuring reproductive survival. Comparing two wheat cultivars differing in carbon isotope discrimination, Condon et al. (2004) demonstrated that superior water use efficiency translated to better crop performance only under high drought stress of soil water storage-driven environments. As shown by Blum (2005), the potential agronomic use from a given mechanism of drought tolerance depends on the characteristics of the drought environment (severity, duration and timing of stress). He critically analyzed the breeding focus on water use efficiency because drought tolerance traits improving plant water extraction and leading to sustained stomata opening and assimilation might even result in lower water use efficiency (Blum 2009). Therefore he suggests a shift to the concept of effective water use which agrees to the conclusion of Jones (2004a) on the key importance of and efficient use of available soil water in field crop production.

Affectivity of water use is considered in Eq. 3 in terms of the proportion of transpiration in relation to the loss components in a water balance frame. In the conceptual model of Hsiao et al. (2007) for dry land cropping, this uptake efficiency would correspond to the combined effect of infiltration, rhizostorage, consumptive and transpiration efficiencies.

An effective water use requires consideration of soil hydrological aspects and their interaction with plant traits. In simplified way water use effects of soil and plant parameters can be characterized by a relationship commonly used in hydrological modelling (e.g. Šimůnek et al. 2008)

$$T_a = ET_p(1-e^{-kLAI})\int_{LR}\alpha(h)b(x)dx \tag{4}$$

where actual transpiration (or water use) is a function of potential evapotranspiration (ET_p), a light extinction coefficient (*k*), leaf area index (LAI), a stress reduction function (α) and root distribution (*b*) over the root depth (LR). Canopy traits (*k*, LAI) influence the surface energy balance and determine the amount of energy available for potential soil evaporation and plant transpiration. In the rhizosphere, soil hydraulic properties and root system characteristics determine actual root water extraction (T_a). Potential water uptake is attributed to distinct soil layers according to the root distribution and adjusted to its actual amount by the soil water status (e.g. soil matrix potential *h*) in the distinct layers using an appropriate functions for α (e.g. Feddes et al. 1974; Van Genuchten 1987).

While plant physiologists, breeders and agronomists have directed most attention on the aboveground plant parts (stomata, leaf, and canopy) and their role for water use efficiency, soil hydrologists focused more on plant water uptake. They tended to reduce water uptake to a macroscopic sink term in their models. If effective water use is an essential target (Blum 2009) together with high water use efficiency, future efforts should be directed to better understand root system processes and root-soil interactions to achieve an overall improvement of agricultural water use.

1.2 Methodological Challenges

The definitions of water use efficiency as given in Table 2 imply that appropriate methods have to be used for quantification at different scales. At the leaf scale, water use efficiency is characterized by measurements of gas exchange and stomatal conductance. The underlying methods of measuring CO_2 and H_2O fluxes are straightforward and several types of measurement devices are available.

A method relying on gas exchange physiology, but providing a time integrated view of water use efficiency is carbon isotope discrimination (Farquhar and Richards 1984). Carbon isotope technique has been used to select genotypes possessing better water use efficiency (Johnson et al. 1990; Martin et al. 1999; Condon et al. 2004). Still the use of carbon isotope discrimination for crop improvement strongly depends on the hydrological regime (Monneveux et al. 2005). It has been applied most successfully to select adapted genotypes in storage driven and terminal drought environments. This was explained by the conservative water use of cultivars with high water use efficiency (low carbon isotope discrimination) ensuring sufficient water availability at grain filling. Also their phenology was adapted to terminal drought environments showing earlier flowering which is a characteristic drought escape strategy (Condon et al. 2004). Under intermittent drought and potential yield conditions, carbon isotope discrimination can also be negatively related to crop performance.

A proper quantification of water use efficiency on the whole plant scale requires an accurate measurement of the transpiration component. Frequently water relations are studied in pot experiments which allow a simple and precise measurement of transpiration when withholding soil evaporation. Still care must be taken when extrapolating results from pot experiments to the field due to (i) alterations of root growth in the confined system and (ii) influences of pot size on water availability and transpiration (Ray and Sinclair 1998).

In field studies, transpiration is mostly calculated via the water balance equation. This however implies at least two uncertainties. First the other components of the water balance (i.e. precipitation/irrigation, runoff, drainage, and change in profile water content) have to be quantified accurately. While runoff can easily be avoided by a proper site selection, the drainage component is very difficult to measure. The most adequate instrument to determine all water balance components are lysimeters. As they are not available in most cases, water use efficiency values are frequently derived from measurements of change in profile water content only using different water monitoring techniques and assuming zero drainage. We therefore assume that differences in water use efficiency estimates found in literature often derive from methodological difficulties of quantification of the water balance components and errors originating in simplified assumptions.

Even with properly measured evapotranspiration, a further uncertainty arises from the separation between soil evaporation and plant transpiration. Although there are efforts to develop methods based on isotope composition (Hsieh et al. 1998), still most studies rely on calculations based on Beer's law and measurements of leaf area index and radiation extinction coefficients (Brisson et al. 2006).

Due to difficulties in measurement, water use efficiency effects are frequently evaluated using simulation models. Policy makers and water resource managers have to deal with multitudinous scenarios of cropping systems, amounts, timing and method of irrigation and fertilizer application for bringing improvement in water use efficiency. Experimentation cannot address all scenarios, but accurate simulation models may fill in the gap when appropriately parameterized and validated.

Different simulation models (e.g. AquaCrop, CropSyst, DSSAT, GOSSYM, WOFOST) have been used to simulate yield and water use under a variety of environmental, management and cropping regimes. Simulation of crop performance in the FAO model, AquaCrop (Steduto et al. 2007) is based on a normalized biomass-to-transpiration ratio, taken the conservative nature of this ratio (Steduto et al. 2007). The model has been used to predict yield and water use under full and deficit irrigation management with sufficient accuracy (Farahani et al. 2009; Fang et al. 2009).

Beside management assessment and decision support, models were also successfully applied to better interpret the potential impact of carbon isotope discrimination on the performance of wheat cultivars under different environmental conditions (Condon et al. 2004).

Although simulation models are based on straightforward physical theory such as the Richards' equation for water flow, an accurate parameterization of plant water uptake is essential. Beside the problem of spatial and temporal variability in soil hydraulic properties, most simulation studies do not have measurements of root distribution that underlie the sink term calculation in water uptake modelling (Feddes and Raats 2004), let alone parameters for more complex root architecture models (Leitner et al. 2010). Furthermore plant-soil interactions involved in water uptake compensation (Šimůnek and Hopmans 2009), root tropism (Eapen et al. 2005) and biochemical signalling (Comstock 2002), that essentially affect plant stress response and water use efficiency, are rarely considered in crop models.

Evett and Tolk (2009) concluded that models adequately simulate water use efficiency under well watered conditions, but tend to misestimate water use efficiency under conditions of water stress. This reveals the need for a better representation of plant-soil interactions in current models, overcoming empirical stress reduction functions and simplified root system descriptions. However, even with more physically based models, a major challenge for their reliable application in agricultural water management will remain the quality of parameterization of sensitive components determining water uptake and plant growth.

2 Better Agronomy

Food and Agriculture Organization (FAO 1997) provided a summary of practical measures recommended in order to improve water use efficiency (Table 3). Measures oriented to enhance crop growth can be classified into those dedicated to crop rotation design and crop husbandry (1–3), fertilizer management (4), soil management (5 and 6) and appropriate irrigation management (7 and 13).

The basic assumption underlying these set of instruments is that any management measure that helps to improve yield will ultimately lead to a better water use efficiency (Gregory 2004; Machado et al. 2008; Ritchie and Basso 2008). This includes changes in transpiration efficiency (e.g. crop type) as well as change in the proportion of transpiration to the loss components in the water balance components by soil and crop management measures (Fig. 2). The affectivity of a given management decision to obtain an improvement in overall water use efficiency will be determined also by its interaction with environmental site characteristics (Abbate et al. 2004).

Table 3 Food and Agriculture Organization recommendations for practical measures to improve agricultural water use efficiency in irrigated agriculture (FAO 1997)

Objective	Measure
Enhancement of crop growth	1. Select most suitable and marketable crops for the region 2. Use optimal timing for planting and harvesting 3. Use appropriate insect, parasite and disease control 4. Apply manures and green manures where possible and fertilize effectively preferably by injecting the necessary nutrients into the irrigation water 5. Use optimal tillage to avoid excessive cultivation 6. Practice soil conservation for long-term sustainability 7. Irrigate at high frequency and in the exact amounts needed to prevent water deficits, taking account of weather conditions and crop growth stage 8. Avoid progressive salinization by monitoring water-table elevation and early signs of salt accumulation, and by appropriate drainage
Conservation of water	9. Reduce direct evaporation during irrigation by avoiding midday sprinkling. Minimize foliar interception by under-canopy, rather than by overhead sprinkling 10. Reduce runoff and percolation losses due to over irrigation 11. Reduce evaporation from bare soil by mulching and by keeping the inter-row strips dry 12. Reduce transpiration by weeds, keeping the inter-row strips dry and applying weed control measures where needed 13. Reduce conveyance losses by lining channels or, preferably, by using closed conduits

The following section will review the potential impact of crop, soil and irrigation management practices as well as the mechanisms underlying their expected effects on water use efficiency.

2.1 Crop Management

Crop management practices include decisions on sowing date, planting density, crop rotation, phytosanitary measures and cultivar selection. These practices influence agronomic water use efficiency by adapting the cropping system to the environmental site conditions and providing optimum growth conditions for the single crop in order to obtain maximum yield with available resources. Crop management practices influence water use efficiency at the level of field crop stands, single plants and physiological processes (Fig. 3). Beside crop husbandry, also management of soil fertility by fertilization is considered here, although it strongly interacts with soil management measures that are considered in Sect. 2.2.

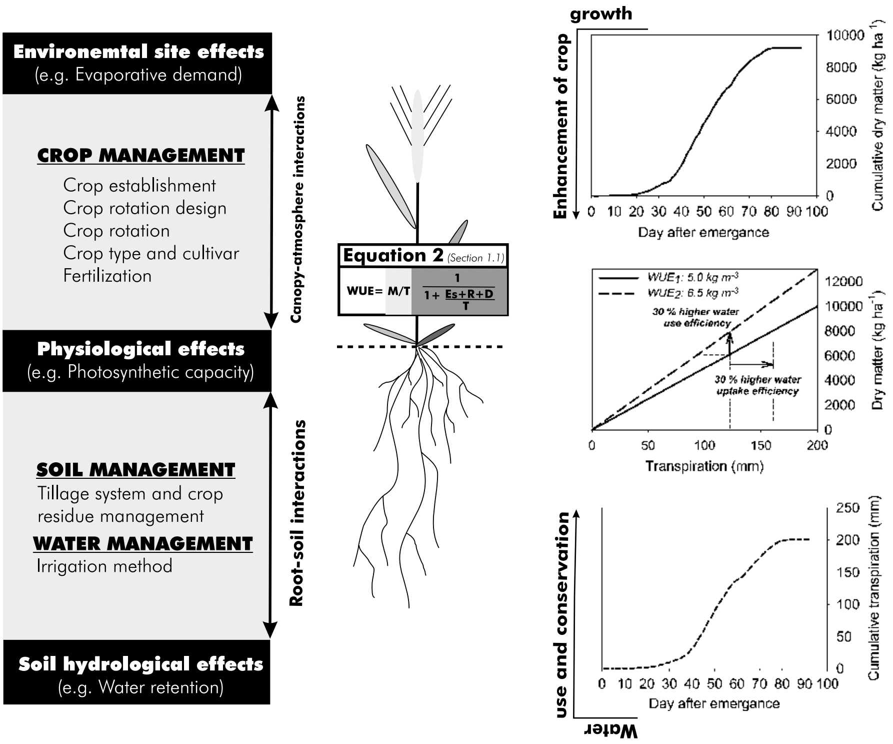

Fig. 2 Effect of management practices on water use efficiency. Management practices can improve water use efficiency by affecting yield and transpiration efficiency. The affectivity of any management practice will depend on its interaction with environment

2.1.1 Sowing and Stand Establishment Practices

Sowing date of crops can significantly affect water use efficiency (Morrison and Stewart 2002; Turner 2004; Gunasekera et al. 2006). Early sowing has frequently been found to improve yield and water use efficiency (Gregory 2004), while yields were reduced by delayed sowing (Oweis et al. 2000; Faraji et al. 2009).

In environments where water is the limiting factor, sowing date should adapt crop growth and development to water availability (water storage, rainfall distribution) within the restrictions imposed by other constraints (early droughts, frost, timing of weed management). An appropriate sowing date can enhance early vigour of the crop with better canopy cover of the soil surface. This reduces evaporation losses in favour of transpiration (Tambussi et al. 2007). Increased water use efficiency of early sown crops and winter-grown varieties is also related to the lower evaporative demand of the atmosphere during part of the growing period (Purcell et al. 2003). Humphreys et al. (2001) showed that early sowing of winter crops immediately after rice harvest increased the water use efficiency of rice-based cropping systems by better use of

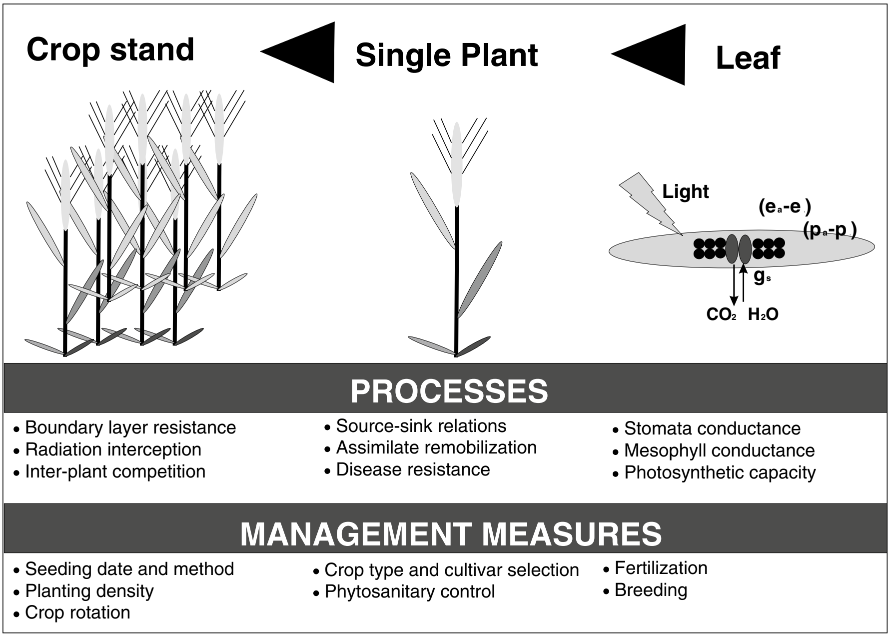

Fig. 3 Measures and processes involved in regulation of water use efficiency. Management measures positively affect physiological processes at single leaf scale. These effects are transformed into better growth of individual plants with consequences of increase in overall water use efficiency of crop stands

stored soil water and capture of winter rainfall instead of loosing it as runoff or deep percolation. An appropriate sowing time of cereals also contributes to avoid summer drought in Mediterranean climates, i.e. it benefits from a drought escape strategy which ensures sufficient water supply for yield formation (Tambussi et al. 2007).

Using appropriate method of sowing can also help to improve water use efficiency. Particularly sowing depth can influence early vigour and hence soil evaporation (Ali and Talukder 2008). Deeper sowing combined with cultivars with longer coleoptiles was found to increase growth vigour, yield and water use efficiency of wheat in environments with early droughts as seedlings could make better use of soil moisture (Rebetzke et al. 2007). Research in southern Queensland found that water use of rice grown on beds was 32% less than when grown using conventional permanent flood, while yields were maintained, resulting in a large increase in water use efficiency (Borrell et al. 1997). Sowing of crops on precisely levelled fields can also affect water use efficiency positively by ensuring uniform distribution of irrigation water over the entire field and thereby ensure homogeneous and quick stand establishment. Laser levelled fields exhibited 98.7% and 29.4% higher water use efficiency as compared to unlevelled and traditionally levelled fields in case of wheat. Use of laser land levelling surely increases grain yield and saves irrigation water as compared to traditional method of sowing (Asif et al. 2003).

Sowing of crops with proper row spacing can also affect water use efficiency. Karrou (1998) found that water use efficiency decreased with increasing row spacing from 12 to 24 cm in wheat. Azam-Ali et al. (1984) on the contrary found that increasing row spacing in pearl millet from 37.5 to 150 cm increased water use efficiency for dry matter production from 2.1 to 4.7 kg m^{-3}. It was due to the reason that widely spaced plants used water more efficiently as compared to narrow and medium spaced plants in this study. A major influence of row spacing is related to soil evaporation that can be reduced by narrowing row distance (Chen et al. 2010). High stand densities increase intra-plant competition. Therefore the effect of row spacing on yield strongly depends on crop species, formation of yield components and seasonal water availability. Ritchie and Basso (2008) for example showed that modern cultivars of maize can be planted at higher densities as traditionally used, thereby increasing yield and decreasing evaporation losses. Crops such a cereals have high plasticity in plant architecture and yield components (Simane et al. 1993) so that yield formation remains unaffected over a wide range of row spacing (Gregory 2004).

The technique of seed priming has been shown to improve plant stands and provide benefits in terms of earlier canopy closure and increased seed yield for a range of crops such as wheat, maize, lentil, chickpea in rain fed as well as for irrigated crops (Ali 2004; Rashid et al. 2002). Seed priming involves soaking seeds in water for a specific period usually overnight, then surface dried and then sown. This technique reduces the pre- or post-sowing irrigation needs, saves water and increases the water use efficiency. Germination and water use efficiency of barley was improved by 95% and 44%, respectively due to seed priming as compared to unprimed seed (Ajouri et al. 2004).

2.1.2 Crop Rotation

Larcher (1994) compared net prime production of agricultural to natural ecosystems. Agricultural systems averaged 0.65 kg m^{-2} of annual dry-matter production, which is in the range of natural grassland and steppe (0.6 kg m^{-2}). Most natural terrestrial ecosystems have a higher productivity than agricultural systems, particularly those with high average leaf area index. This indicates an optimized use of growth factors over the year by natural plant communities. Site specific crop rotation design is intended to achieve a high utilization efficiency of light, water and nutrients to maximize growth and yield.

Crop rotation can optimize water use efficiency by (i) increasing the number of crops grown per year, (ii) more effective use of available resources, and (iii) better phytosanitary conditions.

Passioura (2006) indicates that water use efficiency depends not only on how a crop is managed during its life, but also how it is fitted into the whole management system. Continuous cropping that avoids fallow can increase single crop as well as system water use efficiency and avoids damages caused by bare fallows (Schillinger et al. 1999; Li et al. 2000). Pala et al. (2007) evaluated several wheat based crop rotations under Mediterranean conditions in Syria. Water use efficiency of wheat decreased in the following crop rotation sequence: fallow, medic, lentil, chickpea, and continuous wheat. However, on a system basis, wheat-lentil and wheat-vetch systems were more efficient than the wheat-fallow system. Sadras et al. (2003) proposed a strategy to adapt crop rotation decision flexibly to conditions at the start of the growing season for south-eastern Australian dry-land farming. Introduction of canola (*Brassica napus*) into a wheat based rotation in wetter years improved whole farm profitability and water use efficiency.

Cover cropping is a common crop rotation practice to avoid negative environmental effects of autumn fallows after cash crop harvest by prolonging soil coverage and plant growth over the season (Bodner et al. 2007). It is intended to control erosion, prevent nutrient leaching, fix nitrogen and improve soil conditions. Additional water use of cover crops however could negatively affect soil water availability for the next crop. Bodner et al. (2007) showed that water use efficiency of cover crops species is high compared to cash crops of similar habitat and same families. This is due to the substantially lower evaporative demand of the atmosphere during the vegetation period of the cover crops. Negative effects due to soil water depletion was highest after dry autumn conditions when cover crops continued water extraction from deeper layers, while fallow evaporation was reduced (Islam et al. 2006). Potential yield effects are dependent on the height of winter precipitation, water storage capacity of the soil, phenology and water uptake characteristics of the subsequent cash crop as well as rainfall distribution over the cash crop growing period.

Crop rotation is an important management tool to improve resource use of the cropping system. Interrupting a series of cereal crops by oilseeds or grain legumes can increase the yields of the subsequent cereal crops. The inclusion of oilseed and pulses in traditional, cereal-based cropping systems has been shown to improve nutrient use efficiency (Walley et al. 2007), increase the overall productivity and water use efficiency and improve economic sustainability (Zentner et al. 2002). The role of canola (*Brassica napus)* as a “break” crop in southern Australia has been especially notable (Passioura 2002). The development of winter-growing chickpeas in the Mediterranean region may serve a similar role (Singh et al. 1997). Inclusion of deep rooted legumes like lucerne in farming systems of semi arid regions for 2–3 years has also been suggested as a measure towards efficient utilization of soil water and nutrients by many researchers (Rasse and Smucker 1998; Latta et al. 2001; Ridley et al. 2001). Introducing a legume crop in a cereal rotation can improve soil fertility by nitrogen fixation and addition of organic matter in the soil, increase the yields of the subsequent cereal crops and help to control disease, pests, and weeds that build up in continuous cereal production systems (Papastylianou 1993; Diaz-Ambrona and Miniguez 2001; Ali and Talukder 2008). Wheat–legume rotation systems with additional nitrogen input in the wheat season not only ensure sustainable production, but also are more efficient in utilizing limited rainfall by better root water uptake and increased transpiration efficiency (Pala et al. 2007). Pulse crops with oilseeds or wheat in a well planned crop sequence may improve water use efficiency for the entire cropping systems in semiarid environments. Pulses extract water slowly only from shallower soil depths thereby leaving sufficient water in

Table 4 Effect of crop management practices on water use efficiency

Practice	Increase in water use efficiency (%)	Reference
Seed priming	44	Ajouri et al. (2004)
Sowing time	30	Jalota et al. (2008)
Method of sowing	15–20	Zhang et al. (2007a)
Row spacing	>100	Azam-Ali et al. (1984)
Weed control	>100	Cooper et al. (1987)
Crop rotation	0–57	Pala et al. (2007)

the soil for subsequent crops in rotation (Gan et al. 2009). Effect of crop management practices on water use efficiency is shown in Table 4. These values are indicated here only to demonstrate the potential of a crop management practice on water use efficiency and may vary greatly among regions as well as with application of supporting soil and irrigation management practices.

Appropriate choice of crop sequence can improve water use efficiency by helping to control diseases and weeds. Weeds compete for water and nutrient resources of the main crops. Weeds can considerably decrease crop growth and water use efficiency particularly in food legume crops which have slower initial growth than many cereals. Weed control ensures that water stored in soil is used by the crops (Gregory 2004). Also the efficiency of fallowing to increase water availability for the next season is highly dependent on weed control (Gregory 2004). In lentil for example weed control almost doubled dry matter production and water use efficiency (Cooper et al. 1987). Control of pests and diseases by an appropriate crop rotation can be an efficient way to increase yield and water use efficiency. Paul and Ayres (1984) for example reported that plants infected with leaf rust showed reduced water use efficiency, particularly under dry conditions.

2.1.3 Crop Type and Cultivar Selection

Crop type and cultivar selection contributes to adapt the production system to environmental growth conditions and it is fundamental for site specific optimization of water use efficiency. Distinct response to water limiting conditions occurs due to (i) different photosynthetic pathway and (ii) different energy requirements for yield formation, as well as (iii) progress in breeding of adapted drought tolerant varieties.

Plants with the C_3 photosynthetic pathway are less efficient in water use than plants with the C_4 pathway, especially at higher temperatures and lower CO_2 concentrations (Condon et al. 2004; Long 2006; Ali and Talukder 2008). In species with C_4 photosynthesis high photosynthetic rates can be associated with low stomatal conductance, leading to high water use efficiency (Cowan and Farquhar 1977; Schulze and Hall 1982). In C_4 plants carboxylation is carried out by an enzyme (PEP carboxylase) with stronger affinity for CO_2 than in C_3 species (Rubisco), leading to a lower intercellular CO_2 concentration and thus a higher driving force gradient

Table 5 Water use efficiency (kg m^{-3}) of crops in the Mediterranean region. Values refer to relationship between yield and evapotranspiration (After Katerji et al. 2008)

Crop	Water use efficiency	Reference
Wheat	0.5–9.4	Oweis (1997), Katerji et al. (2005b), Pala et al. (2007)
Corn	1.36–2.15	Karam et al. (2003), Dagdelen et al. (2006)
Sunflower	0.39–0.72	Marty et al. (1975), Katerji et al. (1996)
Soybean	0.39–0.77	Katerji et al. (2003), Karam et al. (2005)
Broad bean	0.45–1.37	Katerji et al. (2003), Katerji et al. (2005a)
Chickpea	0.4–0.98	Oweis et al. (2004), Katerji et al. (2005a)
Lentil	0.36–2.09	Katerji et al. (2003), Oweis (2004)
Cotton	0.61–1.3	Dagdelen et al. (2006), Karam et al. (2006)
Barley	1.46–2.78	Katerji et al. (2006)
Sorghum	0.67–1.59	Mastrorilli et al. (1995)
Potato	16.2–18.5	Katerji et al. (2003)
Sugar beet	6.6–7.0	Katerji et al. (2003)
Tomato	4.4–8.3	Katerji et al. (2003)
Grapes	16–18.1	Rana and Katerji (2007)

for CO_2 uptake (Nobel 1991; Chaves et al. 2004). With rising atmospheric CO_2 levels, it is likely that transpiration efficiency will increase in C_3 crops. Except for maize and sorghum, the world's major food crops are C_3 plants. Field experiments with free-air CO_2 enrichment have shown substantial improvement in biomass, especially where water is limiting. With C_4 crops such as maize and sorghum, free-air CO_2 enrichment experiments have shown negligible growth responses to elevated CO_2 (Passioura and Angus 2010). Some benefit of elevated CO_2 on C_4 crops was shown in drought conditions due to reduced water use (Sun et al. 2009). Following attempts to use conventional hybridization to get C_3–C_4 hybrids, some biotechnological advances to transformed C_3 plants to acquire C_4 characteristics have been reported (Matsuoka et al. 2001; Parry et al. 2005).

In relation to yield, water use efficiency decreases from cereals over legumes to oil crops due to higher energy requirements in yield formation (Steduto et al. 2007; Jones 2004a). High water use efficiencies are obtained in forage crops where the entire aboveground portion of the plant is harvested. Higher water use efficiency for forage crops when compared to seed crops is also related to lower non-productive water losses through evaporation under their closed canopies (Hatfield et al. 2001). Nielsen et al. (2005) found the highest average water use efficiency among forage crops for forage pea (2.28 kg m$^{-3\ 1}$), declining to 1.14 kg m^{-3} for corn silage (Nielsen et al. 2005). Table 5 gives an overview of water use efficiencies of different crops grown under Mediterranean conditions.

Water use efficiency varies between different genotypes of the same crop (Hufstetler et al. 2007; Jaleel et al. 2008; Rajabi et al. 2009). Much effort has been dedicated to breed for higher water use efficiency. Reynolds and Tuberosa (2008) give an overview of breeding advances for improved productivity in drought-prone environments. Following Passioura' framework, most success was achieved via higher harvest index (Condon et al. 2004). Only recently breeding efforts for enhanced

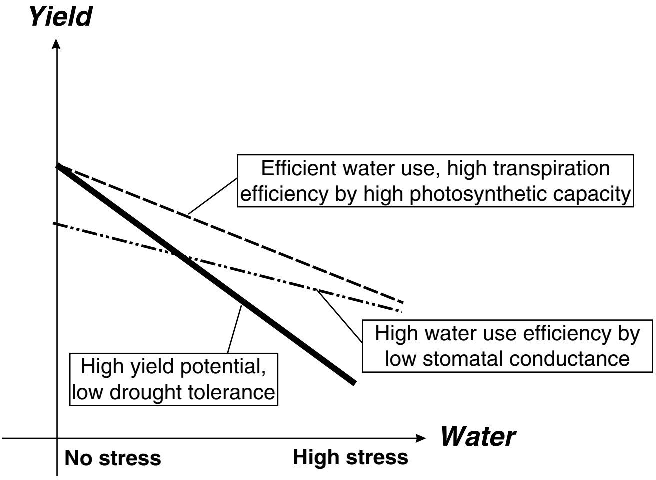

Fig. 4 Response of cultivars under water stress. Cultivars may vary in their response to water stress. High water use efficiency under water stress can be due to increase in transpiration efficiency, low stomatal conductance or high yield potential

water uptake capacity by targeting root parameters are reported (Yusuf Ali et al. 2005; Kato et al. 2006; Gregory et al. 2009). Substantial progress therefore can be expected in future from improved root systems as Waines and Ehdaie (2007) showed that breeding of high yielding "green revolution" varieties has lead to small root systems with low uptake capacity. Useful traits for improved drought tolerance depend on the characteristics of the drought environment itself (van Ginkel et al. 1998). In relation to water use efficiency, Condon et al. (2004) showed that wheat cultivars efficient in water use and selected based on carbon isotope discrimination by reduced stomatal conductance performed better and attained higher yields in stored-moisture environment, than in environments where they have to rely upon in-season rainfall. Genotypes where higher water use efficiency is related to photosynthetic capacity ("capacity types") and not to lower stomatal conductance ("conductance types") would result in sustainable yield improvements. Considering the typically erratic nature of rainfall in dry areas with dry and wet years, Blum (2005, 2009) concluded that sustainable optimization of yield should be obtained by maximising water uptake efficiency rather than water use efficiency. Figure 4 gives an overview of expected yield response to drought of cultivars from these different selection targets.

2.1.4 Fertilizer Management

Relationships between nutrients and water use efficiency were first described by Viets (1962). The roles of different nutrient elements are discussed by Marschner (1995) and their effect on water use efficiency was reviewed by Davis (1994) and Raven et al. (2004).

Water availability and nutrient supply are interacting factors in determining crop growth and crop water use efficiency. The efficiency of nutrients to increase yield depends on water supply according to the law of optimum: For higher production, the plant can make better use of the growth factor being in minimum, the more the other growth factors are within the optimum (Claupein 1993). With increasing water stress, nutrient availability as well as nutrient uptake capacity of the plant are impaired and the marginal return in terms of yield increase per unit of applied nutrient decreases (Ehlers and Goss 2003). Drought can limit nutrient availability due to reduced mineralization of organic matter and lower transport of nutrients to the root. Both, convective transport of non-adsorbing solutes (e.g. nitrate) as well as diffusive transport of adsorbing nutrients (e.g. phosphate) is reduced with increasing water shortage. Decreasing transpiration flux can cause nutrient deficiency in leaves due to reduced xylem transport of dissolved nutrients from roots to the aboveground plant parts (Alam 1999).

Nutrient uptake capacity is significantly influenced by root system parameters. Root growth and root distribution are modified by nutrient availability and distribution in the soil (Hodge 2004). Plants respond to low nutrient availability by enhanced root growth and root exudation. If water use efficiency is related to aboveground biomass or yield, it can even decrease with increasing investment of assimilates and energy into the root system (Raven et al. 2004).

The nutritional status of the crop influences stomatal response and water use efficiency at leaf, whole plant and crop stand scale. Several physiological processes relevant for water use efficiency are affected by nutrient deficiencies, such as osmotic pressure, stomata regulation, photosynthesis and activity of nitrate reductase in plant leaves (Hu and Schmidhalter 2005; Li et al. 2009).

At the whole plant and crop stand scale, the nutrient status influences growth rate, leaf area and green leaf duration as well as assimilate partitioning (Davis 1994; Gregory 2004). When relating water use efficiency to total evapotranspiration, improvement by fertilizer input is obtained via increase in early canopy growth so that it shades the surface and thereby reduces the proportion of soil evaporation on total evapotranspiration (Schmidhalter and Studer 1998; Gregory 2004). Higher nutrient availability leads to a different rate of increase in water use and crop yield. Early studies already reported that improved nutrient status promoted yield more than water use and therefore resulted in better water use efficiency (Power 1983; Ritchie 1983). Also Hatfield et al. (2001) consider fertilization as a principal measure to improve plant growth and yield and thereby increase water use efficiency.

Nitrogen (N) management is one of the major factors to attain higher crop productivity. Nitrogen effects have been described on gas exchange as well as integrative agronomic water use efficiency. Positive effects of nitrogenous fertilizers include increase in leaf area index, green crop duration and dry matter production that ultimately lead to increase in water use efficiency (Latiri-Souki et al. 1998).

Up to 75% of leaf nitrogen is present in the chloroplasts, most of it in the photosynthetic machinery which gives a positive relationship between light-saturated rate of photosynthesis and leaf nitrogen concentration (Evans and Seemann 1989). Leaf nitrogen is correlated with photosynthetic capacity by influencing Rubisco activity and the capacity of electron transport. Although assimilation is not directly proportional to leaf nitrogen, an enhanced photosynthetic capacity due to better nitrogen-supply can results in higher transpiration efficiency at a given stomatal conductance (Shangguan et al. 2000).

Nitrogen deficiency can reduce mesophyll conductance and to a lesser extent, stomatal conductance (Jacob et al. 1995). Also Ciompi et al. (1996) related lower gas-exchange water use efficiency of nitrogen-deficient sunflower leaves to a more pronounced reduction of mesophyll activity compared to stomatal conductance.

Beside physiological processes, a main effect of nitrogen-deficiency on water use efficiency is found on the whole plant and crop stand level. Restricted development of nitrogen-deficient plants is usually due to a lower rate of leaf expansion rather than to a decline in the rate of photosynthesis per unit leaf area (Sage and Pearcy 1987). Reduction in leaf expansion and leaf area under low nitrogen supply decreases radiation interception and leads to higher evaporation losses (Davis 1994). Therefore higher water use efficiency of well fertilized plants is mostly explained by a higher proportion of transpiration in relation to total evapotranspiration. When water use efficiency is related to yield, an additional advantage of nitrogen fertilization is prolonged green leaf area duration and higher harvest index (e.g. Lawlor 2002). However, ample nitrogen supply could also result in abundant vegetative growth which may induce water shortages during yield formation as well as increased lodging (Ehlers and Goss 2003).

The effect of nitrogen on root water uptake capacity is complex (Li et al. 2009). Rational use of fertilizers can enhance root growth, while high levels of nitrogen tend to reduce root penetration into the soil and restrict formation of fine roots and root hairs, which could increase crop susceptibility to temporal water shortage.

Increased water use efficiency due to nitrogen fertilization was reported for grain sorghum and maize by Varvel (1995) and Ogola et al. (2002). Higher water use efficiency due to increased biomass production with improved nitrogen supply have also been reported for wheat and corn by Campbell et al. (1992) and Varvel (1994), respectively. A 25% increase in water use efficiency of chickpea has been reported through application of nitrogen fertilizer (Bahavar et al. 2009). In the Sahel, water use efficiency of Pearl millet was improved through the combination of nitrogen management and increased plant densities (Payne 1997).

The efficiency of nitrogen management to improve water use efficiency is influenced by environmental conditions. Under limited water supply, crop response to higher dose of inorganic fertilizer is restricted (Hatfield et al. 2001). Under such conditions, timing and dose of fertilizer application shall be adjusted based on available soil moisture if positive effects of nitrogen application are to be fully realized (Passioura 2006).

Phosphorus is required for several physiological processes including storage and transfer of energy, photosynthesis, regulation of some enzymes, and transport of carbohydrates (Hu and Schmidhalter 2005). Soils in arid Mediterranean areas as well as large areas in the tropics suffer from low phosphate availability. Phosphorus supply to the plant in these regions is further reduced by dry soil conditions that lower diffusion rates to the roots (Simpson and Pinkerton 1989). Plant phosphorus uptake efficiency is strongly influenced by root traits (Lambers et al. 2006; Lynch 2007) as well as mycorrhization (Bolan 1991), while sufficient soil phosphorus can enhance root growth, water uptake and water extraction from deep soil layers (Dang 1999). Payne et al. (1992) found an increase of transpiration efficiency at the whole plant as well as the leaf scale. Increasing phosphorus availability resulted in stronger increase in photosynthetic rate compared to transpiration rate. Phosphorus deficiency was found to lower the level of light saturation which could explain observed inhibition of photosynthetic rate (Payne et al. 1992). On the whole crop level, strong effects of additional phosphorus supply on dry matter production and water use efficiency, particularly under low water availability, have been reported for millet by Brück et al. (2000). Kundu et al. (2008) showed increasing leaf area index and higher water use efficiency of common bean with higher phosphorus supply. Addition of phosphatic fertilizer has been reported to enhance water use efficiency of different crops (Hatfield et al. 2001), such as pearl millet (Payne et al. 1992, 1995) and chickpea (Singh and Bhushan 1980).

The positive effect of potassium (K) on water stress tolerance is related to several physiological processes (Pettigrew 2008). Potassium maintains the osmotic potential and turgor of the cells (Hsiao 1973) and regulates the stomatal functioning (Kant and Kafkafi 2002; Benlloch-González et al. 2008). Potassium enhances photosynthetic rate, yield and water use efficiency under stress conditions (Tiwari et al. 1998; Egila et al. 2001; Umar and Moinuddin 2002). Improvement of potassium nutritional status has also been found to protect plants against oxidative damage during drought stress (Cakmak 2005).

Potassium promotes root growth of plants which in turn leads to a greater uptake of nutrients and water by plants (Saxena 1985; Rama 1986). Gerardeaux et al. (2010) described effects of potassium deficiency on cotton. Potassium stress during vegetative development decreased plant dry matter production and leaf area, increased dry matter partitioning to leaves and specific leaf weight. Severe deficiency also reduced partitioning to roots and inhibited leaf photosynthetic rates.

Positive effect of potassium on drought tolerance include enhancement of deep rooting, protection against tissue dehydration, optimization of stomatal opening and closure resulting in better water use efficiency, detoxification of toxic oxygen radicals, and improvement in translocation of photo assimilates (Römheld and Kirkby 2010). Higher application of potassium such as 125 and 200 kg ha^{-1} increased water use efficiency of barley for dry matter production by 12% (Andersen et al. 1992). He et al. (1999) conducted experiments to clarify the effects of water, nitrogenous and potassium fertilizer and animal manures on water uee efficiency of potatoes. The results showed that both fertilizer and water supply very significantly increased water use efficiency. Application of farm yard manure and recommended doses of NPK to soybean for three consecutive years increased seed yield and water use efficiency by 103% and 76%, respectively, over the unfertilized control (Hati et al. 2006). Effect of fertilizers on water use efficiency is indicated in Table 6. These values may vary among crops, regions and with other management practices and shall be interpreted with great care.

Table 6 Effect of fertilizers on water use efficiency

Practice	Increase in water use efficiency (%)	Reference
Nitrogenous fertilizers	20–60	Dordas and Sioulas (2008), Bahavar et al. (2009)
Phosphatic fertilizers	35	Singh and Bhushan (1980)
Potassium fertilizers	12	Andersen et al. (1992)
NPK and farm yard manure	7–76	Gu et al. (2004), Hati et al. (2006)

Increased use of chemical fertilizer in dry land farming has doubled grain yields and water use efficiency (Deng et al. 2006). Davis and Quick (1998) suggested that cultivar selection for improved water use efficiency should be based on an understanding of the role of nutrient management on photosynthetic rate, yield, rooting characteristics, and transpiration. To optimize water use efficiency, cultivar and nutrient management decisions have to be made together. Nutrient application decisions for a given crop shall be made based on soil fertility tests and use of balanced nutrition at appropriate time of crop growth can help to obtain better crop yields and water use efficiency.

Fertilizer effects on water use efficiency are related to physiological leaf processes, root system dynamics as well as radiation use within a field crop stand. Nutrient supply and crop water status interact in determining the balance of dry matter accumulation to transpiration losses. Most studies were made on nitrogen fertilization. They suggest that high improvement could be expected at the level of the crop stands by the common effect of better radiation use efficiency and reduced soil evaporation due to enhanced leaf growth rate. Improved photosynthetic capacity of plants with optimum nutrition status seems to contribute also to improve transpiration efficiency. Under water stress, potassium is of particular importance for maintenance of tissue water status, cell expansion and sustained water uptake from the drying soil. Phosphorus is limiting growth in several arid and semi-arid regions of the world, particularly in tropical ecosystems. Root properties are essential to improve the phosphorus status of plants which in turn can lead to better water use efficiency.

Appropriate crop management practices contribute to improve several components of agronomic water use efficiency. Substantial increase of water use efficiency by better crop management is documented by Xu and Zhao (2001) in north China where water use efficiency improved threefold between 1949 and 1996. This was due to a combined effect of water conservation facilities, better soil management, extension of new crop varieties and a continuous increase in the use of nitrogen and phosphorus fertilizers. Progress requires a combination of several crop management practices. While improvement via better transpiration efficiency can be achieved by breeding, crop type and cultivar selection as well as plant nutrition management, reduction of evaporation, drainage and runoff losses can be obtained by proper timing of crop establishment and improved root growth. Optimization of water use efficiency on a system basis can be obtained by crop rotation practices that extended the time of soil coverage and crop growth avoiding prolonged fallow periods. From the farmer's prospective a monetary assessment of costs and benefits will determine which set of management measures for improved water use efficiency should be adopted.

2.2 Soil Management

Following Eq. 2, overall agricultural water use efficiency for a crop with given transpiration efficiency (M/T) will only increase, if transpiration is maximized in relation to unproductive water losses. While transpiration efficiency set the upper limit, soil management determines whether water resources are allocated optimally to sustain plant growth.

Figure 5 gives an overview of relevant soil physical and hydrological properties that might be targeted by management measures to optimize the ratio of transpiration to the sum of soil evaporation, runoff and drainage. Also plant traits influence these hydrological processes as discussed in Sect. 2.1. The efficiency of soil management also depends on non-manageable soil properties such as soil texture as shown by Katerji and Mastorilli (2009) who found a general reduction in water use efficiency on clay soils compared to loam soils.

Tillage operations can influence water use efficiency by (i) changing soil surface properties, (ii) modifying soil hydraulic properties, and (iii) influencing root system formation of crops (Fig. 5). Tillage therefore influences water dynamics and water use efficiency via mechanical effect of the tillage implements, mulching effects related to the amount of residues cover remaining on the soil surface, and biological effects due to modified root system formation and soil microbiological activity. All relevant components of the water balance framework of Gregory (2004) are potentially influenced by these effects of tillage.

Soil surface roughness is higher under more intense tillage compared to minimum and no-tillage (Lampurlanés and Cantero-Martínez 2006). Higher surface roughness can reduce surface runoff by better storage of ponded water in the surface micro-relief. However, Gómez and Nearing (2005) found only a minor effect of different surface roughness on runoff. They also showed that increased surface roughness by higher tillage intensity disappeared after the first rainfall.

Tillage can influence rainfall infiltration via changes of soil surface structure. Barthés and Roose (2002) reported a significant reduction in surface runoff with increased aggregate stability. After 24 years of conservation tillage, Zhang et al. (2007c) found an increase of 52% in macro-aggregate stability and a 3.7 times higher infiltration rate in no-tillage compared to conventional tillage which substantially reduced runoff.

Most benefits of reduced tillage can be attributed to higher soil organic matter and the effects of canopy and residue management that protect the soil surface (Arriaga and Balkcom 2005). Canopy and mulch coverage protect the soil surface, preventing crust formation and maintaining soil infiltration capacity (Armand et al. 2009).

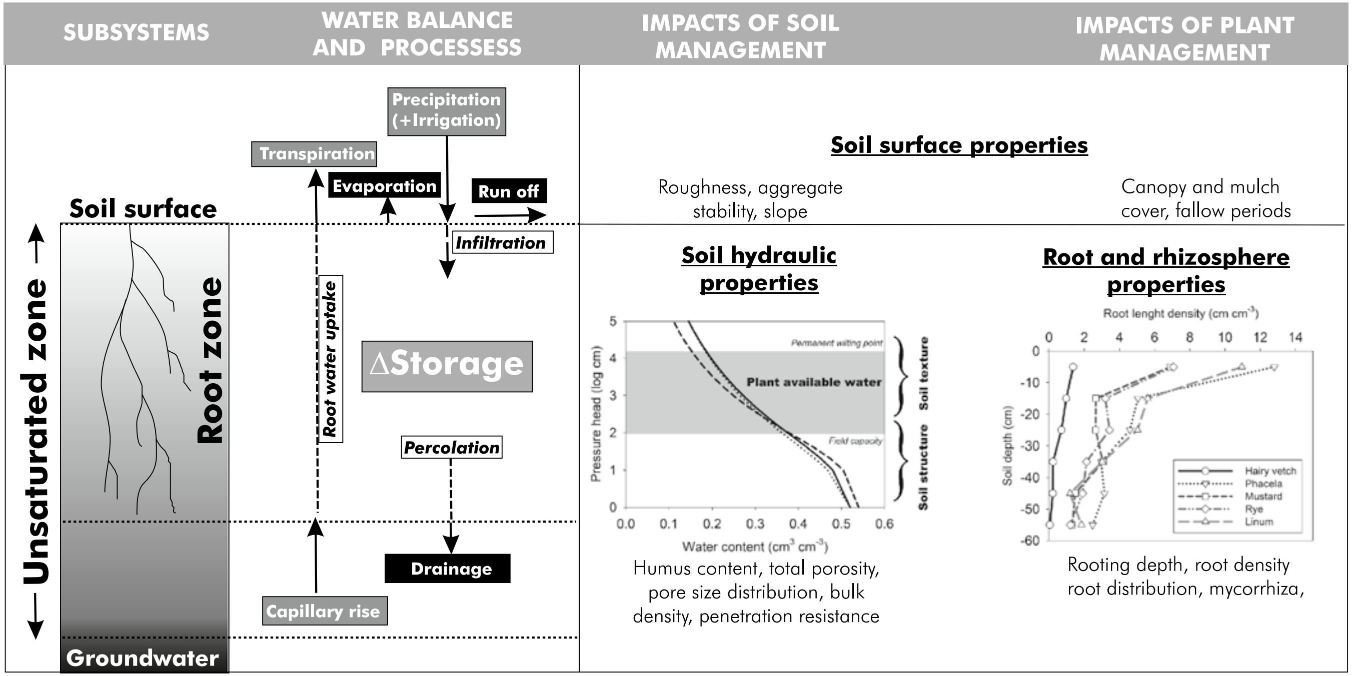

Fig. 5 Effect of management measures on components of water balance. Modifications in soil surface properties, soil hydraulic properties and root and rhizosphere properties induced by crop and soil management practices affect each component of water balance

Zuazo and Pleguezuelo (2008) reviewed the effect of plant covers on soil-erosion and runoff prevention. In average a surface cover of 50% resulted in a reduction of runoff to only 10%. Particularly during intense rainfall runoff can be greatly reduced with a good (>50%) residue cover (Silburn and Glanville 2002).

Also the higher organic matter content in the surface near soil layers under conservation tillage is essential for an enhanced infiltration capacity and thereby reduced runoff losses (Zhang et al. 2007c). Beside enhanced humus content, the conservation of root and earthworm induced continuous biopores in no tillage systems contributes to higher infiltration rates and reduction of runoff (Cresswell and Kirkegaard 1995).

An essential tillage effect for improved water use efficiency is the reduction of evaporation losses from the soil surface. Aase and Pikul (1995) sustained that decreasing tillage intensity tends to improve water use efficiency because of improved soil water availability through reduced evaporation losses. Evaporation losses can be particularly high when rainfall is contributed by frequent small events during the vegetation period (Sadras et al. 2003). In Mediterranean-type environments, 30–60% of the seasonal evapotranspiration of wheat may be lost as evaporation from the soil surface (Siddique et al. 1990). Evaporation losses are affected by the water content of the soil surface. Therefore movement of moist soil to the surface may result in higher losses in mouldboard plough systems (Ritchie 1971). Soil evaporation is influenced by the surface energy balance as well as water transmission properties to the soil surface. Tillage intends to disrupt pore continuity to the soil surface and thereby limit evaporation losses. In case of a fallow soil surface, Moret et al. (2007) found a 20% higher soil evaporation from a no-tillage soil compared to conventional tillage.

Mulching is regarded as one of the best ways to reduce soil evaporation (Steiner 1989; Li and Xiao 1992; Baumhardt and Jones 2002). Residues and mulches limit evaporation by reducing soil temperature, preventing vapour diffusion, absorbing water vapor on to mulch tissue, and reducing the wind speed gradient at the soil–atmosphere interface (Greb 1966; Lagos et al. 2009). Crop residues extend the duration of the first stage of soil drying and most effectively reduce soil evaporation when the soil surface is wet. Unger et al. (1991) however reported that cumulative evaporation from a residue covered soil may become similar to a bare soil upon prolonged drying as the soil generally remains wetter in the upper layers and therefore sustains water transport to the surface for longer time. Effect of mulching on water use efficiency and components of water balance are presented in Table 7. These may vary with residue cover, slope of land, rainfall intensity and region.

Strudley et al. (2008) reviewed tillage effects on soil hydraulic properties. There is no single trend how tillage influences soil hydraulic conductivity and both, increase and decrease in saturated as well as unsaturated hydraulic conductivity have been reported. This indicates a substantial influence of soil texture, crop rotation as well as temporal effects on the measured values (Soracco et al. 2010).

Under reduced and no tillage system, an increase in soil water storage capacity has been found in most studies. e.g. Fernandez-Ugalde et al. (2009) found 32.6%

Table 7 Effect of mulching on water use efficiency and components of water balance

Practice	Effect (range)	Reference
Mulching	Reduction in runoff (10–75%)	Carsky et al. (1998), Silburn and Glanville (2002), Zuazo and Pleguezuelo (2008)
	Reduction in evaporation (11–36%)	Mellouli et al. (1998), Zhang et al. (2007b)
Overall increase in WUE	*10–45%*	Zhao et al. (1996), Zhang et al. (2002), Sarkar et al. (2007), Zhang et al. (2007b)

Table 8 Effect of tillage practices on water use efficiency and components of water balance

Practice	Effect (range)	Reference
Conventional Tillage	Reduction in evaporation (1–20%)	Moret et al. (2007)
	Increase in infiltration rates (35–61%)	Moreno et al. (1997), Lipiec et al. (2005)
	Increase in soil water storage (9–42%)	Selvaraju and Ramaswami (1997), Jin et al. (2007)
No tillage	Increase in soil water storage (8–33%)	Chen et al. (2005), Fernandez-Ugalde et al. (2009), Wang et al. (2010)
Overall increase in WUE	*17–30%*	Peterson and Westfall (2004), Sarkar et al. (2007)
Reduced tillage	Reduction in evaporation (1–19%)	Lopez and Arrue (1997)
	Increase in soil water storage (15–24%)	McHugh et al. (2007)
Overall increase in WUE	*7–30%*	Jin et al. (2009)

higher plant water availability under no-tillage compared to conventional tillage in the upper soil layers where also soil organic matter and water retention at field capacity were significantly increased. Increase in organic matter content leads to higher soil porosity (Rasool et al. 2008) and improved water holding capacity (Hatfield et al. 2001). Thus reduced tillage is likely to influence water holding capacity by a combined effect of organic matter and soil structure. Also Bai et al. (2008) found an improvement in plant water availability and in several pore characteristics related to structure after 9 years of reduced tillage in the Chinese Loess plateau. Feng et al. (2010) reported up to 25% higher soil water storage under no tillage with mulching. Effect of different tillage practices on water use efficiency and components of water balance is summarized in Table 8. Great care shall be exercised in the interpretation of these values as they may vary among regions as well as with soil types, etc.

An increase in water storage is related with a reduction in drainage losses which could be a relevant loss component in humid areas as well as in irrigated fields. Wallace (2000) estimated drainage losses from farmers' fields in humid West Africa as high as 40–50% of incoming rainfall.

For semi-arid ecosystem, an increase of the transpiration component can be achieved by better root growth. Besides crop improvement by breeding for higher root water uptake (Richards et al. 2007), tillage can support root growth by (i) conserving continuous macro pores that serve as preferential growth channel for roots to the subsoil (Rasse and Smucker 1998), (ii) avoiding soil compaction that restricts root growth (Bengough et al. (2006) and (iii) providing a soil structure where roots and root associated microorganisms can proliferate easily (Hinsinger et al. 2009). In their study, Feng et al. (2010) found higher root length density under reduced tillage treatments which might have contributed to better water extraction and reported yield increase. Soil compaction restricts root growth and increases drought susceptibility of crops (Bengough et al. 2006). Conventional tillage has frequently been reported to cause soil compaction, particularly when tillage operations are performed under wet conditions. However also in long term no-till systems, susceptible soils can show compaction due to natural settling (Tebrügge and Düring 1999).

Beside tillage effects on water balance components, their concomitant influence on biomass growth and yields has to be considered in order to evaluate their potential to improve water use efficiency. Jin et al. (2009) reported winter wheat yield and related water use efficiency improvement by 6.7% and 30.1% with conservation tillage compared to the conventional tillage treatments, and for corn, 8.9% and 6.8%, respectively. In the Central Plains of the USA, no-tillage practices have made it possible to intensify cropping from the traditional wheat–fallow system and produce a 30% increase in water use efficiency (Peterson and Westfall 2004). No tillage and sub soil tillage with mulching were found to be the optimum tillage systems for increasing water storage and wheat yields, resulting both in enhancing water use efficiency on the Loess Plateau in China (Su et al. 2007). There have been 50% yield and water use efficiency increases in the North China Plain in winter wheat and maize over the last 20 years associated with combined effect of mulching and improved irrigation scheduling (Zhang et al. 2005). In Australia, Gibson et al. (1992) found that retaining sorghum stubble on the soil increased the sorghum yield by 393 kg ha^{-1} due to increased water use efficiency because of a greater amount of water stored in and extracted from the soil profile compared with conventional tillage.

The role of tillage has been changing and is likely to keep on changing as the advantages of direct-drilling techniques become more widely appreciated, not only for improving crop performance but also for protecting the soil (Passioura 2006). The highest improvement by conservation tillage and mulch management can be expected in sloping soils where runoff is the predominant component of unproductive water losses. Most reports indicate an exponential reduction in runoff losses with increasing soil coverage. For Mediterranean agro-ecosystems where early season rainfall essentially contributes to crop performance, the reduction of evaporation becomes the central target. Reported efficiencies of tillage and mulching practices

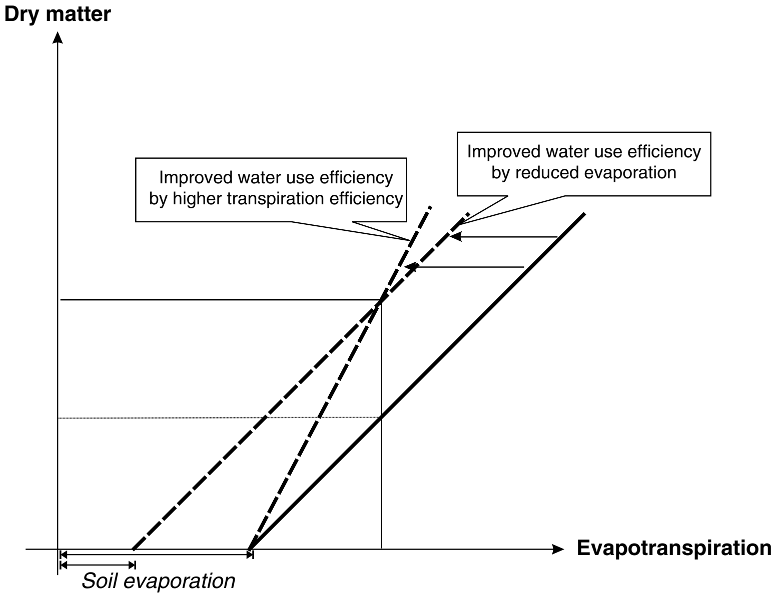

Fig. 6 Relationship between evapotranspiration and dry matter production. Improvement of water use efficiency can be achieved by reduced soil evaporation or higher transpiration efficiency. The impact of soil management is on evaporation and other loss components of field water balance

are variable, ranging from no effect or even higher cumulative losses, to reductions of 25–30%. Improved water use efficiency by 10–20% through reduced soil evaporation and consequently increased water available for plant transpiration were reported by Zhao et al. (1996) and Zhang et al. (2002). Improved water storage capacity is often restricted to the upper soil layers where reduced tillage enhances organic matter accumulation. Although moisture availability in upper layers can be essential for crop growth when the root system is concentrated near the soil surface, an enhanced root penetration to deep layer seems to be more effective to increase plant water availability. Deep rooting crops have access to a higher soil volume, effectively reduce drainage losses and can increase uptake of water as well as mobile nutrients such as nitrate. All these effects will increase the affectivity of water use by the crop and optimize yield under water limited conditions.

Most reported increases in water use efficiency by conservation tillage in agronomic literature are based on evapotranspiration calculated via a water balance. Frequently runoff and drainage are ignored and the ratio is given as biomass or yield to total evapotranspiration. We therefore assume that the higher biomass or yield values in these studies are mainly a result of water redistribution from soil evaporation to productive plant use due to the protective effect of a mulch cover. This effect is expressed in Fig. 6. Thus progress in tillage management will be obtained from its hydrological effects on plant water availability, rather than changes in transpiration efficiency.

2.3 Irrigation Management

Globally 18% of the cultivated area is irrigated. About 40% of global food production comes from irrigated agriculture and about 70% of all freshwater is used in agriculture. Currently low efficiencies in irrigation systems would suggest high potential for improvement in agricultural water use by better irrigation management (Hsiao et al. 2007).

Introducing modern irrigation technology usually implies higher costs, which must be compensated by sustainable yields, increases in water use efficiency with resulting water savings. Sub surface drip irrigation is reported to have significantly increased yield and WUE of many crops as revealed by 15 years of research in United States (Ayars et al. 1999).Twenty-six percent increase in water use efficiency in cotton was observed due to drip irrigation in comparison with check basin (surface flooding) method of irrigation (Aujla et al. 2005). It was found from a study in California that water use efficiency ranged from 60–85% for surface irrigation to 70–90% for sprinkler irrigation and 88–90% for drip irrigation (Cooley et al. 2008). Irrigating pepper with water pillow method – a novel irrigation method that combines drip irrigation and mulching – at 11 days interval helped to obtain significantly higher water use efficiency compared to conventional furrow irrigation (Gercek et al. 2009).

Potential water savings would be even higher if the technology switch were combined with more precise irrigation scheduling and a partial shift from lower-value, water-intensive crops to higher-value, more water-efficient crops (Cooley et al. 2008). Measurement based irrigation scheduling is generally based on soil parameters such as water content or pressure head. While plant based irrigation scheduling methods would have the advantage to directly respond to a crop water stress parameter, they are still limited by practical problems such as automatization (Jones 2004b).

Irrigation management increasingly focuses on more effective and rational uses of limited water supplies with increasing water use efficiency (Marouelli et al. 2004; Payero et al. 2009). Improved efficiency can be obtained by reducing drainage, runoff and evaporation losses by using measurement or model assisted irrigation scheduling (Pereira et al. 2002). Also supplemental irrigation at critical growth stages has substantially improved irrigation efficiency (Oweis et al. 1999).

A proper timing of supplemental irrigation is critical for maximizing yield and water use efficiency. Manipulation of pre- and post-flowering water use in crops can be used to increase harvest index and by using methods of controlled irrigation the optimized water use by stomata can lead to an increase in water use efficiency, without a significant decrease in production and eventually with beneficial effects on quality (Chaves and Oliveira 2004). Examples of some marked increase in water use efficiency by supplemental irrigation are given by Deng et al. (2002), Oweis et al. (2004) and Xue et al. (2006).

Several studies showed that optimizing irrigation not necessarily needs to provide full crop water requirements (English and Raja 1996; Kirda 2002). Water use efficiency can be increased if irrigation water is reduced and crop water deficit is intentionally induced (Zwart and Bastiaanssen 2004). Studies on the effects of limited irrigation on crop yield and water use efficiency show that crop yield can be

Table 9 Effect of irrigation on water use efficiency

Practice	Increase in water use efficiency (%)	Reference
Irrigation scheduling	5–38	Karam (1993), Fare et al. (1993), Tyler et al. (1996), Ismail et al. (2008)
Method of irrigation	7–48	Liu et al. (2003), Aujla et al. (2005), Li et al. (2007), Cooley et al. (2008), Li et al. (2010)
Timing of irrigation	25–57	Guinn et al. (1981), Hu et al. (2002), Buttar et al. (2007)

largely maintained and product quality can, in some cases, be improved while substantially reducing irrigation volume (Kang et al. 1992; Zhang and Oweis 1999; Zhang et al. 1999). For example, Panda et al. (2004) evaluated the effect of different irrigation methods on root zone soil moisture, growth, yield parameters, and water use efficiency of corn and concluded that under water scarcity conditions irrigation should be scheduled at 45% of the maximum allowable depletion of available soil water to obtain high yield and high water use efficiency. When irrigation is above the optimum, an excessive shoot growth can occur at the expense of roots and fruits (Zhang 2004).

Thus, recent efforts in optimizing irrigation have studied practices that intentionally induce slight water deficits to plants such as regulated deficit irrigation and partial root zone drying. When water deficits start to build up, leaf stomatal conductance usually decreases faster than carbon assimilation, leading to increased transpiration efficiency (Chaves et al. 2004).

Regulated deficit irrigation involves the application of irrigation water below the evapotranspiration requirements of crop. It tends to reduce or eliminate drainage and helps to improve water use efficiency (Fereres and Soriano 2007). The basic principle of regulated deficit irrigation is that water is withheld or reduced during a period when vegetative growth is normally high and fruit growth is low. A normal irrigation regime is resumed during the later period of rapid fruit growth. Successful application of regulated deficit irrigation requires careful attention to the timing of the water deficit period and to the degree of stress that is allowed to develop (Loveys et al. 2004; Geerts and Raes 2009). This tactic helps to reduce vegetative growth with little effect on fruit development. In fruit crops like peach, apple and pear balance between vegetative and reproductive development is critical as excessive vegetative vigour may result in mutual shading with consequences of long-term fruitfulness. Knowledge about the phenology of vegetative and reproductive development of fruit crops can be used for saving water through regulated deficit irrigation (Chalmers et al. 1981, 1986). Application of regulated deficit irrigation has doubled water use efficiency when compared with standard irrigation practice (Goodwin and Boland 2002). These improvements are due to improved water use by reducing unproductive losses, reduction in vegetative canopy size, and also due to reduced leaf stomatal conductance during the regulated deficit irrigation period (Boland et al. 1993). Effect of timing, method and scheduling of irrigation practices is summarized in Table 9 to demonstrate the importance of irrigation management.

An irrigation practice that focuses on increasing water use efficiency by controlling stomatal opening is partial root zone drying. Stomatal closure is a common response to root zone stresses including soil drying, soil flooding and soil compaction. Beside hydraulic signals, this response is governed by increased levels of the plant hormone abscisic acid in plant roots and transmitted to leaves especially under dry soil conditions (Loveys et al. 2004). The knowledge about the ability of the particular plant genotypes to sense the onset of changes in moisture availability and fine-tune its water status in response to the environment has lead to the development of partial root-zone drying technique (Wilkinson 2004). In this irrigation method, each side of the root system is irrigated during alternate periods and the maintenance of the plant water status is ensured by the wet part of the root system, whereas the decrease in water use derives from the closure of stomata promoted by dehydrating roots (Davies et al. 2000). It is recognized that stomatal closure and growth inhibition are likely to be responding simultaneously to different stimuli, some of which may operate through common signal transduction systems (Webb and Hetherington 1997; Shinozaki and Yamaguchi-Shinozaki 2000). Physiological data from studies on grapevines under partial root zone drying point to subtle differences between partial root zone drying and deficit irrigation, where the same amount of water is distributed by the two sides of the root system (Souza et al. 2003; Santos et al. 2003). These differences include some reduction of stomatal aperture in partial root zone drying, a depression of vegetative growth, and an increase in cluster exposure to solar radiation, with some potential to improve fruit quality. There is also evidence that partial root zone drying can increase fruit quality in tomato, presumably as a result of differential effects on vegetative and reproductive production (Davies et al. 2000). The root system is also significantly altered in response to partial dehydration, not only in respect to total extension and biomass but also in architecture. Root system tends to grow deeper under partial root zone drying enabling roots to extract water from greater soil depths and provide higher plant water uptake (Dry et al. 2000). It is likely that this alteration in the root characteristics and in the source/sink balance plays an important role in plant performance under partial root zone drying. The technique had been found effective in improving water use efficiency for a wide range of crops in different environments (Kirda et al. 2007; Sadras 2009) and its large scale implementation had been successful for vineyards (Loveys and Ping 2002; Souza et al. 2003; Santos et al. 2003).

Future developments in irrigation technology, better scheduling of timing and amount of water applied as well as new application methods are likely to contribute essentially to improved agricultural water use. Modern irrigation methods like supplemental irrigation, regulated deficit irrigation and partial root zone drying exploit physiological mechanisms to improve instantaneous water use efficiency at the leaf, make use of knowledge on sensitive phenological states of the crop to increase water use efficiency in relation to yield and provide a more effective water use by reducing losses and enhancing root water uptake. Site specific application of proper and efficient irrigation methods can therefore help to improve the overall agricultural water management and save water for other competitive demands (Playan and Mateos 2006).

3 Conclusions and Challenges

Improvement of water use efficiency has been a focus of extensive agronomic, breeding and water management research. This work has provided the basis for the development of management tools to improve agricultural water management. Most comprehensive studies on agricultural water use come to the conclusion that a set of measures is required to achieve higher water use efficiency, while single measures are of limited use. It is particularly important to evaluate agricultural production systems over the whole crop rotation to determine system water use efficiency instead of focussing on single crops.

Based on practical recommendations of FAO, several agricultural management measures were analysed for their effects on water use efficiency and the underlying plant physiological and soil hydrological processes. Only few measures improve water use efficiency due to higher transpiration efficiency which is a rather conservative plant property. Changes in transpiration efficiency are mainly an effect of the type of photosynthesis. However some effects of plant nutrition management and selection of improved cultivars were found. Most studies reporting higher water use efficiency relate dry matter or yield production to total evapotranspiration. Both crop and soil management measures have a huge effect on the components of the water balance, thereby changing the proportion of plant water uptake (transpiration) in relation to losses. In case of erosion-prone sloping fields, conservation tillage systems and residue management that reduce runoff are most effective. Redistribution of evaporative water fluxes from soil evaporation to plant transpiration is the key of many management measures that improve water use efficiency. Use of proper amount of irrigation water as and when needed based on plant requirements and its application with site specific method can ensure reasonable gains in water use efficiency. Use of regulated deficit irrigation and partial root zone drying also offer enormous potential towards bringing improvement in water use efficiency.

From an agronomic point of view the suggestion of Blum (2009) to plant breeders to focus on an efficient water use rather than on water use efficiency alone has particular relevance. We consider that future efforts on the root system, the hidden half of the plant, still have a substantial potential to improve an efficient agricultural water use. The complex dynamics of root-soil interactions and of communication between aboveground and belowground plant parts require an interdisciplinary approach of agronomists, breeders and soil scientists to achieve what we would call “root system management” for better plant water use.

The challenge to feed the rapidly growing population under present scenario of depleting fresh water resources is big. The problem is further aggravated by erratic impacts of forthcoming climatic change. Particularly developing countries suffer for water and food shortages and generally lack resources for several modern technical measures to overcome the adverse effects of droughts and famines.

Challenges for researchers are to improve interdisciplinary approaches to water use efficiency which is a topic that inseparably relates plant, soil and hydrological research. Knowledge about using management practices that are fit for a region based on its environment and its application for improvement of water use efficiency still remain the key concern in some parts of the world as adoption of technology is constrained by cultural and societal issues.

Challenges for policy makers and extension staff are to ensure dissemination and utilization of appropriate production technology packages to the end users. Use of simulation models for decision support can be used to adapt available management tools to local conditions. Still use of models for extension is restricted to developed world. Data bases for model calibration and validation experiments are lacking for many regions of the world, particularly developing countries. Capacity building and technical training of scientists from developing countries for proper application of simulation models is needed (Mathews and Stephens 2002).

Crop water use is likely to stay a main topic for research and practical agriculture, and will probably even gain importance in future. Still there are large options for improved water use efficiency that can contribute to narrow the "yield gap" that is currently building up. Better knowledge of processes and effects across all scales, from physiology to farming system design, will lay the grounds for better management and broad adoption of measures for improved agricultural water use.

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Genetic Mechanisms of Drought Stress Tolerance, Implications of Transgenic Crops for Agriculture

Jyoti Bhardwaj and Sudesh Kumar Yadav

Abstract This chapter review effects of drought stress on plants, and presents a list of transgenic plants tolerating drought stress. Many abiotic and biotic stresses are regularly affecting agricultural production. None are now under direct human control. Abiotic stresses such as drought, extreme temperature and salinity have clearly changed crops growth and yields in last two decades. Drought stress is the major stress affecting crop growth, development and yields. Drought stress may leave the lands barren for years to come if not taken care of at the right time. Drought is a major phenomenon leading to major crop losses. We can see the degree of drought stress severity on plants by symptoms and effects on physiological metabolisms and yield. Many symptoms of drought stress are clear such as leaf rolling, yellowing (chlorosis), browning and wilting. At the physiological level, drought stress alters the complete physiology and metabolism of plants. Drought stress modifies photosynthetic rate, relative water content, leaf water potential, and stomata conductance. Ultimately, it destabilizes the membrane structure and permeability, protein structure and function, leading to cell death.

We reviewed the severity of drought stress and molecular mechanisms adopted by plants. Plants can escape, avoid or tolerate drought stress using unusual mechanisms. Tolerance against drought is provided either directly through metabolites like trehalose, mannitol, glycinebetaine or indirectly through regulation of gene expression by transcription factors and kinases in signal transduction. The molecular response of plants to drought stress has been often considered as a complex process mainly based on the modulation of transcriptional activity of stress-related genes. Understanding the mechanisms behind these molecules and genes is needed for their usage in developing transgenics that would withstand drought stress and improve the agriculture productivity.

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E. Lichtfouse (ed.), *Agroecology and Strategies for Climate Change*,
Sustainable Agriculture Reviews 8, DOI 10.1007/978-94-007-1905-7_9,

Keywords Drought stress • Osmolytes • Drought-responsive genes • Molecular mechanisms

Abbreviations

ROS	reactive oxygen species
SOD	superoxide dismutase
CAT	catalase
POD	peroxidases
GDH	Glutamate dehydrogenase
TPS	trehalose phosphate synthase
GSMT	glycine sarcosine methyltransferase
DMT	dimethyl glycine methyltransferase
COX	choline oxidase
CODA	choline dehydrogenase
ADC	arginine decarboxylase
SPDS	spermidine synthase
ODC	ornithine decarboxylase
SAMDC	S-adenosyl-methionine decarboxylase
P5CS	pyrroline-5-carboxylate synthetase
PEG	polyethylene glycol
IMT	myoinositol O-methyl transferase
LEA	late embryogenesis abundant
HSP	heat shock protein
DREB	dehydration-responsive element binding protein
CBF	C-repeat binding factor
CDPK	calcium dependent protein kinase
MAPK	mitogen activated protein kinase
CBL	calcineurin B-like protein
TF	transcription factors
ERA1	enhanced response to ABA 1 farnesyltransferase

1 Introduction

As industrialization and desertification cover more and more of the terrestrial areas, scarcity of the fresh water resources will globalize, leading to some abiotic stresses such as salinity, drought, freezing and extreme temperature. These stresses are becoming the limiting factors for today's agricultural productivity (Vinocur and Altman 2005). We here, focus on the severity arising due to drought stress. There are different scientific definitions of drought and its subtle and complex. In general, drought can be defined as an extended period of deficient rainfall relative to an average for a region. Drought can be categorized into three types: (1); Meteorological drought which occurs when there is a prolonged period of below average precipitation, creating a natural shortage of available water, (2); Agricultural drought, that often occurs during dry, hot periods of low or average precipitation when the soil conditions or the agricultural technologies require extra water, and (3); Hydrological drought is nothing but prolonged meteorological drought which can occur even during times of average or above average precipitation in case human demands for water are high and increased usage has lowered the water resources below average. The ability of plants to resist drought conditions is crucial for countries worldwide (Umezawa et al. 2006).

Crops can grow and adapt under drought stress by using different mechanisms. Crops resistance to drought stress can be divided into three strategies, (1) drought escape, (2) drought avoidance and (3) drought tolerance. (1) Drought escape is defined as the ability of a plant to complete its lifecycle before serious soil and plant water deficit develops (Mitra 2001). This involves early flowering, early maturity and variation in duration of growth period depending on the extent of water deficit. (2) Drought avoidance is the ability of a plant to maintain relatively high tissue water potential despite a shortage of soil moisture (Mitra 2001). (3) Drought tolerance is the ability to withstand water deficit with low tissue water potential (Mitra 2001). Plants under drought survive by maintaining a balance, using more than one mechanism at a time. This is so because the tolerance mechanisms for abiotic stresses are genetically complex being multigenic in nature (Flowers 2004; Wang et al. 2003).

Some global problems such as increasing human population and decreasing agricultural productivity are raising an alarming situation across the globe. Out of the total potentially arable land only 10% of the world's 13 billion hectares is farmed (Yadav 2009). These two factors lead to a technical bottleneck for the people in all fields of science. In India, the most drought stricken areas are Rajasthan, parts of Gujarat, Haryana and Andhra Pradesh (Mitra 2001). Drought not only individually affects the agriculture but also leads to other abiotic stresses such as salinity, heat stress and scarcity of fresh water etc. in a chain reaction. It single handedly has the power to shake the economy of the world. Hence, we need to develop transgenic crops with better performance leading to stable crop yield in drought prone environments. These have been repeatedly reported. The parameters to evaluate plant stress resistance should generally be the deciding factors for a genetically modified crop but have become the major limitation. This vociferously emphasizes on the urgent need to reframe the criteria for evaluating response of a genetically modified plant in normal and stress conditions (Herve and Serraj 2009). Human malpractices due to insufficient or half knowledge have lead to global warming which ultimately leads to unexpected climate changes (Kerr 2010). The need of the hour is to shed light on new strategies being developed which include adaptive changes ranging from traditional agronomic practices to molecular tailoring of genes (Rivero et al. 2007). For this purpose all the fields of biotechnology and molecular biology aimed at overcoming drought need to be clubbed together and fully implemented complementarily. Several comprehensive reviews on molecular mechanisms adopted by the plants against drought and other abiotic stresses have been recently published (Herve and Serraj 2009; Umezawa et al. 2006; Vinocur and Altman 2005; Mitra 2001). Our review focuses on the severity arising due to drought affecting the agriculture around the globe. We have also tried to understand and present the molecular mechanisms lying beneath the various tolerance mechanisms adopted by transgenic plants.

2 Severity of Drought Stress on Plant Physiology

Different plants respond to drought in a different manner. Drought tolerance is a complex trait being multigenic and pleiotropic in nature (Pardo 2010). At the time of withstanding against drought, plants have to maintain the normal cellular metabolism also. Thus, the whole *in vivo* scenario of the plant becomes too complex to understand. Unavailability of infrastructure, environmental conditions and limited amount of seeds sometimes become a bottleneck in studying drought stress thus, it is inevitable to critically monitor the most relevant phenotypic and physiological parameters in plants (Herve and Serraj 2009). Several phenotypical and physiological changes are observed in plants in responses to drought stress.

Many symptoms such as leaf rolling, yellowing (chlorsis), browning and wilting are the simplest visual observations for assessing the developed drought stress on plant (Fig. 1). Important parameters reported by many authors for judging these phenotypic and physiological effects are plant height, number of leaf, number of branch, plant canopy, photosynthetic rate, relative water content, leaf water potential, transpiration rate and shoot/root biomass (Hu et al. 2006; Babu et al. 2004; Lian et al. 2004; Wang et al. 2005a, b; Capell et al. 2004; Oh et al. 2005; Samarah et al. 2009). All these and other parameters need to be strictly assessed in genetically modified plants under normal and stressed conditions because a single drought trait e.g. early stomatal closure might be beneficial in starting of drought but may have a negative effect in normal conditions.

Abiotic stresses such as salinity, drought, cold, heat and chemical pollution are considered as primary stresses (Bressan et al. 2009). They are all interdependent and lead to secondary stresses such as osmotic and oxidative stresses. Membrane fluidity, changes in temperature, ionic and osmotic effects act as the initial stress signals and trigger a cascade of signaling processes and transcription factor controls (Hey et al. 2010). This leads to reestablishment of homeostasis by activating stress responsive mechanisms, but if there is insufficient sustainability of response at one or more steps at signal transduction and gene level then it might lead to irreversible destruction of functional and structural proteins/membranes leading to cell death (Vinocur and Altman 2005).

Plants avoid drought stress by increasing water use efficiency and shuttling balance between turgor and water loss. Turgor is maintained by increased rooting depth, efficient root system and increased hydraulic conductance (Beck et al. 2007). While reduction in water loss is achieved through lowered evaporation, reduced

Fig. 1 Effect of drought stress on wheat plants. The drought stress was induced to the plants by withholding water for 2 weeks. Picture on right hand side presents a closer view. The damage of the drought stress is seen as retardation in growth (**a**). The yellowing (chlorosis), browning, wilting and rolling of leaves were also observed (**b**)

epidermal conductance and reduced absorption of radiation by leaf rolling/folding (Saruhan et al. 2009). These mechanisms are achieved through increase in cell elasticity, decrease in cell size and solute accumulation in cell i.e. osmotic adjustment (Serrano et al. 2005; Harayama et al. 2006). The difference between sensitive and tolerant plants may be at the level of cellular dehydration (Karakas et al. 1997). The stomatal closure leads to decrease in intercellular CO_2 concentration and dehydration of mesophyll cells which damages the photosynthetic machinery by reducing the capacity of ribulose-1, 5-bisphosphate regeneration and carboxylation efficiency (Escalona et al. 1999; Taiz and Zeiger 1998).

Severe stress disrupts the cellular homeostasis accompanied with the generation of reactive oxygen species (ROS). The ROS are combated by cell's antioxidant system including enzymatic e.g. superoxide dismutase (SOD), catalase (CAT), peroxidases (POD), etc. and non-enzymatic e.g. glutathione (GSH) and ascorbate (Asada 1999; Mittler 2002). Chloroplasts are particularly susceptible to ROS because of the relatively high concentration of oxygen that reacts with electrons which escape from the photosynthetic electron transfer system (Foyer et al. 1994). Scavenging of ROS is brought about by reduction in redox state of ascorbate and glutathione as they shift towards their oxidized forms (Hendry et al. 1992; Tommasi et al. 1999). Changes in the ascorbate and glutathione redox states have been shown to affect gene expression and metabolic pathways (Noctor and Foyer 1998; Catani et al. 2001). Most climate change studies are indicating an expansion of arid zones on our planet. This is due to the direct effect of the global warming. This situation may transform into severe drought conditions across globe. It is therefore, indispensible to understand the molecular mechanisms relating to drought stress tolerance in plants.

Drought stress affects most of the cellular processes in plants. It generates ROS in a plant that disrupts their metabolism. The disturbance in cellular homeostasis leads to the dehydration. Severe drought leads to irreversible destruction of functional and structural proteins leading to various morphological changes and ultimately cell death.

3 Molecular Mechanisms for Drought Stress Tolerance

Important advances have been made in fields of molecular biology like genetic engineering and biotechnology in last two decades (Sinclair et al. 2004). This help us to understand the transcriptional changes induced by drought constraints and in the identification of signaling proteins and transcription factors which regulate the stress-induced gene expression. Golden rice, BT brinjal, flavrsavr tomato were once a farfetched dream for science lovers, but this challenge actualized due to advances in molecular biology. The key point for these success stories lies in the introduction of functional genes from related or unrelated sources (plants, animals, bacteria and fungi etc.) into various types of plants (Passioura 2006). Plants are vulnerable in nature being affected by the slightest of change in environmental conditions like rainfall, temperature and soil conditions like pH, moisture, humidity etc. Nature itself is so uncertain and unpredictable yet, it has simultaneously bestowed upon plants the ability to protect themselves against sudden calamities such as various biotic (bacterial/fungal infections, insects) and abiotic stresses (salinity, desiccation, cold and drought). Out of all these, drought is remained over the years and is still a subject of serious concern becoming a threat for agriculture all over (Nelson et al. 2007; Zhang 2007). Several studies have reported the genes involved in stress signaling and metabolic pathways to have a positive effect in transgenic plants for drought tolerance (Yamaguchi-Shinozaki and Shinozaki 2006). Therefore, it is important to create more genetically modified (GM) plants with desirable traits showing positive effect on agricultural economy (Table 1). To reach this goal, it is

Table 1 Transgenics developed with different genes over the time (1990–2010) against drought stress

Transgenic	Gene name	Gene source	References
Tobacco	*AlSAP*	*A. littoralis*	Saad et al. (2010)
Rice	*SAMDC*	*Datura*	Peremarti et al. (2009)
L. chinensis	*TaLEA*	Wheat	Wang et al. (2009)
Maize	*gdhA*	*E. coli*	Lightfoot et al. (2007)
Bentgrass	*hva1*	Barley	Fu et al. (2007)
Tobacco	*ScTPS1*	Yeast	Karim et al. (2007)
Tobacco	*LEA*	*T. androssowii*	Wang et al. (2006)
Rice	*COX*	*A. pascens*	Jin et al. (2006)
Arabidopsis	*AREB1/ABF2*	*Arabidopsis*	Furihata et al. 2006
Tobacco	*Ots A*	*E. coli*	Jun et al. (2005)
Rice	*MnSOD*	*P. sativum*	Wang et al. (2005a, b)
M. sativa	*WXP1*	*M. truncatula*	Zhang et al. (2005)
Rice	*CBF3/ABF3*	*Arabidopsis*/Rice	Oh et al. (2005)
Arabidopsis/Canola	*ERA1*	*Arabidopsis*	Wang et al. (2005a, b)
Arabidopsis	*AtMYB60*	*Arabidopsis*	Cominelli et al. (2005)
Chinese cabbage	*LEA*	Canola	Park et al. (2005)
Arabidopsis	*GSMT* and *DMT*	*A. halophytica*	Waditee et al. (2005)
Tomato	*TPS1*	Yeast	Cortina and Culianez-Macia (2005)
Petunia	*P5CS*	*Arabidopsis*/Rice	Yamada et al. 2005
Maize	*NPK 1*	Tobacco	Shou et al. (2004)
Rice	*Cod A*	*A. globiformis*	Sawahel (2004)
Rice	*RWC3*	Rice	Lian et al. (2004)
Rice	*Adc*	*Datura*	Capell et al. (2004)
Rice	*HVA1*	Barley	Babu et al. (2004)
Arabidopsis	*SHN1/WIN1*	*Arabidopsis*	Aharoni et al. (2004)
Wheat	*DREB1A/CBF3*	*Arabidopsis*	Pellegrineschi et al. (2004)
Tobacco	*DREB1A/CBF3*	*Arabidopsis*	Kasuga et al. 2004
Arabidopsis	*AREB1/ABF2*	*Arabidopsis*	Kim et al. (2004a, b)
Arabidopsis	*CAZFP1*	Pepper	Kim et al. (2004a, b)
Arabidopsis	*STZ*	*Arabidopsis*	Sakamoto et al. (2004)
Arabidopsis	*ANAC019/055/072(NAC)*	*Arabidopsis*	Tran et al. (2004)
Arabidopsis	*SRK2C*	*Arabidopsis*	Umezawa et al. (2004)
Cotton	*GF14λ*	Cotton	Yan et al. (2004)
Arabidopsis	*DREB1C/CBF2*	*Arabidopsis*	Novillo et al. (2004)
Arabidopsis	*ZmDREB1A*	Maize	Qin et al. (2004)
Arabidopsis	*SPDS*	*C. ficifolia*	Kasukabe et al. (2004)
Tobacco	*ADH*	*S. Liaotungenisis*	Li et al. (2003)
Arabidopsis	*CBL1*	*Arabidopsis*	Cheong et al. (2003)
Rice	*HSP101*	*Arabidopsis*	Katiyar-Agarwal et al. (2003)
Tobacco	*TPS1*	*S. cerevisiae*	Lee et al. (2003)
Rice	*otsA/otsB*	*E. coli*	Garg et al. (2002)
Tobacco	*Chl-NADP-ME*	Maize	Laporte et al. (2002)

(continued)

Table 1 (continued)

Transgenic	Gene name	Gene source	References
E. coli	*CCP-1α*	*B. sexangula*	Yamada et al. (2002)
Sugarbeet	*Sac B*	*B. subtilis*	Pilon-Smits et al. (1999)
Tobacco	*IMT 1*	*M. crystallinum*	Sheveleva et al. (1997)
Tobacco	*P5CS*	Mothbean	Kishor et al. (1995)
Tobacco	*Sac B*	*B. subtilis*	Pilon-Smith et al. (1995)
Tobacco	*BetB*	*E. coli*	Holmstrom et al. (1994)
Tobacco	*SAMDC*	Human	Noh and Minocha (1994)
Tobacco	*SOD*	Pea	Sengupta et al. (1993)
Tobacco	*ODC*	Mouse	Descenzo and Minocha (1993)
Tobacco	*ODC*	Yeast	Hamill et al. (1990)

quite important to understand the molecular mechanisms underlying it in a better manner. This review presents different molecules and their mechanisms of imparting drought tolerance. The genes involved in molecular tailoring are regulatory as well as functional in nature (Umezawa et al. 2006). The products of these genes are categorized into two groups: those which are directly involved in the protection against environmental adversities and those which indirectly do so by regulating the gene expression (Fig. 2).

The attempt towards deciphering the mechanism of drought stress tolerance in plants has suggested the potential role of metabolites, transcriptions factors and genes encoding proteins for diverse functions.

3.1 Metabolites and Chemical Compositions Responses to Drought Stress

Resistance to drought stress is requiring to crops by reprogramming metabolism and gene expression, gaining a new equilibrium between growth, development and survival. Several types of metabolites are widely known to be involved in providing tolerance against drought stress. These are involved directly to combat with drought stress. The important categories of metabolites are mentioned here. Osmolytes also known as compatible solutes are osmotically active compounds which include organic compounds (proline), quaternary and other amines (glycinebetaine), sugar and sugar alcohols (trehalose, mannitol) (Chen and Murata 2002; Vinocur and Altman 2005). A variety of these small organic molecules are involved in osmoregulation and stabilization of protein complexes and membranes at the cellular level (Chen and Murata 2002; Hincha and Hagemann 2004). Their accumulation is a common response to abiotic stresses. Under mild drought stress conditions, loss of turgor in nonacclimated plants can disturb the turgor related functions like stomatal

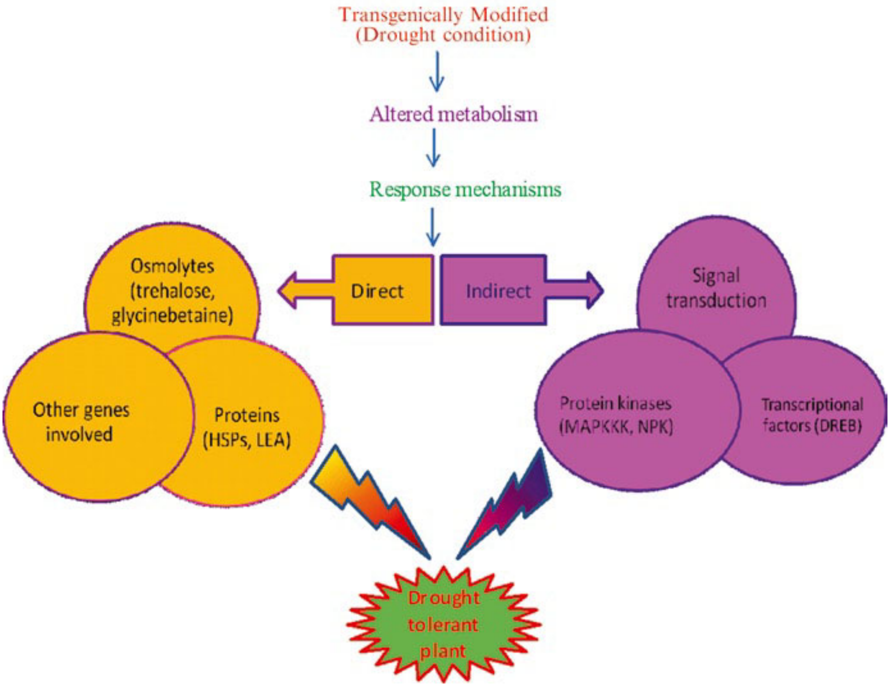

Fig. 2 Response mechanisms adopted by the genetically modified plants to fight against drought stress. These can be achieved directly through osmolytes, proteins like heat shock proteins (HSPs), late embryogenesis abundant (LEA) proteins and/or indirectly through transcription factors (TFs), protein kinases involved in signal transduction (ST) pathways. All these methods ultimately lead to drought tolerant plants which can withstand drought stress

functions and expansive growth (Mathews et al. 1984). During severe drought stress conditions, reduction in water potential leads to different cell dehydration levels which are held responsible for the cell death (Flower and Ludlow 1986). Osmolytes cause osmotic adjustment leading to maintenance of turgor at water potential which could normally eliminate turgor (Beck et al. 2007). Recently, several successful attempts have transferred functional genes encoding enzymes associated with the synthesis of different osmolytes (Dobra et al. 2010; Huh et al. 2010; Goel et al. 2010). Developed transgenic plants have shown drought tolerance.

Trehalose is a non reducing sugar found in the nature in diverse organisms ranging from algae, bacteria, insects, yeast, fungi to animals and plants (Elbein 1974). It is known to accumulate in higher amounts in resurrection plants like *Selagenella lepidophylla* (Zentella et al. 1999; Bianchi et al. 1993), some drought tolerant angiosperms (Drennan et al. 1993) and in anhydrobiotic organisms that survive during complete dehydration (Crowe et al. 1992). There is a unison consensus over the fact that trehalose is synthesized in response to various stresses including drought stress and protects against them (Mackenzie et al. 1988; De Vigilio et al. 1994; Sharma 1997).

Their reversible water absorption capacity protects the biological molecules from drought induced damages. They play a greater role in protecting biological membranes, cellular metabolism than in regulating water potential (Iordachescu and Imai 2008; Rodríguez-Salazar et al. 2009). Trehalose has been demonstrated at very low levels in tobacco and in many higher plants (Goddijn et al. 1997; Kosmas et al. 2006). A yeast gene *ScTPS1* was introduced in tobacco (Karim et al. 2007) and it was found that the transgenics accumulating trehalose exhibited enhanced survival on exposure to drought. It is suggested that trehalose even at low concentrations stabilizes proteins and membrane structures under stress (Colaco et al. 1992, 1995 Iwahashi et al. 1995) because of the glass transistion temperature, greater flexibility and chemical stability. A yeast trehalose phosphate synthase (*TPS1*) gene was introduced into tobacco and dramatic effects were observed on the growth even with low levels of trehalose (Lee et al. 2003). In yeast *S. cerevisiae*, trehalose accumulation has been associated with improvement in response to stresses (Eleutherio et al. 1993; Meric et al. 1995). Transgenic tomato having *TPS1* gene from yeast showed increased shoot growth and survivability under drought stress conditions created by withholding water for few weeks (Cortina and Culianez-Macia 2005). Transgenic tobacco and rice were developed by introducing *otsA* and *otsA/otsB* gene from *E. coli*, respectively (Jun et al. 2005; Garg et al. 2002). The *otsA* gene is homologous to eukaryotic *TPS1* gene encoding for trehalose-6-phosphate synthase and *otsB* gene is homologous to eukaryotic *TPS2* which encodes for eukaryotic trehalose-6-phosphate phosphatase. Their introduction in respective plants showed accumulation of trehalose at higher amounts which imparted tolerance to drought as compared to the wild plants.

Glycinebetaine is one of the major osmoprotectants in halophilic microorganisms (Nyyssola et al. 2000; Waditee et al. 2003). Its accumulation has been widely studied with respect to modifications of several metabolic steps involved in stress tolerance. A betaine aldehyde decarboxylase encoding gene from halophyte *S. liaotungensis* was introduced into tobacco and it was observed that *in vitro* plantlets were significantly resistant to the stress conditions (Li et al. 2003). Higher levels of glycinebetaine were detected in transgenic Arabidopsis having *GSMT* and *DMT* (glycine sarcosine methyltransferase and dimethyl glycine methyltransferase) genes from *A. Halophytica* (Waditee et al. 2005). Betaine molecules protect the cells by stabilization of proteins and cell structure or by scavenging free radicals as well as by osmotic effects (Chen and Murata 2002). Finding of a novel synthetic pathway for glycinebetaine is one of the most recent advances in this area (Waditee et al. 2003). Identifying role of such pathways would be of interest for future agricultural crop improvement strategies. Transgenic rice was developed with *COX* (choline oxidase) gene from *A. pascens* and *CODA* (choline dehydrogenase) gene from *A. globiformis* (Jin et al. 2006; Sawahel 2004). These genes are involved in biosynthesis of glycinebetaine. The transgenic plants were significantly resistant to stress conditions and set seeds in contrast to the wild plants.

A *betB* (betaine aldehyde dehydrogenase) gene from *E. coli*, involved in biosynthesis of glycinebetaine was introduced into tobacco (Holmstrom et al. 1994). Accumulation of glycinebetaine in higher levels confers drought tolerance to the transgenic tobacco. A *P5CS* (pyrroline-5-carboxylate synthetase) gene from mothbean and Arabidopsis/Rice, involved in biosynthesis of proline was used to develop transgenic tobacco and petunia (Kishor et al. 1995; Yamada et al. 2005). The transgenic plants overexpressing *P5CS* gene produced fivefold more proline than control plants. Enhanced flower development and root biomass was exhibited under drought stress condition as a result of overproduction of proline. Polyamines have been genetically engineered for their increased biosynthesis and have resulted in stress tolerant plants. Overexpression of polyamine biosynthetic genes like *ADC* (arginine decarboxylase), *SPDS* (spermidine synthase), *ODC* (ornithine decarboxylase) and *SAMDC* (S-adenosyl-methionine decarboxylase) increase putrescine levels which promote spermine and spermidine biosynthesis under drought stress and thus protect the plants. Capell et al. (2004) introduced Datura *ADC* (arginine decarboxylase) gene for polyamines biosynthesis into rice enhancing drought tolerance. A gene *SPDS* (spermidine synthase) also involved in biosynthesis of polyamines and hence providing stress tolerance was introduced into Arabidopsis from *C. ficifolia* by Kasukabe et al. (2004). Transgenic tobacco with *ODC* (ornithine decarboxylase) gene from yeast and pea was found to be more tolerant to stress than control plants (Hamill et al. 1990; Descenzo and Minocha 1993). A *SAMDC* (S-adenosyl-methionine decarboxylase) gene from human and Datura was put into tobacco and rice, respectively (Noh and Minocha 1994; Peremarti et al. 2009). Transgenic plants were observed to be more tolerant under drought conditions. Pilon-Smits et al. (1995; 1999) introduced *SacB* gene from *B. subtilis* into tobacco and sugarbeet. *SacB* is a gene encoding for levan sucrase which takes part in fructan synthesis. Transgenic plants producing fructan showed more tolerance to polyethylene glycol (PEG) mediated drought stress conditions. *IMT1* (myoinositol O-methyl transferase) gene involved in myo-inositol synthesis from ice plant was introduced into tobacco and transgenic plants were found to be more tolerant to salt and drought stress (Sheveleva et al. 1997). Similar role of mannitol is expected in drought stress tolerance also but remains largely undiscovered and is supposed to be more specific than previously thought. This is so suggested because despite inositol having nearly identical structure and present in equal or higher amounts, it cannot be substituted for mannitol (Karakas et al. 1997). However, function of polyols may be more species and compound specific than known.

LEA (Late Embryogenesis Abundant) proteins are members of a large group of hydrophilic glycine proteins found in plants. They appear during late stages of seed development i.e. maturation of embryos and desiccation of maturing seeds (Soulages et al. 2003). They are also induced in vegetative tissues in response to osmotic stress, low temperature stress and exogenous application of ABA (Liang et al. 2004). Overexpression of some of the LEA genes have been reported to result in detoxification, alleviation of cell damage by enhanced tolerance to dehydration (Vinocur and Altman 2005; Bartels and Sunkar 2005). They do so by acting as molecular chaperones preventing protein aggregation induced by freezing and desiccation, maintain membrane structure, sequester ions and bind water (Close 1997; Browne et al. 2002; Goyal et al. 2005). Although the precise mechanism is still unknown (Shao et al. 2005), the recent computational studies have shown that

LEA proteins act as protective molecules against cellular damage (Wise 2003; Oskman-caldentkey and Sacto 2005). *LEA* genes from some plants have been well characterized and studied (Liang et al. 2004; Ali-Benali et al. 2005; Goyal et al. 2005; Park et al. 2005; Gal et al. 2004; Singh et al. 2005; Porcel et al. 2005; Babu et al. 2004). A novel *LEA* gene (DQ 663481) from *T. androssowii* was used for developing transgenic tobacco (Wang et al. 2006). The results suggested that mechanism of drought tolerance by LEA proteins is through cell membrane protection from damage which is in accordance with studies of Babu et al. (2004) and Fu et al. (2007) who introduced barley *HVA1* gene into rice and bentgrass, respectively. This gene encodes for a group of three LEA proteins which accumulate in vegetative organs during drought stress and provide protection against it. Improved salt and drought tolerance was observed in transgenic chinese cabbage constitutively expressing a *LEA* gene from canola (Park et al. 2005). Transgenic rice and wheat expressing *LEA* gene has been shown to confer tolerance to salt and drought stresses (Xu et al. 1996; Rohila et al. 2002; Sivamani et al. 2000; Wang et al. 2009).

Heat shock proteins (HSPs) prevent protein denaturation during stresses by serving as molecular chaperones that participate in ATP dependent protein assembly and disassembly. HSPs play important role in thermotolerance (Maestri et al. 2002). Under heat stress, organellar HSPs associate with membranes and protect photosynthetic electron transport (Debel et al. 1995; Heckathorn et al. 1998). Correlations between expression of HSPs and thermotolerance have been found in maize, tomato and creeping bentgrass (Park et al. 1996; Ristic et al. 1998). A significant osmoprotective effect was obtained in *E.coli* transformed with the cytosolic chaperonin *CCP-1*α from *B. sexangula* (Yamada et al. 2002). Increase in growth and recovery from heat stress was observed in rice plants overexpressing *HSP101* gene from Arabidopsis (Katiyar-Agarwal et al. 2003).

Several metabolites are known to involve in the mechanism of drought stress tolerance of plants. Among these, proline, glycinebetaine, trehalose, and mannitol are the most common. Additionally, LEA and HSP group of proteins are also identified for their role in drought stress tolerance of plants.

3.2 Transcription Factors

Transcription factors (TFs) are regulatory proteins that modulate gene expression through interactions like sequence specific DNA binding or protein-protein interactions. They can switch on or off the regulatory cascades activating or repressing the transcription of the target genes (Zhang et al. 2005). Many TFs have been found to be involved in the plant response to drought stress. Most of these fall into large TF families such as ERF/ABF2, bZIP, NAC and Cys2His2 zinc-finger. TFs can be of two types; viz. transcription activators and transcription repressors. Transcription activators enhance the drought tolerance by up regulating the stress responsive genes.

The use of point mutations or deletions of inhibitory regions are important in engineering transcription activators. Increased tolerance to drought/freezing/high salt level has been observed in Arabidopsis/rice/tobacco/wheat overexpressing [*DREB1* (dehydration-responsive element binding protein)/*CBF3* (C-repeat binding factor)] showing their control over many stress inducible target genes (Seki et al. 2001; Fowler and Thomashow 2002; Maruyama et al. 2004; Oh et al. 2005; Kasuga et al. 2004; Pellegrineschi et al. 2004). Increased drought and salt tolerance was observed in tobacco transformed with *AlSAP* (A20/AN1 zinc-finger protein) gene from a halophyte grass (Saad et al. 2010). Drought tolerant transgenic Arabidopsis was developed with *AREB1* gene (ABA-responsive element binding protein) which is a basic leucine zipper (bzip) protein belonging to *ABF2* family of transcription factors (Furihata et al. 2006). Introduction of *WXP1* [wax production1; belonging to *AP2/ERF* family (APETALA2/ethyleneresponsive factor)] gene from *M. truncatula* into *M. sativa* resulted in enhanced cuticular wax accumulation and increased tolerance to drought (Zhang et al. 2005). Transgenic Arabidopsis developed by introducing *AREB1/ABF2* and *ANAC019/055/072* (*NAC* family) gene were found to be tolerant to drought stress (Kim et al. 2004a, b; Tran et al. 2004). Enhanced drought tolerance was provided to the transgenic Arabidopsis by the up regulation of Arabidopsis gene for STZ (Cys2His2-type, salt-tolerance zinc finger protein) transcription factor (Sakamato et al. 2004).

Transcription repressors down regulate the gene expression under stress conditions. An Arabidopsis *AtMYB60* gene (belonging to MYB/MYC family) is known to be responsible for regulation of stomatal movements specifically being expressed in guard cells. Down regulation of this gene during drought stress leads to the constitutive reduction of stomatal opening and minimizes wilting (Cominelli et al. 2005). Sometimes, transcription factor modifications can confer novel traits also besides the desired ones as shown by the transgenic Arabidopsis plants expressing an STZ ortholog *CAZFP1* (*Capsicum annuum* Cys2His2-type zinc finger protein), which normally functions as transcription repressor in yeast. It not only showed tolerance to drought stress but also exhibited resistance against bacterial infections (Kim et al. 2004a, b). Introduction of *ZmDREB1A* gene in Arabidopsis from maize made it tolerant to dessication (Qin et al. 2004). Similarly, transgenically modified wheat having *DREB1A/CBF3* gene from Arabidopsis was found to be drought tolerant (Pellegrineschi et al. 2004). Transgenic Arabidopsis developed by introducing *DREB1C/CBF2* using knock out mechanism showed improved drought tolerance (Novillo et al. 2004). Transgenic Arabidopsis were developed expressing *SHN1/WIN1* (shine1/wax inducer 1) gene belonging to AP2/ERF family (Aharoni et al. 2004). These genes are responsible for cuticular wax accumulations which help in providing tolerance against drought stress.

In the mechanism of drought stress tolerance, transcription factors transmit the sense signal from the site of its reception to the target genome. TFs can act as either activators or repressors. Transcription activators enhance the drought tolerance by up regulating the stress responsive genes, while repressors down-regulate the gene expression under stress conditions.

3.3 Signal Transduction and Protein Kinases

Signal transduction as the name suggests means passing on of various signals by involving protein phosphorylation and dephosphorylation, phospholipid metabolism, calcium sensing and protein degradation (Boudsocq and Lauriene 2005; Bartels and Sunkar 2005; Vinocur and Altman 2005). The complexity of these signaling processes lies in the mesh like network of cross talks, feed backs and other cascade interactions to deliver right information to right target at right time. This web of different interactions makes understanding of signal transduction even more difficult. When the plants are affected by the primary stresses like drought, cold, heat, salinity and chemical pollution, it leads to development of secondary stresses like osmotic and oxidative stresses inside the plant. This leads to disruption of normal cell homeostasis damaging the protein and membrane structure/function. This imbalance is perceived by the osmosensors (AtHK1: *Arabidopsis thaliana* histidine kinase-1) and calcium sensors of the signal transduction pathway. This stress situation is passed on as a signal to the secondary messengers (Ca^{2+}, ROS, etc.) and protein kinases (CDPK: calcium dependent protein kinase; MAPK: mitogen activated protein kinase). Further, transcriptional control (CBF/DREB, ABF, bZIP, etc.) and stress responsive mechanisms (osmolytes, detoxification enzymes, chaperones etc.) are activated. Gene activation by these control systems lead to reestablishment of normal structure/function of proteins and membranes providing stress tolerance to plants. It is known that various signal transduction systems function in abiotic stress responses and several genes encoding the signaling factors acting during drought stress have been identified (Zhang et al. 2004; Shinozaki et al. 2003; Chinnusamy et al. 2004). NPK1 (Nicotiana protein kinase 1) is a member of MAPKKK (mitogen-activated protein kinase kinase kinase) family and plays critical roles in cytokinensis, nuclear localization, oxidative stress and auxin signaling (Ishikawa et al. 2002; Kovtun et al. 2000). The damage caused by drought to the photosynthetic machinery can be avoided by activation of stress genes by NPK1. Introduction of tobacco *NPK1* gene into maize showed enhanced tolerance to drought stress (Shou et al. 2004). Drought tolerant Arabidopsis were achieved by introducing *SRK2C* gene [belonging to SnRK2 family (SNF1- related protein kinase 2)] from Arabidopsis (Umezawa et al. 2004). These kinases have been found to be activated in response to ABA or osmotic stress and provide tolerance against them. The importance of the signal transduction pathways lies in the fact that if at any time a signal is not perceived or wrongly perceived it can lead to complete disruption of homeostasis and ultimately death of the plant as all the other stress tolerance molecules or factors are interrelated and much dependent on receiving the right information for fighting the stress.

Plants respond to any signal by perceiving the signal, transmitting the signal through cascade mechanism and acting through gene expression and metabolite adjustment. Protein kinases have been identified as major player in signal transduction pathways involving the one during drought stress in plants.

3.4 Other Genes Involved

Besides the main categories mentioned above, some other types of genes have also been found to be involved in drought stress tolerance. Glutamate dehydrogenase (GDH) is an important enzyme of nitrogen and carbon metabolism. Both the metabolic processes are essential for normal and healthy plant growth but are severely affected under drought stress conditions. Upon introduction of *gdhA* (NADPH-dependent glutamate dehydrogenase) gene from *E. coli* into maize, germination and water deficit tolerance was found to be increased in transgenic maize (Lightfoot et al. 2007). SOD is an important enzyme of ROS scavenging system. These ROS species are generated during stress arising due to drought. Pea *Cu/ZnSOD* (superoxide dismutase) and *MnSOD* (manganese superoxide dismutase) genes were introduced into tobacco and rice, respectively (Sengupta et al. 1993; Wang et al. 2005a, b). Their results suggested improved drought tolerance in transgenic plants. Down regulation of α or β subunit of farnesyltransferase enhances response to ABA and drought tolerance. *ERA1* (enhanced response to ABA 1, farnesyltransferase) gene from Arabidopsis was introduced into Canola/Arabidopsis (Wang et al. 2005a, b). Aquaporins regulate the movement of water for the benefit of the plant under drought stress conditions. Introduction of *RWC3* gene encoding for an aquaporin from rice into rice imparted drought tolerance (Lian et al. 2004). Similarly, *GF14λ* (14-3-3 protein) from cotton was introduced into cotton (Yan et al. 2004). This protein controlled the senescence and photosynthesis system in transgenic plants under drought stress. An Arabidopsis calcium sensor *CBL1* gene (calcineurin B-like protein) which plays role in signal transduction pathway perceiving drought stress and other control factors, was put into Arabidopsis and increased drought tolerance was observed (Cheong et al. 2003). A maize *Chl-NADP-ME* (chlorophyll-targeting NADP-malic enzyme) gene was put into tobacco (Laporte et al. 2002). The transgenic plants showed enhanced plant growth, stomatal conductance and chlorophyll content under stress conditions.

Role of several genes have been documented in drought stress tolerance through generating transgenic plants. Overexpression of genes encoding enzymes of ROS quenching pathway, aquaporins and CBL have been found as a potential candidate for imparting drought stress tolerance.

4 Conclusion

Drought is one of the most serious abiotic stresses affecting the agriculture world over. Natural shortage of water or prolonged periods of below average rainfall/precipitation along with increased human demands for water continuously leads to different types of drought conditions. Most of the plants are unable to responses to drought stress. Plants can response and adapt to drought stress by using one of these strategies escape, avoidance and tolerance. Several morphological, physiological and biochemical changes in plants to response to drought stress. It virtually affects all aspects of plant metabolism. Drought is one of the primary stresses which further leads to secondary stresses like osmotic and oxidative affecting plant growth and development. This imbalance in normal cell homeostasis is perceived by ABA-dependent or ABA-independent pathways. Further, the signal is passed on by the secondary messengers like osmo- and calcium sensors to a cascade of protein kinases and transcriptional factors. This activates various molecules and enzymes like osmolytes (trehalose), chaperones (heat shock proteins), antioxidant enzymes (superoxide dismutase) etc. Their activation leads to reestablishment of normal cellular homeostasis under drought stress conditions. To circumvent this problem, we need to make use of modern tools like genetic engineering and biotechnology to explore new resources for improving drought tolerance in plants. Several genes have been identified and found responsible for providing drought stress tolerance. It is indispensible to understand the mode and mechanisms of action lying behind the molecules identified to present a clear picture about it. Thus, introducing the mentioned genes responsive to drought stress in plants can help in improving crop quality and agricultural productivity.

Acknowledgements We are grateful to Dr. P. S. Ahuja, Director, IHBT, for his continuous encouragement and guidance. JB would like to acknowledge Council of Scientific and Industrial Research, Govt. of India for providing Diamond Jubilee Research Internship and Department of Science and Technology, Govt. of India for providing research funds to the laboratory.

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Plant Parasitic Nematode Diversity in Pome, Stone and Nut Fruits

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Abstract Plant parasitic nematodes such as *Pratylenchus, Meloidogyne, Paratylenchus, Criconemoides* and *Heliocotylenchus* represent a worldwide concern for pome, stone and nut fruit growers. This chapter contains lists of nematodes in apple, peach, pear, plum, cherry, almond, apricot, walnut, pecan and walnut. Nematodes have various attack strategies, feeding ectoparasitically and endoparasitically causing necrosis and galls on the roots, stunted plant growth, varying degree of chlorosis, wilting of foliage and sometimes death of the plants. Other parasitic nematodes such as *Xiphinema*, *Longidorus*, *Trichodorus* and *Paratrichodorus* are also vectors of transmission of viruses to plants. The plant roots weakened and damaged by nematodes are easy prey to many types of pathogenic fungi and bacteria which invade the roots and accelerate root decay. The negative effects on plant growth decrease yields and plant growth. Annual yield loss of 13.54% has been estimated to world's major horticultural crops due to damage caused by plant parasitic nematodes. Studies reveal a 16% yield suppression of peach due to single nematode species *Pratylenchus vulnus.* Growth suppression of apple can be caused by 15 *Pratylenchus penetrans*/100 g soil, 30/100 g for pear, 80/100 g for cherry and 320/100 g for plum. Similarly 5,000 and 4,200 *Criconemella xenoplax*/100 g soil can suppress the growth of peach and walnut, respectively. The great loss of some fruits are due to increased rates of tree mortality due to disease complex such as cherry decline and peach tree short life syndrome where stress caused by nematode parasitism results in an increase in susceptibility of the tree to other pathogens. This

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E. Lichtfouse (ed.), *Agroecology and Strategies for Climate Change*,
Sustainable Agriculture Reviews 8, DOI 10.1007/978-94-007-1905-7_10,

ultimately leads to a reduction in agricultural sustainability. Nematode management therefore becomes a priority for the security of food supply. Hot water treatment of planting materials, soil manipulation, use of certified planting materials, dipping the planting materials in systemic chemicals having nematicidal properties, pre and post planting treatment of nurseries with nematicides, soil fumigation, soil treatment with chemical nematicides, application of oil seed cakes in tree basins, use of bioagents and of course, the identification of nematode resistant rootstocks/cultivars are some of the management strategies which need to be applied in an effective manner for their inclusion in integrated nematode management programme.

Keywords Nematodes • Pome fruit • Stone fruit • Nuts • Bacteria • Fungi • Virus

1 Introduction

Pome, stone and nut fruits are considered a major commercial venture throughout the temperate regions of the world, because of higher remuneration per unit area and the realization that consumption of fruits is essential for human health and nutrition. Among the major fruit growing countries of the world, China ranks first in the production of apple, pear and plum, USA of almond and walnut, Italy of peaches and Turkey of apricot and hazelnuts (Awasthi 2006). Apple, pear and plum together account for 15% of the world fruit production (Griesbach 2007). As far as overall global production is concerned apple is followed by pear, peach, plum, cherry and almonds. The average productivity of temperate fruits in the world is 7.4 ton/ha (Awasthi 2006).

Plant parasitic nematodes continue to threaten fruit crop production throughout the world. They cause serious damage to many fruit and horticultural trees (Askary et al. 2000; Askary and Haider 2010). They are microscopic, unsegmented, triploblastic, bilaterally symmetrical, pseudocoelomate vermiform animal that feed on roots, buds, stems, crowns, leaves and developing seeds (Parvatha Reddy 2008). The extent of damage caused to plants by these tiny organisms vary with the genera and species. Estimated overall average annual yield loss of the world's major horticultural crops due to damage caused by plant parasitic nematodes is 13.54% (Parvatha Reddy 2011).

The study on biodiversity of plant parasitic nematodes on fruit crops dates back to 1889 when Neal reported root-knot nematode infestations in peach and oranges from Florida. The discovery of citrus nematode *Tylenchulus semipenetrans* in 1912 (Thomas 1913; Cobb 1913) was another breakthrough in nematological research on fruit crops. However, in the middle of the century, the discovery of certain chemicals and other soil fumigant nematicides amply demonstrated the destructive role of plant parasitic nematodes (Sharma 2000). Since then a lot of research work has been done on this aspect in different parts of the world. Plant parasitic nematodes are considered major pathogens in their own right as they cause stunted plant growth, varying degree of chlorosis and wilting of foliage. The deleterious effect on plant growth result in reduced yields and poor quality of crops. The roots damaged by nematodes are not efficient to utilize available moisture and nutrients in soil that results in reduced functional metabolism in plants, however, their interactions with other disease causing agents such as bacteria, fungi and viruses further aggravates the problem. Interaction of nematodes with these microorganisms lead to orchard decline whereby fruit trees that have previously produced profitable yield, no longer grow or produce satisfactorily (McElory 1972). Researchers have revealed that these tiny organisms are not only the major limiting factors in horticulture economy but also the basic cause of most diseases of complex nature like shortening of tree production life, replant disease, die back as well as root and rhizome rot. Disease complexes such as cherry decline and peach tree short life syndrome are of major concern for fruit growers as they cause great losses due to increased rate of tree mortality (Bridge and Starr 2007). Management of plant parasitic nematodes is therefore important for high yields and good quality of crops that can be achieved by host resistance and suppression of nematode population through physical, cultural, chemical, biological and integrated methods.

In this chapter an attempt has been made to highlight the occurrence of plant parasitic nematodes and their diversified nature of attack in pome, stone and nut fruits. Also keeping in view the overall problem caused by these microorganisms, management strategies have been suggested in such a way that they may fit well in agroecosystem.

2 Nematodes of Pome Fruits

2.1 Apple (Malus sp.)

Apple is considered as one of the most important deciduous tree fruit in the world which are propagated by budding or grafting the desired scion onto the seedling rootstock in the nursery. A large number of plant parasitic nematodes belonging to different genera have been reported to attack apple trees (Table 1). Among them *Pratylenchus, Meloidogyne, Paratylenchus, Xiphinema* and *Longidorus* are of major economic importance as they cause pronounced deleterious effects on plant growth and productivity (McElory 1972). Plant parasitic nematodes present in the soil parasitize the roots of apple plant and thus the disease acquired in the nursery later on introduce into the orchard. Besides, some nematode groups belonging to *Xiphinema* and *Longidorus* have also been reported to act as vectors for transmission of virus in apple trees.

2.1.1 Lesion Nematode (*Pratylenchus* sp.)

Several species of lesion nematodes are known to attack apple, the most important of which is *Pratylenchus penetrans.* This nematode is the cause of ‘soil sickness’ of apple nurseries and orchards. In the United States, the nematode causes decline in apple and other tree fruit orchards (Arneson and Mai 1976; Mai et al. 1970). *Pratylenchus* sp., 25–150/100 cm^3 are considered damaging but the number can

Table 1 Nematode diversity in apple (*Malus* sp.)

Nematodes	Location	Reference
Aglenchus siddiqui	Swat valley, Pakistan	Islam et al. (1996)
Aglenchus sp.	Pakistan	Islam et al. (2006)
Helicotylenchus hazratbalensis	Srinagar, India	Fotedar and Handoo (1974)
H. indicus	Bulchistan, Pakistan	Maqbool et al. (1988)
H. pseudorobustus	Swat valley, Pakistan	Islam et al. (1996)
Hemicycliophora planiannulatum	Manali, India	Singh and Khan (1999)
Hoplolaimus sp.	India	Zaki and Mantoo (2003)
Longidorus elongates	Kumaon, India	Szczygiel (1976)
Meloidogyne incognita	India	Sharma and Kaur (1985)
M. mali	India	Sharma and Kaur (1985)
Meloidogyne sp.	Swat valley, Pakistan	Islam et al. (1996)
Orientylus himprus	Chamba, India	Sultan (1980)
Paratylenchus prunii	India	Sharma and Kaur (1985)
P. hamatus	India	Sharma and Kaur (1985), Khan et al. (1988)
P. projectus	Swat valley, Pakistan	Khan et al. (1996)
P. manaliensis	India	Khan and Sharma (1991)
Paratylenchus sp.	India	Zaki and Mantoo (2003)
Pratylenchus ekrami	India	Bajaj and Bhatti (1984)
P. curvitatus	Kullu, India	Khan et al. (1989)
P. scribneri	Swat valley, Pakistan	Islam et al. (1996)
P. penetrans	USA	Mazzola et al. (2009), Arneson and Mai (1976), Mai et al. (1970)
	Baluchistan, Pakistan	Maqbool et al. (1988)
P. neglectus	Baluchistan, Pakistan	Maqbool et al. (1988)
P. vulnus	California, USA	Siddiqui et al. (1973)
Pratylenchus sp.	India	Zaki and Mantoo (2003), Sharma and Kaur (1985)
Psilenchus hilarulus	Swat valley, Pakistan	Khan et al. (1996)
	Poland	Pacholak et al. (2006)
Scutylenchus quettensis	Baluchistan, Pakistan	Maqbool et al. (1988)
Trichodorus nanjingensis	China	Yujkin et al. (1998)
Tylenchorhynchus similis	Greece	Karanastasi et al. (2006)
Tylenchorhynchus sp.	Pakistan	Islam et al. (2006)
Tylenchus indicus	India	Khan et al. (1969)
Xiphinema americanum	India	Sharma and Sharma (1988b)
X. insigne	India	Zaki and Mantoo (2003)
X. rivesi	Swat valley, Pakistan	Islam et al. (1996)
	USA	Forer et al. (1984)
Xiphinema sp.	USA	Thorne (1961)

vary depending on soil texture, climate and additional pathogens (Nyczepir and Halbrendt 1993). In Netherlands, 65% of the apple orchards were found infested with *Pratylenchus* sp. (Bridge and Starr 2007). Crossa Raynand and Audergon (1987) reported that an initial population of 15 *P. penetrans*/100 g soil can cause growth reduction in apple trees.

Symptoms

Pratylenchus sp. are migratory endoparasitic form of nematodes which cause distinct necrotic lesions and discolorations of roots that are usually reddish brown at first but later on turn dark and finally black (Parvatha Reddy 2008). The lesions enlarge, coalesce and ultimately result in complete girdling of roots, followed by the loss of cortical tissues through sloughing off (Swarup et al. 1989). There may be substantial reduction in the occurrence of feeder roots. In case of severe infection, the entire root system may be destroyed. Severely affected plants can be easily pulled from the soil. The aerial symptoms on plants are in the form of stunted growth, yellow to yellowish brown leaves and wilting of plants during hot sun hours.

Life Cycle

The juveniles of *Pratylenchus* sp. enter the roots wherever the tissue is immature so that the penetration may become easy. They move inter and intracellulary, feed on root cortex and multiply (Walia and Bajaj 2003). Migration through host tissues and feeding activities result in destruction of host cells which leads to the formation of necrotic lesions. Sexual reproduction is common in *P. penetrans.* Eggs are laid singly inside the roots or in the soil (Parvatha Reddy 2008). Four moulting takes place. The first moult takes place within the egg and three moults occur outside. All the life stages except the J_1 are parasitic. Entire life cycle completes in 30–45 days. Since *Pratylenchus* sp. is an endoparasite, therefore its population densities are typically much greater in plant roots than in the surrounding soil.

Disease Complex

Utkhede et al. (1992) studied the interaction of *P. penetrans* with soil fungi *Phytophthora cactorum, P. cinnamomi* and *P. parasitica.* The results indicated that addition of *P. cactorum* to apple replant disease soil containing the nematode significantly reduced plant growth compared with the corresponding individual treatments. *P. parasitica* did not by itself reduce plant height but in the presence of nematode it reduced plant height to a greater extent than did the nematode alone.

Management

(a) Use of certified planting material: Nematode free planting material should be made available to the apple growers.

(b) Green manuring: Kauri Paasuke (1973) reported that the soil sickness in apple nurseries caused by *P. penetrans* can be controlled by green manuring or adding milled peat to the soil.

(c) Chemicals: Khan et al. (1996) tested carbofuran and polychlorinated petroleum hydrocarbons against *P. neglectus* and found that both the chemicals significantly reduced the nematode population densities. Maqbool et al. (1988) reported that use of carbofuran (20 g active ingredient/tree) in apple orchard reduced the population of *Pratylenchus* sp. by 80–90%. In an experiment in Poland it was observed that soil application of aldicarb significantly reduced the number of nematodes belonging to genus *Pratylenchus* (Pacholak et al. 2006).

(d) Host resistance: Resistance to *P. penetrans* in apple have not been reported so far. However, research workers have got little success where apple rootstocks favour very low population of nematodes. Mazzola et al. (2009) in an experiment found that apple rootstocks from the Geneva series supported lower population of *P. penetrans*.

2.1.2 Pin Nematode (*Paratylenchus* sp.)

They are smallest among the plant parasitic nematodes and are common in the rhizosphere of plants. *Paratylenchus* sp. are ectoparasitic nematode which feed on growing points of roots and thus provide hindrance for them to function in a normal manner. Males and fourth stage pre-adults of *Paratylenchus* do not feed (Walia and Bajaj 2003). However, feeding by adults is limited to epidermal cells and base of root hairs.

Symptoms

Paratylenchus sp. pierce root cells from the soil outside of the plant and remain motile throughout their lives. At times they imbed their anterior portion in the roots and establish longer time feeding sites there (Jenkins and Taylor 1967; Evans et al. 1993). The feeding results in general decline, poor root system and brown necrotic areas on roots. Braun et al. (1966) reported that the cause of dwarfism in apple nursery seedlings is due to heavy infestation of *Paratylenchus* sp. These nematodes are suspected as the basic cause of pre-mature leaf fall in apple tree (Khan et al. 1988; Khan and Sharma 1991).

Life Cycle

Reproduction takes place by amphimixis or parthenogenesis (Walia and Bajaj 2003). The female lays eggs in soil from which second stage juveniles hatch out. Males as well as the fourth stage pre-adults of *Paratylenchus* do not feed. Young juveniles stages feed on the root hairs. Under favourable conditions these nematodes are capable of increasing to tremendous numbers.

Management

(a) Use of certified planting material: Certified planting material should be made available to apple growers.
(b) Hot water treatment: The roots of the plant should be dipped in water at temperature above 40°C (Sharma 2000).
(c) Oil cakes: Application of oil seed cakes like neem and mustard in tree basins have been found effective in reducing the nematode population (Sharma 2000).
(d) Chemicals: Carbofuran and polychlorinated petroleum hydrocarbons have been found effective in reducing the population of *Paratylenchus projectus* to a significant level (Khan et al. 1996).

2.1.3 Dagger Nematode (*Xiphinema* sp.)

Xiphinema sp. are commonly considered as dagger nematode due to their long dagger shaped spear. They are migratory ectoparasites and feed on newly emerging rootlets. These nematodes are of major economic importance in apple growing regions throughout the world (Abawi and Mai 1990). Thorne (1961) reported that *Xiphinema* sp. were extensively prevalent in declining apple orchards in USA. The damage threshold limit of *Xiphinema* sp. is 1/g of soil (Bonsi et al. 1984). Nyczepir and Halbrendt (1993) observed a significant reduction in fresh and dry weight of apple seedlings when 100 *X. americanum* was present in 1 cc soil.

Symptoms

Nematodes feed behind the root-tip which results in the formation of cork due to impregnation of cell walls with suberin and phelloderm (Cohn and Orion 1970; Walia and Bajaj 2003). During feeding nematode thrusts its stylet which causes rupture and killing of epidermal and cortical cells and as a result cells undergo necrosis. Plant growth is retarded (Swarup et al. 1989) but at the later stage, the root system is completely destroyed, with roots near the tip become curled and swollen and proximal parts of the root shrivel up showing signs of severe necrosis. The galls produced by *X. diversicaudatum* contain necrotic cells and occur on the distal portion of root.

Life Cycle

Reproduction occurs at a very low and slow rate and entire life cycle is completed in the soil. Reproduction is either by cross fertilization or parthenogenesis (Swarup et al. 1989) when males are rare or absent. Adult females deposit eggs singly in the soil adjacent to their feeding sites (Brown and Coire 1983). Four moulting takes place and all the four juvenile stages occur outside the egg. Juvenile stages differ from the adults in having two stylets i.e. functional and replacement. The replacement stylet is called odontostyle which lies within the walls of anterior part of oesophagus (Walia and Bajaj 2003). Duration of individual stage and total life cycle of *Xiphinema* varies with species and the environmental conditions.

Disease Complex

Forer et al. (1984) reported the transmission of tomato mosaic ring spot virus in apple by *X. rivesi* and also correlated the prevalence and severity of the disease in several apple orchards in USA with the incidence and population densities of *X. americanum* and *X. rivesi.* Cherry rasp leaf virus transmitted by *Xiphinema* sp. is reported to cause flat apple disease in the cultivars, Red and Yellow delicious (Nyczepir and Halbrendt 1993).

Management

These nematodes can survive without host for several years. They have wide host range and are also reported to parasitize perennial crops, therefore crop rotation and fallowing are not very much successful in their management. However, common methods of nematode management such as application of oil seed cakes like castor, neem or mustard in the soil are advised to use for minimizing their population.

(a) Chemical: Khan et al. (1996) tested carbofuran and polychlorinated petroleum hydrocarbons against *X. rivesi* and found the population reduction of nematodes to a significant level.
(b) Host resistance: Nyczepir and Halbrendt (1993) reported some apple rootstocks resistant to tomato mosaic ring spot virus are M4, M7, Ottawa3 and Novole whereas apple cultivars resistant to tomato mosaic ring spot virus are Quinte, Red Delicious, Jonathan, Tydeman's Red and Jerseymac.

2.1.4 Needle Nematode (*Longidorus* sp.)

They are large in size, possessing a long needle like spear in their mouth and are ectoparasitic on roots. They feed deeply within root tips. The feeding apparatus i.e. spear of *Longidorus* sp. has two parts. Anterior portion is referred to as the odontostyle, and is used to penetrate root cells. The posterior portion is referred to as the odontophore which contains nerve process adjacent to the food canal and is supposed to enable the nematode to discriminate between sites deep within plant roots (Robertson and Taylor 1975). During the feeding process viruses are acquired. These viruses are later on transmitted by the nematodes.

Symptoms

Stunting of plants, branching, swelling and curling of root tips and necrosis are some of the common symptoms produced by *L. elongatus* on apple plants (Szczygiel 1976). *Longidorus* sp. invariably feeds at root tips that transform into terminal galls (Cohn 1975; Sijmons et al. 1994).

Life Cycle

They are ectoparasitic nematode and complete their life cycle in the soil. Reproduction takes place either by cross-fertilization or parthenogenesis when males are rare or absent (Walia and Bajaj 2003). Adult female lay eggs in the soil. After hatching first stage juveniles come out. The juvenile undergoes four successive moultings to reach the adulthood.

Management

Application of oilseed cakes like castor, neem or mustard in the soil is generally advised to reduce the nematode population in soil.

2.2 *Pear (Pyrus communis)*

Pear is the second most important deciduous tree fruit, grown commercially in almost every temperate country and are propagated by budding the desired scion onto a rootstock in the nursery. Several nematode species are reported to be associated with pear (Table 2) but only few of them have evidence of parasitism. Needle nematode, *Longidorus elongatus* and lesion nematode, *Pratylenchus penetrans* are considered of major economic importance in Europe whereas in Japan, root-knot nematodes,

Table 2 Plant parasitic nematode diversity in pear (*Pyrus communis*)

Nematodes	Location	Reference
Crossonema spinosus	Nagaland, India	Singh and Khan (1998)
Longidorus elongates	Europe	Wehunt and Golden (1982)
Meloidogyne hapla	Japan	Wehunt and Golden (1982)
M. incognita	Japan	Wehunt and Golden (1982)
Paratrichodorus porosus	China	Lirong et al. (2005)
Pratylenchus penetrans	Europe	Wehunt and Golden (1982)
P. vulnus	Western United States	Siddiqui et al. (1973)
Trichodorus nanjingensis	China	Lirong et al. (2005)
T. rinae	China	Lirong et al. (2005)
T. cedarus	China	Lirong et al. (2005)
Xiphinema basiri	India	Yadav and Varma (1967)

M. hapla and *M. incognita* are parasitic on pears (Wehunt and Golden 1982). Siddiqui et al. (1973) has reported attack of pear roots by *P. vulnus* in western United States. Nyczepir and Halbrendt (1993) reported that *Pratylenchus* sp. is the only nematode important for pear production in North America. In the United States and Canada *P. penetrans* is a part of pear replant (Wehunt and Golden 1982). An initial population of 30 *P. penetrans*/100 g soil is responsible for causing a growth reduction in pear replant problems in USA and Canada (Nyczepir and Halbrendt 1993).

3 Nematodes of Stone Fruits

Stone fruit mainly comprises of peach, plum, cherry, almond and apricot which are commonly grown in temperate regions of the world. These crops are attacked by several plant parasitic nematodes belonging to different genera and species. A brief description of key nematode pests associated with different stone fruits have been discussed below.

3.1 Peach (Prunus persica)

Several plant parasitic nematodes such as *Meloidogyne, Circonema, Pratylenchus, Xiphinema* and *Paratylenchus* are reported to be associated with peach trees (Table 3), some of which are economically of much importance and of major concern for the peach growers. Walters et al. (2008) in an experiment found that *Mesocriconema, Pratylenchus* and *Xiphinema* are the limiting factors in peach production in Southern Illinois. Meyer and Hugo (1994) found *X. americanum* coincident with heavy damage in peach in South Africa. One experimental study reveals a 16% yield suppression in peach due to *P. vulnus* (Bridge and Starr 2007). Growth suppression in peach can be caused by >5,000 *C. xenoplax*/100 g soil (Raski 1986), 5 *Pratylenchus penetrans*/100 g soil (Barker and Olthof 1976), 100 *Xiphinema* sp./100 g soil (Bonsi et al. 1984), 20 *Paratylenchus prunii*/100 g soil (Sharma and Sharma 1988a) and 13 *P. neoamblycephalus*/100 g soil (Braun et al. 1975).

3.1.1 Root-Knot Nematode (*Meloidogyne* sp.)

Root-knot nematodes (*Meloidogyne* sp.) are widespread, diverse and considered serious pathogens in agricultural crops. They cause an estimated 12% annual yield loss of the world's major crops (Sasser 1980). James et al. (1989) reported 20% loss in cumulative fruit weight in Lovell rootstocks of peach due to root-knot nematode *Meloidogyne* sp. These nematodes are sedentary endoparasites which produce swellings or galls on roots. The nematode infestation results in stunted plant growth, reduced fruit quality and poor yield of the crop. Peach rootstocks are susceptible to four species of root-knot nematodes. They are (i) *M. incognita*, (ii) *M. javanica*, (iii) *M. arenaria* and (iv) *M. hapla* (Nyczepir 1991).

Table 3 Plant parasitic nematode diversity in peach (*Prunus persica*)

Nematode	Location	Reference
Aglenchus muktii	Assam, India	Phukan and Sanwal (1980)
Aglenchus sp.	Pakistan	Islam et al. (2006)
Criconema serratum	Almora, India	Khan and Siddiqi (1963)
Criconemella xenoplax	USA	Raski (1986)
Criconemella sp.	North Carolina and Maryland	Chitwood (1949)
Gracilacus peperpotti	Solan, India	Khan et al. (1989)
Helicotylenchus indicus	Baluchistan, Pakistan	Maqbool et al. (1988)
H. pseudorobustus	Southern Illinois, USA	Walters et al. (2008)
H. platyurus	Southern Illinois, USA	Walters et al. (2008)
H. kashmirensis	Srinagar, India	Fotedar and Handoo (1974)
Helicotylenchus sp.	Costa Rica	Arroyo et al. (2004)
Hemicriconemoides conicaudatus	Assam, India	Phukan and Sanwal (1982)
Hoplolaimus sp.	Southern Illinois, USA	Walters et al. (2008)
Lobocriconema bhowaliensis	Nainital, India	Singh and Khan (1999)
L. sherpai	Darjelling, India	Singh and Khan (1999)
Meloidogyne javanica	Greece	Vlachopoulos (1991)
	Brazil	Gomes et al. (2000)
M. incognita	Brazil	Rossi and Ferraz (2005)
Meloidogyne sp.	United States	Neal (1889)
	Southern Illinois, USA	Walters et al. (2008)
Mesocriconema xenoplax	Brazil	Gomes et al. (2000)
	Southern Illinois, USA	Walters et al. (2008)
Paratylenchus prunii	Himachal Pradesh, India	Sharma and Sharma (1988a)
Pratylenchus dianthus	Southern Illinois, USA	Walters et al. (2008)
P. projectus	Southern Illinois, USA	Walters et al. (2008)
P. vulnus	Georgia	Fliegel (1969)
	Southern Illinois, USA	Walters et al. (2008)
P. penetrans	Baluchistan, Pakistan	Maqbool et al. (1988)
	Southern Illinois, USA	Walters et al. (2008)
P. neglectus	Baluchistan, Pakistan	Maqbool et al. (1988)
P. brachyurus	Florida	Stokes (1966)
P. hamatus	California	Lownsbery et al. (1974b)
Scutellonema brachyurum	South Carolina	Nesmith et al. (1981)
Scutylenchus quettensis	Baluchistan, Pakistan	Maqbool et al. (1988)
Seriepinula truncatum	Nagaland, India	Singh and Khan (1998)
Tylenchorhynchus annulatus	Southern Illinois, USA	Walters et al. (2008)
T. claytoni	Southern Illinois, USA	Walters et al. (2008)
Tylenchulus palustris	Virginia	Eisenback et al. (2007)
T. hamatus	Southern Illinois, USA	Walters et al. (2008)
T. prunii	Srinagar, India	Gupta and Uma (1981)
Xiphinema americanum	USA	Wehunt and Good (1975)
	Southern Illinois, USA	Walters et al. (2008)
X. basiri	India	Yadav and Varma (1967)

Symptoms

Invasion of roots by second stage juveniles which is the only infective stage, results in gall formation on the roots of plant (Bird 1972). The root tip is devitalized and elongation of root ceases. Oftenly on infected roots, branches from near the region of invasion, result in dense hairy type of root system. The above ground symptoms are yellowing of leaves, stunted growth, premature leaf abscission, wilting and early senescence of plant which ultimately leads to reduced fruit production and yield loss (Jonathan 2010).

Life Cycle

Four moulting takes place, once inside the egg and three times after hatching (Fig. 1). Second stage juvenile is the only infective stage which enters the root near the root tip and after finding a suitable tissue settles there (Jonathan 2010). The juvenile begins to swell. Feeding is accomplished by inserting the stylet into the cell. The cell contents are liquefied and semi-digested extra-corporeally with the help of hydrolytic enzymes secreted by oesophageal gland. The nematode enzymes induce excessive conversion of tryptophan into indole acetic acid (Dasgupta and Gaur 1986). This results into enlargement and coalescing of the pericycle cells into a group of multinucleate giant cells around the nematode's head (Bird 1962; Haung 1985; Pasha et al. 1987). Giant cells serve as a food source for the nematode. The cortical parenchymatus cells around the giant cell undergo excessive multiplication giving rise to tiny swellings on the roots or primary galls (Loewenberg et al. 1960). The primary galls may coalesce to form multiple galls. Sex differentiation takes place after the third moult. After final moult eel shaped males emerge out of roots and become free living in the soil. Adult females are pear-shaped, shiny white and immobile (Fig. 2). The mature female deposits several hundred eggs in gelatinous matrix (Jonathan 2010) which protect the eggs from external shock and resist drying. At favourable moisture and temperature, eggs hatch and second stage juveniles come out and move in the soil in search of new host.

Management

(a) Use of certified planting material: The menace of root-knot nematode can be eliminated by selection of nematode free planting material.

(b) Hot water treatment: Temperature above 40°C are generally lethal for plant parasitic nematodes but when embedded deep into plant tissues, higher temperature are required for killing them. However, a very high temperature is also deleterious for plant tissue. Therefore, time-temperature combinations should be carefully worked out for different planting material (Sharma 2000). Parvatha Reddy (2008) reported that hot water treatment of peach seedling roots at 50–52°C for 5–10 min eliminates the root-knot nematode infection.

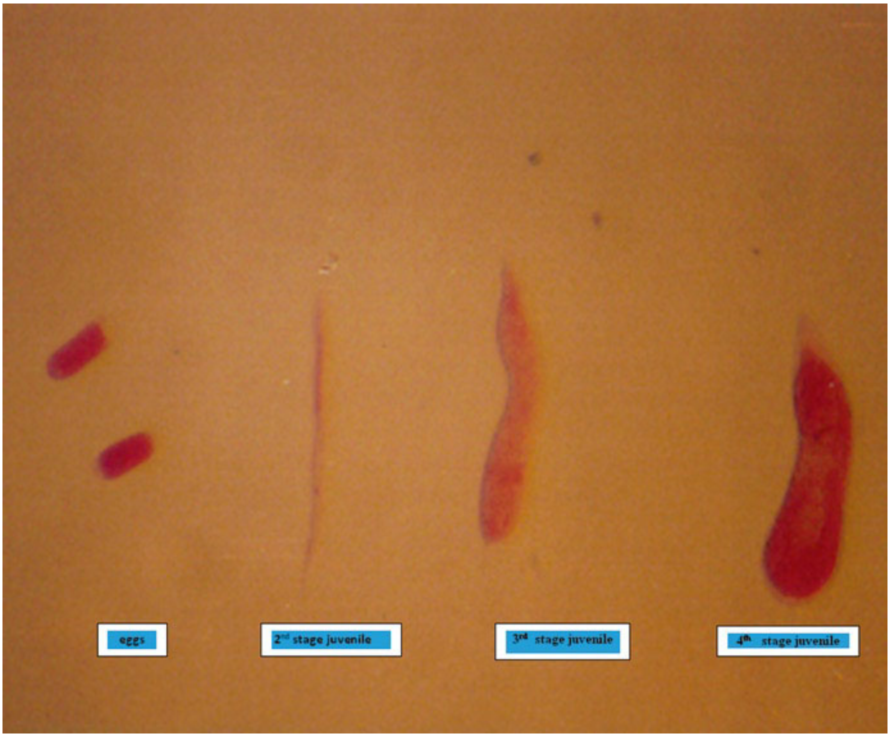

Fig. 1 Eggs and different juvenile stages of root-knot nematode

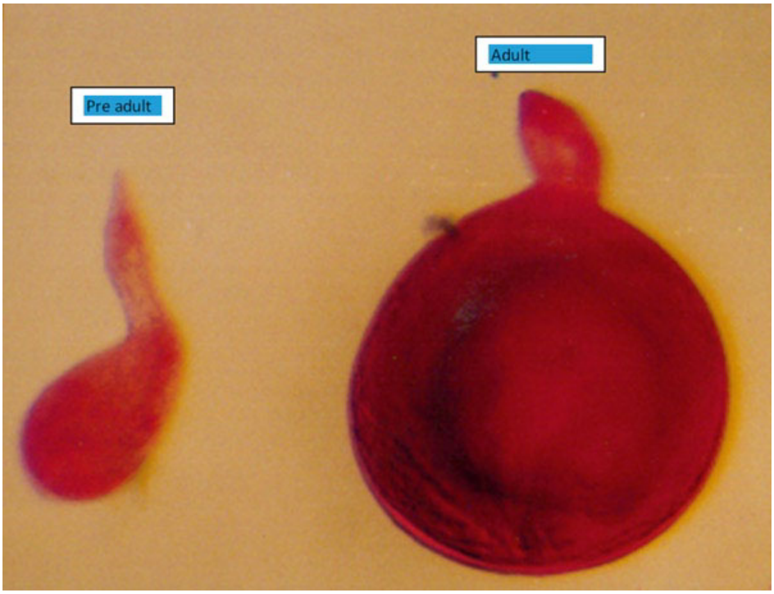

Fig. 2 Pre-adult and adult female of root-knot nematode

Table 4 Plant parasitic nematode resistant cultivars/rootstocks of peach

Resistant cultivars/rootstocks	Nematode	Reference
Greenpac	*Meloidogyne incognita*, *M. javanica*	Pinochet (2009)
Mantianhong	*M. incognita*	GengRui et al. (2008)
Okinawa, R-15-2, Aldrighi	*M. incognita*, *M. javanica*	Fachinello et al. (2000)
G x N No.1	*M. incognita* *M. arenaria*	Marull et al. (1991)
GF 557	*M. incognita* *M. arenaria*	Esmenjaud et al. (1994)
Tsukuba-4, Tsukuba-5	*M. arenaria*	Wang et al. (2008)
GF-31, G x N No. 15, Torinel, AD-101, Monopol, Nemaguard, Cadamum	*M. incognita, M. javanica, M. arenaria, M. hapla, M. hispanica*	Pinochet et al. (1996)
GF-305	*M. arenaria*	Esmenjaud et al. (1994), Marull et al. (1991)
Hansen-5	*M. incognita*	Marull et al. (1991)
Nemaguard x Okinawa	*M. javanica, M. incognita*	Layne (1974)
China flat, Bidbilles Early, Japanese Double, Elberta	*M. incognita*	Verma (1987)
Zhubo 4, Zhubo 5	*Meloidogyne* sp.	Hang et al. (2006)
Halford	*Criconemella xenoplax*	Wehunt et al. (1976)
Lovell	*C. xenoplax*	Rom et al. (1985)
Nemared, G x N No.9	*Pratylenchus vulnus*	Pinochet et al. (1996)
Rubira, Pisa, Rutgers Red Leaf, Txim Pee Tao, Rutgers Red Leaf x Txim Pee Tao	*P. penetrans*	Nyczepir and Halbrendt (1993)

(c) Chemicals: Pre-planting and post-planting treatment of nursery with carbofuran @ 3 kg active ingredient/ha is reported to reduce the nematode infestations (Sharma 2000). Reed (1963) reported that a nematicidal dip (Phorate 3G @ 2%, 4%, 5%, and 8%) of peach rootstock Lovell can reduce the infestation of root-knot nematode, *Meloidogyne* sp.

(d) Biological: *Glomus mosseae* and *M. javanica* when inoculated simultaneously on peach cv. Floridasun, the fungus negated the growth suppressive effect of nematode and reduce the nematode population (Parvatha Reddy 2008).

(e) Host resistance: In the recent years some cultivars/rootstocks resistant to different species of root knot-nematodes have been identified (Table 4).

3.1.2 Ring Nematode (*Criconemella* sp.)

They are ectoparasitic nematode bearing long stylet which they utilize to reach cortical cells below the root epidermis. They are widely distributed in peach growing areas. Chitwood (1949) reported a large number of ring nematodes from peach orchards in North Carolina and Maryland. These nematodes are considered as one of the factors in bacterial canker and peach tree short life syndrome disease. Wehunt et al. (1980) reported a loss of 30–70% after 5 years in peach orchards suffering from peach tree short life syndrome in Georgia. The nematode shortens the tree life and its incidence are mostly found on replanted trees.

Symptoms

The infected plant roots are darkened and often contain longitudinal cracks. The most serious infection appears in the form of the death of finer roots due to direct feeding by nematodes. Due to excessive killing of feeder roots, plants are stunted, showing mineral deficiency syndrome, and more susceptible to water stress. Hung and Jenkins (1969) reported that *Criconemoides curvatum* causes pits and lesions on peach roots under sterile conditions. Lownsbery et al. (1973) found that *C. xenoplax* cause chlorosis and leaf drop under green house conditions and soil in pots infested with this nematode tended to be waterlogged. In an experiment it has been found that *C. rustica* is the source of withering and injury of trunks of young peach trees (Kamio and Taguchi 2009).

Life Cycle

Eggs are deposited singly in the soil. An adult female can lay 8–15 eggs per day (Seshadri 1964). Four moulting take place, first inside the egg and the rest three outside. Second stage juveniles hacth out of the eggs and feed ectoparasitcally on roots of the plant. After fourth moult adults are produced. Entire life cycle from egg to egg is completed in 25–34 days (Seshadri 1964).

Disease Complex

Okie et al. (2009) reported that *C. xenoplax* is implicated in peach tree short life, a disease syndrome which leads to collapse and death of trees above the soil line in late winter and spring following freeze injury and/or bacterial canker caused by *Pseudomonas syringae*. Bacterial canker damaged or freeze injured bark is invariably invaded and colonised by cytospora canker fungi, *Leucostoma persooni* (Ritchie and Clayton 1981). In fact the injury caused by *C. xenoplax* on roots provide entry site for bacterial canker (Lownsbery 1959; Lownsbery et al. 1968, 1973). Nyczepir (1990) also reported that peach tree in south eastern USA infested with *C. xenoplax* were predisposed to cold injury and/or bacterial canker (*Pseudomonas syringae* pv. *syringae*). Simultaneous occurrence of root-knot nematodes and crown gall bacteria in peach has also been reported (Esser et al. 1968). Nigh (1966) found that *Meloidogyne javanica* increased the incidence of crown gall of peach roots caused by *A. tumefaciens*.

Kaul et al. (1993) investigated the infestation of peach rootstocks by the root-knot nematode, *M. javanica* under field conditions. Most of the galls investigated on the peach and hybrid rootstocks contained either developing or degenerating female nematodes and the population of juveniles in the soil was also low. Histological changes in the infested roots were investigated. Transverse sections of the gall indicated the coalesced condition of the multinucleated giant cells or a degenerating syncytium. Bacterial cells identified as *A. tumefaciens* were observed inside cortical cells of galls, highest incidence was found in cells near the root-knot nematode, *Meloidogyne* sp. and lesion nematode, *Pratylenchus* sp. Presence of *A. tumefaciens* in galls has also been confirmed by other researchers (Pinochet et al. 2002).

Infection on peach roots by virus takes place with the aid of nematode and once established within the root, the virus multiplies usually become systemic throughout the plant. Klos (1976) reported the role of nematode in transmission of peach rosette mosaic virus causing a disease on peach trees in USA. The leaves of the affected peach tree showed distortion and chlorotic mottling, internodes were shortened producing a rosette appearance and delayed defoliation. In Canada, *Longidorus didecturus* was reported as the vector of peach rosette mosaic virus in peach orchard. However, the other nematode, *Xiphinema americanum sensu stricto* was also present and transmitting peach rosette mosaic virus at the site (Eveleigh and Allen 1982).

Management

(a) Cultural: Soil manipulation and application of hydrated lime is reported to alter soil moisture, temperature and pH and can bring down the population of *C. xenoplax* (Wehunt et al. 1980; Wehunt and Weaver 1982).

(b) Chemical: Nyczepir and Rodriguez-Kabana (2007) conducted a study on a site infested with *C. xenoplax* and having a previous history of peach tree short life. The experiment was conducted from 1998 to 2003 wherein sorghum was used as a preplant green manure biofumigant management system of *C. xenoplax*. The results indicated that sorghum as a green manure with and without tarp was comparable with methyl bromide fumigation in suppressing the population of *C. xenoplax* in the early stages of the experiment. Nematode population densities were suppressed 11 months longer in sorghum with tarp and urea plots than in sorghum without tarp and urea plots. However, nematode population densities in sorghum with tarp and urea plots were not suppressed as long as in fumigant methyl bromide plots.

(c) Host Resistance: Okie et al. (2009) in a an experiment in the southern United States found that peach rootstock ‘BY520-9’ survive better on sites previously planted with peaches which often suffer from peach tree short life syndrome. Mantianhong, a new peach cultivar used as an ornamental and food has a high resistance to root-knot nematode, *M. incognita* (GengRui et al. 2008). Some peach cultivars/rootstocks resistant to different plant parasitic nematodes have been enlisted (Table 4).

Table 5 Plant parasitic nematode diversity in Plum (*Prunus domestica*)

Nematode	Location	Reference
Circonema xenoplax	USA	Majtahedi et al. (1975)
Helicotylenchus indicus	Baluchistan, Pakistan	Maqbool et al. (1988)
	Himachal Pradesh, India	Sharma et al. (1988)
H. dihystera	Himachal Pradesh, India	Sharma et al. (1988)
H. thornei	Himachal Pradesh, India	Sharma et al. (1988)
Longidorus distinctus	South Eastern Slovakia	Liskova (2007)
Lobocriconema rishikensis	Rishikesh, India	Singh and Khan (1999)
Macroposthonia xenoplax	Himachal Pradesh, India	Sharma and Sharma (1990)
Meloidogyne incognita	Himachal Pradesh, India	Sharma and Sharma (1990)
Paratylenchus prunii	Himachal Pradesh, India	Sharma and Sharma (1990)
Pratylenchus prunii	Himachal Pradesh, India	Sharma et al. (1988)
P. neglectus	Baluchistan, Pakistan	Maqbool et al. (1988)
P. penetrans	Baluchistan, Pakistan	Maqbool et al. (1988)
Scutylenchus quettensis	Baluchistan, Pakistan	Maqbool et al. (1988)
Tylenchulus indicus	North West Frontier Province, Pakistan	Islam et al. (2006)
Xiphinema diversicaudatum	Slovak Republic	Liskova et al. (1993)
X. americanum	Chile	Auger (1989)

3.2 Plum (Prunus domestica)

Plum trees are subjected to severe nematode attack. However, among several nematode species, root lesion nematode, *Pratylenchus* sp., pin nematode, *Paratylenchus* sp., dagger nematode, *Xiphinema* sp. and ring nematode, *Criconema xenoplax* are reported to be dominant in plum growing areas throughout the world (Table 5). Braun and Lownsbery (1975) reported that infestation of *Paratylenchus neoamblycephalus* on plum results in dark as well as small roots having only few feeder roots. The damage threshold limit of *Pratylenchus penetrans* on plum is 320/100 g soil (Nyczepir and Halbrendt 1993; Bridge and Starr 2007).

3.2.1 Disease Complex

Some nematode species are also reported to cause complex diseases in plum. Interaction of root-knot nematode *Meloidogyne* sp. with the bacterium *Agrobacterium tumefaciens*, the causal agent of crown gall has been reported in peach by Rubio Cabetas et al. (2001). Majtahedi et al. (1975) reported that causal agent of bacterial canker, *Pseudomonas syringae* in plum trees was most extensive whose roots were infested with *C. xenoplax*. Auger (1989) reported ring spot nepovirus associated with brownline disease of plum trees in Chile and the nematode acting as a vector in transmission of the virus was *X. americanum.*

Table 6 Plant parasitic nematode resistant cultivars/rootstocks of plum

Resistant cultivars/rootstocks	Nematode	Reference
Pixy, San Julian 655–2, Marianna 2624, Damsons PSM 101	*Meloidogyne incognita*	Pinochet et al. (1990)
P2175	*M. arenaria*	Esmenjaud et al. (1996)
P2032	*M. javanica* *M. hispanica*	Esmenjaud et al. (1994)
Torinel, Red glow	*Pratylenchus vulnus*	Alcaniz et al. (1996)

3.2.2 Management

(a) Chemical: Halbrendt and Shaffer (1989) evaluated the effect of methyl bromide and fenamiphos for the control of dagger nematode, *Xiphinema* sp. in a plum orchard in USA. It was observed that methyl bromide caused a significant reduction in the population of nematodes whereas fenamiphos showed moderate reduction as compared with control. However, application of both the nematicides simultaneously gave greater reduction in nematode populations.

(b) Host resistance: Some cultivars/rootstocks of plum resistant to different plant parasitic nematode species have been enlisted (Table 6).

3.3 Cherry (Prunus avium/P. cerasus)

Cherry plants are attacked by a large number of nematodes belonging to different species (Table 7). Brinkman (1977) reported rust brown colouration on cherry roots caused by *Paratylenchus hamatus*. Root lesion nematode, *Pratylenchus penetrans* has been attributed to cause root injuries in a number of cases (McElory 1972). Severely attacked roots lack feeder rootlets. In some cases the affected roots develop witches brown symptoms appearing as tufts of short, partially dead roots. The damage threshold limit of *P. penetrans* in cherry is 80/100 g soil (Crossa Raynand and Audergon 1987; Bridge and Starr 2007).

3.3.1 Disease Complex

The dagger nematode, *Xiphinema* sp. and needle nematode, *Longidorus* sp. are reported to be associated with the transmission of cherry leaf roll virus (Harrison 1964; McElory 1972). Halbrendt (1993) reported that *X. americanum* acts as a vector in transmission of a virus, the causal agent of cherry rasp leaf disease. The leaves of the diseased cherry trees have enations on their underside, appearing as leafy outgrowths. The disease symptoms first appear on the lower leaves from where the disease slowly spreads causing death of the affected spurs. The branches of the affected trees produce an open, bare appearance. Brown et al. (1994) described cherry rosette virus affecting cherry trees in the Arth region of Switzerland and the nematode acting as a vector in the transmission of disease was *L. arthensis*.

Table 7 Plant parasitic nematode diversity in cherry (*Prunus avium/P. cerasus*)

Nematode	Location	Reference
Criconema xenoplax	Michigan, USA	Melakeberhan et al. (1994)
Criconemoides sp.	Australia	Walker and Wachtel (1988)
Helicotylenhus sp.	Kashmir, India	Waliullah and Kaul (1997
	Australia	Walker and Wachtel (1988)
Longidorus athesinus	Italy	Coiro and Sasanelli (1995)
	East Switzerland	Kunz (2003)
	Central Switzerland	Kunz and Bertschinger (1998)
L. macrosoma	Germany	Buser (1999)
Meloidogyne hapla	Kashmir, India	Waliullah and Kaul (1997)
Nothocriconema digitatum	Himachal Pradesh, India	Singh and Khan (1998)
Paratrichodorus lobatus	Australia	Walker and Wachtel (1988)
Pratylenchus penetrans	Netherlands	Hoestra and Oestenbrink (1962)
	Poland	Szczygiel and Rebandel (1990)
	Michigan, USA	Melakeberhan et al. (1994)
Pratylenchus sp.	Kashmir, India	Waliullah and Kaul (1997)
Rotylenchus sp.	Kashmir, India	Waliullah and Kaul (1997)
Tylenchorhynchus basiri	Kashmir, India	Waliullah and Kaul (1997)
Xiphinema basiri	Kashmir, India	Waliullah and Kaul (1997)
X. americanum		Halbrendt (1993)
X. diversicaudatum	Slovak Republic	Liskova et al. (1993)

The diseased plant show steady decline in vigour with accompanying leaf symptoms such as distortion, enations, rosetting and oil-flecking in which the leaves appear to have been contaminated with drops of oil. Such affected plants die eventually (Brown et al. 2004). Kunz and Bertschinger (1998) analysed two cherry orchards in central Switzerland for the progression of cherry rosette disease. They also observed that *L. arthensis* acts as a vector in transmission of cherry rosette nepovirus, the causal agent of the disease. Transmission of cherry rosette virus by nematode has also been reported from East Switzerland (Kunz 2003).

3.3.2 Management

(a) Hot water treatment: Parvatha Reddy (2008) reported that hot water treatment of cherry seedlings at 50–52°C for 5–10 min eliminates the root-knot nematode infection.

(b) Chemical: Cherry seedlings when dipped in Diazinon (10%) for 30 min reduced the infestation of *P. penetrans* (Sher 1960). Walker and Wachtel (1988) evaluated three nematicides *viz.*, aldicarb, fenamiphos and carbofuran at three different doses i.e., 16.3, 24.4 and 15.0 g/tree for control of nematodes on sweet cherry (*Prunus mahaleb*) in Australia. The results indicated that carbofuran significantly reduced the number of *Paratrichodorus lobatus* but none of the nematicides used in the experiment produced significant reduction in population of *Criconemoides* or *Helicotylenchus* sp.

Table 8 Plant parasitic nematode diversity in almond (*Prunus amygdalus*)

Nematode	Location	Reference
Criconema laterale	Srinagar, India	Khan and Siddiqi (1964)
Helicotylenchus dihystera	Himachal Pradesh, India	Khan and Sharma (1992)
Meloidogyne javanica	Greece	Vlachopoulos (1991)
M. incognita	Himachal Pradesh, India	Khan and Sharma (1992)
Meloidogyne sp.	Morocco	Abbad et al. (1993)
Pratylenchus vulnus	Spain	Marull et al. (1990)
P. neglectus	Spain	Marull et al. (1990)
P . thornei	Spain	Marull et al. (1990)
P . penetrans	Himachal Pradesh, India	Khan and Sharma (1992)
Scutellonema unum	Tunisia	Khan and Khan (1985)
Tylenchorhynchus mashhoodi	Himachal Pradesh, India	Khan and Sharma (1992)
Zygotylenchus guevarai	Spain	Marull et al. (1990)

(c) Host resistance: Direct control of the virus or nematode is difficult but the use of resistant graft, *viz.*, cob and colt showed potential in this regard (Kunz 1998). Cherry rootstock cob and colt is also reported to be resistant to pfeffinger disease caused by raspberry ringspot nepovirus transmitted by the nematode, *L. macrosoma* (Buser 1999). Cherry rootstocks *viz.*, Mazzard, Stockton Morello, English Morello and Montmorency have been found completely resistant to root-knot nematodes whereas cherry replants on Mahaleb rootstock were resistant to lesion nematode, *P. vulnus* and *P. penetrans* (Parvatha Reddy 2008).

3.4 Almond (Prunus amygdalus)

Almond is considered to be a native of Mediterranean region and is grown in almost all the temperate region of Europe, Asia and America. It requires a fairly warm dry weather during ripening of the fruit. Like other stone fruits, almond is also subjected to attack by several plant parasitic nematode species (Table 8). However, *Pratylenchus vulnus* and *Meloidogyne* sp. are the main nematodes associated with this crop.

3.4.1 Disease Complex

There are some reports of nematode-bacterium disease complex in almond, however, not much research have been done in this field. Therefore, very little information is available on this aspect. Almond trees have been observed to have severe infections of crown gall caused by *Agrobacterium tumefaciens* in presence of heavy nematode populations (Sharma and Sharma 1988b).

Table 9 Plant parasitic nematode diversity in Apricot *(Prunus armeniaca)*

Nematode	Location	Reference
Criconemella xenoplax	India	Sharma and Kaur (1985)
Macroposthonia xenoplax	Solan, India	Sharma et al. (1991)
Meloidogyne incognita	Italy	Siniscalco et al. (1976)
Pratylenchus vulnus	India	Sharma and Kaur (1985)
P. penetrans	India	Sharma and Kaur (1985)
P. neoamblycephalus	India	Sharma and Kaur (1985)
Tylenchorhynchus sp.	India	Sharma and Kashyap (2009)
Tylenchulus indicus	North West Frontier Province, Pakistan	Islam et al. (2006)

3.4.2 Management

(a) Host resistance: Marull and Pinochet (1991) identified almond rootstocks *viz.*, D-3-5, GxN No. 9 and Cachirulo as resistant to *M. javanica.* D-3-5 has also been found resistant to *P. vulnus* (Pinochet et al. 1996).

(b) Chemical: Abbad et al. (1993) conducted a field experiment to manage root-knot nematode, *Meloidogyne* sp. on almond plants in nurseries. The results indicated that Metam-sodium at 600 and 1,000 g active ingredient/ha allowed an improvement of growth and vigour to treated rootstocks. Treatment with Metam-sodium gave good protection of roots against infesting second stage juveniles during spring. Management of *P. vulnus* in almond nurseries by soil treatment with chemicals such as methyl bromide, 1, 3-D and fenamiphos has also been reported (Lamberti et al. 2001).

3.5 Apricot (Prunus armeniaca)

Association of nematodes like *Criconemella xenoplax, Pratylenchus* sp., *Tylenchorhynchus* sp., *M. incognita* and *Tylenchus indicus* have been reported on apricot trees (Table 9), however, this fruit tree is considered practically not much vulnerable to plant parasitic nematode attack. Therefore, little work has been done on this crop regarding management of plant parasitic nematodes. In India, *C. xenoplax* and *Pratylenchus* sp. have been reported to cause problem in apricot trees (Sharma and Kashyap 2009).

3.5.1 Management

(i) Cultural: Sharma and Kashyap (2009) reported that intercropping of apricot trees with marigold and oat are safe and effective method in the management of plant parasitic nematodes.

(ii) Chemical: Soil application of Phorate @ 0.03 g active ingredient/m^2 has been found effective in reducing the population of *Criconemella xenoplax*, *Tylenchorhynchus* sp., *Pratylenchus* sp. and *Meloidogyne* sp. (Sharma and Kashyap 2009).

4 Nematodes of Nuts

4.1 *Pecan (Carya illinoensis)*

Not much research work has been done on nematode association with pecan. Few nematodes are reported on pecans of which root-knot nematode, *Meloidogyne,* are widely distributed and most likely to be pathogenic (Table 10). Johnson et al. (1975) observed in pecan trees distorted, yellow colour foliage with zinc deficiency symptoms accompanied with root-knot infection.

4.1.1 Disease Complex

Nyczepir and Wood (2008) studied the effect of interaction between *Meloidogyne partityla* and *Mesocriconema xenoplax* on nematode reproduction and vegetative growth of pecan in field microplots. The results indicated that the presence of the two nematode species together caused a greater reduction in root growth than *M. xenoplax* alone, but not when compared to *M. partityla* alone. Mouse-ear symptom severity in the pecan leaves was increased in the presence of *M. partityla* as compared to *M. xenoplax* and uninoculated control. Infection with *M. partityla* increased severity of mouse-ear symptoms expressed by foliage. It was concluded that *M. partityla* is more detrimental pathogen to pecan than *M. xenoplax.* Hsu and Hendrix (1973) reported that *Criconemella rusium* cause necrosis on pecan roots in the presence of *Pythium irregularae* and *Fusarium solani*. The nematode alone did not affect root weight, whereas both the fungi reduced root weight. The effect was synergistic when nematode was combined with either and both of the fungi.

4.2 *Walnut (Juglans regia)*

Among several plant parasitic nematodes associated with walnut (Table 11), *Mesocriconema xenoplax, Pratylenchus vulnus* and *Cacopaurus pestis* are the key

Table 10 Plant parasitic nematode diversity in Pecan (*Carya illinoensis*)

Nematode	Location	Reference
Criconemella rusium	Georgia, USA	Hsu and Hendrix (1973)
Meloidogyne partityla	Georgia, USA	Nyczepir et al. (2002)
	Crisp county, Georgia, USA	Willers and Daneel (1993)
	Madison county, Florida, USA	Crow et al. (2005)
	Laeveld, South Africa	Willers and Daneel (1993)
M. javanica	Spain	Pinochet et al. (1993)
Meloidogyne sp.	Texas, USA	Johnson et al. (1975)
Mesocriconema xenoplax	USA	Nyczepir and Wood (2008)
Pratylenchus vulnus	Spain	Pinochet et al. (1993)

Table 11 Plant parasitic nematode diversity in walnut (*Juglans regia*)

Nematode	Location	Reference
Cacopaurus pestis	California	Thorne (1943)
Ditylenchus dipsaci	North West Frontier Province, Pakistan	Islam et al. (2006)
Longidorus sp.	France	Lorrain (2000)
Macroposthonia pruni	Bajore agency, Pakistan	Khan and Bilqees (1993)
Meloidogyne incognita	USA	Buzo et al. (2006)
Meloidogyne sp.	France	Lorrain (2000)
Mesocriconema xenoplax	Italy	Ciancio and Grasso (1998)
Pratylenchus vulnus	California	Lownsbery (1956)
	USA	Buzo et al. (2006)
Pratylenchus sp.	France	Lorrain (2000)
Psilenchus minor	Bajore Agency, Pakistan	Khan and Bilqees (1993)
Tylenchorhynchus sp.	North West Frontier Province, Pakistan	Islam et al. (2006)
Xiphinema sp.	France	Lorrain (2000)

nematode pests that are highly pathogenic, widely distributed and considered a threat to walnut industry. Infestation of *M. xenoplax* on walnut causes pruning and necrosis of fine feeder roots, especially on young plants and also feeds older parts of roots (Lownsbery et al. 1977). Lownsbery et al. (1974a) in an experiment in California observed that *Juglans hindsii, J. major, J. nigra, J. regia* and *J. microcarpa* were susceptible to *P. vulnus*. In California, roots of walnut have been reported to be parasitized by *C. pestis*, a sedentary ectoparasitic nematode feeding on epidermal cells (Thorne 1943). The body of the female stayed on the outside of the root and eggs were deposited in a gelatinous matrix exuded from the posterior end of the female. Lownsbery *et al.,* (1978) reported damage threshold limit of *M. xenoplax* on walnut to be >4,200/100 g soil.

4.2.1 Management

(i) Cultural: Nematodes free planting materials should be used.
(ii) Host resistance: Walnut cv. Paradox with its hybrid vigour is the most tolerant to infestation by *Pratylenchus* sp.

4.3 Hazelnut (Corylus avellana)

Little research has been done on the nematodes of hazelnut and therefore not much information is available on this aspect. However, like other nuts, association of many plant parasitic nematodes *viz.*, *Coslenchus* sp., *Ditylenchus* sp., *Filenchus afghanicus*, *Filenchus* sp., *Helicotylenchus* sp., *Hemicycliophora punensis*, *Hemicycliophora* sp. and *Merlinius* sp. have been reported on this crop (Kepeneckci 2002). In Spain, *Pratylenchus vulnus* is reported to cause infestation on hazelnut (Pinochet et al. 1992).

5 Conclusion

In the foregone review, the various diseases of pome, stone and nut fruits caused by different plant parasitic nematodes singly and in association with certain microorganisms have been discussed. It is evident from the literature that the nematodes have diversified nature of attack and therefore, the above ground and underground symptoms on the affected plant also varies. Also damage threshold limit varies for different nematode species. Hence, to bring an improvement in management strategies to meet the challenges requires both broader and deeper knowledge of crop diseases caused by nematodes. Work on disease complexes where nematodes and soil microorganisms are involved needs to be intensified with adequate collaboration between nematologists and plant pathologists. A prior knowledge of host parasite relationship of major nematode pests and techniques for precise determination of damage threshold limit of nematode populations is a must for a successful nematode management programme. Also while adopting a management strategy economy and ecology must be taken into consideration. The different management methods described in the chapter is need based and each has its own importance. Therefore, integrated nematode management strategies should be adopted by bringing all the methods together such as deep summer ploughing, minimal use of nematicides like nursery bed treatment and bare root dip treatment, hot water treatment of planting material, application of potential biocontrol agents and use of nematode resistant cultivars/rootstocks.

Chemical methods of nematode control is no doubt effective and are widely used, however, the hazardous nature of chemical require a continuous research to find ways to reduce its application and rates wherever possible (Rich et al. 2004). Hot water treatment of planting material has long been used to kill plant parasitic nematodes (Jenkins 1960; Towson and Lear 1982) but the temperature required to kill nematodes in plant tissues are more or less similar to the temperature required to kill plant tissues (Bridge 1996). Therefore, temperature range for each plant species need to be worked out based on water volume, number and size of plants to be treated, time of treatment and other factors (Halbrendt and LaMonida 2004). A safe method of nematode management is application of biocontrol agents but its survival and potentiality is still a debatable issue before the research workers. Therefore, attempts should be directed for exploration of potential biocontrol agents and its sustainability under field conditions needs to be assured for a successful nematode management programme. Evaluation of germplasm and subsequent breeding programme to develop cultivars/rootstocks resistant or tolerant to plant parasitic nematodes is an important and cost effective method of nematode management. In the recent years some cultivars/rootstocks resistant to plant parasitic nematodes have been developed. However, for an encouraging result more emphasis is required in this field by identifying new sources of plant resistance and its incorporation into crops by traditional breeding or genetic engineering biotechnology.

Acknowledgements The authors would like to thank all those who have contributed to the preparation of this chapter but are particularly indebted to all the nematologists who have generated the information present in this chapter.

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Fly Ash for Agriculture: Implications for Soil Properties, Nutrients, Heavy Metals, Plant Growth and Pest Control

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Abstract Annual fly ash production ranges from 2 MT in the Netherlands to 112 MT in India, whereas fly ash utilisation ranges from 100% in the Netherlands to 38% in India. Over the past few decades there has been interest in developing strategies to use fly ash in agriculture. It is indeed economical to use fly ash as a soil amendment. Reviews on fly ash in agriculture are scarce. The potential of fly ash as a resource material is due to its specific physical properties such as texture, water holding capacity, bulk density, and pH. Moreover fly ash contains almost all essential plant nutrients. Fly ash can be used as an amendment in soil. Fly ash can improve soils physical and chemical properties, reduce pest dammade on crops and increase crop yields. The amount and method of fly ash application to soil depend on the type of soil, the crop grown and fly ash characteristics. Besides positive effects fly ash may contain also toxic metals and radionuclides. Therefore use of fly ash should be done with care, notably by taking into account the uptake of metals by plants. This chapter describes the properties of fly ash, and the effect of fly ash on soil properties, nutrients, heavy metals uptake by plants, yields and pest control.

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Sustainable Agriculture Reviews 8, DOI 10.1007/978-94-007-1905-7_11,

Keywords Agricultural application • Soil quality • Fly ash • Plant growth • Nutrients • Heavy metal • Radionuclide

1 Introduction

Fly-ash, an end residue from combustion of pulverized bituminous or sub-bituminous coal (lignite), is one of the major causes of particulate air pollutant that developing countries are facing. They are generated due to excessive use of fossil fuels especially wood and coal. Since independence, there has been rapid increase in power generation in India. Power Generation is largely dominated by coal based generation with thermal generation constituting about 79% of total generation. In India, presently, the combustion of coal products are produced each year is around 112 MT(metric ton), which is likely to exceed and reach up to 170 MT by 2012 (Dhadse et al. 2008) (Table 1). In India, the power generation has increased from 1,362 MW(megawatt) (1947) to 120,000 MW (During 2004–2005) (Kumar et al. 2005). Government of India has planned for further enhancement of installed capacity to 200,000 MW by 2012 and to 300,000 MW by 2017 (Kumar et al. 2005). An Indian energy sector accounts for nearly 13 million tons of fly ash generation per year. The disposal of such a huge quantity of fly ash is a big problem in an area around the thermal power station.

Various types of residues such as fly ash, bottom ash, and flue gas desulphurization waste, fluidized bed boiler waste and coal gasification ash are produced due to coal combustion. The residues from coal combustion entering the flue gas stream are known as fly ash. Fly ash is also generated by factory boilers, cement industry etc. which adds more to this quantity. Therefore there is an urgent need of new and innovative methods for reducing the negative impacts on the environment and promoting the beneficial aspect. The fly ash formation depends on quality as well as ash content of the coal. Though low in sulpur Indian coals contains higher amount of

Table 1 Generation and utilization of fly ash in different countries (Source: Dhadse et al. 2008)

S. No.	Country	Annual fly ash production (MT)	(%) Utilization
1	India	112	38
2	China	100	45
3	USA	75	65
4	Germany	40	85
5	United Kingdom (UK)	15	50
6	Australia	10	85
7	Canada	6	75
8	France	3	85
9	Denmark	2	100
10	Italy	2	100
11	Netherlands	2	100

ash (about 35–45%), hence the generation of huge quantities of fly ash in India. In Indian, the fly ash utilization was 3% of 40 MT production in 1994, has increased and reached about 38% (42 MT) of total production i.e., 112 MT during 2004–2005 which is far below the global utilization rate (Dhadse et al. 2008) (Table 1). The causal of low fly-ash utilization in India is the unavailability of appropriate cost-effective technologies as well awareness among peoples. In India, the majority of fly ash produced is disposed off in ash ponds and landfills and rest of fly ash (<15%) is being used for preparing bricks, ceramics and cements (Pandey et al. 2009).

Earlier by-products of coal combustion were largely treated as waste materials. However, in the recent past years many applications have been recognized due to the presence of essential mineral elements resembling earth's crust, which makes them excellent substitution for natural materials. They can be used as a substitute for Portland cement in manufacturing roofing tiles and as structural fills, sheetrock, agricultural fertilizer and soil amendments. In 2004–2005, total utilization of fly ash was about 42 Million tonnes per year. The highest utilization was in cement industry (≈49%), whereas agricultural sector contributed very less (≈1%). The common practice to dispose huge quantity of fly ash is disposal at the dumping site, which requires huge quantities of land and causes deterioration of air, soil and water quality. According to World Bank, India will require 1,000 km^2 of land for the coal ash disposal till 2015 (Parisara 2007). Earlier fly ash was seen as a waste but now time has changed and it is now considered as a valuable resource. Fly ash can be utilized as a soil amendment in agriculture, improving soil texture (Chang et al. 1977; Phung et al. 1978; Garg et al. 2003), improving nutrient status of the soil (Rautaray et al. 2003), wasteland reclamation (American Coal Ash Association 1998; Jala and Goyal 2006) etc. But most of the fly ash still remains in the ash pond, causing many deleterious effects on the environment, resulting in the degradation of land due to accelerated erosion rates and ground water pollution problem.

The present review governs the positive and negative aspect of agricultural utilization of fly ash. Positive aspects namely: Improvement of the nutrient levels, increasing the water holding capacity, texture, reducing the acidity of the soil, use as an insecticide to effectively control various pests infesting several vegetables etc. However, negative aspects namely; toxic heavy metals and radioactive content in fly ash. Negative aspect can be nullified and be helpful in tackling the waste management problem of fly ash.

2 Physico-Chemical Properties of Fly Ash

The physicochemical properties of fly ash depends primarily on the parent coal composition of which it is produced and secondly on its combustion condition. Due to varying nature of coal the fly ash characteristics are also changing. The coal is a complex polymeric solid having no repeating monomeric units. The chemical characteristics of coal are described by the parameters such as molecular weight, carbon aromaticity, normal aromatic and aliphatic structure and functional groups.

Table 2 Comparison of physico-chemical characteristics of fly ash and soil

Properties	Fly ash[a]	Fly ash[b]	Soil[a]
pH (1 : 5)	7.84	8.12	6.81
E. C. (ms cm^{-1})	4.90	3.54	7.40
Water holding capacity (%)	73.36		43.53
Organic C (%)	0.97	1.7	1.96
Total N (%)	0.676	–	1.183
Total K (%)	0.98	–	0.028
Metals (mg kg^{-1})			
Fe	3,976	20,054	2942.00
Zn	65.88	94.7	22.60
Cu	42.63	–	27.40
Ni	19.67	23.44	11.93
Cd	19.67	31.23	0.45
Pb	5.08	26.81	2.61
Cr	9.23	–	6.06
Metalloids (mg kg^{-1})			
B	18.06	–	<0.004

[a] Tripathi et al. (2008)

[b] Gupta and Sinha (2008)

The rank of coal is described by criteria like its anthroxylon content, oxygen content, calorific value, ultimate analysis, fixed carbon etc. (Hodgson et al. 1982). Generally Indian coals have a high mineral matter percentage, low sulphur content, high moisture, high ash content and low calorific value of 3,500–4,000 kcal kg^{-1}. Ash content of Indian coals varies between 15% and 30% and the S content is generally less than 1% (Srivastava 2003; Bhatt 2006). It is very hard to generalize the composition of ashes. Physically fly ash is very fine glass like particles with an average diameter of less than 10 mm, having low to medium bulk density, large surface area and very light texture whereas its chemical composition depends on the parent coal quality and its operating conditions. Fly ash consists of approximately 95–99% oxides of Si, Al, Fe and Ca and about 0.5–3.5% of Na, P, K and S and the remaining ash is trace elements. Typical coal fly ash constituents are SiO_2 (49–67%), Al_2O_3 (16–29%), Fe_2O_3 (4–10%), CaO (1–4%), MgO (0.2–2%), SO_3 (0.1–2%). Certain characteristics of fly ashes are fairly uniform. Fly ashes consists of many minute glass like particles of 0.01–100 mm size (Davison et al. 1974) having specific gravities 2.1–2.6 g m^{-3} (Bern 1976). Some spheres of FA are hollow (cenospheres), while others (plerospheres) are filled with small amorphous particles (Hodgson and Holliday 1966). Bulk density of fly ash ranges from 1 to 1.8 g cm^{3} whereas pH varies from 4.5 to 12.0 depending on parent coal S content (Plank and Martens 1974). The alkaline pH of fly ash may be due to the presence of Ca, Na, Mg and OH along with other trace metals. CaO, a major constituent of the fly ash, forms Ca $(OH)_2$ with water and, thus, attributes towards alkalinity (Hodgson et al. 1982). The particle size of fly ash greatly influences its composition; however, it also affects the soil physical properties. All the metals present in soil are found in the fly ash. Comparative study of physico-chemical characteristics of fly ash and soil is given in Table 2. The concentration of various elements found in fly ash varies according to the particle size (Davison et al. 1974; Khan and Khan 1996). Some of the important elements constituting fly ash are Si, Ca, Mg, Na, K, Cd, Pb, Cu, Co, Fe, Mn, Mo, Ni, Zn, B, F and Al. So fly ash contains all the important metals needed for plant growth and its metabolism except organic carbon and nitrogen. Fly ash contains very less or no nitrogen as the N present in the coal is volatilized during its combustion (Bradshaw and Chadwick 1980; Singh and Yunus 2000), however it has high concentration of phosphorous (P) (400–8,000 mg P kg^{-1}), but the form of P is not readily available to plants, probably due to interactions with Al, Fe and Ca present in alkaline fly ash.

The radionuclides which contribute most to the environmental radiation are the member of the natural radioactive series and 4°K. Coal contains trace quantities of the naturally occurring radionuclides arising from Uranium and Thorium series and 4°K. The concentration of theses lives radionuclides are usually low in the coal, when it is burnt in power plant, the fly ash that is emitted through the stack gets enriched in some of the radionuclides (Yeledhalli et al. 2008).

Presence of radionuclides in fly ash has been reported by several workers but the literature on their impact has been few (Coles et al. 1978; Gowiak and Pacynas 1980; Mittra et al. 2003; Yeledhalli et al. 2008). Mittra et al. (2005) in a study analyzed the radioactivity (Bq kg^{-1}) of fly ash and reported higher radioactivity of ^{226}Ra, ^{228}Ac and 4°K was recorded in soil treated with fly ash at 40 t ha^{-1}. The radioactivity due to addition of fly ash was subjected to dilution effect in soil. However, these marginal variations remained within the safe limit (Mittra et al. 2005).

3 Effect on Soil Properties

The effect of fly ash amendment on soil has been extensively investigated by many workers (Plank and Martens 1974; Adriano et al. 1980; Elseewi and Page 1984). Fly ash amendment in soil affects all its physical characteristics such as bulk density, pH, water holding capacity, electrical conductivity etc. (Table 3). The fly ash addition alters soil physical properties such as its texture, bulk density, water holding capacity (Chang et al. 1977) and particle size distribution (Sharma 1989) (Table 3). Campbell et al. (1983) found that fly ash addition at the rate of 10% increased the water holding capacity 7.2 and 413.2 times for fine and coarse sands respectively. The fly ash amendment also stabilizes soil aggregates as it works as soil binders or stabilizers of self cementing material which result in reduced leachable contaminants in the fly ash. The impact of fly ash amendment depends largely on the properties of parent coal and the soil. The electrical conductivity of the soil was increased as a result of fly ash amendment as the levels of soluble major and minor inorganic constituents' increases in soil (Adriano et al. 1980; Eary et al. 1990; Adriano and Weber 2001) (Table 3). The Indian fly ashes are mostly alkaline in nature, hence their application increases the soil pH (Gupta and Sinha 2006, 2009; Pandey et al. 2009). The pH of soil increases as a result of fly ash amendment with its alkaline nature due to rapid release of Ca, Na Al and OH^- from the fly ash

Table 3 Change in soil physico-chemical properties after application of different levels of Fly ash

Properties	Effect	References
Physical		
pH	Decrease	Wong and Wong (1986), Pathan et al. (2003)
	Increase	Sinha and Gupta (2005), Gupta and Sinha (2006, 2009), Tripathi et al. (2008), Pandey et al. (2009)
Bulk density (BD)	Decrease	Page et al. (1979), Pandey et al. (2009)
Water holding capacity (WHC)	Increase	Singh and Siddiqui (2003), Tripathi et al. (2008), Pandey et al. (2009)
Porosity	Decrease	Page et al. (1979), Pandey et al. (2009)
	Increase	Singh and Siddiqui (2003)
Chemical		
Electrical conductance (EC)	Increase	Adriano et al. (1980), Eary et al. (1990), Mishra et al. (2007)
	Decrease	Gupta and Sinha (2006, 2009), Tripathi et al. (2008)
Cation exchange capacity (CEC)	Increase	Singh and Siddiqui (2003), Mishra et al. (2007)
	Decrease	Sinha and Gupta (2005), Gupta and Sinha (2006, 2009)
Organic carbon/organic matter	Decrease	Gupta and Sinha (2006, 2009)
Fe, Cu, Zn, Mn	Increase	Tripathi et al. (2004, 2008), Mishra et al. (2007), Gupta and Sinha (2006, 2008, 2009), Singh et al. (1997)
Toxic elements (Cd, Pb,Ni etc.)	Increase	Gupta and Sinha (2006, 2009), Mishra et al. (2007), Singh et al. (1997), Tripathi et al. (2008)

(Wong and Wong 1986) (Table 3). As fly ash contains hydroxide and carbonate salts it has an ability to neutralize acidity in soils (Pathan et al. 2003). This property of fly ash can be used in neutralizing the acidic soil, but using excessive quantities of fly ash for altering soil pH can cause increase in soil alkalinity especially with unweathered fly ash (Sharma et al. 1989). Some fly ashes are acidic in nature which can be used in reclaiming alkaline soils (Table 3). Soil texture of sandy and clayey soil was altered to loamy soil as a result of fly ash addition at the rate of 70 t/ha (Fail and Wochok 1977).

A gradual increase in fly-ash amendment in the normal field soil (0%, 10%, 25%, up to 100% v/v) was reported to increase the water holding capacity, electrical conductivity, EC, and pH and (Sinha and Gupta 2005; Gupta and Sinha 2006, 2009). This improvement in water holding capacity is beneficial for the growth of plants especially under rainfed agriculture. Amendment with fly ash up to 40% also increased soil porosity from 43% to 53% and water holding capacity from 39% to 55% (Singh and Siddiqui 2003).

Recently, Pandey et al. (2009) carried out a study at Balarampur, Uttar Pradesh, India to examine the influence of fly ash amendment into garden soil for *Cajanus cajan* L. cultivation and on accumulation and translocation of hazardous metals to edible part. *C. cajan* L. were grown in varying concentrations of fly ash (0%, 25%, 50% and 100% w/w). Fly ash amendment from 25% to 100% in garden soil increases the levels of pH, particle density, porosity and water holding capacity from 3.47% to 26.39%, 3.98% to 26.14%, 37.50% to 147.92% and 163.16% to 318.42%, respectively, than the control while bulk density decreases respectively from 8.94% to 48.89%.

Generally, the bulk density of soil decreased due to fly ash addition, which in turn decreases porosity and enhanced water holding capacity (Page et al. 1979). The fly ash amendment increases the water holding capacity of sandy and loamy soils by 8% yet fly ash alone, is not very effective in retaining water (Chang et al. 1977). The higher B availability from fly ash limits its use in crop production (Aitken and Bell 1985), by proper weathering of fly ash this problem can be overcome, as it reduces the B availability below the toxic levels (Cope 1962; Townsend and Gillham 1975).

The fly ashes are also rich in heavy metals; the soil chemical property is affected too (Table 3). As the fly ash contains trace elements as well as heavy metals, it may contaminate the soil. The metals can readily percolate down and contaminate ground water or it may contaminate the nearby water body. Nearly 5–30% of toxic elements present in fly ash, especially Cd, Cu and Pb is leachable (Natusch and Wallace 1974). At higher level of fly ash amendment some heavy metals might become more active and hinder the microbial activity (Adriano et al. 1978). Alteration in soil texture has been reported by some workers due to amendment of fly ash in soil (Chang et al. 1977; Carlson and Adriano 1993) (Table 3).

4 Effect on Nutrients and Heavy Metals Status in the Soil

In most instances, fly ash is added to soils primarily to affect chemical properties such as pH and fertility, and loading rates are limited by chemical effects in the treated soils. Plant growth on fly ash-amended soils is most often limited by nutrient deficiencies, excess soluble salts and phytotoxic B levels (Page et al. 1979; Adriano et al. 1980). Fly ash usually contains virtually no N and has little plant-available P (Bradshaw and Chadwick 1980; Singh and Yunus 2000; Jala and Goyal 2006; Basu et al. 2009). Application of fly ash to soil may cause P deficiency, even when the ash contains adequate amounts of P, because soil P forms insoluble complexes with the Fe and Al in more acidic ashes (Adriano et al. 1980) and similarly insoluble Ca-P complexes with Class C ashes. Amendment of K-deficient soil with fly ash increases plant K uptake, but the K in fly ash is apparently not as available as fertilizer K, possibly because the Ca and Mg in the fly ash inhibit K absorption by plants (Martens et al. 1970).

Factors against fly ash disposal in agricultural soils are especially the content of potentially toxic elements (Ni, Pb, Cd, B, Se, Al, etc.), high salinity and reduced solubility of some nutrients due to high pH (<7.5) of fly ash (Carlson and Adriano 1993; Gupta and Sinha 2006). As already noted the pH of fly ash can vary from 4.5 to 12 depending mainly on the S content of the parent coal (Plank and Martens 1974; Page et al. 1979). The pH of some alkaline ashes can exceed 12 and this may be a factor limiting plant growth, particularly on unweathered deposits (Carlson and Adriano 1993). A high pH can induce deficiencies of essential nutrients such as

P and essential trace elements such as Fe, Mn, Zn and Cu in plants grown in ash deposits and soils amended with substantial amounts of ash (Cary et al. 1983; Carlson and Adriano 1993; Adriano et al. 2002).

Application of fly ash to agricultural soil generally results in increased soil concentrations of extractable Ca, Ba, Mo, Se, S, B, Pb, and Cd other elements may also be enriched depending on the rate of its application, type and composition of the soil and properties of the fly ash (Page et al. 1979; Adriano et al. 1980; Carlson and Adriano 1993; Bilski et al. 1995; Jala and Goyal 2006; Basu et al. 2009). Fly ash also has been shown to supply essential nutrients to crops on nutrient-deficient soils and has been reported to correct deficiencies of B, Mg, Mo, S and Zn (Carlson and Adriano 1993; Singh and Yunus 2000; Jala and Goyal 2006). The availability of Mg, Mo, S and Zn in some ashes is comparable to the availability of these nutrients in commonly used fertilizers (El-Mogazi et al. 1988). Elevated concentrations of B, Se, As, Mo, Sr and S are commonly reported for plants growing in fly ash or fly ash-amended soil (Adriano et al. 1980, 2002; Carlson and Adriano 1993).

By contrast, fly ash application may tend to decrease the uptake of some elements. Concentrations of metals such as Fe, Mn, Zn, Ca, Cr, Cd as well as P in plant tissues have after been found to decrease when fly ash is added to the soil (Adriano et al. 1980, 2002; Wong et al. 1996; Gorman et al. 2000; Ciccu et al. 2003; Sinha and Gupta 2005; Gupta and Sinha 2006, 2009; Gupta et al. 2007). Although, an exact mechanism of element retention by fly ash is unclear, the main reasons are believed to be (I) an increase in pH causing the precipitation of insoluble phases and (II) an increase in a specific surface area, promoting metal sorption via surface complexation, cation exchange reactions or both.

A pots study aimed to effect of fly ash on growth and metal accumulation in tomato plant was conducted by Khan and Khan (1996). They found that the gradual increase in fly-ash concentration in the normal field soil from 0%, 10%, 20% up to 100% v/v increased the pH, thereby improving the availability of sulfate, carbonate, bicarbonate, chloride, P, K, Ca, Mg, Mn, Cu, Zn and B. They also found that addition of fly ash to acidic and alkaline soil decreased the amounts of Fe, Mn, Ni, Co and Pb released from acid soil. However, the release of these metals from alkaline soil remained unchanged.

Sinha and Gupta (2005) studied on the plants of *Sesbania cannabina* Ritz grown on different amendments of fly ash with garden soil. They reported that the application of fly ash reduced the levels of tested metals extracted by the diethyelen triamine penta acetic acid (DTPA) and subsequently its accumulation in *S cannabina*, from 10% to 50% of the fly ash amendment. Another pots experiment was conducted by Gupta and Sinha (2006) to study the potential of *Brassica juncea* for the phytoextraction of metal from fly ash amended soil and to study correlation between different pool of metals (total, DTPA, $CaCl_2$ and NH_4NO_3) and metal accumulated in the plant in order to assess better extractant for plant available metals. They found that the levels of all the tested metals were decrease with an increase in fly ash amendments ratio from 10% to 75% fly ash. Correlation coefficient between metal accumulation by the plant tissues and different pool of metals showed better correlation with DTPA in case of Fe, Zn and Ni, whereas, Cu was significantly correlated with ammonium nitrate (NH_4NO_3) and other metals (Pb, Mn) with $CaCl_2$. Alkaline ash can also cause increased accumulation of some non-essential trace elements in plants such as As, Se and V whose solubility increase with increasing pH (Page et al. 1979; Adriano et al. 1980).

5 Effect on Heavy Metal Uptake by Plants

The effect of fly ash addition on the uptake or enrichment of various nutrients and heavy trace elements in soil as well as various crops have been investigated with safe use of crop produced for human consumption (Page et al. 1979; Doran and Martens 1972). Brake et al. (2004) reported variation in uptake of different metals studied in young, middle age and mature basil (Genovese), tomato, zucchini and sunflower plants grown in soil amended with 5%, 10% and 20% fly ash (w/w). Uptake of As and Ti was increased by increasing FLY ASH amendment rates, As exceeded the toxic level in basil and zucchini (7 ppm).

Mishra et al. (2007) reported that the fly ash application did not change the Na content of rice-roots, but the contents of K, P, Mn, Ni, Co, Pb, Zn, Cu, Cr, and Cd showed a progressive increase. Seeds of plants grown in fly ash amended soils accumulated Cu, Pb, Cr and Cd in amounts below allowable limits. Accumulation of Fe was maximum in all the parts of plant followed by Si and both metals showed more translocation to leaves while Mn, Zn, Cu, Ni and Cd showed lower accumulation and most of the metal was confined to roots in all the three cultivars. As was accumulated only in leaves and was not found to be in detectable levels in roots and seeds (Dwivedi et al. 2007). In all the three cultivars of rice heavy metal accumulation was Fe > Si > Mn > Zn > Ni > Cu > Cd > As in all the plant parts.

Pandey et al. (2009) in a pot experiment, found that accumulation and translocation of heavy metals in *Cajanus cajan* L depends on fly ash amendment ratios. Addition of fly ash at lower ratios (25%) shows positive results in most of the studied growth and yield parameters than the respective control. Means concentration of Zn, Cu, Cr and Cd in edible parts (seeds) were found below the respective critical value of 100–900, 20–100, 2–30 and 0.7–200 $\mu g\ g^{-1}$dw (Marchner, 1995). However, Pandey et al. (2009) reported that lower concentration of fly ash (25%) is safe for *C. cajan* cultivation as it not only enhanced the yield of *C. cajan* L. significantly but also ensured the translocation of heavy metals to edible parts within the critical limits. Recently, Gupta and Sinha (2009) have reported that the accumulation of metals in the plant of *Vigna radiata* increased with increasing fly ash amendment and was greater in shoots than in roots (except for Mn and Cu) and seeds (except Mn).

In contrast fly ash application might also decrease the uptake of heavy metals including Cd, Cu, Cr, Fe, Mn and Zn in plant tissues (Petruzzelli et al. 1986), which could be probably due to the increased pH of fly ash amended soil. According to El-Mogazi et al. (1988), the supply of As from fly-ash to plants might be short-term.

Integrated nutrient treatments involving fly ash at 10 t ha^{-1}, organic wastes and chemical fertilizers resulted in higher uptake of N, P, K, Ca, Mg, Fe, Mn, Zn and Cu in rice grain than application of only chemical fertilizers, which in turn was responsible for higher rice yield (Sajwan et al. 1995; Sarangi et al. 1997; Rautaray et al. 2003). They also observed lower concentration of Cd and Ni in both grain and straw of rice and the reason might be the increase in soil pH due to the application of fly ash to the rice crop which precipitated the native Cd and Ni.

6 Effect on Plant Growth

As fly ash contains almost all the essential plant nutrients needed for their growth and metabolism it can be a good source of soil amendment. The use of fly ash amendment in agriculture has been stimulated since it assists in tackling the fly ash disposal problem and saves the large amount of land required for land filling. Generally fly ash amendment in soil increases plant growth and nutrient uptake (Aitken et al. 1984; Furr et al. 1977). Experiment was carried out by Singh et al. (1997) to study the impact of fly ash amendment on seed germination, seedling growth and metal composition of *Vicia Faba* L. fly ash of Talkatora thermal power plant was amended in soil at different ratios 5%, 10%, 20% and 30%. The experiment was carried out in an earthen pot. It was found that lower fly ash amendment enhances the seed germination significantly by 68%, whereas at 30% fly ash application rate, seed germination was inhibited. The 20% fly ash amendment delayed the seed germination by 4 days. It might be due to higher concentration of trace elements such as Cu, Co, Ni, Se, Al, and Cr etc. at higher application rates which delayed or inhibited the process (Vollmer et al. 1982). Lower application rate also enhanced the plant growth, leaf area and plant height whereas higher dose (30%) retarded the plant growth and dry matter production was reduced by 27%. The concentrations of all the metals were higher in roots than that in tops. It has been reported that fly ash amendment at maximum rate of 10% in agricultural soil is beneficial for plant growth (Singh et al. 1997).

Khan and Khan (1996) conducted a study to find out the most suitable level of fly ash dose for addition in the soil to improve its fertility leading to higher productivity of tomato crop, *Lycopersicum esculentum*. Pot experiment was carried out using following doses 0%, 10%, 20%, 30%, 40%, 50%, 60%, 70%, 80%, 90% and 100% of fly ash amendment. Tomato plants responded positively to fly ash amendment showing luxuriant growth. Shoot length enhanced in 40–90% fly ash whereas root length increased in 20–80% fly ash amendment in comparison to unamended soil (Khan and Khan 1996). However, shoots and roots were 9% and 5% longer in 100% fly ash than the control, whereas, 50% and 60% fly ash amendment had greatest enhancement (34.7% and 54.9%, respectively) (Table 4).

Ajaz and Tiyagi (2003) conducted a field experiment to study the effect of different concentrations of fly ash (0%, 10%, 25%, 50%, 75%, 90% and 100%) on growth of cucumber plant i.e., *Cucumis Sativus*. Normal soil without fly ash amendment was treated as control. Fly ash amendment in to the soil also improves the plant

Table 4 Effect of fly ash amendment on growth, yield and heavy metal accumulation in plants

Plants	@ Fly ash in to soil	Effects on growth and yield	Effects on heavy metal accumulation in plants	Reference
Turf grass	@ 0, 280, 560 and 1,120 Mg ha^{-1}	Plants height and root depth were not adversely affected, however, dry matter yields throughout the study period affected	–	Adriano and Weber (2001)
Cucumis Sativus	@ 0%, 10%, 25%, 50%, 75%, 90%, 100% (w/w)	FA amendment in the soil improves the plant growth characters such as length, fresh as well as dry weights, net primary productivity and leaf area. Plant fresh weight was found to be decreased at higher FA amendment rates	–	Ajaz and Tiyagi (2003)
Vicia faba L	@ 0, 10, 25, 50 and 100	Growth and biomass of the plant increased (<25%) followed by decreased with application of FA as compared to GS	–	Rai et al. (2003)
Rice plant (*Oryza sativa*) Pant-4, Pant-10 and Pusa Basmati	@ 0%, 20%, 40%, 60%, 80% and 100%	Application of 20% and 40% FA with soil caused a significant increase in plant growth and yield of all the three cultivars followed by decreased at higher percentage (60%, 80% and 100%)	–	Singh and Siddiqui (2003)
Sesbania cannabina L.	@ 0%, 10%,25%,50%, 75% and 100% (w/w)	Growth and biomass of the plant increased (<25%) followed by decreased with application of fly ash as compared to garden soil	Metal accumulation was found to be in the order Fe > Mn > Zn > Cu > Pb > Ni after 90 d of exposure	Sinha and Gupta (2005)

(continued)

Table 4 (continued)

Plants	@ Fly ash in to soil	Effects on growth and yield	Effects on heavy metal accumulation in plants	Reference
Brassica juncea L. var. vaibhaw	@ 0%,10%,25%,50% and 100% (w/w)	25% fly ash amendment shown significant increase in plant biomass, shoot and plant height, whereas, no significant effect was observed in root length	The metal accumulation in total plant tissues was found in the order of Fe > Ni > Zn > Mn > Cu > Pb and its translocation was found more in upper part	Gupta and Sinha (2006)
Rice plant (*Oryza sativa*)	@ 0, 40, 80, and 120 Mg ha^{-1}	The highest rice yields were achieved following the addition of ≈80 Mg ha^{-1} fly ash	The application of fly ash increased Si, P and K uptake by the rice plants	Lee et al. (2006)
Brassica napus (canola)	@ 0%, 5%, 10%, 20%, 50% and 100%	Increases early growth vigour and seed yield by 20%	–	Yunusa et al. (2006)
Cicer arietinum L. varieties (var. CSG-8962 and var. C-235)	Various combinations of fly ash amended with garden soil (GS), press mud (PM) or saw dust (SD)	Fly ash amended with GS or PM led to a 5–10 times increase in biomass compared to FA control and was most pronounced in the less metal tolerant variety CSG-8962	Amendment of FA with either GS or PM only moderately increased the contents of some essential metals whereas the non-essential Cd and Cr remained similar or decreased slightly compared to FA control	Gupta et al. (2007)
Three rice cultivars viz., Saryu-52, Sabha-5204, and Pant-4	@ 10%, 25%, 50%, 75% and 100% (w/w)	Higher application (>50%) of FA caused reduction in growth parameters viz., plant height, root biomass, number of tillers, grain and straw weight	The metal accumulation order in three rice cultivars was Fe > Si > Mn > Zn > Ni > Cu > Cd > As in all the plant parts	Dwivedi et al. (2007)
Rice plant (*Oryza sativa*)	@ 0, 1, 2.5, 5, 10 and 15 t ha^{-1}	Growth (shoot length, leaf area and pigment composition) and yield (panicle length, seeds per panicle, seed weight and yield per plant) of rice increased with an increase in FA amendments	Contents of Mn, Ni, Co, Pb, Zn, Cu, Cr, and Cd progressively increased with FA application	Mishra et al. (2007)

Phaseolus vulgaris	@ 0%, 10% and 25%% (w/w)	Results indicated that lower amendment favored the growth of the plant	Translocation of metals was more from roots to shoots in the plants grown on FA amended soil	Gupta et al. (2007)
Beta vulgaris L. var All Green H1	@ 0%, 5%, 10%, 15% and 20% (w/w)	FA caused significant reductions in growth, biomass and yield	Concentrations of all the tested heavy metals increased significantly with increasing concentrations of FA	Singh et al. (1997)
Brassica napus (canola)	@ 0, 5, 25, 125, and 625 Mg/ha	FA at low to moderate rates of up to 25 Mg/ha enhanced growth and yield of canola	FA application did not influence accumulation of B, Cu, Mo, or Zn in the stems at any stage of plant growth or in the seed at harvest	Yunusa et al. (2006)
Cajanus cajan L.	@ 0%, 25%, 50% and 100% (w/w)	Lower concentration (25% FA) application had shown positive results in most of the studied parameters of growth and yield	–	Pandey et al. (2009)
Vigna radaiata L var PDM 54 (mung bean)	@ 0%, 10% and 25% (w/w)	Growth parameters increased with increasing FA amendment compared with GS. An increase in dry biomass was also observed with increasing FA amendment compared to GS	Accumulation of metals by the plants increased with increasing FA amendment and was greater in shoots than in roots (except for Mn and Cu) and seeds (except Mn)	Gupta and Sinha (2009)

growth characters such as length, fresh as well as dry weights, net primary productivity and leaf area, which increases gradually up to 50% fly ash amendment. The fresh weight of cucumber increased maximally by 114.91% at 25% fly ash amendment followed by 10% and 50% fly ash amendments. Plant fresh weight was found to decrease at higher fly ash amendment rates (Ajaz and Tiyagi 2003) (Table 4).

Sinha and Gupta (2005) reported, increase in root as well as shoot length of *Sesbania cannabina* grown at lower fly ash amendment rates (10% and 25% fly ash). Growth and development of the plants occur as a result of an overall balance between synthesis and proteolysis of proteins (Sinha and Gupta 2005) (Table 4). A study conducted by Mishra et al. (2007) reported that the application of fly ash caused significant improvement in soil quality and germination percentage of rice seeds. They found that shoot length, leaf area and pigment composition, and panicle length, seeds per panicle, seed weight and yield per plant of rice increased with an increase in fly ash amendments. Pandey et al. (2009) reported that growth variables such as root and shoot length, plant height, total leaf area, number of nodules per plant and biomass increased with a decreasing ratio of fly ash incorporation. Even fly ash addition in to the soils also affected its chemical composition due to increased concentration of various elements, which is beneficial for plant growth when applied at low concentrations but becomes toxic at higher doses (Gupta et al. 2004; Sinha and Gupta 2005). Pandey et al. (1994) reported, increase in plant growth, number of leaves, leaf area and biomass of *Helianthus annuus* L. grown at 0.5, 1 and 1.5 kg m^{-2} fly ash amended soil as compared to respective unamended control (Table 4). Recently, Gupta and Sinha (2009) have reported that the plant height, root and shoot lengths and dry biomass of the *Vigna radiata* increased with increasing fly ash amendment compared with garden soil (Table 4).

7 Role of Fly Ash in Agricultural Diseases Control

Several reports have revealed that fly ash can be used as insecticide in agricultural areas (Table 3). Narayanasamy and Gnanakumar Daniel (1989) have reported the insecticidal property of lignite fly ash as an insecticide against a range of lepidopterous and coleopterous pests infesting rice, vegetables, greens and certain other field crops. Sankari and Narayanasamy (2007) worked on Bio-efficacy of fly ash based herbal pesticides against pests infesting rice and vegetables. Amongst all the treatments, fly ash with 10% turmeric dust and fly ash with 10% neem seed kernel dust were found to be the most effective against all the test insects, including Epilachna on brinjal and Spodoptera on okra, followed by fly ash with 10% vitex dust and fly ash with 10% eucalyptus dust and fly ash with 10% ocimum dust. The whole study showed that fly ash could be a potential insecticide and an active carrier in certain insecticide formulations like dust, wettable powder and granules. It is concluded by successive studies that fly ash could effectively control various pests infesting several vegetables both under laboratory and field conditions.

8 Conclusion

In view of the above discussions, the striking points from this chapter could be summarized as follows: (A) Benefit of fly ash use in agriculture: (i) fly ash having almost all the essential plant nutrients i.e., macronutrients including P, K, Ca, Mg and S and micronutrients like Fe, Mn, Zn, Cu, Co, B and Mo, except organic carbon and nitrogen. (ii) Its application also increases the soil pH, water holding capacity etc. It will certainly reduce the availability of heavy metal in the soil subsequently its uptake in to the plant. (iii) Fly ash is also useful for stabilizing erosion-prone soils. (iv) fly ash is also useful to effectively control various pests infesting several vegetables.

(B) Fly ash utilization in agricultural sector also has some disadvantages especially with natural radionuclide and toxic heavy metal content.

However, care must be taken while using fly ash in agriculture. Attention should also be given on some important areas related to its utilization, such as long term studies of impact of fly ash on soil health, crop quality, and continuous monitoring on the characteristics of soil as well as fly ash. There is also need of study on presence of radionuclides in fly ash as there are very few reports on this.

Acknowledgement Amit K. Gupta and Rajeev P Singh are thankful to UOU and USM respectively for Postdoctoral fellowship and necessary help.

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Organic Farming History and Techniques

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Abstract Organic farming involves holistic production systems that avoids the use of synthetic fertilizers, pesticides and genetically modified organisms, thereby minimizing their deleterious effect on environment. Agriculture area under organic farming ranges from 0.03% in India to 11.3% in Austria. Organic farming is beneficial for natural resources and the environment. Organic farming is a system that favors maximum use of organic materials and microbial fertilizers to improve soil health and to increase yield. Organic farming has a long history but show a recent and rapid rise. This article explains the development stages, techniques and status of organic farming worldwide. The sections are: the development and essential characteristics of organic farming; the basic concepts behind organic farming; historical background; developmental era of organic farming; methods of organic farming; relevance of organic farming in the Indian context; comparative account between organic farming and conventional farming; importance of organic farming in environmentally friendly approaches; working with natural cycles; relevance of organic crop production in food security; yield potential and trends of organic farming; rural economic linkage its scope and limitations; and legislation procedures adopted by various countries. Organisations and financial aspects of organic farming are briefly discussed.

Keywords Organic farming • Farming system • Biodiversity • Arbuscular mycorrhizal fungi • Conventional agriculture • Nutrient management • Habitat management

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1 Introduction

Organic agriculture is one among the broad spectrum of production methods that are supportive of the environment. Agriculture remains the key sector for the economic development for most developing countries. It is critically important for ensuring food security, alleviating poverty and conserving the vital natural resources that the world's present and future generations will be entirely dependent upon for their survival and well-being. The world populations will inevitably double by the middle of the twenty-first century, that we are soon to enter, that is in the space of just two generations. Over 90% of the developing nations, especially in Asia and to an ever greater extent will be in the urban areas which follow up the green revolution strategy (Rothschild 1998).

Green revolution technologies such as greater use of synthetic agro chemicals like fertilizers and pesticides, adoption of nutrient responsive, high-yielding varieties of crops, greater exploitation of irrigation potentials etc. has boosted the production output in most of cases. Without proper choice and continues use of these high energy inputs is leading to decline in production and productivity of various crops as well as deterioration of soil health and environments. The most unfortunate impact on Green Revaluation Technology (GRT) not only on Indian Agriculture but also the whole world is as follows:

1. Change in soil reaction
2. Development of nutrient imbalance/deficiencies
3. Damage the soil flora and fauna
4. Reduce the earth worm activity
5. Reduction in soil humus/organic matter
6. Change in atmospheric composition
7. Reduction in productivity
8. Reduction in quality of the produce
9. Destruction of soil structure, aeration and water holding capacity

All these problems of GRT lead to not only reduction in productivity but also deterioration of soil health as well as natural eco-system. Moreover, today the rural economy is now facing a challenge of over dependence on synthetic inputs and day by day it change in price of these inputs. Further, world Agriculture will face the market competition due to globalization of trade as per World Trade Organization (WTO). Thus apart from quantity, quality will be the important factor. Such as Agriculture gave birth to various new concepts of farming such as organic farming, natural farming, bio-dynamic Agriculture, do-nothing agriculture, eco-farming etc.

The essential concept of the practices is "Give back to nature", where the philosophy is to feed the soil rather them the crop to maintain the soil health. Therefore, for sustaining healthy ecosystem, there is need for adoption of an alternatives farming system like organic farming.

2 The Features of Organic Farming

Organic farming gives importance to environmental protection and helps to sustain ecological issues such as soil conservation. Farmers who undertake organic farming practice crop rotation to enrich the soil with natural mineral resources. Organic farmers have to follow the norms set by the local organic farming associations and they are not allowed to cultivate genetically modified (GM) crops (Alistair 2007; Haslberger 2010). The minerals for the crop known as crop nutrients are given using insoluble nutrient sources through soil microorganisms that increase nitrogen levels in the soil. For instance, alternating legumes with the main crop would increase nitrogen levels in the soil. Chemical drugs are not administered on farm animals to control fleas or parasite problems. Instead, these problems are controlled by moving the animals to new pastures and by using home remedies to control the plant and animal pests. Organic gardening, including vegetable gardening, is also a part of organic farming. Many flower and vegetable gardens are using composite manure for their flowering plants and shrubs, instead of chemical fertilizers (Haslberger 2001; Rai 2006).

The basic concepts behind organic farming are:

1. It concentrates on building up the biological fertility of the soil so that the crops take the nutrients they need from steady turnover within the soil nutrients produced in this way and are released in harmony with the need of the plants.
2. Control of pests, diseases and weeds is achieved largely by the development of an ecological balance within the system and by the use of bio-pesticides and various cultural techniques such as crop rotation, mixed cropping and cultivation.
3. Organic farmers recycle all wastes and manures within a farm, but the export of the products from the farm results in a steady drain of nutrients.
4. Enhancement of the environment in such a way that wild life flourishes.

In a situation where conservation of energy and resources is considered to be important community or country would make every effort to recycles to all urban and industrial wastes back to agriculture and thus the system would be requiring only a small inputs of new resources to "Top Up" soil fertility (Table 1).

India represents only 0.03% area (43,000 ha) out of total cultivated (143 million ha) area.

Table 1 Area under organic farming in % of total agricultural area in important countries (Bhattacharya and Gehlot 2003)

Country	% of cultivated area	Country	% of cultivated area
Austria	11.30	Australia	2.31
Switzerland	9.70	France	1.40
Italy	7.94	USA	0.23
Denmark	6.51	Japan	0.10
Sweden	6.30	China	0.06
United Kingdom	3.96	India	0.03
Germany	3.70		

2.1 Essential Characteristics of Organic Farming

The most important characteristics are as follows:

1. Maximal but sustainable use of local resources.
2. Minimal use of purchased inputs, only as complementary to local resources.
3. Ensuring the basic biological functions of soil-water-nutrients-human continuum.
4. Maintaining a diversity of plant and animal species as a basis for ecological balance and economic stability.
5. Creating an attractive overall landscape which given satisfaction to the local people.
6. Increasing crop and animal intensity in the form of polycultures, agroforestry systems, integrated crop/livestock systems etc. to minimize risks.

Many scientists at different levels have elaborated the concept of organic farming but according to Lampkin (1990) Organic farming is a production system which avoids or largely excludes the use of synthetic compounded fertilizers, pesticides, growth regulators and live stock feed additives. According to national organic standards board of the U.S. defines organic farming as an ecological production management system that promotes and enhances bio diversity, biological cycles and soil biological activity. Organic farming refers to organically grown crops which are not exposed to any chemicals right from the stage of seed treatments to the final post harvest handling and processing (Ram and Pathak 2008).

According to IFOAM (2010) Organic farming "should sustain the health of soil, plant animal, human and planet". It relies on ecological processes, biodiversity and cycles adapted to local conditions, rather than the use of inputs with adverse effects. Organic agriculture combines tradition, innovation and science to benefit the shared environment and promote fair relationships and a good quality of life for all involved. It relies on the four principles of health, ecology, fairness and care.

Organic farming relies on crop rotation, crop residues, animal manures, legumes, green manures, off-farming organic wastes, agricultural cultivation, mineral bearing rocks and aspect of biological pest control to maintain soil productivity and tilth to supply plant nutrients and also to control insects, weeds and other pests (Lampkin 1990). In a broader sense it includes bio-fertilizers, bio diversity and biotechnology.

3 History of Organic Farming

The concept of organic farming was started 1,000 years back when ancient farmers started cultivation near the river belt depending on natural resources only. There is brief mention of several organic inputs in Indian ancient literature like Rig-Veda, Ramayana, Mahabharata and Kautilya Arthasashthra etc. In fact, organic agriculture has its roots in traditional farming practices that evolved in countless villages and farming communities over the millennium.

3.1 *Historical Perspective of Organic Farming*

Organic farming is an oldest practice dating back to 'Neolithic age', practiced by ancient civilization like Mesopotamia, Hwang Ho basin etc. The scripts of Ramayana describes that all dead things – rotting corpse or stinking garbage returned to earth are transformed into wholesome things that nourish life. Such is the alchemy of mother earth as interpreted by C. Rajagopalachari. The Mahabharata (5500 BC) mentions of Kamadhenu,the celestial cow and its role on human life and soil fertility. Kautilya Arthashastra (300 BC) mentioned manures like oil cake, excreta of animals. Brihad-Sanhita by Varahmihir described how to choose manures for different crops and the methods of manuring. Rig Veda (2500–1500 BC) mention of organic manure in Rig Veda 1, 161, 10. Similarly, Green Manure in Atharva Veda II (1000 BC) 8.3, in Sukra (IV, V, 94, 107–112) it is stated that to cause healthy growth the plant should be nourished by dung of goat, sheep, cow, water as well as meat. A reference of manure is also made in Vrksayurveda by Surpala (manuscript, oxford, No 324 B, Six, 107–164).The Holy Quran (590 AD) stated that at least one third of what you take out from soils must be returned to it implying recycling as post-harvest residue. A number of studies have revealed the importance to organic farming systems in the present era for sustainable development of human existence. Worldwide concerned have been raised both developed and developing countries for personal health, safe environment, food security and fight against global warming through organic farming, while others have cited the challenge of organic production and ability to use specialized skills (i.e. human capital) as drivers of conversion of organic agriculture (Midmore et al. 2001; Niemeyer and Lombard 2003; Padel 2001a; Lairon 2010). Ideological, philosophical, and religious beliefs can also motivate towards organic farming alongside concerns over profitability and market demand food quality and safety environmental protection and more broadly, levels of pesticide use (Conacher and Conacher 1998; Willer and Gillmor 1992; Hong 1994; Rigby et al. 2001; Svensson 1991; Howlett et al. 2002; Kaltoft 1999). Broadly speaking, these motives include concern over the environmental impact of farming system, personal, family, or consumer health, safety and farm profitability (Cacek and Langner 1986; Lockeretz and Madden 1987; Henning et al. 1991; Henning 1994 ; Hall and Mogyorody 2001). Additional factors in the Canadian and US context include dissatisfaction with farm work, the decline of the family farm, financial problems associated with conventional farming, lifestyle and the desire to live harmoniously with nature (Hall and Mogyorody 2001; Sullivan et al. 1996). The conversion for tradition farming towards organic is by no means exhaustive, it does illustrate that the trends are multi-factorial. Based on the literature, we conclude that there are four broad themes underlie in organic farming: (1) profit/economic/financial issues; (2) environmental concerns; (3) health and safety concerns and (4) ideological/philosophical motives. The relative importance of these four themes does not appear to be consistent across the various studies, suggesting variation across countries, commodities, etc. Moreover, the relative importance of these studies appears to be changing over time. For example, only 9% of respondents in the study of Henning et al. (1991) indicate that profitability is the most important factor in their decision to go for organic farming, while 56% of producers surveyed by Hall and Mogyorody (2001) cite profitability as a very important factor for organic agriculture and stated that a shift has occurred in the ideological orientation of organic farming. Similar conclusions have been drawn in the European and US in this context (Padel 2001a, b; Rundlof and Smith 2006).

Organic farming practice is known since ages. The ancient Indian manuscripts also describe the importance of dead and decaying matter in nourishment of life and soil fertility, respectively. Importance of organic manure and recycling post-harvest residues has also been dealt in various sections of these literatures. Organic farming has been recognized worldwide for personal health, safe environment, food security and fight against global warming. Ideological, philosophical and religious beliefs have also triggered the use organic farming with a commercial outlook taking care of environment and quality product.

4 Developmental Era of Organic Farming

The development of the organic farming era worldwide had gone through mainly three stages, Emergence, Development, and Growth in chronological sequence.

4.1 Era of Emergence (1924–1970)

The beginning of organic farming could trace back to 1924 in Germany with Rudolf Steiner's course on *Social Scientific Basis of Agricultural Development*, in which his theory considered the human being as part and parcel of a cosmic equilibrium that he/she must understand in order to live in harmony with the environment. Therefore, a balance must be struck between the spiritual and material side of life (Herrmann and Plakolm 1991). Pfeiffer has applied these theories to agriculture and gave birth to biodynamic agriculture (Kahnt 1986). It was developed at the end of the 1920s in Germany, Switzerland, England, Denmark and the Netherlands (Herrmann and Plakolm 1991; Kahnt 1986; Diercks 1986). In Switzerland in 1930, politician Hans Mueler gave impetus to organic-biological agriculture. His goals were at once economic, social and political as they envisioned autarchy of the farmer and a much more direct and less cluttered connection between the production and consumption stages (Herrmann and Plakolm 1991; Niggli and Lockeretz 1996). Maria Mueler applied these theories to orchard production (Niggli and Lockeretz 1996). Austrian doctor, Hans Peter Rush adapted these ideas and incorporated them in a method founded on maximum utilization of renewable resources (Gliessman 1990). Hans Mueler and Hans Peter Rush laid the theoretical foundation for the organic-biological agriculture and its development in the Germanic speaking countries and regions (Niggli and Lockeretz 1996; Rigby et al. 2001). Sir Albert Howard was the founder of the organic farming movement. His book ***An Agricultural Testament*** summarized his research works of 25 years at Indore in India, where he developed the famed Indore Composting Process, which put the ancient art of composting on a firm scientific basis and explained the relationship between the health of the soil, the health of plants and the health of animals (Du and Wang 2001). Rodale. J. I. began his research and practice on organic farming in the United States of America. His primary goal was to develop and demonstrate practical methods of rebuilding natural soil fertility. By 1942, he published the magazine ***Organic Gardening*** (Coleman (1989)). Lady Eve Balfour started the Haughley Experiment the first study comparing conventional and natural farming methods. Her ideas inspired the formation of the Soil Association that was founded in 1946 in England. The Soil Association attempted to return humus and soil fertility to their basic place in the biological balance. It was founded on the theories propagated by Sir Albert Howard in his agricultural testament of 1940 (Soil Association 2001). During 1950–1960s thanks to doctors and consumers whose awareness constantly grew with regard to food and its effect on health, organic fanning (lemaire-boucher) began to take hold in France (SOEL 2002). Nature and Progress Association was founded. Mokichi Okada started natural agriculture in1935 in Japan. His main thoughts were to respect and emphasize the function of nature and soil in the agricultural production and to coordinate the relationship between human being and nature through increasing soil humus to get the yields without fertilizer and agricultural chemicals. The environmental and health issues exacerbated in the 1950s–1960s of the last centuries in Japan facilitated the development of natural agriculture. The essentials of natural agriculture became the important contents of Japanese agricultural, standard of organic agricultural products (Sheng et al.1995; Yu and Dai 1995).

4.2 Era of Development (1970–1990)

The research and practice of organic agriculture expanded worldwide after the 1960s. In particular, the expansion and dual polarity of organic agriculture started with the oil crisis of 1973 and the growing sensitivity to agro-ecological issues. This was a time of new ideas, significant sociological transformations, protest movements and the proliferation of alternative life styles. The new thoughts in terms of using natural resources rationally, protecting the environment, realizing low input and high efficiency, ensuring food security, returning to the earth and maintaining a sustainable development of agriculture, such as organic, organic-biological, biodynamic, ecological, and natural agriculture were remarkably developed in their concepts, research and practical activities (Herrmann and Plakolm 1991; Rigby et al. 2001; Du and Wang 2001; May 2001; Pacini et al. 2002 ; Conacher and Conacher 1998).William Albrecht gave a definition of ecological agriculture in 1970, in which the ecological principle was introduced to the production system of organic agriculture (Coleman 1989). In England the Soil Association created a logo and in parallel introduced the notion of legally formulated specifications and quality controls that gave a legally binding guarantee for the consumers (Yussefi and Willer 2003; Soil Association 2001). The largest non-governmental organization of organic agriculture in the world-IFOAM (International Federation of Organic Agriculture Movements) was founded in 1972 (Niggli and Lockeretz 1996). The major organic agriculture associations and research institutions in the world, such as FNAB (Federation Nationaled' Agriculteurs Biologiques), FIBL (For Schungs Institute Fuer Biologischen Landbau), now the largest organic research institute worldwide, were founded during 1970s–1980s (FAO 2007; Greene 2001). These organizations played an important role in standardizing the production and market of organic products and promoting research and consumer's awareness. The legislative action on organic farming started gradually in the different countries and regions as the guidelines for organic farming. In the United States the regulation on organic farming was implemented in the state of Oregon in 1974 and in the state of California in1979, respectively (Greene 2001). The United States Department of Agriculture (USDA) made an investigation on a large scale on organic farming in the 69 organic farms of 23 states and published the *Report and Recommendations on Organic Farming,* in which the development status and potential remained as issues and the research directions were analyzed. In this report the definition and guideline for the organic farming were given, and an action plan for the development of organic farming was called for. The publication of this report was a milestone in legislation and development of organic farming in the United States (USDA 1980). In France, the organic farming regulation was implemented in 1985 (Graf and Willer 2001; Dai 1999).

The development of organic agriculture initiated the use of natural resources to protect the environment and to ensure food security with sustainable development of agriculture. Subsequently many organizations and Associations were created with legally formulated specifications and quality controls. All these organizations played a pivotal role and made valiant efforts to investigate large scale organic farming with precise scientific validation.

4.3 Era of Growth (Since 1990)

The organic farming worldwide entered a new stage of growth in the 1990s. The trade organizations for organic products were founded, organic farming regulations were implemented and organic farming movement was promoted by both governmental and nongovernmental organizations. In 1990, the first BioFach Fair – now the biggest fair for organic products worldwide, emerged in Germany (ITC 1999). The federal government of the United States published the regulation for organic food products in 1990 (Greene (2001)). The European Commission adopted EU regulation 209191 on organic agriculture in 1991. This regulation became a law in 1993 and was granted in almost all European Union countries since 1994

(IFOAM and FAO 2002). In the North America, Australia and Japan, the major markets for organic products, published and implemented organic regulations in succession (Yussefi and Willer 2003; Niggli and Lockeretz 1996). The International Federation of Organic Agriculture Movements (IFOAM) and the Food and Agriculture Organization of the United Nations (FAO) set out *Guidelines for the Production, Processing, Labeling and Marketing of Organically Produced Foods* in 1999. This guide line is of importance to international harmonization of the organic farming standards (FAO and WHO 2001). Organic farming had rapidly developed worldwide during this stage. The main drivers of steady market and production growth were the commitment of many retail chains as well as favorable policy conditions. Together these had created conditions favoring a harmonious increase in supply and demand. The state support for organic farming research and legal frame work was increasingly gaining importance since the end of the 1990s. Organic agriculture is holistic production management systems which promotes and enhances agro-ecosystem health, including biodiversity, biological cycles, and soil biological activity. It emphasizes the use of management practices in preference to the use of farm inputs, taking into account that regional conditions require locally adapted systems. This is accomplished by using, where possible, cultural, biological and mechanical methods, as opposed to using synthetic materials, to fulfils any specific function within the system terms, such as Organic, Biological, Biodynamic, and Ecological are recognized as organic farming in the EU regulations (Yussefi and Willer 2003; FAO 2002; FAO and WHO 2001). Although organic agriculture is one among the broad spectrum of methodologies which are based on the specific and precise standards with different names such as organic, biological, organic-biological, bio-dynamic, natural and ecological agriculture, there are some common followed principles in the organic agriculture (Henmann et al. 1991; Kahnt 1986; Niggli and Lockeretz 1996; IFOAM and FAO 2002; FAO and WHO 2001). These principles are summarized as follows:

1. Maintain long-term soil fertility though biological mechanism.
2. Recycle wastes of plant and animal origin in order to return nutrients to the land, thus minimizing the use of external inputs outside systems, and keep the nutrients cycle within the system.
3. Prohibit the use of synthetic materials, such as pesticides, mineral fertilizers, chemical ingredients and additives.
4. Using natural mechanism and rely on renewable resources to protect the natural resources.
5. Raise animals in restricted areas and guarantee the welfare of the animals.
6. Adapt local environment and diversified organization.

The rapid growth of organic farming at global scale started during the end part of twentieth century, several trade organizations were founded, regulations were implemented and movements were promoted by both governmental and nongovernmental organizations. This led to rapid development of organic farming with co-ordinate and rational approach.

5 Methods of Organic Farming

The farming practice which involves the use of eco-friendly methods to grow crops and the exclusion of synthetic products, such as chemical fertilizers, insecticides and pesticides are described as organic farming. It is practiced on 32.2 million hectares of land over the world (Bhattacharya and Gehlot 2003). The *International Federation of Organic Agriculture Movements* (IFOAM) carries out the tasks related to setting standards and regulation of organic farming activities worldwide. A holistic approach towards growing crops, organic farming methods helps apply simple and eco-friendly techniques in farming. Use of compost fertilizers, crop rotation and biological pest control, are some of the features of organic farming methods. The farming methods that make use of the various traditional agricultural practices like minimum tillage, composting, crop rotation, biological pest control, etc., and exclude the application of synthetic fertilizers, insecticides, growth regulators and genetic modification of crop species, are included in organic farming methods. The use of modern technology in combination with organic farming practices helps in creating a balanced and sustainable environment for crop growth (Anonymous 2000). Organic farming methods take a integrated approach in growing crops rather than exploiting the available natural resources The use of organic farming methods is aimed at enhancing the productivity of crops without the use of any kind of synthetic materials and adopting a sustainable approach towards farming (Luttikholt 2007).

Organic agriculture systems are based on four strongly interrelated principles under autonomous ecosystems management: mixed farming, crop rotation and organic cycle optimization. The common understanding of agricultural production in all types of organic agriculture is managing the production capacity of an agro-ecosystem. The process of extreme specialization propagated by the green revolution led to the destruction of mixed and diversified farming and ecological buffer systems. The function of this autonomous ecosystem management is to meet the need for food and fibres on the local ecological carrying capacity (Smukler et al. 2010).

5.1 Cultivation

Polyculture is an important aspect of organic farming. In the traditional form of farming monoculture is practiced, which includes growing a single crop in a given piece of land (Hansen and Jones 1996; Edwards-Jones and Howell 2001). Though the motive behind cultivating a single crop is to reduce cost incurred in fertilizers, seeds and pesticides etc.; however, it creates problems in the long run. The reduction in the fertility of the soil owing to the extraction of nutrients over a long period and soil erosion result from the practice of monoculture. Moreover, the pests become immune to the chemicals used for their control. Polyculture is a completely different approach towards farming as compared to monoculture. In this method of farming, a variety of crops are cultivated on a single piece of land. It helps attract different soil microbes. Some crops act as repellents to pest and these results in pest control, in an organic manner (Walker 1992; Gitay et al. 1996).

In organic agriculture systems, one strives for appropriate diversification, which ideally means mixed farming, or the integration of crop and livestock production on the farm. In this way, cyclic processes and interactions in the agro-ecosystem can be optimized, like using crop residues in animal husbandry and manure for crop production. Diversification of species biotypes and land use as a means to optimize the stability of the agro-ecosystem is another way to indicate the mixed farming concept. The synergistic concept among plants, animals, soil and bio-sphere support this idea (James 1998; Albrecht and Mattheis 1998).

5.2 Fertility

Organic farming has expanded rapidly in recent years and is seen as a sustainable alternative to intensive agricultural systems, developed over the last 50 years (Stockdale et al. 2001). Nutrient management in organic systems is based on fertility building leys to fix atmospheric nitrogen (N), combined with recycling of nutrients via bulky organic materials, such as farmyard manure (FYM) and crop residues, with only limited inputs of permitted fertilizers (Torstensson 1998; Faerge and Magid 2003). Composts are used to enhance soil fertility in organic farming methods. Green manuring too, is a nice way to add nutrients to the soil. It is the practice of growing plants with prolific leaf growth like alfalfa and burying them in the soil before the cultivation of the main crop. The green manuring crops add organic matter to the soil that is necessary for plant growth (Berry et al. 2002; Pulleman et al. 2003).

5.3 Crop Rotation

Within the mixed farm setting, crop rotation takes place as the second principle of organic agriculture. Besides the classical rotation involving one crop per field per season, inter cropping, mixed cropping and relay cropping are other options to optimize interactions. In addition to plant functions, other important advantages such as weed suppression, reduction in soil-borne insects and diseases, complimentary nutrient supply, nutrient catching and soil covering can be mentioned (Wibberley 1996; Berzsenyi et al. 2000).

5.4 Organic Cycle Optimization

Organic farming is considered a promising solution for reducing environmental burdens related to intensive agricultural management practices. These changes in agricultural practices led to numerous environmental problems like high consumption

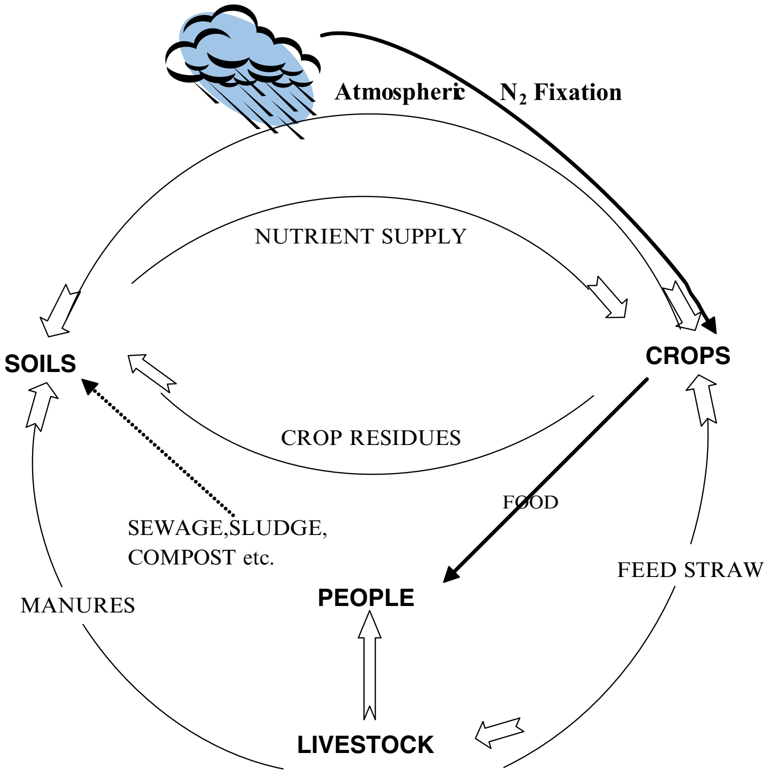

Fig. 1 Organic cycle of an organic farming system

of non-renewable energy resources, loss of biodiversity, pollution of the aquatic environment by the nutrients nitrogen and phosphorus as well as by pesticides (Feber et al. 1997).

Each field, farm, or region contains a given quantity of nutrients. Management should be used in such a way that optimal use is made of this finite amount (Fig. 1).

(i) This means that the nutrients should be recycled and used a number of times in different forms.
(ii) Care should be taken that only a minimum amount of nutrients actually leave the system so that "import" of nutrients can be restricted.

The quantity of nutrients available to plants and animals can be increased within the system by activating the edaphon, resulting in increased weathering of parent material.

5.5 *Pest Control*

Organic farming may contribute substantially to future agricultural production worldwide by improving soil quality and pest control, thereby reducing environmental impacts of conventional farming (Bengtsson et al. 2005). It is an important aspect in the growth of any crop. Organic pest control involves undertaking various activities to control pests without using chemical pesticides and insecticides. The growth of beneficial insects is encouraged by growing suitable plants which attract them. Beneficial insects are actually predators which control harmful insects. Disease resistant varieties are chosen for cultivation, in order to keep diseases at bay without having to spend money on costly pesticides. Special types of crops known as companion crops are grown to control pests (Mader et al. 2002; Oehl et al. 2004). These crops help in diverting or discouraging the growth of harmful pests. Biological pesticides such as neem extract are useful in controlling many different pests. The practice of crop rotation helps in disturbing the reproduction cycles of pests, thereby inhibiting their growth and protecting the crops (Iglesias et al. 2003).

6 Organic Farming in India: Relevance in Present Context

- In India, only 30% of total cultivable area is covered with fertilizer, where irrigation facilities are available and in the remaining 70% of arable land, which is mainly rainfed, negligible amount of fertilizers is being used. Farmers in these areas often use organic manure as sources of nutrients are readily available either in their own farm or in their locality.
- The North Eastern Hills of India provides considerable opportunity (18 million hectare) for organic farming due to least utilization of chemical inputs, which can be exploited for organic production.
- India is an exporting country and does not import any organic products. The main market for exported products is the European Union. Recently India has applied to be included on the “EU-Third-Country-List”, another growing market is USA.
- There has been plenty of policy emphasis on organic farming and trade in the recent years in India.
- There are many states and private agencies involved in promotion of organic farming in India. These include-various ministries and department of the government at the central and state levels such as;
    - Universities and Research centres
    - Non Govt. organizations (NGO)
    - Eco farms
    - Certification bodies like INDOCERT, ECOCERT, SKAL and APOF etc.

The central and state governments have also identified *Agri-Export Zone* for agricultural exports in general and organic products in some states:

- In Uttar Pradesh and Uttaranchal the Diversified Agriculture Support Project (DASP) is promoted for organic farming.
- In Bangalore (Karnataka) and Nilgiris (Tamil Nadu); with 50 outlets in south India helps for supply the organic products from small growers.

Table 2 Conventional farming vs organic farming

Conventional farming	Organic farming
i. It is based on *economical* orientation, heavy mechanization, specialization and misappropriates development of enterprises with unstable market oriented programme	i. It is based on *ecological* orientation, efficient input use efficiency, diversification and balanced enterprise combination with stability
ii. Supplementing nutrients through fertilizers, weed control by herbicides, plant protection measures by chemicals and rarely combination with livestock	ii. Cycle of nutrients within the farm, weed control by crop rotation and cultural practices, plant protection by non-polluting substances and better combination of livestock
iii. Based on philosophy of to feed the crop/ plants	iii. 'Feed the soil not to the plant' is the watch word and slogan of organic farming
iv. Production is not integrated into environment but extract more through technical manipulation, excessive fertilization and no correction of nutrient imbalances	iv. Production is integrated into environment, balanced conditions for plants and animals and deficiencies need to be corrected
v. Low input : output ratio with considerable pollution	v. High input : output ratio with no pollution
vi. Economic motivation of natural resources without considering principles of natural up gradation	vi. Maximum consideration of all natural resources through adopting holistic approaches

- IRFT (International Recourses for Fairer Trade) based in Mumbai, procures organic cotton and agro products to sell them to Indian & foreign buyers to help the rural marginal farmers.
- Ion Exchange, Mumbai; a private company is engaged for export and domestic marketing of organic products in India.
- In Himachal Pradesh; the net incomes per hectare from organic farming was found to be 2–3 times higher both in case of maize and wheat due to higher production and also for higher price were obtained by organic produce.
- In Haryana; net returns was higher (2–3 times) in basmati rice, soybeans, arhar and wheat because of 25–30% price premium on organic produce and lower cost of production and marketing.
- In Maharashtra; popularization of organic cotton production was due to high cost benefit ratio of organic cotton 1:1.63 as against 1:1.47 for conventional cotton.
- In Gujarat; organic production of chickoo, banana and coconut had higher profitability.
- In Karnataka; groundnut, jowar, cotton, coconut and banana were grown as organic. The major problems faced by organic farmers were found to be initial lower yields, no price incentives, no separate markets for organic produce, besides lack of and high costs of certification (Table 2).

7 Environmentally Friendly Production System

Since one of the key aspects of organic farming is to forsake the use of synthetic chemical fertilizers, pesticides, and feed additives, in contrast to other agricultural production approaches, organic farming is conducive to protection of surface and underground water from these pollutants. Organic farming benefits the environment through protection of wildlife habitats, conservation of landscapes, and reduction of environmental pollution. It is well documented that organic agriculture contributes to long-term conservation of soil, water, air and protection of wild life, their habitats, and their genetic diversity (Redman 1992; Van Mansvelt and Mulder 1993; Lampkin 1997). Reganold et al. (2001) assessed the environmental impact of organic and conventional apple production systems by using a rating index employed by scientists and growers to determine the potential adverse impact of pesticides and fruit thinners (Reed 1995). The results show that the total environmental impact rating of the conventional system was 6.2 times that of the organic system. Organic farming also aims to maintain and improve soil fertility over the long run. It may be expected to produce a satisfactory and high quality crop with minimal use of resources. An organic farming system requires the use of catch crops, the recycling of crop residues, and the use of animal manure and the use of organic rather than artificial fertilizer. All these measures are assumed to promote accumulation of organic matter in the soil (Hansen et al. 2001). Organic farming prohibits the use of pesticides and artificial fertilizers and encourages sympathetic habitat management, such as nitrogen-building leys to increase soil fertility (Lampkin 1990). Organic matter has profound impacts on soil quality, such as enhancing soil structure and fertility and increasing water infiltration and storage. If the soil organic matter content drops below3.5%, the soil suffers an increased risk of erosion (Brady and Weil 1999; Redman 1992). Stolze et al. (2000) concluded that organic farming performs better than conventional farming with regard to soil organic matter. A major objective of organic farming is to encourage a higher level of biological activity in the soil, in order to sustain its quality and thereby promote metabolic interactions between the soil and plants. Axelsen and Elmholt (1998) estimated that a transition to 100% organic farming in Denmark would increase microbial biomass by 77%, the population of springtails by 37%, and the density of earthworms by 154% as a nationwide average. Conversion to organic farming provides opportunities to significantly increase biological activity of the soil. Microbial biomass in soil was higher in organic farming systems receiving higher amounts of organic inputs (Gunapala and Scow 1998; Bossio and Scow 1998; Lundquist et al. 1999). In a long-term field trial in northwestern Switzerland, the effects of organic and conventional land use managements on earthworm populations and on soil erodibility were investigated. The study result shows that earthworm biomass and density, as well as the population diversity were significantly greater in the organic plots than in the conventional plots. Likewise, the aggregate stability of the organic plots, when determined by means of percolation, was significantly better. Therefore, erosion susceptibility is greater on plots farmed conventionally (Siegrist et al. 1998).

Organic farming is a concept for following the rule of nature. It is also operates on the natural principles of sustainability. Soil is one of the most important natural resources, which needs proper management for organic production requirement. For doing so, one should rely on organic techniques like crop rotation, using natural manures and green manures, no addition of synthetic substances, proper management of air and water, providing drainage, following integrated pest control, using biological methods of disease and pest control. Using traps, use of predators, increasing the population of beneficial plants and animals, addition of organic material in the soil, using legume, use of bio fertilizers, modifying cropping systems, use of cover crops, catch crops and establish proper soil-crop-animal-human being system. Such a system should follow an integrated system approach so as to make the entire production system biologically active, ecologically sound and economically viable. In short locally available natural material should be used to increase soil productivity by improving soil environment.

Organic farming is considered a promising solution for reducing environmental burdens related to intensive agricultural management practices. Organic agriculture combines tradition, innovation and science to benefit the shared environment and promote fair relationships and a good quality of life for all involved. The main strengths lie in better resource conservation, since the farm relies mainly on internal resources and limits the input of external auxiliary materials. This results in less fossil and mineral resources being consumed. A further important effect is the very restrictive use of pesticides, leading to markedly lower eco-toxicity potentials on the one hand and higher biodiversity potentials on the other.

7.1 Quality Product

In the consumer's mind, organic produce must be better and healthier than that produced under conventional farming system. This image is also the main motive for consumers who are willing to pay premium prices for purchasing organic food. Organic agriculture can be viewed as an attempt to overcome at the individual, as much as the collective, level the "risky freedoms," such as contamination of food supplies with pesticides, pollution, and radioactive fallout etc., associated with processed food and a chemically based agriculture (Lockie et al. 2000). From a scientific point of view, however, it is difficult to provide or substantiate the supposed health benefits, since food quality is composed of various partial aspects and without uniform evaluation standards. Crop quality is put forward as an important argument for organic farming (Adam 2001; Koepf et al. 1976). Several investigations have clearly shown that the type of fertilizations, contrary to the principle of organic farming, does not affect plant quality (Hansen 1981; Evers 1989a, b, c). Crop quality is not dependent on the principle difference between inorganic fertilization and organic manuring. Side-effects caused by synthetic pesticides and drug feeding are not found in organic farming, which is a positive result. The use of herbicides has been documented to increase cyanide, potassium nitrate, and other toxins in crops (Freese et al. 2000; Uzogara 2000). However, the exclusion of pesticides may also result in increased concentrations of secondary plant metabolites and of mycotoxins of field fungi. Eltun (1996) reported higher concentrations of deoxynivalenol and nivalenol in grain samples from organic than from conventional farming. Furthermore, in the same experiment, no pesticide residues were found in grain samples grown conventionally. The exclusion of pesticides does not necessarily mean that crop products do not contain unwanted substances. The evaluation of food quality by taking into account the criteria, such as appearance and nutritional value exclusively is not satisfying. Today we have to consider ethical criteria such as environmental, social, and political dimensions of food production, processing, and packaging. Regarding the latter, more or less discussions have been mentioned in the preceding sections. Here, only the differences of product appearance and nutritional value between organic and conventional are discussed (Ploeger and Vogtmann 1996).

There appears to be a common perception amongst consumers that organic methods result in foods of higher nutritional quality. Nevertheless, there are scanty reports, which compare the quality of organic food with foods grown conventionally, under comparable and controlled conditions, in terms of their nutrient composition or their effects on humans and animals. Adverse effect of chemicals, used in conventional framing, on mankind cannot be overlooked. Unintentional consumption of pesticides or chemical containing food has imposed severe health risks. This has made organic farming an alternative and better source of food production.

7.2 Appearance

Normally, product appearance refers to size, shape, color, and taste, etc. Organically produced food sometimes fails to match the perfection achieved through conventional farming, especially for fruit and vegetables. It is widely believed that organically produced food tastes better than conventional, but conclusive scientific evidence to prove that this is the case is hard to come by. Lindner (1985) using a panel of 30–50 consumers who were deliberately not informed about the basis of the comparison, found that vegetables produced organically under carefully controlled experimental conditions did taste better. However, in the same study, a panel of trained tasters found no significant differences (Lindner 1985). Duden (1987) has also found taste differences in favor of organically produced tomatoes and potatoes respectively. It is also demonstrated that in all aspects of fruit quality, the organic fruit was at least equal to fruit produced in the conventional farming system, and was higher in some important variables (taste, firmness, dietary fiber, phenolic compounds, vitality index) (Weibel et al. 1998; Reganold et al. 2001).

7.3 Nutritional Value

Nutritional value can be measured mainly by chemical contents of a product. Harmful substances include pesticide residues, nitrates, natural toxins, and heavy metals, etc., while beneficial nutrients encompass protein, vitamins, trace elements, etc. Organic food shall come from an organic production system with sound environment. During the production, processing, and handling of organic food, only natural substances and operational methods with minimum pollution to environment are allowed to be used. However, synthetic chemical pesticides, fertilizers, growth regulator and genetic engineering are prohibited (IFOAM 2000). In contrast to conventional produce, organically produced products should be environmental-safe and healthier, and the risk of produce grown organically being contaminated with pesticide residues is much smaller than with conventionally produced crops. Schupbach's experiment implies that there are in fact differences between organic and conventional produces as far as pesticide residues concerned. When food genuinely produced using organic methods are tested, the result is much more clear-cut (Schupbach 1986).

Concerning uptake and utilization of nitrates by plants, work in Switzerland has compared nitrate levels in vegetables from organic and conventional production systems and shows clear differences between the two. Not only is nitrate accumulation lower in organically produced vegetables, but the ratio of protein-nitrogen to nitrate-nitrogen is much higher (Temperli et al. 1982; Vogtmann et al. 1984). Twenty-nine valid studies that compared the nutrient contents of organic and non-organic foods showed significantly higher amounts of minerals, vitamins, and dry matter in organic food (Adam 2001).

The presence or absence of harmful substances in food is still only one side of the issue of nutritional value. Various studies have shown increased use of nitrogen fertilizers result in not only higher levels of nitrate, but also higher levels of free amino acids, oxalates and other undesirable compounds, as well as in lower levels of vitamin C in particular. Calcium, phosphorus, magnesium, and sodium contents are also affected by levels of fertilizer use, and so are trace elements. The use of organic manure and appropriate soil management practices in organic agriculture means that a much wider and more balanced range of nutrients are available to crops than is the case when readily soluble NPK mineral fertilizer is applied and taken up directly by the plant (see, Schuphan 1975). Hundreds of rigorous tests have failed to reveal better-tasting properties or improved nutritional value, but have consistently shown that organic produce has lower nitrate and protein contents. Conventionally farmed food seems to be better for children, although rodents apparently favor organic food (Trewavas 2001; Woese et al. 1997).

Food myco-toxins from contaminating fungi (which can be controlled by specific fungicides) definitely contribute to European cancer rates and threaten food safety. Fumonisin and patulin are both reported to be higher in organic products and failure to use effective fungicides on organic farms has led to these farms acting as repositories of disease (Lovejoy 1994; Kirchmann and Thorvaldsson 2000;

Zwankhuizen et al. 1998; Eltun 1996). All the above quality characteristics can be measured quantitatively thus providing a basis for comparison. But subjective values will also play a major role in the consumer's perception of quality. The main reason of consumer's increasing recognition of and interests in organic food is due to consumer's identification that comparing with conventional farming approaches, organic plays a significant role in environmental protection and farming sustainability.

8 Working with Natural Cycles

In organic farming, the agro-ecosystem is considered as a whole. All living organisms within the 'farm ecosystem' are considered to be in a dynamic equilibrium with each other. This concept applies to crops, pests and their natural enemies, as well as to farm animals, wildlife or microorganisms in compost and soil. It is applied regardless of the underlying mechanisms (predator–prey relationship; parasite-host relationship; competition for substrate, light, space etc.) (Roger 1987; Oram 2003). The equilibrium can be influenced by appropriate management practices, which are themselves part of the natural cycles (indirect control). This is preferable to direct control of pests or diseases, which represents an intervention from outside the agro ecosystem (Hald 1999; Gabriel et al. 2006). In other words, the difference is whether the farmer lets and helps nature find a new equilibrium between pests and beneficial, or whether he himself attempts to control the pest (by spraying).Farm animals and their health are also considered in the context of the entire farm ecosystem and the same conclusions apply. Another implication of the principle is that all measures taken should have as little impact on natural cycles as possible. This applies particularly to effects of crop protection measures on non-target organisms, and to the side-effects of veterinary drugs on animals, and on the environment after excretion. This principle also emphasizes the importance of the flow of materials within the 'farm ecosystem', which is also the unit that is subject to inspection and certification. Materials originating from outside the farm are called 'off-farm inputs' or simply 'inputs'. The use of inputs always means an open cycle on the farm and should be minimized (although it can never be zero). If inputs have to be used, they should preferably come from other organic farms, thus closing the cycle on a wider scale (Thorup-Kristensen et al. 2003; Zehnder et al. 2007).

8.1 Soil Fertility

Organic farming also aims to maintain and improve soil fertility over the long run. It may be expected to produce a satisfactory and high quality crop with minimal use of resources. An organic farming system requires the use of catch crops, the recycling of crop residues, the use of animal manure, and the use of organic rather than artificial fertilizer. All these measures are assumed to promote accumulation of organic matter in the soil (Hansen et al. 2001). Organic farming prohibits the use of pesticides and artificial fertilizers and encourages sympathetic habitat management, such as nitrogen building leys to increase soil fertility (Lampkin 1990). Organic matter has profound impacts on soil quality, such as enhancing soil structure and fertility and increasing water infiltration and storage. If the soil organic matter content drops below 3.5%, the soil suffers an increased risk of erosion (Brady and Weil 1999; Redman 1992). Stolze et al. (2000) concluded that organic farming performs better than conventional farming with regard to soil organic matter. A major objective of organic farming is to encourage a higher level of biological activity in the soil, in order to sustain its quality and thereby promote metabolic interactions between the soil and plants. Axelsen and Elmholt (1998) estimated that a transition to 100% organic farming in Denmark would increase microbial biomass by 77%, the population of springtails by 37%, and the density of earthworms by 154% as a nation wide average. Conversion to organic farming provides opportunities to significantly increase biological activity of the soil. Microbial biomass in soil was higher in organic farming systems receiving higher amounts of organic inputs (Gunapala and Scow 1998; Bossio and Scow 1998; Lundquist et al. 1999).

In a long-term field trial in northwestern Switzerland, the effects of organic and conventional land use managements on earthworm populations and on soil erodibility were investigated. The study result shows that earthworm biomass and density, as well as the population diversity, were significantly greater in the organic plots than in the conventional plots. Likewise, the aggregate stability of the organic plots, when determined by means of percolation, was significantly better. Therefore, erosion susceptibility is greater on plots farmed conventionally (Siegrist et al. 1998).

8.2 Nutrient Management

Nutrient elements, essential to crop growing, include N, P, K, Ca, Mg, and some trace elements. Among them, nitrogen is of great importance in organic plant growing because of its influence on plant yields. The N-cycling of an organic farm should be based mainly on a site-specific and market-oriented crop rotation including green manure planting and on an optimized manure handling and application system. Nutrient cycling is relatively efficient in organic farming system (Cobb et al. 1999). Long term rotation trials on sandy loam confirm the outstanding importance of leguminous fodder crops in terms of humus accumulation (26 t/ha after five courses of a 5-year crop rotation) and continuous yield security of succeeding crops. A biennial alfalfa crop could accumulate 1,000 kg N per ha, of which 600 kg was used as animal fodder, 320 kg bound in the roots, and 80 kg calculated as loss due to volatilization and de-nitrification. A substantial amount of the residual N could be determined as additional N2 sources for the succeeding crops (Rauhe et al. 1987). Hodtke et al. (1998) reported that if maize was inter cropped with either cowpea or jack bean in an organic farming system, N-content in the leaves of the maize was significantly increased and grain yield of the maize was markedly improved too.

8.3 Role of Arbuscualr Mycorrhizal Fungi (AMF)

Organic farming has developed from a wide number of disparate movements across the world into a more uniform group of farming systems, which operate broadly within the principals of the International Federation of Organic Agriculture Movements (Stockdale et al. 2001). Though the exact production methods vary considerably, general principals include the exclusion of most synthetic biocides and fertilizers, the management of soils through addition of organic materials and use of crop rotation (IFOAM 1998). The exclusion of soluble mineral fertilizers and the very limited use of biocides in organic agriculture mean that it is reliant largely on biological processes for supply of nutrients, including the reliance on N_2 fixation as the main source of N_2 to crops, and for protection of crops from pests and disease. Indeed, it is one of the central paradigms of organic agriculture that an active soil microbial community is vital for functioning of the agro ecosystem (Lampkin 1990). Within this paradigm, AMF (Arbuscualr Mycorrhizal Fungi) are usually considered to play an important role and it is assumed that they can compensate for the reduced use of P fertilizers (Galvez et al. 2001).

Many authors report higher levels of AMF colonization, higher propagules numbers or higher diversity in organic farming. However, the actual importance of AMF to the functioning of organic agro ecosystems and in particular to crop performance remains to be determined. Some evidence indicates that AMF are indeed capable of compensating for lower inputs of P fertilizer in organic systems. Kahiluoto and Vestberg (1998) found that AMF in an organically managed soil were as effective at increasing crop available P as super phosphate was on a conventional soil. However, this does not always translate into higher yields even when phosphorus use efficiency is higher (Ryan et al. 1994; Galvez et al. 2001). Prolific AMF colonization in organic systems may even be associated with reduced yield in some cases because of the carbon drain by the AMF (Dann et al. 1996). Other authors have found AMF to be no more effective, and in some cases less effective than rock phosphate at increasing crop growth on organically managed soils (Scullion et al. 1998). Dann et al. (1996) showed that even where there was good, AMF colonization on an organically managed soil, crops responded positively to super phosphate fertilizer in a similar way to crops on conventional soil, suggesting that AMF do not provide a unique method of accessing Phosphorous to the host plant, a conclusion also reached by Ryan and Ash (1999).

Determining the reason for the apparently poor performance of AMF in some organic systems is difficult because organic systems vary considerably in the detail of their management practices and the practices used prior to conversion. As a result, there are likely to be different reasons for poor performance of AMF in different systems. Long-term conventional, high input management reduces AMF diversity and may favour inefficient AMF (Helgason et al. 1998; Daniell et al. 2001; Johnson et al. 1992; Johnson 1993).

Thus, at conversion the AMF population may be reduced to a small number of species tolerant of intensive farming practices. Building up species diversity will be important to ensuring the development of an effective AMF community. However, there are no available data to indicate the mechanisms involved in the re-colonization of agricultural land, the time required, or the most effective management options to accelerate the process. Some data have indicated that organic systems may fail to develop an effective AMF community even after several years (Scullion et al. 1998). This may be the result of management practices unfavorable to AMF. For instance, soil P concentrations may remain too high if the P fertilizers permitted in organic production are used frequently (Dekkers and Vander Werff 2001; Scullion et al. 1998). Excessive tillage to control weeds and frequent cultivation of non-mycorrhizal crops could also hamper development of a diverse AM community. Unfavorable soil moisture and temperature, and plant disease, can also suppress the AM association and consequently community development. Another reason for the failure of some organic systems to develop an effective AMF community may be the limited availability of AMF propagules of new species. Re colonization is likely to occur from adjacent natural and semi-natural habitats such as hedges, woodland and unmanaged grassland. The vectors of propagules may include animals, growing roots, agricultural machinery and soil eroded by wind and water (Ryan and Graham 2002; Warner et al. 1987). While root growth and movement by animals is likely to be slow and involve small numbers of propagules, tillage operations can move soil and propagules more than a meter in a single operation, depending on the machinery in question and the slope (Rew et al. 1996; Tsara et al. 2001; van Muysen and Govers 2002; Quine et al. 2003). Single water erosion events can move soil several hundred meters while wind can disperse spores very large distances as can farm machinery. Evidence from re-colonization of abandoned agricultural land suggests large numbers of AMF species can establish after only 2 years (Warner et al. 1987; Morschel et al. 2004; Hedlund 2002; Hedlund and Gormsen 2002).

However, the early stages of re-colonization of soils are characterized by significant heterogeneity including areas with potentially very low infectivity. This is likely to be especially true of large fields where distance from the source of propagules may be large, or in intensively managed landscapes, where semi-natural habitats may be few in number. Another factor that may help explain the poor performance of AMF in some organic systems is the suggestion that modern crop cultivars are not responsive to AMF and therefore receive little benefit from the AM association, even though colonization with effective AMF may be high (Boerner et al. 1996; Manske 1990; Hetrick et al. 1996; Aguilera-Gomez et al. 1998). However, a wide degree of variation in AMF dependency in both modern and old cultivars has been demonstrated. Stoppler et al. (1990), Hetrick et al. (1993, 1996) suggesting that this is not the only factor. The apparent lack of benefit for the host crop may even be simply a result of the host crop receiving benefits other than those being measured.

9 Status of Organic Crop Production in Food Security

Global food production increased by 70% from 1970 to 1995, largely due to the application of modern technologies in developing countries, where food production increased by 90%. However, global food production must grow to the same extent in the coming three decades, as pointed out above, to meet human demand (Bruinsma 2003; Cassman et al. 2003; Eickhout et al. 2006). Two principal possibilities for achieving this increase have been identified: intensifying agricultural production on existing cropland or ploughing up natural land into cropland, i.e. clearing pastures and rangelands, cutting forests and woodland areas, etc. Some experts have a positive view that food production can be greatly increased if high-yielding production is widely applied and the expansion of arable land in the world is expected to only slightly increase from 1,400 Mha in 2006 to 1,600 Mha in 2030 (Bruinsma 2003; FAO 2007; Bouwman et al. 2005). In 2025, the world's farmers will be expected to produce an average world cereal yield of about 4 metric tons per hectare if conditions are optimized. There are recent claims that sufficient food can be produced by organic agriculture, expressed in terms such as 'organic agriculture can feed the world (Dyson 1999; Woodward 1995; Vasilikiotis 2000; Leu 2004; Tudge 2005; Badgley and Perfecto 2007). The following three arguments have been put forward: (i) Lower production of most crops can be compensated for by increased production of legumes, in particular of grain legumes, while a change to a diet based mainly on vegetables and legumes will provide enough food for all (Woodward 1995). (ii) Realities in developing countries must be taken into account: Increased food supply does not automatically mean increased food security for all. Poor and hungry people need low-cost and readily available technologies and practices to increase food production (Pretty et al. 2003). (iii) Organic agriculture can get the food to the people who need it and is therefore the quickest, most efficient, most cost-effective and fairest way to feed the world (Leu 2004). These arguments confuse the original scientific question with other realities interacting with food sufficiency, such as change in dietary composition, poverty, finance, markets, distribution system, etc. However, the basic scientific question remains and requires a stringent review and evaluation of the production potential of organic and conventional systems. A fundamental question is whether organic yields can be increased radically or whether more natural ecosystems have to be converted into cropland. The following four observations indicate that intensification rather than area expansion is necessary:

(1) Agricultural land is steadily decreasing as it is being taken over for urban or industrial use (Blum et al. 2004), (2) global warming may reduce the potential for higher yields in large parts of the world (Parry et al. 2005), (3) significant areas of farmland may be used for fuel production, competing with food production (Nonhebel 2005) and (4) cropland simply cannot be expanded, due to shortage of suitable land. On the other hand, current yield increases appear to be falling below the projected rate of increase in demand for cereals challenging scientists to do their best to increase crop productivity per unit area (Cassman et al. 2002; Evans 1998). Food production is coupled to a moral imperative, as sufficient food supply is a cornerstone of human welfare. Development of agricultural practices ensuring food sufficiency is a basic human requirement, a prerequisite for satisfactory social conditions and a necessity for civilizations to flourish. Lack of food, on the other hand, is a tragedy leading not only to suffering and loss of life but also to inhuman behavior, political instability and war (Borlaug 1970). In fact, eradication of famine and malnutrition has been identified as the most important task on Earth

(UN Millennium Project 2005). Thus, when discussing different forms of crop production, it is of the utmost importance to examine without prejudice the forms of agriculture that can contribute to food sufficiency and security, at present and in the future. Separation of facts and wishful thinking is absolutely necessary and only an unbiased review of the scientific literature can provide objective answers to the questions put forward below. A strong belief and enthusiasm for certain solutions cannot be allowed to hamper the search for objectivity. The overall aim of this chapter was to examine a morally important aspect of organic agriculture. This was achieved by examining the following questions:

1. Can sufficient crop production be obtained through conversion to and/or introduction of organic production?
2. Can future food demand be covered by organic agriculture?
3. Is it possible to significantly increase organic yields in the future

10 Yield Attributes of Organic Farming

A review by Badgley et al. (2007) points out that organic agriculture is misjudged concerning crop production and its potential to supply sufficient food. According to their review, only small yield reductions occur through organic agriculture in developed countries, but organic yields are higher than conventional yields in developing countries. This conclusion is supported by a large number of other papers, which may be taken as evidence of its scientific reliability. We re-examined the papers cited by Badgley et al. (2007) to determine whether their conclusions are based on valid assessments. However, due to their limited accessibility and often lower scientific credibility, non-peer-reviewed conference papers, institution reports and magazine articles were not considered. The reexamination of papers reporting high organic yields showed that the data were used in a biased way, rendering the conclusions flawed. Firstly, none of the organic studies cited reported higher crop output from organic production than from conventional over a whole rotation, but only for single years. Secondly, when yields were higher during a single year in organic production, this was coupled to one or both of the following conditions: (1) The amount of nutrients applied to the organic system through manure and compost was equal to or even higher than that applied to the conventional system through inorganic fertilizers, (2) non-food crops (legumes) were grown and incorporated in the preceding year to provide the soil with N. Thirdly, on-farm data were compared with mean yield data within a region. Such comparisons have no validity, since the possible factors behind the differences are not given.

In summary, the yield data reported were misinterpreted and any calculations based on these data are likely to be erroneous. The paper by Badgley et al. (2007) also presents comprehensive yield figures from developing countries. However, of the 137 yield figures reported, 69 originate from the same paper (Pretty and Hine

2001). A closer inspection revealed that crop yields were based on surveys and there was no possibility to check crop performance variables and the science behind the data. In fact, only six papers for developing countries cited by Badgley et al. (2007) were derived from peer-reviewed journals. In four papers, rice yields in conventional systems were compared with so-called intensified rice production. However, intensified rice production uses mineral fertilizers, although at lower rates, and is not an organic form of agriculture by European standards (Sheehy et al. 2004; Latif et al. 2005).

Our conclusion is therefore that the argument that organic agriculture can produce similar or even higher yields than conventional does not hold given the boundary conditions outlined above.

11 Trends in Organic Crop Yields

Yield trends over time were analyzed in four Swedish comparative studies to determine the potential to increase production through organic and conventional management. The underlying question is whether yields are following the same trends in organic agriculture as in conventional. In the study by Kirchmann et al. (2007), the initial 10-year period was characterized by a relatively constant yield difference between the organic and conventional system. Thereafter, yields increased in both systems but the increase was larger in the conventional system than in the organic, despite higher additions of animal manure to the organic system. In two other studies without animal manure which used green manure for organic production and fertilizer for conventional, the relative yield differences between systems were much larger (Torstensson et al. 2006; Aronsson et al. 2007). Furthermore, no yield increase was observed in the organic system over the 5–6-year experimental period, where as conventional yields increased in one experiment and remained constant in the other. In studies without animal manure, there is good reason to assume that organic yields barely increase over the longer term, as residual soil nutrients are depleted at faster rates than in studies with manure application. For instance, in relatively fertile soils, a decade or more may be needed before residual soil nutrients are sufficiently exhausted for a yield reduction to become apparent (Denison et al. 2004). In another experiment run for 12 years at a fertile site, each crop in the rotation was grown every year and animal manure was applied in relation to the level of nutrient removal by harvested crops (Ivarson and Gunnarsson 2001). Differences between organic and conventional yields were smaller at this site, in particular for forage crops. However, there were no indications that organic yields would increase more or decrease less over time than conventional yields. Based on the four experiments presented above, we conclude that there is no evidence that yields increase more in organic agriculture than in conventional. However, there is evidence that conventional agriculture has a greater capacity for increased yields than organic agriculture.

12 Global Scale Food Production

In summary, this review shows that the reduction in crop yields through large-scale conversion to organic agriculture would, on average, amount to 40%, with a range of variation of 25–50%. A 40% reduction in yield on a global scale is equivalent to the amount of crops required by 2.5 billion people. This estimate is in fact identical to that calculated by Smil (2001), who assessed the role of industrial nitrogen fixation for global food supply. Smil (2001, 2002) concluded that the Haber-Bosch process for industrial fixation of atmospheric nitrogen provides the very means of survival for 40% of humanity and that only half of the current world population could be supported by pre-fertilizer farming, even with a mainly vegetarian diet. The similarity of these estimates confirms the strategic role of fertilizers as a keystone for the well-being and development of mankind. It is obvious that worldwide adoption of organic agriculture would lead to massive famine and human death. This is something that advocates of organic agriculture are silent about, perhaps because of the severe moral dilemma it poses.

13 Restoration of Biodiversity

Organic agriculture relies largely on locally available resources and is dependent upon maintaining ecological balance, developing biological processes to their optimum and respecting natural evolution processes of plants, animals, and landscapes. Organic agriculture, which provides more habitats for various organisms, has a much higher biodiversity potential than conventional farming systems do (Redman 1992; Mander et al. 1999).Organic agriculture is also committed to conservation of biodiversity within the agricultural system, both from a philosophical perspective and from the practical viewpoint of maintaining productivity. Biological pest control on organic farms, for example, relies on maintaining healthy populations of pest predators. By adopting a crop rotation system, in time (over several years rotations) or in space (through intercropping or by growing several different crops on a holding at any onetime), the build up of harmful pests and disease can be reduced and biodiversity increased (Stolton et al. 2000; Zhu et al. 2000; Jackson 1997).

In recent years, researches have been carried out on organic agriculture's effects on biodiversity (Youngberg et al. 1984; Isart and Llerena 1996; Whalen et al. 1998; Feber et al. 1997, 1998; Chamberlain et al. 1999; Van Elsen 2000; Haas et al. 2001). Many investigations show positive effects of organic farming on the diversity of arable field plants. In organically farmed fields, the density and species diversity of the weed flora is larger than in conventional managed fields. For example, at both English and Danish locations, about five times as much weed biomass, 2.4–5.3 times greater weed density, significantly greater species diversity was found in the former than in the latter (Hald and Reddersen 1990). These effects on the weed flora are primarily the result of the ban on herbicides in organic farming (Reddersen 1999).

Compared to conventional farms, 2–3 times more individual birds; greater numbers of earthworms and biomass; more individuals species of spiders; more non-pest species of butterflies were found on organic farms (Braae et al. 1988; Whalen et al. 1998; Feber et al. 1997, 1998; Krebs et al. 1999; Chamberlain et al. 1999). Mander et al. (1999) showed that organic agriculture had a large positive impact on biological and landscape diversity. The diversity (population or species or individuals) of vascular plants, different invertebrate groups and birds was 0.5–20 times higher on organic than on conventional farms. Cobb et al. (1999) captured significantly more butterflies and spiders, in terms of both individuals and species, from the organic than the conventional fields. It was also found that in contrast to the conventional management system, the populations of endangered species in organic fields were considerably higher (Albrecht and Mattheis 1998). Through crop rotations in organic farming encourages diversity at the landscape scale. Such retention of a diversity of habitats renders obvious benefits on local wildlife populations (Edwards and Howells 2001). On the other hand, sometimes conversion shows only small benefits to species diversity because of a long history of mechanical weeding and the use of herbicides before conversion (Albrecht and Mattheis 1998). Kleijn et al. (2001) found no positive effects on plant and bird species diversity infields where farmers were paid to delay mowing or grazing, and to reduce the amount of fertilizer they used. The four most common wader species were observed even less frequently on those fields. By contrast, hoverflies and bees showed modest increases in species richness. Birds actually seemed to prefer intensively farmed fields possibly because reduction in fertilizer use led to smaller invertebrate populations and so less food for birds. Further more, it is also often over looked that some conventional mixed farming can maintain species diversity. For example, conventional mixed farming in smaller plots (providing more field margins) or farming based on the traditionally system (for example under sowing wheat with legumes) maintains conventional yields and low costs. The benefits for wildlife equal those provided by organic farming but at a far lower cost to the consumer (HLSCEC (1999)). However, it can be argued that agriculture has, to a certain extent, responsibility for all species and communities which co-evolved with farming over 10,000 years irrespective their utility (Wood and Lenné 1999).

14 Linkage to Rural Economy

More recently, researchers have focused their attention to evaluate the efficacy of organic farming in the rural economy and specifically, the potential for organic farming to contribute to rural development (Darnhofer 2005; Marsden et al. 2002; Pugliese 2001). In this context it is frequently argued that organic farming can promote much employment in rural areas and thus contribute to rural development by reducing the wide gap between rich and poor (Morison et al. 2005; Smith and Marsden 2004; Midmore and Dirks 2003; Hird 1997). Despite these claims, it has been also argued that research on the wider “social impacts of organic farming is very limited" (Morris et al. 2001). Significantly, Smith and Marsden (2004) have argued that considering organic farming as a panacea for the problems of "rural economic development has to be seriously qualified by examining particular types of overall supply chain dynamics which are operating in particular types of organic sectors indifferent local, regional and national settings". In parallel with the growth of, and interest in, the organic sector, 'local food' has also taken on increased economic, environmental and symbolic importance. Much of this is concerned with reducing environmental costs, particularly food miles, but also a desire to increase local economic multipliers and contribute to the reconnection linkage of farmers and consumers (Cranbrook 2006; Ilbery and Maye 2005; Pretty et al. 2005). It has also been suggested that patterns of increased local food purchases, rather than revealing a strong turn to quality and locally produced organic food, actually points to a politics of "defensive localism" (Winter 2003). Although organic produce is not necessarily 'local' (even locally supplied organic boxes may not contain exclusively locally produced food), and local produce does not equate with organic, there is never the less a perceived close alliance between local food and organic food movements. For instance, although the majority of organic sales via supermarkets, sales through direct routes, such as local box schemes, rose by 53% between 2005 and 2006 (Soil Association 2007). Combining a greater degree of localness in food sourcing with increased organic production would lead to considerable savings associated with the reduction of environmental externalities (Pretty et al. 2005). Where as the economic and social benefits of reducing negative externalities and increasing positive externalities have long been recognized, the renewed research focus on the 'local economy' and interactions, clusters and networks within it may point to a role for organic farming and local food in developing and sustaining local economies(Winter and Rushbrook 2003). Certainly writers such as Van der Ploeg and Renting (2000) have suggested that the operators of farm businesses have particular advantages to bring to the process of rural development, while Renting et al. (2003a; b) have demonstrated aggregate benefits in terms of additional net value added stemming from a number of "short food supply chains" (including organics and direct sales) and Smithers et al. (2008) pointed to the benefits of retaining a greater proportion of farming and food expenditure within the local economy. Similarly, in discussing the multiple rationales associated with the promotion of locally sourced organically produced food. Seyfang (2006) argues that such food supply chains can, amongst other things, favour new socially embedded economies of place and make a significant contribution to rural development by giving farmers greater control of their market and retaining a greater proportion of food spend in the local economy. The assumed localized nature of organic food and associated social and economic benefits are not uncontested. For instance, Clarke et al. (2008) have recently commented on the "supposedly localized nature of organic food" and called for more critical and reflexive accounts of what it is organic food networks can do for us. Against the background of claims concerning the rural development potential of farmers generally and organic farming in particular, Building on a methodology developed by Harrison (1993) and modified by Errington and Courtney (2000) emphasized the socio-economic linkages associated with different types of farming and also evidence of social embedded ness of the principal farmer.

14.1 Rural Economies Versus Organic Farming

For most purposes the term ‘rural economy’ is a shorthand way of considering a range of ‘economies’ rather than discussing a discrete, unified and homogenous economy (Winter and Rushbrook 2003). These various economies may share similar characteristics but may also be quite different in terms of economic linkages with the wider economy and reliance on different sectors, for instance. The shift in rural policy towards more of a territorial focus and the growing policy emphasis on regional and local sustainable economic development is associated with the development of research addressing interactions within ‘local’ economies. For example, writers such as Courtney et al. (2007), Courtney and Errington (2000) have considered economic linkages between businesses and localities. Analysis of purchase and sales links provides a method of exploring the extent to which farms (or indeed, any business) of different types are connected to local economies. There are a number of ways of approaching the concept of economic connectivity. Earlier studies of economic linkages (focused on the proportions of sales and purchases by businesses within certain localities (Curran and Blackburn 1994) whereas Harrison (1993) extended the approach to include the monetary values of sales and purchases. Clearly, the local economic impact of a farm, whether it is organic or not goes beyond the employment issues (Bateman et al. 1993).

15 Challenges of Sustainable Agriculture

There are several challenges that must be overcome to achieve sustainable agriculture in Asia. First, Asian countries must impose restrictions on environmentally damaging activities, review the ways they go about development, and create ways to support the development and deployment of eco-friendly technologies. For example, pesticide damage must be addressed by quickly teaching farmers how to properly use the chemicals, by carrying out comprehensive registration and management, and by banning or regulating hazardous pesticides. To address the problem of unsuitable irrigation schemes, it is imperative that small-scale environmentally compatible projects be implemented in place of standardized large-scale projects that ignore local environmental conditions. Promoting the development of IPM and other agro ecological technologies is also essential (Marsden et al. 2000; Potter and Burney 2002). Prerequisites for these initiatives are support for the transition to eco-friendly farming, and the reevaluation of public research agencies, which should take the lead in developing basic technologies because these are not considered important in commercial development by businesses (UNDP 2003; Holzschuh et al. 2007). Second is enhanced monitoring of agribusiness, which is the primary entity behind the internationalization of agro-food issues, and international growth management for agriculture- and food-related trade and investment of export-oriented agriculture, and the internationalization of trade and investment have expanded rapidly, but the flip side is trans border environmental damage. As in the conventions on prior informed consent and persistent organic pollutants and the resource management project for shrimp farming (Wood et al. 2006; Hole et al. 2005). There is a growing necessity to create an Asian system—with the same level of regulatory measures as those in other parts of the world, that can formulate business codes of conduct and environmental conventions in order to internationally control the chaotic development of agribusiness, and that can use capital investment returns to benefit local environmental conservation. An international framework like this and action based on it would make it possible to steer the growth of trade and investment in a sustainable direction. Asian governments must also reevaluate their agricultural policy in connection with food imports. Some countries have become dependent on imports for basic foods because of their policy emphasis on industrialization or production for export, but since the Asian economic crisis some Southeast Asian countries have a renewed awareness about the importance of food security. Under the WTO system, domestic policies cannot be adequately implemented due to limitations imposed from above on protecting domestic agriculture, but the sustainable development of agriculture and food production is indispensable to attain food sovereignty (Pretty et al. 2005; Pugliese 2001). Third is bringing together the actors who will achieve sustainable agriculture and food production. Fixing the current agro-food system, which is the cause of environmental damage and food uncertainty, requires that governments switch to eco-friendly policies that protect agriculture, receive the support of international agencies, and regulate and monitor agribusiness. But such policies will become reality only through collaboration among NGOs, farmers' organizations, labor unions, cooperatives, and other entities as they raise questions and exercise their influence toward creating that policy. Consumers have to rethink their lifestyles and how excessive food consumption and imports affect the environment. Producers must take advantage of both modern environmental science and traditional local knowledge while working toward eco-friendly farming and local resource management. It would be the first step toward achieving the development of sustainable agriculture in which both farmers and consumers take the initiative in cooperating globally and locally (Allan and Kovach 2000; Courtney et al. 2006; Lamine and Bellon 2009).

15.1 Advantages of Organic Farming

1. The economics of organic farming is characterized by increasing profits via reduced water use, nutrient-contamination by pesticides, reduced soil erosion and carbon emissions and increased biodiversity.
2. Organic farming produces the same crop variants as those produced via conventional farming methods, but incurs 50% lower expenditure on fertilizer and energy, and retains 40% more topsoil.
3. This type of farming effectively addresses soil management. Even damaged soil, subject to erosion and salinity, are able to feed on micro-nutrients via crop rotation, inter-cropping techniques and the extensive use of green manure.

4. Farming the organic way enables farmers to get rid of irksome weeds without the use of any mechanical and chemical applications. Practices such as hand-weeding and soil enhancement with mulch, corn gluten meal, garlic and clove oil, table salt and borax not only get rid of weeds and insects, but also guarantee crop quality.
5. The use of green pesticides such as neem, compost tea and spinosad is environmentally friendly and non-toxic. These pesticides help in identifying and removing diseased and dying plants in time and subsequently, increasing crop defense systems.

15.2 Disadvantages of Organic Farming

1. In 1998, increased risk of E. coli infection via consumption of organic food rather than non-organic food was publicized by Dennis Avery of the Hudson Institute.
2. A 2008 survey and study conducted by the UN Environmental Program concluded that organic methods of farming result in small yields even in developing areas, compared to conventional farming techniques.
3. The Father of the Modern Green Revolution, Norman Borlaug, argues that while organic farming practices are capable of catering to the demands of a very small consumer fraction, the expanding cropland is dramatically destroying world ecosystems.
4. Research conducted by the Danish Environmental Protection Agency revealed that organic farms producing potatoes, seed grass and sugar beet are barely able to produce half of the total output churned out from conventional farming practices.
5. Organic agriculture is hardly able to address or combat global climate change. Though regenerative organic farming practices are recognized as effective strategies for reducing CO2 emissions to an extent, the impact is not dramatic.

16 Conclusion

This chapter has focused on agricultural sustainability, and its relationship to various alternative agricultural approaches. It has, quite deliberately, not offered any new definitions of sustainability or sustainable agriculture. Sustainable practices will vary both temporally and spatially and can only truly be identified in retrospect. It is not simply a question of tools and inputs, but the context in which they are used. Farming meant many different things to many different people: “its lack of specific definition allowed many of us to associate it with certain important characteristics of scale, locality, control, knowledge, nutrition, social justice, participation, grower/eater relationships and the connections with schools and communities". Duesing goes on to contrast this with the current situation. He argues that these desirable food system characteristics seem threatened as the definition of organic farming and food is narrowed to a set of standards which deal with growing and processing methods. The exclusively organic standards become established in an increasing number of countries, and these standards become more co-ordinate and integrated, the degree to which the organic producer and organic consumer may be geographically separated grows. Furthermore, the trade in organic farm inputs may also grow, with organic producers having the option of buying in mulch or organic fertilizers from distant sources. There may be doubts regarding the sustainability of the systems which have generated these purchased inputs. In addition, organic producers may be skeptical of such developments because they farm in this way to escape from many aspects of the global trade in food stuffs, and aim to produce for local markets because of concern regarding the energy deficiency implications of such a trade in organic products. Producers, traders, and consumers of organic food regularly use the concept of the natural naturalness to characterize organic agriculture and or organic food, in contrast to the unnaturalness of conventional agriculture. Critics sometimes argue that such use lacks any rational of scientific basis and only refers to sentiment. The organic agriculture movement had its roots in a philosophy of life and not in the agricultural science (Kirchmann, 1994). A common belief within the organic movement is that natural products are good, whereas man-made chemicals are bad or at least not as good as natural ones. This idea may also be used to explain why organic farming avoids the use of synthetic fertilizers and pesticides etc. In any case, one fundamental reason for increasing interests in organic agriculture is due to the requirements and attention of health, environmental protection, and food safety. This paper shows that organic agriculture has obvious environmental benefits. The basic standards of organic farming provide suitable tools to minimize environmental pollution and nutrient losses on the farm level However, there is a high variability within organic farms in relation to their efforts and their nutrient efficiency. Concerning soil fertility and nutrient management, comparative studies show that organic farming is suited to improve soil fertility and nutrient management markedly on the farm level. With reference to biodiversity, organic agriculture is committed to conservation of biodiversity within agricultural systems. Research projects have accumulated evidence that organic systems are beneficial to biodiversity. In relation to product quality, there is no sufficient evidence for a system-related effect on product quality due to the production method. Product quality is primarily a function of farm management, showing a high variability in both organic and conventional production. Organic farming emphasizes integrated strategies, rather than individual control methods, both in crop protection and animal husbandry. Biological control methods may be components of such strategies. Conservation biological control and the use of predators and parasites are favoured methods. However, on-native predators and parasites should only be used if this causes no threat to the native fauna. The use of microbial control agents is also possible, but is not favoured by the major regulations and standards. In the authors' personal view, the use of microbial control agents can be preferable to the use of plant or mineral derived pesticides, incases in which this causes less side-effects on the environment. In contrast, the use of genetically modified biological control agents is not allowed. Strategies for organic crop protection are available for a few crops, but are still lacking for many others. Strategies for control of diseases and parasites in organic animal husbandry are even scarcer. In conclusion, there is a need for research in organic crop protection and animal husbandry practices including, but not limited to, biological control methods. So, from the different aspect of the present reviewed paper, it is clear that organic farming is practical proposition for sustainable agriculture if adequate attention is paid to this issue. There is urgent need to involve more and more scientists to identify the thrust area of research for the development of eco-friendly production technology.

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E. Lichtfouse (ed.), *Agroecology and Strategies for Climate Change*, Sustainable Agriculture Reviews 8, DOI 10.1007/978-94-007-1905-7,