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TROPICAL FORESTS AND THE GREENHOUSE EFFECT: A MANAGEMENT RESPONSE

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Abstract. The buildup of carbon dioxide in the global atmosphere represents one of the principal causes of the greenhouse effect that is overtaking the Earth's climatic systems and that threatens salient sectors of economic development in both the developed and developing worlds. A management response appears to offer substantial scope to counter the buildup of carbon dioxide, even though it has been little addressed in systematic fashion. It is a massive tree-planting programme in the humid tropics. Tree plantations absorb carbon dioxide from the atmosphere, and the humid tropics with year-round warmth and moisture are by far the best place for fast-growing tree plantations. Reforestation on a suitable scale in the humid tropics--accompanied of course by measures to halt deforestation--could eventually serve to sequester carbon in amounts significant for our efforts to counter the greenhouse effect.

Introduction

Amid the debates on the greenhouse effect, one potential management response is occasionally mentioned but rarely examined in substantive detail. It is tropical reforestation, undertaken on a scale to restrict or even reduce the buildup of carbon dioxide in the global atmosphere.

The merits of this approach are persuasive, in principle at least: it would serve to sequester substantial amounts of carbon from the global atmosphere. Of course it would work only if it were accompanied by efforts to reduce or even halt tropical deforestation, and thereby to stem the release of carbon dioxide (also of methane, nitrous oxide and other greenhouse gases) from the tropical forest zone. While there are many reasons to stop tropical deforestation, none of them seems to have been enough to do the job. The climate connection might prove to be the decisive factor that persuades political leaders and policy makers to get to final grips with the deforestation problem.

A number of key questions arise. How much would tropical reforestation help to relieve the greenhouse effect--marginally, significantly, crucially? What other 'co-benefits' might be generated (such as rehabilitation of watersheds through restored tree cover) and thus serve to support the case for reforestation? What technical contributions could come into play, such as genetically engineered tree species and provenances with ultrarapid growth? What would be some costs involved, and how could they be equitably shared among the community of nations?

The conceptual framework for these considerations is illuminating. The carbon dioxide issue is generally broached only from the standpoint of supply-side factors (Goreau, 1987). Yet the major sources (as well as sinks) of atmospheric carbon dioxide are not industrial but biotic. True, the largest pools of carbon are abiotic, including not only fossil fuels but the deep ocean and limestones. But they exchange carbon with the atmosphere only slowly, whereas tropical biotas, while forming much smaller pools, feature much more rapid fluxes of carbon. So a key to the carbon dioxide problem is to enhance the metabolism of tropical biotas as a primary determinant of atmospheric composition.

To date, however, scant attention has been directed at the potential of tropical reforestation to relieve the greenhouse effect (though for some very preliminary writings, see Dyson, 1977; Dyson and Marland, 1979; and Stewart, 1978; and for some more recent analysis, albeit exploratory and tentative, see Cooper, 1983; Goreau, 1990; Goreau and de Mello, 1988; Marland, 1988; Myers, 1984, 1989; and Sedjo and Solomon, 1988). The neglect is ostensibly due to the putative cost of broad-scale reforestation, many billions of dollars. But as the concealed costs of the greenhouse effect become more apparent worldwide, so the cost of grand-scale tropical reforestation seem more acceptable.

For instance, the Netherlands government already spends more than \$8 billion (6% of GNP) each year on maintaining a complex set of dykes, seawalls and other structures to protect the nation against the sea. To stem a 1-m rise in sea level, as could readily be entrained by the greenhouse effect, could cost at least as much again (Goemans and Visser, 1987). Great Britain may have to spend between [sterling]5 billion and [sterling]8 billion on improved coastal defenses (Boorman *et al.*, 1988), while the United States might well face a cost of \$110 billion to protect its coastal areas against a similar 1-m sea level rise (Kaufman and Pilkey, 1988; Smith and

Tirpak, 1988). To revamp the U.S. network of dams and irrigation systems in the wake of a greenhouse effect could cost anywhere from \$7 billion to \$23 billion (Dudek, 1987), while to adapt irrigation systems worldwide could eventually require an investment of \$200 billion (Postel, 1987). Overall, then, the costs due to the greenhouse effect could amount to an annual total of tens of billions of dollars, possibly much more.

Amounts of Carbon in Question

Two points arise. First, how much carbon is being ejected into the atmosphere from tropical forests--and hence how much additional carbon would be retained in their biotic sinks if tropical deforestation were to be halted? Secondly, how much atmospheric carbon could be 'soaked up' and sequestered in biotas through reforestation of the humid tropics?

The amount of carbon now being released by burning and other forms of elimination of tropical forests is considered to be in the order of 2.4×10^{12} kg (Houghton, this volume). This total is to be compared with a current annual fossil-fuel release of around 5.6×10^{12} kg. Moreover, the amount of tropical-forest release is increasing steadily as the rate of deforestation accelerates (Myers, this volume), whereas the fossil-fuel amount has shown little annual increase during the late 1980s.

Of the carbon dioxide ejected into the atmosphere from both biotas and fossil fuels, only around half remains there, the rest ostensibly disappearing into the oceans and being absorbed by biotas (through the so-called fertilizer effect) among other putative though unknown sinks (Schneider, 1989). Overall, then, the current annual buildup of atmospheric carbon dioxide can be put at about half the combined total of 5.6 and 2.4×10^{12} kg from fossil fuels and tropical forests, respectively, or some 4.0×10^{12} kg. Were tropical deforestation to be reduced forthwith by rather more than half, the carbon buildup could be cut by 1×10^{12} kg, leaving the net annual carbon amount to be tackled at 3.5×10^{12} kg.

We should bear in mind, moreover, that only about half the greenhouse effect is caused by carbon dioxide. The rest stems from other trace gases such as methane and nitrous oxide, in large part derived from the tropics. The effects of deforestation on production of these gases is complex and poorly understood (Goreau and de Mello, 1988).

Tree Planting as a Counter-CO₂ Measure

How fast can a tropical tree plantation absorb atmospheric carbon dioxide? Through photosynthesis a plantation can accumulate between 15 and 25 t of dry biomass per hectare per year, with a working mean figure of 20 t (Evans, 1982, 1987; Pandey, 1983; Tang *et al.*, 1988; and Zsuffa, 1984; see also Brown *et al.*, 1985, and Cropper and Ewel, 1987). As a measure of the conservative nature of these figures, note that eucalyptus plantations in southern Brazil have been regularly averaging over 30 t/ha/yr (Brandao, 1985). Roughly half the plant growth is made up of carbon, so a plantation can assimilate 10 t (a mean working figure) of atmospheric carbon per hectare per year. In turn this means that planting trees in 100 million ha, or 1 million km², could absorb 1 gigaton of carbon from the atmosphere per year for as long as the trees continue to grow, a period that could be as long as 30-40 years (Houghton, 1990; Houghton and Woodwell, 1987).

Parallel figures and calculations, with rather different conclusions, have been adduced by Marland (1988, and this volume; for some further analysis, see Dudek, 1988; Perlack and Ranney, 1987), who determines that a mean volume increment for tropical plantations is only 9.6 m³/ha/yr--a figure based largely on a literature review by Brown *et al.* (1985), also Nambiar (1984), who present findings from earlier experiences with plantation forestry in the tropics. Note, however, that Marland also asserts that the carbon-sequestration potential of pine plantations ranges between 6 and 18 t/ha/yr, and of eucalyptus plantations between 10 and 24. The right tree species in the right places can surely do the job.

Moreover, the figures presented for this paper's argument, viz. 1 gigaton of carbon sequestered in 1 million km² of tropical tree plantations, are cautious and conservative. They ignore, for instance, factors such as carbon formation in soils beneath trees, which can add a further 0.5 t of carbon per hectare per year (Houghton and Woodwell, 1989; Postel and Heise, 1988).

More importantly still, the figures reflect plantation forestry of the 1970s and early 1980s. They take no account of recent research in advanced plant-breeding techniques for tropical trees, whether species, varieties or provenances: our treebreeding systems are still at a rudimentary stage as compared with what has been achieved through Green Revolution technology for food-crop plants (Leakey, 1987). Moreover, just three categories of tree species, viz. pine, eucalyptus and teak, make up 87% of tropical plantations (Vietmeyer, 1986), yet there are 50 000 tree species in the humid tropics, almost entirely untested as regards growth rate and yield, among other basic characteristics. Were we to mobilize the latest and most sophisticated breeding strategies (e.g., selection and cloning for better uptake of mineral nutrients, drought tolerance and pest resistance), it should be possible to achieve major advances in growth rates (Farnum *et al.*, 1983). As a measure of what could be achieved, the Aracruz Forestal plantations in southern Brazil have boosted annual eucalyptus yields from 33 to 70 t/ha in just the 15-year period 1970-1985 (Brandao, 1985). Yet more significant still, the potential of genetic engineering has hardly been applied to tree species, despite the remarkable potential of tissue culture, protoplast fusion and related techniques (Adlard, 1998; Hanover and Keathly, 1988; Namkoong, 1986; Pearce, 1986; Ranney *et al.*, 1987). By e.g. partitioning photosynthates to above-ground wood rather than roots and leaves, it should eventually be possible to double productivity.

To gain a sense of how large a challenge we would encounter in a tree-planting program of the scale proposed, note that in 1980 the amount of tree plantations that had been established in the humid tropics was 110 000 km² for an establishment rate only one-tenth of the deforestation rate.

As mentioned, a massive tree-planting program would have to be accompanied by a parallel effort to stem further deforestation. This would require far more vigorous measures than have been implemented to date. Fortunately there is growing support for such initiatives, as witness assertions from political leaders and policy makers in many tropical-forest countries. President Aquino of the Philippines, former Prime Minister Rajiv Gandhi of India and President Daniel Arap Moi of Kenya have all spoken of deforestation in their countries as a 'national emergency', and there have been similar statements from the governments of Thailand, Pakistan, Brazil, Colombia, Costa Rica, Nigeria, Madagascar and Vietnam (though regrettably not from certain other leading countries such as Malaysia, Zaire and Peru). Development agencies too are

boosting the prospects of saving tropical forests; forestry funding on the part of the World Bank, the United Nations Development Programme and related agencies has grown from \$450 million in 1985 to over \$1 billion in 1990, with emphasis shifting from production forestry to protection forestry.

In sum, tree planting across 1 million km² (as a minimum effort), in conjunction with greatly enhanced forest protection measures to reduce deforestation by half, could mean that the tropical forest zone would start to account for an overall reduction of carbon emissions of 2×10^{12} kg/yr, with a net reduction of atmospheric carbon accumulation of 1×10^{12} kg/yr. Were the tree-planting effort to be doubled to 2 million km² (a huge effort that is probably the most that can be envisaged at present), the overall reduction of carbon emissions would rise to 3×10^{12} kg/yr, meaning the net reduction of carbon accumulation would expand to 1.5×10^{12} kg/yr--a figure to be compared with that for the net overall accumulation of carbon dioxide each year, 4×10^{12} kg. So tropical reforestation on the scale proposed could eliminate 37.5% of the problem.

Just 1 million km² is a lot of land. It is quite a bit bigger than California, Oregon and Washington combined, or equivalent to Britain, France and Germany together. In tropical terms, it is more than three times the size of the Philippines, and almost one-third the size of Brazilian Amazonia. Fortunately a good deal of already deforested lands remain available, i.e., they have not been taken for permanent settlement by human communities. They include the alangalang grasslands and degenerate scrublands of Southeast Asia, some 500 000 km² and a similar amount of 'wasted lands' in tropical Africa and Latin America. Indeed, according to Houghton and Woodwell (1989), there could be as much 5 million km² of deforested lands awaiting productive use, while Grainger (1988) postulates 7.6 million km².

In addition, 1.6 million km² of upland watersheds urgently need reforestation for the purpose of restoring watershed functions such as hydrological regulation (World Resources Institute and World Bank, 1985). On top of this, 550 000 km² of fuelwood lots are required--often to be planted around homesteads and on farm perimeters, i.e., on lands not already taken for other purposes (World Resources Institute and World Bank, 1985). True, we can count, for carbon-sequestration purposes, only those fuelwood areas that are planted over and above those areas that are felled for burning. Extrapolating from FAO estimates of unmet fuelwood needs (Food and Agriculture Organization, 1983), we can reasonably assume that about 100 000 km² of fuelwood plantings would be burned without replenishment, while 450 000 km² would serve to expand the resource base and thereby accumulate atmospheric carbon as long as the trees continue to grow. In addition there would be some overlap with watershed areas. Suppose the two together amount to 1.9 million km² (World Resources Institute and World Bank, 1985). In addition again, the humid tropics offer much scope, as well as urgent need, for plantations of commercial wood for lumber and paper pulp; say another 100 000 km² (Food and Agriculture Organization, 1987). This means that 2 million km² need to be reforested for reasons other than control of the greenhouse effect.

When we add this 2 million km² to the 1 million km² of 'wasted lands' noted earlier, we find there should be no insurmountable difficulty, in principle at least, to finding 3 million km² of land for reforestation in the humid tropics. So the target figure proposed for present purposes, 2 million km², should be available without too much difficulty.

Nor need there be any eventual wood-storage problem. Trees can continue to grow, and store carbon, for 30 or even 40 years. This should surely give us enough time to move beyond the fossil-fuel-based economy, whereupon the tree-planting measure would become a stop-gap affair to help us through an energy/climate bottleneck. In the circumstances, carbon-sequestering wood is continuously 'stored' as long as it keeps on growing in plantations. Moreover there is the prospect that emergent technologies could enable plantation trees to be chipped for pyrolytic power generation; if the exercise were conducted on a self-sustaining basis, this would mean that tree material burned would be immediately replaced by still more trees planted, thus opening the way for 'energy plantations' to sequester large quantities of carbon permanently (Ogden and Williams, 1989).

The Role of Social Forestry, Agroforestry and Non-Governmental Organizations

One need not envisage vast tree plantations stretching from one horizon to another. (In any case, there are well-known problems with monoculture plantations; see e.g. Fearnside, 1988.) Other tree-planting strategies are available, notably social forestry and agroforestry (Allen, 1988; Floyd and Lassoie, 1987; Stepler and Nair, 1987), both of which entail lots of localized plantings. Indeed the 2 million km² of tree plantations required should primarily and most productively be accomplished through many millions of small-scale woodlots, at village and farm level, planted around homesteads, as intercroppings, along farm perimeters, as windbreaks, along paths and roads, and in a multitude of similar mini-modes. Both agroforestry and social forestry utilize land locally available--and as a further bonus, they mobilize on-ground labor (Cernea, 1989).

A related factor in both strategies is that they depend upon strong grass-roots involvement from start to finish. This goes a long way to explain their success as compared with 'top down' efforts at tree planting. But this implies a high degree of ultra-local organization. Increasingly this is being undertaken by non-governmental organizations (NGOs), which deploy unrivaled experience and expertise at 'bottom up' activities (Durning, 1989; Roggeri, 1986; Schneider, 1988). Following a remarkable outburst of new NGOs in recent years, there are now 600 environmental groups in Indonesia, at least 3000 church-based groups in the Philippines, 8000 Sarvodaya Shramadana or 'village awakening' groups in Sri Lanka, and 12 000 grass-roots organizations in India, with similarly sizeable numbers in Kenya, Colombia and Brazil. As a result of the spread of NGOs in Haiti, an Agroforestry Outreach Project, sponsored by the U.S. Agency for International Development and with a \$27-million budget, has administered through three American NGOs working in conjunction with 170 Haitian NGOs; together they have mobilized 130 000 farmers who have planted 35 million trees across some 500 km², for an average planting rate of almost 270 trees per farmer (or 54 trees per year over 5 years) and 700 trees per hectare (Conway, 1987; Winterbottom and Hazelwood, 1987).

The average planting rate in the Haiti project throws light on another crucial calculation. If 2 million km² of tree plantations are required, this amounts, at a rate of 700 trees per hectare, to 140 billion trees. In turn, and using the Haitian farmer/tree-planting rate, this requires almost 260 million farm families in the humid tropics planting 54 trees per year throughout the 10-year effort. If there are 2 billion farming people in the humid tropics and an average family size is six persons, this works out to 333 million such families. So every family would have to plant 42

trees per year. If only, say, half of all families could be persuaded to join in the campaign, then each family would find itself having to plant 84 trees per year--no great task.

Tree-Planting Costs

What would the entire effort cost? At 1988 prices for seedlings and the like, an agroforestry plantation--such as would be suitable for the bulk of the program, and including free land and labor, plus maintenance and protection activities--costs between \$200 and \$500/ha (Harrison, 1987; Siebert and Lassoie, 1987). By contrast, a commercial-timber plantation, generally established without free inputs, costs around \$2000/ha. Suppose the costs average \$400/ha, a reasonable working estimate (Postel and Heise, 1988). This means that the total cost of planting 2 million km² with trees would amount to \$80 billion. Of course the entire program would not be implemented all at once. Were it to be spread out over, say, 10 years, the annual cost would be only \$8 billion--a sound investment indeed when compared with some concealed costs of global warming mentioned at the start of this paper. Moreover tree planting seems to be an unusually cost-effective way to tackle carbon dioxide buildup in the global atmosphere. It has been variously estimated to cost only \$10-16 per tonne of carbon avoided, by contrast with wind power (as an alternative to fossil-fuel energy) \$95, geothermal power \$110, nuclear power \$535 and photovoltaic power \$819 (Buchanan, 1989; see also Flavin, 1989; Fulkerson *et al.*, 1990).

Moreover, a sum of \$8 billion flowing each year into tropical-forest countries would be seven times more than current funding for tropical forestry provided by the Tropical Forestry Action Plan. Since it would presumably be supplied only to those countries that make substantive efforts to curb deforestation, it would offer greatly enhanced incentive for tropical forest countries to get to final grips with deforestation.

Who would pay for grand-scale tree planting? Herein lies a major issue. Those countries that most need watershed rehabilitation, fuelwood supplies and commercial timber would reap a sizeable benefit. They could also gain through trees planted for windbreaks, living fences, fertilizer effects (in the case of nitrogen-fixing species) and a range of similar spinoff benefits. So they would presumably be inclined to assume much of the tree-planting costs themselves. The fact that they have not yet undertaken tree-planting activities of sufficient scale is partially explained by sheer shortage of funds--a factor that argues for a greater injection of financial support on the part of developed nations. Support from developed nations makes sense in two ways: partly on conventional grounds of development needs, and partly in light of the developed nations' emergent interest in mitigating the greenhouse effect.

But, to adopt an alternative approach, if one accepts the principle of 'the polluter pays' it becomes reasonable for the costs to be allocated among the community of nations in proportion to their current rates of fossil-fuel combustion. How about taxing all fossil fuels at a rate sufficient to pay for a tree-planting effort of the scope proposed (Goreau, 1987)? With reforestation costs of \$8 billion per year, and 5.2×10^{12} kg of fossil-fuel carbon emitted per year, this would require a tax of only \$1.5 per tonne of fossil fuel. Such a tax would be no more than a tiny fraction of the taxes we already pay for fossil fuels; in most developed countries, moreover, taxes already account for the bulk of fossil-fuel costs.

How would this allocation of costs work out in practice? The amount of fossil-fuel carbon emitted by the United States into the global atmosphere each year is now around 1.15 billion t/yr (23% of all such emissions), the amount emitted by the Soviet Union is almost 940 million t (18%), by China 450 million t (9%), by Japan 230 million t (4%) and by all others 2.4 billion (46%) (Brown *et al.*, 1989). Figures of this sort could serve as a basis for assessing each country's tax liability in support of a tropical tree-planting campaign.

In similar style, a tax could conceivably be considered for carbon emissions from the burning of tropical forests. But tropical-forest countries would surely reject any tax idea, however equitable it may seem in principle. They will protest that fossil-fuel burning has been going on for well over a century, whereas widespread tropical-forest burning is a phenomenon of the last three decades at most. They will further protest that the great bulk of carbon dioxide buildup is the developed nations' responsibility; and that it is the developed nations that have the most incentive to counter the greenhouse effect. Politically a tax on forest burning is surely a non-starter, for the time being at least.

Some Parallel Initiatives

The essential idea of grand-scale tree planting to sequester carbon dioxide has received some recent support. The Intergovernmental Panel on Climate Change recommends that 2.4 million km² should be planted with trees, albeit in various parts of the world. The Netherlands government aims to open two 600-MW coal-fired electricity plants by 1997, emitting 6 million t of carbon dioxide per year. To offset these emissions, the government plans to spend over \$1 billion on reforestation of 2500 km² in Bolivia, Peru, Ecuador, Colombia and Costa Rica over a period of 25 years, starting in 1991; these carbon-sink forests can be established at less than one-twelfth the cost of undertaking the task in the Netherlands. Similarly a Connecticut, U.S.A., utility, Applied Energy Services, is building a power plant which will emit 105 million t of carbon during its 40-year life. To compensate, the corporation is funding the planting of 52 million trees in 1000 km² of Guatemala (Trexler *et al.*, 1989).

Conclusion

Grand-scale reforestation in the humid tropics could alleviate part of the global carbon dioxide problem at relatively small cost. Even if the 2-million-km² program set out above were to prove beyond the resources and capabilities of countries concerned, partial implementation could make a sizeable contribution to the carbon dioxide issue, in conjunction of course with other measures such as greater energy efficiency, energy conservation and use of non-fossil fuels.

We would all benefit in different ways and to differing degrees from a reforestation effort. Developed countries would bear a cost by financing the greater part of the budget; and tropical countries would bear a cost by providing land and labor. At the same time tropical countries would enjoy ancillary benefits in the form of watershed protection, erosion control and the like.

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