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An Evaluation of Indices of Biotic Integrity for Algal and BMI Assemblages in Streams of the Los Angeles Region

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Research Impact Statement: The biotic integrity of algal assemblages containing diatoms, described by the Algal Stream Condition Index, are reliable indicators of biological water quality in Los Angeles watersheds.

ABSTRACT: The Los Angeles region contains a number of heavily altered watersheds, resulting in the degradation of both water and habitat quality along numerous streams. Assessing the impacts of these anthropogenic stressors on biological communities has primarily focused on the California Stream Condition Index (CSCI), a measure of the biotic integrity of benthic macroinvertebrate assemblages. To complement the CSCI an Algal Stream Condition Index (ASCI) was developed to assess the biotic integrity of both soft-bodied and diatomaceous algal assemblages. Using random forest modeling, we evaluated the performances of the CSCI, the ASCI for diatom assemblages (D_ASCI), and the ASCI for hybrid assemblages containing both diatoms and soft-bodied algae (H_ASCI). We found that our models of the D_ASCI and H_ASCI could account for approximately 77% and 78% of their observation variation across the watersheds of the Los Angeles region, nearly as high as the 82% accounted for by the CSCI. This indicates the future potential of using indices of biotic integrity based on, or in part, diatom assemblages for streams in this region as additional forms of bioassessment.

(KEYWORDS: biotic integrity; California Stream Condition Index; Algal Stream Condition Index; chemical water quality, habitat quality, benthic macroinvertebrates; algae; random forest.)

INTRODUCTION

The health of watersheds in the Los Angeles region within southern California plays a large role in supporting local freshwater and coastal ecosystems (Smith et al. 1999; Anderson et al. 2002; Dudgeon et al. 2006). However, heavy development in watersheds stresses these key ecosystems and has resulted in their degradation (Carpenter et al. 1998; Merhaut et al. 2013; Paerl et al. 2016). These stressors, and their effects, are particularly pronounced in the Los Angeles Watershed, a highly urbanized region located within one of the 36 global biodiversity "hotspots" (Myers et al. 2000; Calsbeek et al. 2003; Gillespie et al. 2018).

Despite having a water quality regulatory framework that is over 50 years old to regulate the discharge of pollutants in water bodies in California, many water bodies still face impairment and require restoration (State Water Resources Control Board 2017). Within the watersheds of the Los Angeles region, water quality monitoring efforts currently track a wide variety of environmental variables in order to make regulatory decisions ranging from water chemistry to streambed modifications (California Regional Water Quality Control Board 2014). Included in these monitoring efforts are assessments of biological quality, primarily focused on metrics based on the composition of assemblages of benthic macroinvertebrates (BMIs) (Mazor et al. 2016).

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Benthic macroinvertebrates have a diverse array of pollution tolerances and ecological niches (Solek et al. 2011; Chang et al. 2014) used in the majority of biological assessments for streams (Rehn and Ode 2005). In Californian streams, biological assessments using BMIs are often quantified using the California Stream Condition Index (CSCI; Rehn et al. 2015). This index compares metrics, based on the compositions of BMI assemblages, to counterparts found at undisturbed reference sites, based on local environmental variables such as geology, climate, and watershed area (Mazor et al. 2016). The CSCI was also developed to provide reliable assessments of the biotic integrity of BMI assemblages across various environmental gradients found in California (Rehn et al. 2015).

The CSCI has proven to be a reliable bioassessment metric in the watersheds of the Los Angeles region, and California at large, that they are now incorporated into reports to Congress (State Water Resources Control Board 2017). However, while BMIs have been demonstrated to be useful indicators of biological conditions in streams, they represent only a portion of these ecosystems. To help expand the scope of bioassessment for streams, other types of biological assemblages have been investigated as potential bioindicators (Paul et al. 2017; Atique et al. 2019; Fierro et al. 2019; Moyle and Marchetti 2020).

One type of biological assemblage of interest in constructing stream bioassessment is algae. In streams, algae help to support many food webs (Hogsden and Harding 2012; Vadeboncoeur and Power 2017), and with species-specific variations in nutrient requirements and pollution tolerances have also shown promise as complementary bioindicators to those based on BMIs (Paul et al. 2017; Fierro et al. 2019; Qu et al. 2019). As with BMIs, algal communities are also influenced by both anthropogenic and natural factors (Cao et al. 2007; Passy and Blanchet 2007; Schneck et al. 2011). For these reasons, recent efforts in stream bioassessments in California have focused on the development of stream conditions based on algal communities (Theroux et al. 2020), as well as developing more holistic bioassessments of streams which synthesize information on the condition of both algal and BMI assemblages (Beck et al. 2019).

There have been a number of difficulties though in developing indices of algal biotic integrity which are as reliably predicted by environmental gradients as those developed for BMIs. Early attempts focusing on soft-bodied algae alone found the development of indices which were moderately predictive of environmental conditions in streams, but far less so than existing efforts focused on BMI assemblages (Mazor et al. 2006). Similar limitations in constructing reliable bioassessments were also found with earlier models which focused on diatoms (Chessman et al. 1999; Ritz 2010). Indices of biotic integrity for diatom assemblages, or hybrid assemblages of diatoms and soft-bodied algae, began to improve in reliability with the incorporation of a more diverse array of environmental predictors and greater taxonomic resolution of algal taxa (Feio et al. 2012; Pardo et al. 2018).

Focusing on assessing conditions in California watersheds, this work has led to the development of an Algal Stream Condition Index (ASCI; Theroux et al. 2020). This index, which is split into a component for diatoms (D_ASCI), soft-bodied algae (S_ASCI), a hybrid of both assemblages (H_ASCI), was developed to quantify the biotic integrity of various algal assemblages in order to help provide a more holistic assessment of California streams. Similar to the construction of the CSCI, the ASCI characterizes the response of algal diversity, both taxonomic as well as functional, to environmental gradients as a means of bioassessment for freshwater streams (Theroux et al. 2020). However, stronger variation in algal turnover and a poor understanding of algal taxonomy tends to limit the number of well-characterized widespread indicator species useful for constructing bioassessments over the extent of California (Theroux et al. 2020). This is especially the case for soft-bodied algae, with the performance of the S_ASCI being poor enough that the developers of the ASCI not to recommend its use in stream bioassessments (Theroux et al. 2020).

To evaluate the reliability of the ASCI as an additional bioassessment for streams, across the watersheds of the Los Angeles region, we compared its responsiveness to a variety of natural and anthropogenic gradients with those of the CSCI, a more established bioassessment, using random forest modeling. We chose to limit our geographic scope to the Los Angeles region to avoid potential issues stemming from a relative lack of widespread algal taxa with which to construct the ASCI. Random forest was chosen as our modeling technique due to prior evidence of its low sensitivity to skewed data, relatively low risk of overfitting to data, and robust performance with large numbers of variables (Evans et al. 2011). It has also been found to be useful in assessing the response of assemblages of BMIs to changes in the abiotic environment (Maloney et al. 2009; Waite et al. 2010; Desrosiers et al. 2019; Park et al. 2021). Here, we evaluate the performances of the D_ASCI, H_ASCI, compared to the CSCI, as indices of biological water quality in the Los Angeles region.

METHODS

Scope of Data

The scope of our data covers 234 stream samples gathered during the late spring and summer months, approximately May through September, over 20 years (2000–2019) from within Region 4 (Figure 1), one of the nine regions of the California State Water Resources Control Board (SWRCB), which covers the Los Angeles region (Figure 1). Each stream sample contains the following data: a bioassessment index score based on a composite of taxonomic and functional diversity within BMI assemblages known as the CSCI, a set of bioassessment index scores for assemblages of algae and their soft-bodied algae and diatom components known as the ASCI, the concentrations of various chemical analytes, measures of stream habitat structure and quality, and a

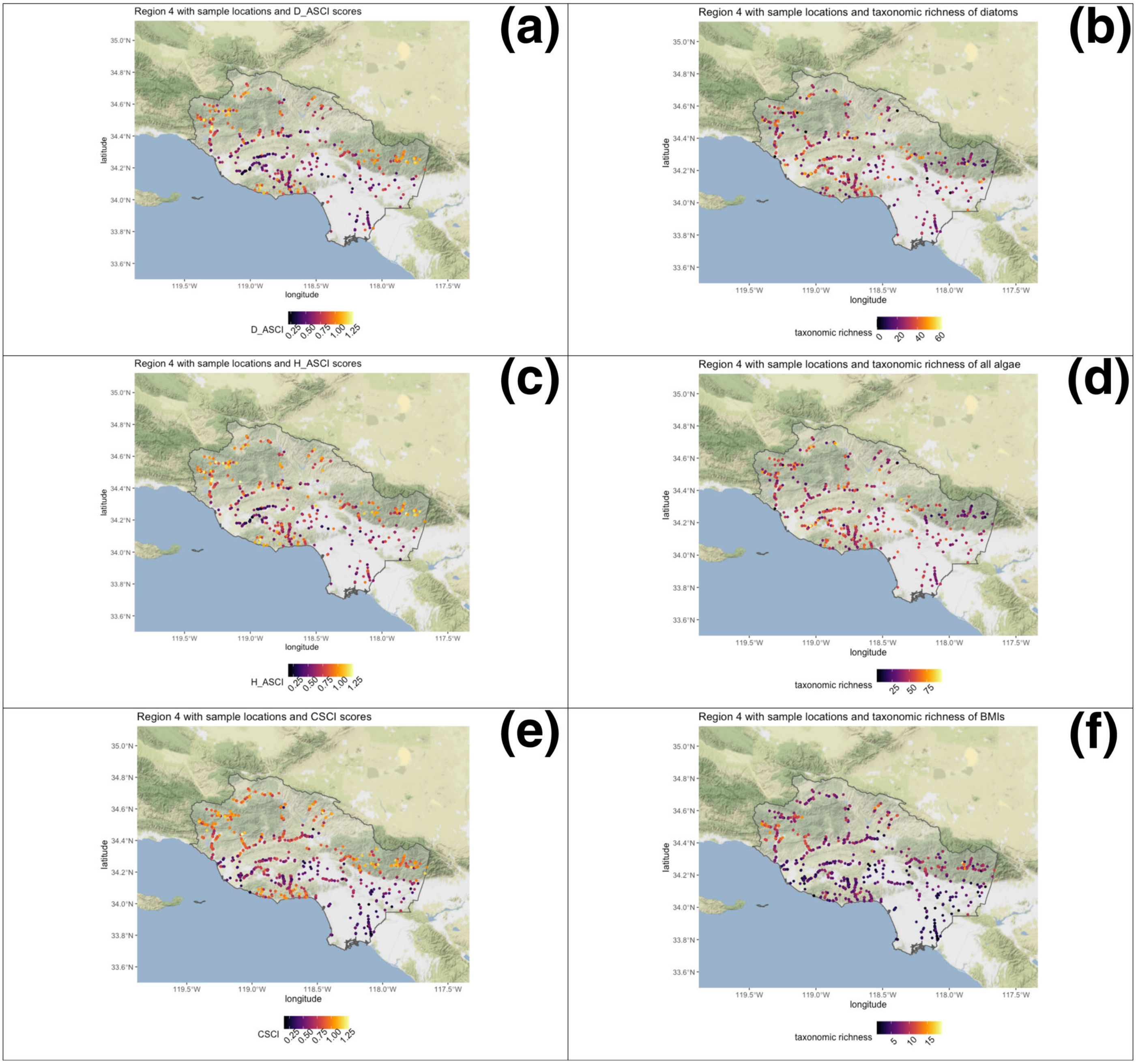

FIGURE 1. Sample sites, bounded by Region 4, colored by the D_ASCI (a), taxonomic richness of diatoms (b), H_ASCI (c), taxonomic richness of all algae (d), the CSCI (e), and taxonomic richness of BMIs (f). ASCI, Algal Stream Condition Index; BMI, benthic macroinvertebrate; CSCI, California Stream Condition Index.

watershed as defined by an eight-digit United States Geological Survey Hydrologic Unit Code (Seaber et al. 1987).

Collecting BMI Data and Calculating the CSCI

The CSCI was designed to produce consistent assessments of biological conditions across the major natural gradients found in California (Reynoldson et al. 1997; Hawkins et al. 2010). In order to calculate the CSCI for a given location one needs to obtain a representative sample of the BMI assemblages found at a stream sample site. For BMI assemblages sampled in order to calculat the CSCI 55% were collected using a reach-wide protocol (Peck et al. 2006) while the remainder were collected using targeted riffle protocols, which produce comparable data on the composition of BMI assemblages (Gerth and Herlihy 2006; Herbst and Silldorff 2006; Rehn et al. 2007). Most BMIs were then enumerated and classified to standardized taxonomic level (Richards and Rogers 2006) of either genus or, for chironomids, sub-family (File S1). Samples BMIs were then assigned to one of eight functional feeding groups, using CAMLnet, as a means of quantifying functional diversity (Ode 2003).

In order to calculate the CSCI for a BMI assemblage, we first utilized its taxonomic and functional diversity to calculate: (1) a ratio of observed-to-expected taxa (O/E) and (2) a predictive multi-metric index (pMMI) made of six metrics related to ecological structure and function of the BMI assemblage. Both the O/E and pMMI compare the taxonomic and functional completeness of a sampled BMI assemblage at a given site to values expected under undisturbed reference conditions based on site-specific landscape-scale environmental variables, such as watershed area, geology, and climate (Mazor et al. 2016). Across the diverse environmental gradients of California, the CSCI has been found to provide reliable assessments of the biotic integrity of BMI assemblages (Mazor et al. 2018).

Collecting Algal Data and Calculating the ASCI

The ASCI was developed to provide a reliable assessment of the biotic integrity of algal assemblages in California streams (Theroux et al. 2020), especially in conjunction with assessments of BMI assemblage biotic integrity. All algal samples in order to determine their ASCI scores were collected following the SWAMP protocol for algal collection (Ode et al. 2016). This protocol involves the collection of algal subsamples, which contain both soft-bodied algae and diatoms, along 11 transects within a 150 m stream reach, which are then composited across multiple stream substrata (e.g., cobbles, sand, large wood, etc.) in proportion to their abundance across the reach. Each sample was then sorted morphologically, generally to genus or species (File S2), and counted as members of either soft-bodied algae or diatom communities (Stancheva et al. 2015). Taxonomies were standardized using a combination of AlgaeBase (algaebase.org) and Biodata species names (http://aquatic.biodata.usgs.gov). Assigning unique algal taxa to functional categories involved the use of a variety of algae attribute lists (Bahls 1993; Van Dam et al. 1994; Potapova and Charles 2007; Porter et al. 2008; Spaulding et al. 2010; Fetscher et al. 2014; Paul et al. 2020).

For the ASCI, we calculated both an O/E and pMMI for assemblages of diatoms, soft-bodied algae, and a combination of the two (Theroux et al. 2020). For each sampled algal assemblage, both their O/E and pMMI values were calculated by comparing the taxonomic and functional completeness, respectively, of a sampled algal assemblage acquired with similar site-specific landscape-scale environmental variables but with minimal human disturbance. These algal O/E and pMMI values were then used to calculate the biotic integrity of algal assemblages, such as for diatoms (D_ASCI), and a hybrid of diatoms and soft-bodied algae (H_ASCI).

Classifying Sampled Sites by Biological Condition

Using these indices, samples were then classified into categories of biological condition using thresholds for both the CSCI and ASCI (Beck et al. 2019). Using these thresholds, we then calculated the fraction of samples under different levels of biological condition for both BMI and algal assemblages (Table 1).

Chemical and Habitat Data

We selected a diverse array of variables corresponding to both measures of the chemical

TABLE 1. Percent of samples under each biological condition. Likely intact (CSCI >0.92, ASCI >0.93), Possibly altered (CSCI: 0.79–0.92, ASCI: 0.83–0.93), Likely altered (CSCI: 0.63–0.79, ASCI: 0.70–0.83), Very likely altered (CSCI <0.63, ASCI <0.70).

	CSCI	D_ASCI	H_ASCI
Likely intact	28.2	22.5	24.0
Possibly altered	15.4	11.7	12.7
Likely altered	23.5	12.6	17.0
Very likely altered	32.9	53.2	46.3

composition of water at a sample site, as well as the physical habitat of the streambed and banks. These variables have been found to influence both the taxonomic and functional diversity of algal and BMI assemblages (Richards et al. 1997; Pan et al. 1999; Wang et al. 2007), and subsequently the values of both the ASCI and CSCI at a given location (Mazor et al. 2016; Theroux et al. 2020).

Water from each sampling location was measured by field crews for pH, specific conductance, dissolved oxygen, salinity, and alkalinity. Measurements were done using digital field sensors, or by collecting samples for lab analyses. Additional samples of stream water were collected for measurements of various analytes, including total suspended solids, total hardness as measured by the concentration of calcium carbonate, silica, sulfate, nutrients, dissolved and total metals, and pyrethroid pesticides (S. W. A. M. P. Q. A. Team 2008).

In order to assess physical habitats, each sampling location was first divided into 11 transects within a 150 m stream reach. At each of these transects, the following parameters were measured: bank dimensions, wetted width, water depth in five locations, substrate size, cobble embeddedness, bank stability, microalgae thickness, presence of coarse particulate organic matter, presence of attached or unattached macroalgae, presence of macrophytes, riparian vegetation, instream habitat complexity, canopy cover using a densitometer, human influence, and flow habitats (Peck et al. 2006; Fetscher et al. 2009; Ode et al. 2016). These habitat parameters were further organized into environmental variable types (Table S1; File S3). Water surface slope was calculated over the entire reach, and measurements from each transect were then used to calculate habitat metrics for each sampling location (Kaufmann et al. 1999).

The full set of both quality measurements, and assessments of physical habitat, are not consistently measured at each sample location. However, in order to enable the use of random forest modeling, all variables must have an existing value for each sample. We selected our 234 samples on this basis.

Statistical Analyses

We built and evaluated an initial set of 1,000 random forest models including the indices of biotic integrity as a function of habitat quality various chemical analytes. The source data for each model were obtained by first randomly selecting 140 samples from our study area. We were able to consistently model the CSCI, D_ASCI, and H_ASCI below our significance threshold ($p < 0.05$) using only 140 samples (Table S2). Each of these sample groups was split into training and testing sets using a fivefold partitioning with the *kfold* function within the R package *dismo* (Hijmans et al. 2017). On each training set, we built a random forest model using the function *tuneRF* within the R package *randomForest* (Liaw and Wiener 2002). For *tuneRF* we used default settings for all parameters, except stepFactor was set to a value of 1 and doBest was set as “true.” The predicted index scores for each of our testing sets were calculated using the model built with our training sets and function *predict* within *randomForest*. These predictions were evaluated using a Pearson correlation coefficient.

To compare the relative importance of environmental variables within our models we used the function *partial* within the R package *pdp* (Greenwell 2017). The relative importance of our model variables was calculated as the mean decrease in their node purity across all iterations, with a larger value denoting a greater relative importance (File S4).

The accuracy of each instance of both indices was calculated using the Pearson correlation coefficient between the index scores in our testing sets and those generated by the predict function within the dismo package. We calculated the mean and standard deviation on our Pearson correlation coefficient values under a Fisher transformation using the *FisherZ* function within the R package *DescTools* (Signorelli et al. 2019). The average and standard deviation were then inverse Fisher transformed using the function *FisherZInv* within the *DescTools* package. We used a Fisher transformation as it has been found to produce less biased summary statistics for a set of Pearson correlation coefficients (Corey et al. 1998).

To visualize the relative importance of environmental variables in each of the index models we used the functions *ggplot* and *facet_grid* within the R package *ggplot2* (Wickham et al. 2016). These relative importance values were grouped by environmental variable type for each index and then plotted using the function *geom_violin*.

RESULTS

Performance of Index Models

We found our random forest models of the CSCI, D_ASCI, and H_ASCI could account for most of their observed variation across the Los Angeles region (Table 2). Though our model of the CSCI was the most consistent of the three models of biotic integrity in accounting for its observed variations, its

TABLE 2. The mean and standard deviations on the Pearson correlation coefficients between actual and indices of biotic integrity as predicted using random forest modeling.

Index of biotic integrity	***r***
CSCI	0.82 (0.13)
D_ASCI	0.77 (0.14)
H_ASCI	0.78 (0.14)

performance was only slightly more reliable than either the H_ASCI or D_ASCI.

Comparing the Relative Importance of Environmental Variable Group Types

In modeling our indices, we observed a number of commonalities with regards to the relative importance of certain environmental variable group types. For all indices, we found environmental variables within the group types “Algae Cover,” “Bank Morphology,” “Channel Morphology,” “Channel Sinuosity and Slope,” “Field Measures,” “Riparian Vegetation Cover and Structure,” and “Velocity and Discharge” tend to be of low relative importance (Figure 2). For streams in the Los Angeles region, we found all four indices of biotic integrity to be largely driven by environmental variables within the group type “Chemical,” “Habitat Complexity and Cover,” “Human Influence,” “Reach Condition,” and “Substrate Size and Composition” (Figure 2).

Between indices, we found some additional similarities in the mean relative importance of environmental variables, by group type, and modeling various indices. For all indices, the group type of environmental variables with the greatest relative importance was “Reach Condition” (Table S3). All of the algal indices shared the same environmental group type with the second highest mean relative importance, “Habitat Complexity and Cover,” while for the CSCI this was “Percent Cascade/Falls of Reach” (Table S3).

The Relative Importance of Environmental Variables in Modeling Indices

We then compared the 10 environmental variables with the greatest relative importance in modeling our indices (Table 3). In general, we found our indices to be responsive more to habitat rather than chemical variables, especially with regards to the CSCI. With

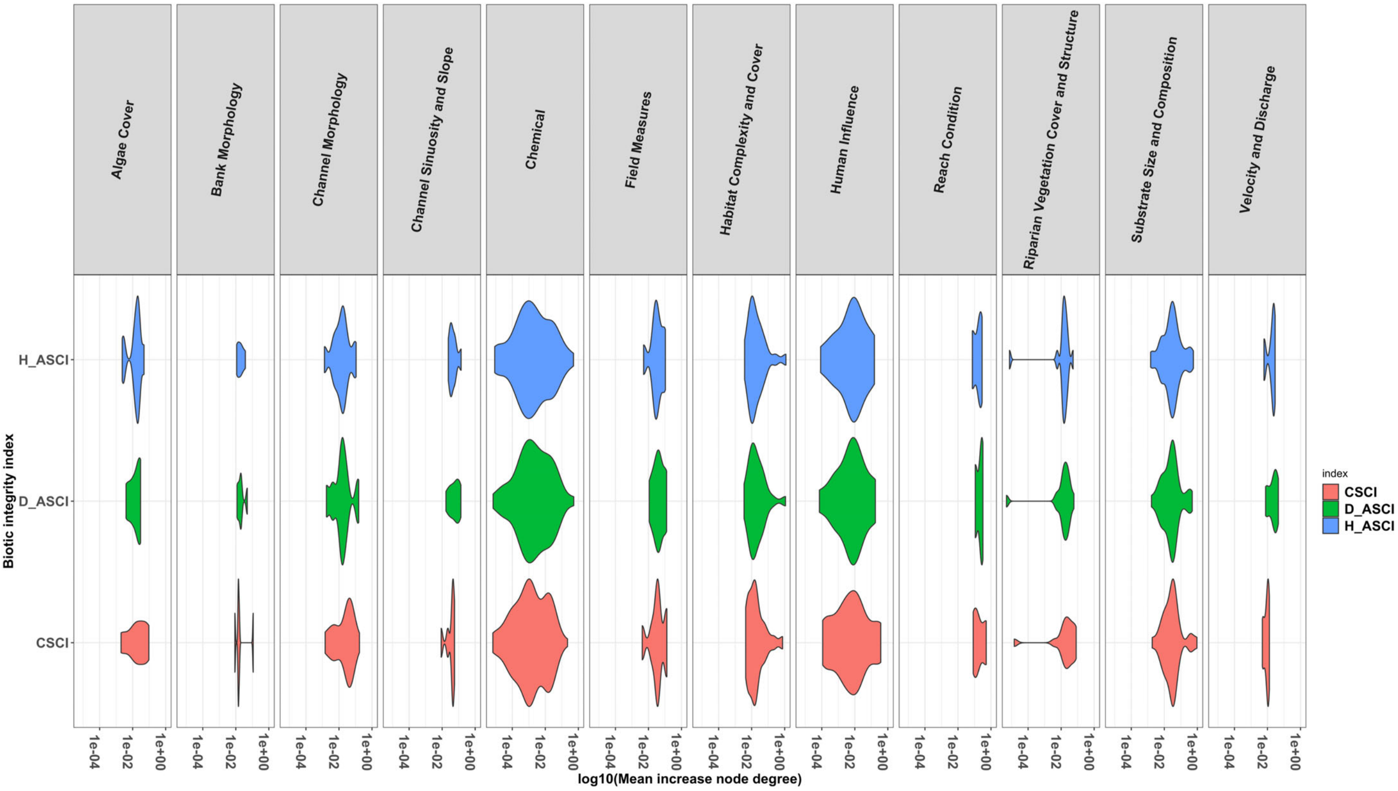

FIGURE 2. The base-10 log of the relative importance of physicochemical variables, by group, to random forest models of indices of biotic integrity. The relative importance of variables is calculated as the mean decrease in node purity, with higher values indicating greater importance. Note: The category “Percent Cascade/Falls of Reach” only contains 1 variable, and as a result no violin plot could be generated.

TABLE 3. The 10 variables with greatest relative importance (environmental variable group), ranked, for each modeled index of biotic integrity.

Importance rank	CSCI	D_ASCI	H_ASCI
1	Percent Substrate Larger than Fine Gravel (>16 mm) (Substrate Size and Composition)	Mean Boulders cover (Habitat Complexity and Cover)	Mean Boulders cover (Habitat Complexity and Cover)
2	Mean Boulders cover (Habitat Complexity and Cover)	Chloride (Chemical)	Percent Substrate Larger than Fine Gravel (>16 mm) (Substrate Size and Composition)
3	RBP Epifaunal Substrate/Available Cover (Reach Condition)	Percent Substrate Larger than Fine Gravel (>16 mm) (Substrate Size and Composition)	Chloride (Chemical)
4	Shannon Diversity (H) of Natural Substrate Types (Substrate Size and Composition)	Phosphorus as P (Chemical)	Percent Boulders — small (Substrate Size and Composition)
5	Combined Riparian Human Disturbance Index — EMAP (Human Influence)	Percent Cobble (Substrate Size and Composition)	Phosphorus as P (Chemical)
6	Percent Cobble (Substrate Size and Composition)	RBP Channel Alterations (Reach Condition)	Percent Cobble (Substrate Size and Composition)
7	Combined Riparian Human Disturbance Index—SWAMP (Human Influence)	Percent Boulders—small (Substrate Size and Composition)	Nitrate + Nitrite as N (Chemical)
8	Boulders cover present (Habitat Complexity and Cover)	RBP Epifaunal Substrate/Available Cover (Reach Condition)	RBP Channel Alterations (Reach Condition)
9	Chloride (Chemical)	Big shelters cover (sum large wood, boulder, undercut banks, artificial) (Habitat Complexity and Cover)	Big shelters cover (sum large wood, boulder, undercut banks, artificial) (Habitat Complexity and Cover)
10	Percent Cascade/Falls of Reach (Percent Cascade/Falls of Reach)	Combined Riparian Human Disturbance Index—SWAMP (Human Influence)	RBP Epifaunal Substrate/Available Cover (Reach Condition)

our habitat variables, we found some measures of anthropogenic disturbance, such as "Combined Riparian Human Disturbance Index — EMAP" and "Channel Alterations," to be of high relative importance for all our indices. However, of the variables in this study we did find certain measures of riverbank and streambed structures, such as "Mean Boulders cover" and "Percent Cobble," were highly predictive of all of our models of biotic integrity.

For our models of algal biotic integrity, we found our list of the most important variables to contain more chemical variables than for our model of BMI biotic integrity (Table 3). Of the most important chemical variables, measurements associated with the concentration of nutrients, such as nitrates and phosphorus, to be the most strongly predictive (Table 3). Both models of algal and BMI biotic integrity also found a highly relative importance for the concentration of chloride (Table 3), typically associated with salinity.

Trends between Environmental Variables and Indices

Within our study area, we found significant degrees of correspondence between all three indices of biotic integrity, with the CSCI correlated with the D_ASCI ($r = 0.467$, $p < 10^{-4}$) and H_ASCI ($r = 0.448$, $p < 10^{-4}$), and the D_ASCI and H_ASCI strongly correlated with each other ($r = 0.819$, $p < 10^{-4}$). These correspondences indicate a tendency for locations with degraded algal assemblages to also have ones where BMI assemblages are degraded as well.

All of the indices were found to decline with a rise in the concentrations of the chemical analytes with the highest relative importance (Table 4). For the CSCI, D_ASCI, and H_ASCI, we found significant declines associated with a rise in chloride concentration. All algal indices were found to decline with a rise in the concentrations of various nutrients, particularly compounds containing phosphorus and nitrogen.

For indices of both algal and BMI biotic integrity, we found the most important variables in our random forest models to be associated with measures of riverbank and streambed structure, specifically "Percent Substrate Larger than Fine Gravel (>16 mm)" and "Mean Boulders cover" (Table 4). Although, among the most important variables in our biotic integrity models, we found variables associated with the chemical environment to be more frequently predictive of the D_ASCI and H_ASCI, while the CSCI

TABLE 4. Pearson correlation coefficients between the 10 variables with the greatest relative importance and the modeled index of biotic integrity (n.s. $p > 0.05$, *$p < 0.05$, **$p < 10^{-2}$, ***$p < 10^{-3}$).

CSCI	D_ASCI	H_ASCI
Percent Substrate Larger than Fine Gravel (>16 mm) (0.60***)	Mean Boulders cover (0.59***)	Mean Boulders cover (0.60***)
Mean Boulders cover (0.58***)	Chloride (−0.53***)	Percent Substrate Larger than Fine Gravel (>16 mm) (0.57***)
RBP Epifaunal Substrate/Available Cover (0.56***)	Percent Substrate Larger than Fine Gravel (>16 mm) (0.54***)	Chloride (−0.54***)
Shannon Diversity (H) of Natural Substrate Types (0.52***)	Phosphorus as P (−0.24***)	Percent Boulders—small (0.48***)
Combined Riparian Human Disturbance Index — EMAP (−0.61***)	Percent Cobble (0.52***)	Phosphorus as P (−0.48***)
Percent Cobble (0.47***)	RBP Channel Alterations (0.48***)	Percent Cobble (0.54***)
Combined Riparian Human Disturbance Index — SWAMP (−0.60***)	Percent Boulders—small (0.45***)	Nitrate + Nitrite as N (−0.27***)
Boulders cover present (0.55***)	RBP Epifaunal Substrate/Available Cover (0.46***)	RBP Channel Alterations (0.50***)
Chloride (−0.55***)	Big shelters cover (sum large wood, boulder, undercut banks, artificial) (0.48***)	Big shelters cover (sum large wood, boulder, undercut banks, artificial) (0.52***)
Percent Cascade/Falls of Reach (0.35***)	Combined Riparian Human Disturbance Index—SWAMP (−0.47***)	RBP Epifaunal Substrate/Available Cover (0.48***)

was more often predicted by variables associated with the physical habitat (Table 3). For all three indices, we found a positive correlation between biotic integrity and these measures of riverbank and streambed structure, while they were all three found to decline with measures of anthropogenic disturbances such as the “Combined Riparian Human Disturbance Index — SWAMP” or “RBP Channel Alterations.”

DISCUSSION

This study compares the behavior and performance of various indices of biotic integrity to variations in several environmental variables, with a focus on the future use of any indices of biotic integrity beyond the CSCI for the purposes of bioassessments in the Los Angeles region. Our findings provide further validation of the use of the D_ASCI and H_ASCI, which is increasingly being used to evaluate water quality in southern California (Stein et al. 2022). In modeling these three indices of biotic integrity, we found that thay could all be reliably predicted given data on both water chemistry and physical habitat across the Los Angeles region. However, indices of the biotic integrity of algal assemblages tended to be more reliably predicted given variations in water chemistry, while those of BMI assemblages were better predicted given data on the state of the local physical habitat.

Comparing Performances of Indices across Assemblages

We found all the indices to be responsive to variations in the environment, with random forest-based models of their behavior yielding similarly consistent results in capturing variations in the biotic integrity of both BMI and algal assemblages in the Los Angeles region (Table 2). While prior studies have demonstrated the poor performance of indices of biotic integrity of soft-bodied algae assemblages relative to those based on diatoms, all algae, or BMIs, their incorporation into diatom assemblages have also been found to yield a slight improvement in index performance as reflected in a comparison of the D_ASCI and H_ASCI (Mazor et al. 2006; Fetscher et al. 2014; Theroux et al. 2020). This slight improvement in the performance of the H_ASCI over the D_ASCI, despite the poorer understanding of the response of soft-bodied algae to environmental gradients, may also simply reflect slight improvements from an overall increase in the amount of algal diversity data with which to model environmental responses.

Comparing Indices across Environmental Gradients

Looking at the most important variables in our models of biotic integrity, we found the biotic integrity of algal assemblages to be more often predicted by variations in the chemical environment, rather than physical habitat, with the opposite observed for the biotic integrity of BMI assemblages (Figure 2; Table 3).

These trends have been observed in other stream systems for both algae (Sonneman et al. 2001; Hering et al. 2006; Johnson and Hering 2009; Rehn 2016; Pardo et al. 2018), as well as BMIs (Voss et al. 2012; Ferreira et al. 2014). Reflecting prior observations, for BMI and all algal assemblages, this study found declines in biotic integrity associated with both rise in nutrient levels and decline in the physical habitat quality of streambed and bank surfaces commonly associated with heavily urbanized watersheds (Paul and Meyer 2001; Brown et al. 2009). Direct comparisons of the behaviors of the CSCI and ASCI in southern California have demonstrated a greater role for chemical variations in the environment, rather than physical habitat, in predicting the composition of algal assemblages over those of BMIs (Beck et al. 2019). So, for example, we would expect that the biotic integrity of algal assemblages would be more often predicted by the concentrations of nutrients such as nitrates and phosphates from urban runoff, while the biotic integrity of BMI assemblages will more often be predicted by the changes in boulder cover associated with channelization and urban development. This does not indicate a particular weakness for either the ASCI or CSCI, rather that the former is predicted more by measures of water chemistry and the later of habitat alteration, both of which are measures of anthropogenic disturbance (Beck et al. 2019).

We note that a number of the environmental variables used in our models of biotic integrity may be strongly associated with other measures of anthropogenic disturbance, potentially confounding a holistic interpretation of our results. For example, we do find that “Habitat complexity and cover” is predictive of our algal indices of biotic integrity while “percent cascades and falls” is predictive of BMI biotic integrity. In both cases, such variables are related to changes in the stream environment which alter its flow, which have been found to alter the composition of both BMI (Poff et al. 2007; Rehn 2009) and algal assemblages (Allan 2004; Lange et al. 2016). However, modifications to the physical environment, such as channel concretization and boulder removal, are often associated with a broad array anthropogenic activities, such as an increase in the impervious cover of a watershed, which impact the biological condition of streams (Beck et al. 2019; Peek et al. 2022). This does not necessarily reduce the utility of either the ASCI or CSCI, but it does indicate caution in labeling relationships between environmental variables and biotic integrity as causative rather than predictive.

We found similar responses of both models of the D_ASCI and H_ASCI to environmental conditions, with the H_ASCI able to capture slightly more variation in algal biotic integrity than the D_ASCI with the incorporation of data on soft-bodied algal assemblages. This is somewhat surprising as the ASCI for soft-bodied algae alone has previously been found to be a poor indicator of biotic integrity (Theroux et al. 2020), possibly stemming from a poorer understanding of their functional and taxonomic diversity as compared to diatoms (Fetscher et al. 2014; Lange et al. 2016; Stancheva and Sheath 2016). Furthermore, the lower dispersal activity of soft-bodied algae compared to diatoms (Schneider et al. 2012; Padial et al. 2014) has further complicated efforts at calibrating the environmental responses of soft-bodied algal assemblages across a wide area due to a relative lack of cosmopolitan species (Soininen et al. 2004; Potapova and Carlisle 2011; Schneider et al. 2012). Despite these limitations, the addition of soft-bodied algal assemblages to diatoms does not appear to reduce the utility of the H_ASCI vs. the D_ASCI, possibly because enough soft-bodied algal species are comparatively sensitive to environmental changes as diatoms (Stancheva and Sheath 2016).

CONCLUSIONS

The watersheds of the Los Angeles region have been subject to a number of anthropogenic stressors, necessitating assessments of the biotic integrity of various assemblages for the purpose of environmental management and restoration. To complement the successful implementation of the CSCI in assessing California streams based on the biotic integrity of assemblages of BMIs, recent work has focused on the development of complementary indices based on the biotic integrity of various algal assemblages. We find that while the D_ASCI and H_ASCI are reliable bioassessments to complement the CSCI in the Los Angeles region. The performance of the H_ASCI is slightly improved by the addition of data on the compositions of soft-bodied algal assemblages, despite greater difficulties in characterizing many such species responses to environmental changes. We find this work to help illustrate the potential of diatom assemblages, alone or in combination with soft-bodied algae, in assessing biological conditions across a heavily developed region. Ultimately, future refinements in our understanding of both the functional and taxonomic diversity of soft-bodied algal assemblages will be needed in order to reliably assess their condition or to improve other algal biological indices.

DATA AVAILABILITY STATEMENT

The data used in generating this manuscript are freely available from the Southern California Coastal

Water Research Project (SCCWRP). All source data, and scripts to analyze them, are available here: https://github.com/LAWaterKeeper/LAWK.

SUPPORTING INFORMATION

Additional supporting information may be found online under the Supporting Information tab for this article: This section contains details on species and environmental variables used in this analysis.

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AUTHOR CONTRIBUTIONS

Ariel Levi Simons: Conceptualization; methodology; software; writing – original draft; writing – review and editing. Sophia Bozone: Formal analysis; writing – original draft; writing – review and editing. Cella DePrima: Project administration; supervision; writing – original draft; writing – review and editing. Lester Diaz: Investigation; writing – original draft; writing – review and editing. Veronica Lu: Formal analysis; writing – original draft; writing – review and editing. Colbert Manson: Investigation; validation; writing – original draft; writing – review and editing. Ayahna Mack: Software; visualization; writing – review and editing. Corisa Wong: Data curation; project administration; writing – original draft; writing – review and editing.

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