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Algal Attributes: An Autecological Classification of Algal Taxa Collected by the National Water-Quality Assessment Program

By Stephen D. Porter

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Conversion Factors

Multiply	By	To obtain
	Length	
centimeter (cm)	0.3937	inch (in.)
millimeter (mm)	0.03937	inch (in.)
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
	Volume	
liter (L)	0.2642	gallon (gal)
	Mass	
gram (g)	0.03527	ounce, avoirdupois (oz)

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:

°F=(1.8×°C)+32

Temperature in degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) as follows:

°C=(°F-32)/1.8

Concentrations of chemical constituents in water are given either in milligrams per liter (mg/L) or micrograms per liter (µg/L).

Algal Attributes: An Autecological Classification of Algal Taxa Collected by the National Water-Quality Assessment Program

By Stephen D. Porter

Abstract

Algae are excellent indicators of water-quality conditions, notably nutrient and organic enrichment, and also are indicators of major ion, dissolved oxygen, and pH concentrations and stream microhabitat conditions. The autecology, or physiological optima and tolerance, of algal species for various water-quality contaminants and conditions is relatively well understood for certain groups of freshwater algae, notably diatoms. However, applications of autecological information for water-quality assessments have been limited because of challenges associated with compiling autecological literature from disparate sources, tracking name changes for a large number of algal species, and creating an autecological data base from which algal-indicator metrics can be calculated. A comprehensive summary of algal autecological attributes for North American streams and rivers does not exist. This report describes a large, digital data file containing 28,182 records for 5,939 algal taxa, generally species or variety, collected by the U.S. Geological Survey's National Water-Quality Assessment (NAWQA) Program. The data file includes 37 algal attributes classified by over 100 algal-indicator codes or metrics that can be calculated easily with readily available software. Algal attributes include qualitative classifications based on European and North American autecological literature, and semi-quantitative, weighted-average regression approaches for estimating optima using regional and national NAWQA data. Applications of algal metrics in water-quality assessments are discussed and national quartile distributions of metric scores are shown for selected indicator metrics.

Introduction

Algae can be found in all aquatic habitats. In most streams and rivers, algae are the most diverse assemblage of organisms that can be sampled easily and identified readily to species or variety (Stevenson and Smol, 2003). Algal species are excellent indicators of water quality and environmental change (Patrick, 1948, 1977; Dixit, Smol, and others, 1992). The autecology, or physiological requirements and tolerance of algal species to nutrients (nitrogen and phosphorus concentrations), organic enrichment, dissolved oxygen, major ions (such as calcium, chloride, iron, and sulfate), temperature, or pH, can be classified qualitatively from literature accounts or semi-quantitatively using weighted-average regression and calibration approaches with large regional or national data sets such as those generated by the National Water-Quality Assessment (NAWQA) Program of the U.S. Geological Survey (USGS). Autecological metrics derived from algal-community data have been used, individually, as indicators of trophic and organic-enrichment conditions in streams and rivers (Lowe, 1974; Lange-Bertalot, 1979; van Dam and others, 1994; Kelly and Whitton, 1995; Cuffney and others, 1997; Peterson and Porter, 2002; Carpenter, 2003; Potapova and Charles, 2007; Porter and others (2008), and collectively, in algal indices of biological integrity (Bahls, 1993; Mills and others, 1993; Hill and others, 2000; Fore and Grafe, 2002; Griffith and others, 2005; Wang and others, 2005).

Nutrient and Organic Enrichment

Although humans most likely had some rudimentary understanding of the relation between excessive growths of algae and poor water quality for thousands of years (Prescott, 1968), systematic study of algal species relations with water quality began in central Europe during the late 1800s, following the development of fully-corrected optical microscopes (Stoermer and Smol, 1999). By 1902, researchers with the Royal Institute for Water Supply and Sewage Disposal in Germany had introduced the term "saprobia" for organisms with "dependence on decomposing organic nutrients," and classified more than 250 algal species into indicator categories of oligosaprobia, mesosaprobia, and polysaprobia along a gradient of nutrient and organic enrichment (Kolkwitz and Marrson, 1908). The "saprobien system" approach has often been criticized and (or) refined during the past 100 years (for example, Hustedt, 1938-39; Cholnoky, 1968; Palmer, 1969; Lange-Bertalot, 1978, 1979; Sladecek, 1986). However, saprobien algal metrics continue to persist in recent autecological literature (Lowe, 1974; Lange-Bertalot, 1979; VanLandingham, 1982; van Dam and others, 1994) and serve as the foundation for algal metrics indicating “pollution tolerance” (for example, Palmer, 1969; Bahls, 1993) and tolerance to low dissolved-oxygen concentrations (Lowe, 1974; van Dam and others, 1994).

Classification of algal species relative to stream trophic condition and nitrogen-uptake metabolism (consult van Dam and others, 1994) is closely related to the saprobien system. The trophic state of lakes and reservoirs traditionally has been described in relation to concentrations of inorganic nitrogen and phosphorus and (or) algal biomass (for example, Naumann, 1921; Smith, 1966; Hutchinson, 1967; Round, 1981; Reynolds, 1984). Previous summaries of trophic-state autecology have relied on a consensus approach based on the number of published reports of taxa predominant in oligotrophic, mesotrophic, or eutrophic lakes. Many algal-taxonomic references (such as Prescott, 1962; Patrick and Reimer, 1966; Wehr and Sheath, 2003) provide descriptive autecological information for some algal species, such as “common in eutrophic lakes and reservoirs.” Experimental evidence of nutrient requirements has been reported for certain phytoplankton species that can be maintained in laboratory cultures (such as Tilman, 1977, 1982; Tilman and others, 1982); however, data are too sparse to allow assignment of experimentally-derived indicator values to many species. Nitrogen-heterotrophic algae have the ability to use simple organic compounds such as amino acids for nutrition and as an energy source to supplement photosynthesis (Cholnoky, 1968; Hellebust and Lewin, 1977; Tuchman, 1996). Thus, the relative abundance of nitrogen heterotrophs can be used as an indicator of organic nitrogen compounds and (or) reduced light availability.

Nitrogen-fixing algae are able to use dissolved atmospheric nitrogen (N_2) as a nutrient source (Fogg and others, 1973; Komarek and others, 2003); these taxa can form large populations in streams when dissolved nitrogen concentrations (or ratios of nitrogen to phosphorus) are low (Fairchild and Lowe, 1984; Fairchild and others, 1985; Peterson and Grimm, 1992; Lowe, 2003). Nitrogen fixation traditionally has been associated with filamentous blue-green algae (cyanobacteria) containing heterocytes (specialized cells that fix N_2 under anaerobic conditions). More recent research (Geitler, 1977; Floener and Bothe, 1980; DeYoe and others, 1992) indicates that certain diatoms (order Rhopalodiales) contain endosymbiotic, coccoid cyanobacteria (lacking heterocytes) that also are capable of nitrogen fixation. Paerl and Bebout (1988) reported nitrogen fixation in marine populations of *Oscillatoria* (also lacking heterocytes). Although heterocytous cyanobacteria, *Epithemia*, and *Rhopalodia* have a demonstrated capability to fix N_2, improved classification of other potential nitrogen-fixing taxa will require additional physiological research.

Classification of dissolved oxygen (DO) requirements or tolerance is based primarily on modifications to the saprobien system developed by Hustedt (1938–39) and Cholnoky (1968). The classification presumes that polysaprobic conditions (for example, heterotrophic streams with gross organic enrichment, high biochemical oxygen demand (BOD), and persistently low DO concentrations) would restrict algal taxa to those that can tolerate these conditions, whereas algal communities in oligosaprobic systems (for example, autotrophic streams with little organic enrichment, low BOD, and DO concentrations near saturation) would be dominated by species associated with continuously high DO concentrations (consult van Dam and others, 1994). Algal-taxonomic references occasionally report descriptive information for certain species such as “occurring in well-oxygenated streams.” The oxygen-requirements metric may not correlate well with DO concentrations measured in eutrophic, lentic streams characterized by large concentrations of dissolved nutrients but relatively little indication of organic enrichment because of considerable diel variability of DO concentrations associated with primary productivity. Measurements obtained at the time of sampling, particularly during the afternoon, may not have reflected ambient DO conditions during the time of algal colonization and growth. Porter and others (2008) reported that the abundance of taxa with continuously high DO requirements decreased significantly with increases in nutrient and suspended-sediment concentrations.

Major Ions and pH

Algal communities, notably diatoms, are known to respond along salinity and specific conductance (conductivity) gradients (Kolbe, 1927; Patrick, 1948; Lowe, 1974; Blinn, 1993; van Dam and others, 1994). Halophilic algae include taxa with extraordinary capability of osmoregulation, notably those taxa that occur in coastal estuarine settings where salinity or conductivity may vary considerably over a tidal cycle. The original halobien system (Kolbe, 1927) focused on chloride concentrations in marine, brackish, and fresh waters; however, subsequent research (for example, Carpelan, 1978; Hammer, 1978, 1986; Blinn, 1993) has illustrated the importance of other major anions in inland waters, such as sulfate and bicarbonate. The abundance of halophilic algae has been used to assess the influence of winter road deicing in northern freshwater systems (Dickman and Gochnauer, 1978; Hoffman and others, 1981; Tuchman and others, 1984), and as indicators of hydrologic and climatic change in lakes and wetlands (see review by Fritz and others, 1999). Porter and others (2008) reported that the abundance of halophilic diatoms also increased significantly with concentrations of nutrients and suspended sediment.

Although calcium and magnesium are not known to be limiting to algal growth, major differences in algal species (and overall algal productivity) among physiographic regions often are highly correlated with concentrations of these elements (or related properties such as alkalinity or hardness), probably because of the association with bicarbonate ions that provide a supplemental supply of carbon dioxide for photosynthesis (Smith, 1950) and the importance of the carbonate-bicarbonate buffering system that controls pH (Hutchinson, 1967; Patrick, 1977). Considerable descriptive information is available regarding algal-species preferences for hard (alkaline) and soft (acidic) waters in algal-taxonomic references (for example, Smith, 1950; Prescott, 1962; Patrick and Reimer, 1966; Whitford and Schumacher, 1973; Wehr and Sheath, 2003), as well as other literature (for example, Camburn and Charles, 2000).

The pH spectrum derived from Hustedt (1938–39) commonly is used in recent autecological classifications of diatoms (Lowe, 1974; van Dam and others, 1994), which classify species optima along a pH gradient ranging from acidobiontic (best development below 5.5) to alkalibiontic (occurring only in alkaline water (Lowe, 1974)). Diatom indicators of pH have been used extensively in paleolimnological studies to trace the pH and acidification history of lakes (Charles and Whitehead, 1986; Charles and others, 1990; Dixit, Dixit, and Smol, 1992; Battarbee and others, 1999). In some cases, the pH spectrum may have strong correspondence with indicators of nutrient enrichment (VanLandingham, 1982). Eutrophic habitats typically are base rich, characterized by high alkalinity and pH, whereas oligotrophic habitats usually are base poor, with lower alkalinity and pH values. Diatom species indicative of elevated iron concentrations or tolerance to trace elements (Patrick and others, 1968; Patrick, 1977) typically are found in acidic, soft-water habitats because of the increased availability of trace metals in those habitats.

Microhabitat Traits

Algal taxa can be classified with regard to their specific habitat, such as planktonic (sestonic) or benthic, motility, and a variety of physiognomic characteristics (cell size, growth form, and method of attachment). Classification of microhabitat traits currently is limited to specific habitat and motility; those traits were obtained primarily from algal-taxonomic literature (identified previously) and introductory algal-biology texts (for example, Prescott, 1968; Werner, 1977; Bold and Wynne, 1978; Round, 1981). Most small, flowing streams are dominated by benthic algae; however, the percentage of sestonic algae would be expected to increase with stream size (Vannote and others, 1980; Round, 1981; Jones and Barrington, 1985), and in low-gradient, agricultural streams with high rates of metabolism (Porter, 2000). Nationally, Porter and others (2008) reported significant ($p<0.001$) positive correlations between the percentage of sestonic algae and concentrations of total phosphorus and suspended sediment. Classification of sestonic and benthic taxa is confounded by the occurrence of "tychoplanktonic" taxa that are normally associated with benthic habitats but often are found suspended in stream water.

Motile algae have the ability to move through the water column (algae with flagellae) or in association with submerged surfaces (gliding movement of raphid diatoms and certain blue-green algae). Motility provides an ecological advantage to algal cells living on unstable sediments (Round and Happey, 1965; Round and Eaton, 1966; Harper, 1969, 1977), and a "siltation index" (Bahls, 1993; Stevenson and Bahls, 1999) has been proposed based on the relative abundance of three motile diatom genera: *Navicula, Nitzschia, and Surirella*. Nationally, Porter and others (2008) reported significant positive correlations between the percentage of motile algae and concentrations of suspended sediment and nutrients.

Understanding of algal-species colonization and community-successional stages (for example, Hoagland and others, 1982; Stevenson, 1983) and physiognomy, the relative size, growth form, and method of attachment of algal species, can be applied to assessments of hydrologic disturbance (Biggs, 1995; Biggs and Thomsen, 1995; Hambrook and others, 1997; Porter, 2000; Francoeur and Biggs, 2006; Passy, 2007) and stream habitat quality (for example, Kutka and Richards, 1996). Assessments of recent hydrologic disturbance and microhabitat conditions in streams and rivers could be enhanced by the addition of physiognomic metrics to the autecological data file.

Semi-Quantitative Approaches for Evaluating Algal Species Autecology

Originally applied to paleolimnological research, weighted-averaging regression and calibration methods (Birks and others, 1990; Line and others, 1994; Juggins, 2003) increasingly have been used to quantify relations between species and various environmental variables (Kelly and Whitton, 1995; Pan and others, 1996; Leland and Porter, 2000; Winter and Duthie, 2000; Leland and others, 2001; Munn and others, 2002; Potapova and others, 2004). The weighted-average estimate of a species optimum is simply the mean of a measured environmental variable (such as total phosphorus concentration or pH) weighted by the abundance of the species in a sample data set, whereas species tolerance is the weighted standard deviation. Published optima and tolerance ranges for algal species (for example, Lowe and Pan, 1996; references cited above) vary among geographic regions and investigators, probably because of regional differences in the range of constituent (for example, nutrient) concentrations and differences in land use, geochemistry, and climate.

As part of a cooperative agreement with the NAWQA Program, scientists with the Academy of Natural Sciences of Philadelphia (ANSP) calculated national and regional diatom species-indicator values and optima and tolerance for concentrations of total nitrogen (TN) and total phosphorus (TP) (Potapova and Charles, 2007), and national optima and tolerance values for "soft" algae (algae exclusive of diatoms) (Potapova, 2005). The optima and tolerance values represent results from more than 1,000 streams and rivers sampled by the NAWQA Program during 1993–2001 using nationally consistent methods for sample collection and analysis (Porter and others, 1993; Gilliom and others, 1995; Charles and others, 2002; Moulton and others, 2002; Berkman and Porter, 2004). National results also are available for specific conductance and chloride and calcium concentrations (diatoms and soft algae; Potapova and Charles, 2003, and Potapova, 2005, respectively) and for pH and suspended-sediment concentrations (soft algae; Potapova, 2005).

Tolerant and Sensitive Species

The understanding of tolerant algal taxa is relatively good, in part because of the long history (more than 100 years) of studying algal-species distributions in polluted streams and a presumed global distribution of tolerant species. By contrast, the understanding of sensitive species in North America is relatively poor because (1) species classified as sensitive in Europe can be found commonly in impaired North American streams, (2) a number of undescribed, possibly endemic, North American diatom species appear to be sensitive and regionally distributed, and (3) autecology for many algal species (particularly soft algae) is unknown or poorly understood. The ANSP maintains an algal-image library (http://diatom.acnatsci.org/AlgaeImage/) that should be consulted for undescribed taxa (for example, *Cymbella* sp. 2 MP), particularly sensitive species with low optima for nutrient or other constituent concentrations.

Objectives and Scope

The purpose of this report is to describe the content and format of the Algal Attributes autecological data file and identify considerations for summarizing and analyzing algal-autecological data and creating water-quality metrics. The Algal Attributes data file contains published indicator values for algal metrics commonly used in water-quality assessments plus new metrics derived from NAWQA periphyton and water-chemistry data. A supporting data file is provided which links current (2006) taxonomic nomenclature with previous algal-species names. Autecological information is provided for both current and previous species names, with linkage to the ANSP's NADED (North American Diatom Ecological Database) identification system. Algal metrics indicating water-quality and stream condition can be generated easily when species listed in the autecological data file and sample data are joined in a relational data base or other data-analysis software. The goal of this work has been to facilitate water-quality assessments with algal data by providing a web-accessible compilation of autecological attributes for North American species identified from periphyton samples collected by the NAWQA Program.

Acknowledgments

The author acknowledges the contributions of the many algal ecologists whose research over the past 100 years made this autecological data file possible to compile, NAWQA biologists and their technicians for collecting the algal samples, and the Academy of Natural Sciences of Philadelphia, specifically Don Charles, Marina Potapova, and Frank Acker, for rigorous attention to algal taxonomy and ecology. Several USGS scientists provided helpful comments on algal autecology and previous versions of the autecological data file, including Julie Hambrook Berkman, Barbara Scudder, Kurt Carpenter, Mark Munn, Amanda Bell, and Tom Cuffney. Technical reviews by Julie Hambrook Berkman and Don Charles improved the quality of this report.

Methods

The Algal Attributes data file contains 28,182 records for 5,939 algal taxa representing 440 genera and consists of a matrix of metric codes organized by taxa (rows) and attribute (columns). This file is provided in tab-delimited, text file format to facilitate importing into a variety of computerized data analysis programs. Published literature citations on which the metrics are based are included in the References Cited section of this report. The 37 algal attributes and 101 metric codes are grouped into five general categories: national indicators of nutrient concentrations and trophic condition (table 1), regional indicators of nutrient concentrations and trophic condition (table 2), indicators of organic enrichment (table 3), indicators of pH, salinity, specific conductance, and chloride concentrations (table 4), and indicators of microhabitat traits, suspended-sediment, and calcium concentrations (table 5). Metric codes can be continuous; for example, trophic condition (TROPHIC) ranging along a gradient from 1 (oligotraphentic diatoms) to 6 (hypereutraphentic diatoms), or binary. Binary codes can represent the presence or absence of an attribute, such as whether or not an algal taxon is capable of fixing atmospheric N_2 (yes, NF = 1; no, NF = 2) or is a eutrophic species (yes, EUTROPHIC = 1; no, EUTROPHIC = <null>). Binary codes also are used to denote "high" and "low" water-chemistry categories; for example, diatom taxa with high or low optima for total phosphorus concentrations (high, DIATASTP = 1; low, DIATASTP = 2), and to denote different states of an attribute, such as whether a taxon is benthic or sestonic (benthic, BEN_SES = 1; sestonic, BEN_SES = 2).

Indicators of Nutrient Concentrations and Trophic Condition

Eight national (table 1) and ten regional (table 2) algal metrics are included in the autecological data file. Nitrogen-fixing algae (NF) were classified by the occurrence of heterocytes (blue-green algae) or endosymbiotic blue-green algae (certain diatom genera) known to be sites of nitrogen fixation (Geitler, 1977; Bold and Wynne, 1978; previous literature citations). Trophic condition (TROPHIC) is attributed in accordance with van Dam and others (1994), with a new combination (TR_E, eutrophic diatoms) created by combining TROPHIC Metric Codes 4 + 5 + 6. Eutrophic soft algae (algae exclusive of diatoms; EUTROPHIC_SOFT = 1) were classified in relation to basic taxonomic literature and other sources cited previously, whereas the "eutrophic algae" attribute (EUTROPHIC = 1) was based upon whether the diatom (TR_E) or soft algae (EUTROPHIC_SOFT) metric indicated eutrophic conditions. Other algal metrics listed in tables 1 and 2 were based on weighted-average (WA) optima (Potapova, 2005 [soft algae]) or a combination of indicator-species analysis (common taxa) and WA optima (relatively rare taxa; Potapova and Charles, 2007 [diatoms]) based on NAWQA data. Definitions of "high" and "low" indicator and optima categories are provided in the Metric Description columns of tables 1 and 2.

Indicators of Organic Enrichment

Six national algal metrics indicative of organic enrichment are included in table 3. The SAPROBIC, ORG_N, and OXYTOL attributes were classified in accordance with van Dam and others (1994), whereas other "pollution tolerance" metrics from central Europe (Lange-Bertalot, 1979) and North America (Bahls, 1993) were based on those literature sources. The nitrogen metabolism attribute (ORG_N) was simplified by combining van Dam's nitrogen-heterotroph metric codes 3 and 4 (table 3, metric label ON_NH), in part because of uncertainty over "facultative" and "obligate" classifications of nitrogen heterotrophy. The NUISANCE ALGAE attribute was created from the EUTROPHIC metric based on those taxa with the potential for forming nuisance growths of filamentous, benthic algae (metric code = 1) or nuisance blooms of sestonic (phytoplankton) algae (metric code = 2).

Indicators of pH, Salinity, Specific Conductance, and Chloride Concentrations

Nine national algal attributes are listed in table 4. The pH and SALINITY attributes were based upon van Dam and others (1994), whereas the other attributes in table 4 were created from WA optima for soft algae (Potapova, 2005), diatoms (Potapova and Charles, 2003), or a combination thereof (for example, NAWQA_COND and NAWQA_CL). Definitions of "high" (Metric Code = 1) and "low" (Metric Code = 2) optima are provided in the Metric Description column of table 4. van Dam's SALINITY attribute was simplified by creating a "halobiontic diatoms" metric (Metric Codes 3 + 4), resulting in three possible categories: halophobic diatoms (Metric Code 1), halophilic diatoms (Metric Code 2), and halobiontic diatoms (Metric Codes 3 + 4).

Indicators of Microhabitat Traits, Suspended Sediment, and Calcium Concentrations

BEN_SES (table 5) was based on taxonomic and related references (cited previously) in accordance with whether taxa primarily are attached to (or loosely associated with) stream-bottom habitats (including filamentous "tychoplanktonic" taxa; Metric Code = 1) or whether taxa generally are found suspended in the water column (Metric Code = 2). MOTILITY is based on whether the taxon is capable of movement through the water column or in association with submerged surfaces (motile; Metric Code = 1). Taxa attached to benthic surfaces or transported passively downstream were classified non-motile (Metric Code = 2). Classification of soft-algae optima for total suspended-sediment concentrations (SOFT_TSS) and diatom optima for calcium concentrations (DIAT_CA) are based on Potapova (2005) and Potapova and Charles (2003), respectively. Definitions of "high" and "low" optima categories are provided in the Metric Description column of table 5.

Calculating Algal Metrics

Algal metrics can be calculated in a variety of ways. A primary procedure is to create two tables by importing the Algal Attributes data file and a sample data set (species [rows] by samples [columns]) into a relational data base such as Microsoft Access. The sample data set could contain relative abundance, relative biovolume, or presence/absence data, depending on objectives of the analysis. If the sample data set does not contain TaxonID codes (= NADED ID codes) (Academy of Natural Sciences, 2008), it will be necessary to populate TaxonID codes for each species in the sample data set, using the Algal Attributes file as a reference. The TaxonID variable in the sample data set is then joined with TaxonID in the autecology table, and relational integrity is established between the two tables. A series of summation queries can be used to generate the relative abundance (or biovolume or richness [number of taxa]) for each metric code. For example, if the percentage (or richness) of "most tolerant diatoms" (table 3; POLL_CLASS, metric label: PC_MT) is a desired indicator metric, then the percentage (or count) of algal taxa with Metric Code = 1 is summed and reported as the relative abundance (or number of species) of tolerant diatoms. The relative abundance (or count) of taxa with a <null> value for Metric Code represents the percentage (or number) of taxa in a sample without an autecological classification for that attribute. The percentage of unclassified taxa can be large in some streams; this attribute should be used to help judge the efficacy of assigning a state of stream condition (for example, eutrophic or organically enriched) based on the primary algal attribute, for example, TROPHIC (table 1) or SAPROBIC (table 3).

Alternatively, the relative abundance or biovolume of species can be calculated on the basis of only classified taxa (consult Stevenson and Pan, 1999) rather than all taxa. This alternate method generates larger relative-abundance values than those calculated with all taxa in the sample results (consult Porter and others, 2008). Similarly, the abundance for diatom metrics could be relativized by the total abundance of diatoms (or only diatoms with autecological classifications); a similar case could be made for the soft-algae metrics.

Although many environmental-assessment studies have used relative abundance (less frequently, richness) to create algal metrics, relative biovolume-based metrics also should be considered for certain studies, such as eutrophication assessments of streams with large growths of filamentous algae. Biovolume accounts for differences in cell size among algal taxa; thus, a predominance of large-celled species (for example, *Cladophora*, *Rhizoclonium*, or *Hydrodictyon*) may be represented better by relative biovolume than by cell abundance.

Discussion

The Algal Attributes data file represents the most comprehensive lists of algal-species autecology currently available to North American stream ecologists. Many algal metrics are valid only at a taxonomic resolution of species or variety, and summaries of algal autecology at higher taxonomic levels (for example, genus or family) are not recommended. Other algal metrics, particularly those describing functional attributes such as nitrogen fixation, motility, and specific habitat, could be summarized at higher taxonomic levels, such as Order (for example, Nostocales or Rhopalodiales for nitrogen-fixing algae; Chlorococcales for eutrophic, sestonic algae).

Relatively recent changes in diatom and blue-green algal nomenclature (for example, Round and others, 1990; Komarek and others, 2003) have presented a challenge to aquatic scientists who have relied on previous autecological literature (and former algal-species names) to make water-quality assessments. A supporting nomenclatural data file (Algal_Attributes_Nomenclature_v9.txt) is provided that contains a list of current (2006) and former names applied to taxa identified from NAWQA samples over the past decade. Although this list was not intended to provide an extensive review of all nomenclatural changes that have occurred during the period, many commonly reported species are included. Metric codes are provided for both the current and former taxa names in the autecological data file.

Many algal metrics indicating tolerance to nutrient or organic enrichment are significantly ($p<0.001$) correlated with nutrient and suspended-sediment concentrations. Nationally, Porter and others (2008) reported 17 autecological metrics with positive correlations with one or more forms of nutrients and 19 metrics with positive correlations with suspended-sediment concentrations. These metrics include indicators of attributes other than nutrients and organic enrichment; for example, salinity (halobiontic diatoms), motility, and the percentage of sestonic algae. These results tend to indicate that autecological metrics of tolerance derived primarily in Europe can be applicable in North American streams and rivers. By contrast, only three algal-metric indicators of "sensitivity" (nitrogen-fixing algae [table 1; NF_YS], diatoms with requirements for continuously-high dissolved oxygen [table 3; OT_AH], and "less tolerant (3b) diatoms" [table 3; PT_LB]) exhibited significant negative correlations with nutrient and suspended-sediment concentrations. This may reflect differences in reference conditions and concepts of "sensitive" species in European and North American streams. Scudder and Stewart (2001) also reported significant positive correlations between the abundance of pollution-tolerant diatoms (Lange-Bertalot, 1979) and nutrient and suspended-sediment concentrations in agricultural streams of eastern Wisconsin. The abundance of sensitive diatoms was unrelated to nutrient concentrations, and was only weakly correlated (negatively) with suspended-sediment concentrations. The use of low-nutrient indicator and optima metrics derived from NAWQA data (tables 1 and 2) may provide a greater degree of accuracy than European metrics (and those derived from European metrics such as Bahls (1993)) for assessing high-quality streams with low nutrient and suspended-sediment concentrations because the metrics were derived from North American biological and water-chemistry data.

Several investigators have reported significant algal-metric responses to human-disturbance gradients. Coles and others (2004) found that the percentage of tolerant, eutrophic, nitrogen-heterotrophic, and motile diatoms increased significantly with urban intensity in coastal New England streams. Total nitrogen concentrations and specific conductance also increased with urban intensity in this study, so algal communities may have been responding along nutrient and (or) salinity gradients rather than to other factors associated with urbanization. Fore and Grafe (2002) reported that the percentage of eutrophic and nitrogen-heterotrophic diatoms in Idaho rivers increased significantly with the percentage of urban and agricultural land cover. The percentage of polysaprobic diatoms increased with urban land use, whereas the percentage of alkaliphilous diatoms increased with agricultural land uses. Peterson and Porter (2002) found that algal metrics (nitrogen-fixing algae; eutrophic and nitrogen-heterotrophic diatoms) were superior to nutrient concentrations for evaluating nonpoint-source eutrophication in the Yellowstone River basin. Nationally, Porter and others (2008) reported that median values for six primary algal metrics (ON_NH, PC_MT, TR_E, SL_HB, OT_AH, and NF_YS) in streams draining undeveloped ("reference") basins differed significantly from those in agricultural or urban streams; however, those differences did not occur uniformly in all regions of the continental United States.

Summary

Algal Attributes, a data file containing metrics indicating physiological optima or tolerance to nutrients and other water-quality constituents, was created to enhance analysis, interpretation, and understanding of trophic condition (and other water-quality conditions) in U.S. streams and rivers. The file contains over 5,900 algal taxa, including current (2006) and former species names as well as a large number of undescribed species that can be accessed via the algal-image library of the Academy of Natural Sciences of Philadelphia (*http:/diatom.acnatsci.org/AlgaeImage/*). Over 100 algal metrics can be calculated by joining TaxonID numbers in the sample and autecological tables in a relational data base and performing a series of summation queries. Qualitative algal-tolerance metrics, derived primarily from European literature sources, are highly correlated with nutrient and suspended-sediment concentrations and respond significantly along human-disturbance gradients (for example, agricultural and urban land uses) in the Untied States. The autecology of "sensitive" species, and algal metrics designed to indicate high-quality stream conditions, may differ between European and North American streams. Weighted-average regression approaches for classifying species with low water-chemistry optima (or indicators of low nutrient concentrations) based on data collected by the U.S. Geological Survey's National Water-Quality Assessment Program may be superior to existing, qualitative metrics indicating oligotrophy, sensitive, or intolerant species, or other indicators of high-quality streams in Europe. Species optima and tolerance to nutrient concentrations vary within the continental United States because of regional differences in physiography, geochemistry, climate, and land cover. Regionalized high- and low-nutrient indicator metrics (table 2) may be more accurate than national (or global) scale indicators of trophic condition.

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Data Files

(When a question mark (?) appears in the data files, it is sample specific and includes taxonomic forms where the genus or species could not be determined accurately during sample enumeration because the position of the diatom encountered on the slide was unfavorable for accurate species determination (for example, a girdle view) or the condition of the specimen was suboptimal for species determination. The taxon is designated as a distinct species (such as summaries of taxa richness); however, the determination of the correct (accurate) name was not possible for that sample or slide.)

Data file	Brief Description
Algal_Attributes_v9.txt	List of algal taxa with metrics indicating physiological optima or tolerance to nutrients and other water-quality constituents. (Tab-delimited text file; 539 Kilobytes) **NOTE**: A question mark (?) appears in the taxon name when it is included as part of the Academy of Natural Sciences of Philadelphia (ANSP) North American Diatom Ecological Database (NADED) identification (ID) coding system.
Algal_Attributes_Nomenclature_v9.txt	List of algal taxa linking current (2006) and former names, including associated ANSP NADED ID codes. (Tab-delimited text file; 69 Kilobytes) **NOTE**: When both the official ANSP taxon name and the NADED ID code included a question mark (?), a ? appears in the Nomenclature file.

Table 1. National algal-metric indicators of nutrient concentrations and trophic condition.

[>, greater than; ≥, greater than or equal to; <, less than; ≤, less than or equal to; µg/L, micrograms per liter; mg/L, milligrams per liter; NAWQA, National Water-Quality Assessment Program; NF, nitrogen-fixing algae; +, plus; TN, total nitrogen concentration; TP, total phosphorus concentration]

Attribute (number of taxa classified)	Metric Label	Reference	Metric Code	Metric Name	Metric Description
NF (5,935) [various codes]	NF_YS		1	Nitrogen-fixing algae	Taxon capable of fixing atmospheric nitrogen
	NF_NO		2	Not nitrogen-fixing algae	Taxon not capable of fixing atmospheric nitrogen
TROPHIC (719) [new combination of codes]	TR_OL	van Dam and others (1994)	1	Oligotraphentic diatoms	Oligotrophic
	TR_OM		2	Oligotraphentic-mesotraphentic diatoms	Oligotrophic-mesotrophic
	TR_MT		3	Mesotraphentic diatoms	Mesotrophic
	TR_ME		4	Mesotraphentic-eutraphentic diatoms	Mesotrophic-eutrophic
	TR_ET		5	Eutraphentic diatoms	Eutrophic
	TR_PT		6	Hypereutraphentic diatoms	Polytrophic (hypereutrophic)
	TR_EY		7	Eurytraphentic diatoms	Indifferent; wide range of tolerance to nutrients
	TR_E		4 + 5 + 6	Eutrophic diatoms	Tolerance or requirements for high nutrient concentrations
EUTROPHIC SOFT (711) [various codes]	ES_YS		1	Eutrophic soft algae	Tolerance or requirements for high nutrient concentrations
EUTROPHIC (1,038) [new combination of codes]	EUTROPHIC		1	Eutrophic algae (TR_E + EUTROPHIC SOFT)	Eutrophic algae (diatoms + soft algae)
DIATASTN (136)	DTN_HI	Potapova and Charles (2007)	1	High TN indicator (diatoms): all samples	TN > 3 mg/L or TN optima > 75th percentile (rare taxa)
	DTN_LO		2	Low TN indicator (diatoms): all samples	TN < 0.2 mg/L or TN optima < 25th percentile (rare taxa)
SOFTASTN (75)	STN_HI	Potapova (2005)	1	Total nitrogen optimum: high (soft algae): all samples	TN optima > 3 mg/L; all NAWQA samples
	STN_LO		2	Total nitrogen optimum: low (soft algae): all samples	TN optima ≤ 0.65 mg/L; all NAWQA samples
DIATASTP (149)	DTP_HI	Potapova and Charles (2007)	1	High TP indicator (diatoms): all samples	TP ≥ 100 µg/L or TP optima > 75th percentile (rare taxa)
	DTP_LO		2	Low TP indicator (diatoms): all samples	TP ≤ 10 µg/L or TP optima < 25th percentile (rare taxa)
SOFTASTP (174)	STP_HI	Potapova (2005)	1	Total phosphorus optimum: high (soft algae): all samples	TP optima ≥ 0.10 mg/L; all NAWQA samples
	STP_LO		2	Total phosphorus optimum: low (soft algae): all samples	TP optima ≤ 0.04 mg/L; all NAWQA samples

Table 2. Regional algal-metric indicators of nutrient concentrations and trophic condition.

[>, greater than; ≥, greater than or equal to; <, less than; ≤, less than or equal to; μg/L micrograms per liter; mg/L, milligrams per liter; TN, total nitrogen concentration; TP, total phosphorus concentration]

Attribute (number of taxa classified)	Metric Label	Reference	Metric Code	Metric Name[1]	Metric Description
WMTP (69)	WMTP_HI	Potapova and Charles (2007)	1	High TP indicator (diatoms): western mountain region	TP ≥ 100 μg/L or TP optima > 75th percentile (rare taxa)
	WMTP_LO		2	Low TP indicator (diatoms): western mountain region	TP ≤ 10 μg/L or TP optima < 25th percentile (rare taxa)
WMTN (73)	WMTN_HI	Potapova and Charles (2007)	1	High TN indicator (diatoms): western mountain region	TN ≥ 3 mg/L or TN optima > 75th percentile (rare taxa)
	WMTN_LO		2	Low TN indicator (diatoms): western mountain region	TN ≤ 0.2 mg/L or TN optima < 25th percentile (rare taxa)
WPTP (84)	WPTP_HI	Potapova and Charles (2007)	1	High TP indicator (diatoms): central and western plains region	TP ≥ 100 μg/L or TP optima > 75th percentile (rare taxa)
	WPTP_LO		2	Low TP indicator (diatoms): central and western plains region	TP ≤ 10 μg/L or TP optima < 25th percentile (rare taxa)
WPTN (96)	WPTN_HI	Potapova and Charles (2007)	1	High TN indicator (diatoms): central and western plains region	TN ≥ 3 mg/L or TN optima > 75th percentile (rare taxa)
	WPTN_LO		2	Low TN indicator (diatoms): central and western plains region	TN ≤ 0.2 mg/L or TN optima < 25th percentile (rare taxa)
GNTP (58)	GNTP_HI	Potapova and Charles (2007)	1	High TP indicator (diatoms): glaciated north region	TP ≥ 100 μg/L or TP optima > 75th percentile (rare taxa)
	GNTP_LO		2	Low TP indicator (diatoms): glaciated north region	TP ≤ 10 μg/L or TP optima < 25th percentile (rare taxa)
GNTN (70)	GNTN_HI	Potapova and Charles (2007)	1	High TN indicator (diatoms): glaciated north region	TN ≥ 3 mg/L or TN optima > 75th percentile (rare taxa)
	GNTN_LO		2	Low TN indicator (diatoms): glaciated north region	TN ≤ 0.2 mg/L or TN optima < 25th percentile (rare taxa)
EPTP (98)	EPTP_HI	Potapova and Charles (2007)	1	High TP indicator (diatoms): eastern plains region	TP ≥ 100 μg/L or TP optima > 75th percentile (rare taxa)
	EPTP_LO		2	Low TP indicator (diatoms): eastern plains region	TP ≤ 10 μg/L or TP optima < 25th percentile (rare taxa)
EPTN (97)	EPTN_HI	Potapova and Charles (2007)	1	High TN indicator (diatoms): eastern plains region	TN ≥ 3 mg/L or TN optima > 75th percentile (rare taxa)
	EPTN_LO		2	Low TN indicator (diatoms): eastern plains region	TN ≤ 0.2 mg/L or TN optima < 25th percentile (rare taxa)
EHTP (68)	EHTP_HI	Potapova and Charles (2007)	1	High TP indicator (diatoms): eastern highlands region	TP ≥ 100 μg/L or TP optima > 75th percentile (rare taxa)
	EHTP_LO		2	Low TP indicator (diatoms): eastern highlands region	TP ≤ 10 μg/L or TP optima < 25th percentile (rare taxa)
EHTN (80)	EHTN_HI	Potapova and Charles (2007)	1	High TN indicator (diatoms): eastern highlands region	TN ≥ 3 mg/L or TN optima > 75th percentile (rare taxa)
	EHTN_LO		2	Low TN indicator (diatoms): eastern highlands region	TN ≤ 0.2 mg/L or TN optima < 25th percentile (rare taxa)

[1] Metric Names are defined in Potapova and Charles (2007)

Table 3. Algal-metric indicators of organic enrichment.

[BOD, biochemical oxygen demand; DO, dissolved oxygen; O_2, dissolved oxygen; <, less than; >, greater than; µg/L, micrograms per liter; mg/L, milligrams per liter; N, nitrogen; +, plus]

Attribute (number of taxa classified)	Metric Label	Reference	Metric Code	Metric Name	Metric Description
SAPROBIC (713)	SP_OL	van Dam and others (1994)	1	Oligosaprobous diatoms	class: I, I-II; O_2 saturation: >85%; BOD$_5$ (mg/L): < 2
	SP_BM		2	β–mesosaprobous diatoms	class: II; 0_2 saturation: 70-80%; BOD$_5$ (mg/L): 2-4
	SP_AM		3	α–mesosaprobous diatoms	class: III; 0_2 saturation: 25-70%; BOD$_5$ (mg/L): 4-13
	SP_AP		4	α-meso/polysaprobous diatoms	class: III-IV; 0_2 saturation: 10-25%; BOD$_5$ (mg/L): 13-22
	SP_PS		5	Polysaprobous diatoms	class: IV; 0_2 saturation: <10%; BOD$_5$ (mg/L): >22
ORG_N (644) [new combination of codes]	ON_AL	van Dam and others (1994)	1	N autotrophic diatoms - low organic N	taxa generally intolerant to organically-bound nitrogen (OBN)
	ON_AH		2	N autotrophic diatoms - high organic N	taxa tolerant to OBN
	ON_HF		3	N heterotrophic diatoms - high organic N (facultative)	taxa requiring periodic elevated concentrations of OBN
	ON_HO		4	N heterotrophic diatoms - high organic N (obligate)	taxa indicative of elevated concentrations of OBN
	ON_NH		3 + 4	N heterotrophic diatoms	taxa indicative of elevated concentrations of OBN
POLL_CLASS (705)	PC_MT	Bahls (1993)	1	Most tolerant diatoms	very tolerant to nutrient and organic enrichment
	PC_LT		2	Less tolerant diatoms	somewhat tolerant to nutrient and organic enrichment
	PC_SN		3	Sensitive diatoms	sensitive to nutrient and organic enrichment
POLL_TOL (122)	PT_VT	Lange-Bertalot (1979)	1	Very tolerant (1) diatoms	polysaprobic: extremely degraded conditions
	PT_TA		2	Tolerant (2a) diatoms	alpha-meso/polysaprobic: highly degraded conditions
	PT_TB		3	Tolerant (2b) diatoms	alpha-mesosaprobic: degraded conditions
	PT_LA		4	Less tolerant (3a) diatoms	beta-mesosaprobic: somewhat degraded conditions
	PT_LB		5	Less tolerant (3b) diatoms	oligosaprobic: low amounts of organic enrichment
OXYTOL (644)	OT_AH	van Dam and others (1994)	1	diatom oxygen tolerance: always high	nearly 100% DO saturation
	OT_FH		2	diatom oxygen tolerance: fairly high	> 75% DO saturation
	OT_MD		3	diatom oxygen tolerance: moderate	> 50% DO saturation
	OT_LW		4	diatom oxygen tolerance: low	> 30% DO saturation
	OT_VL		5	diatom oxygen tolerance: very low	about 10% DO saturation or less
NUISANCE ALGAE (175) [various codes]	NU_BB		1	benthic algal bloom producers	benthic algal bloom producers
	NU_SB		2	sestonic algal bloom producers	sestonic algal bloom producers

Table 4. Algal-metric indicators of pH, salinity, specific conductance, and chloride concentrations.

[~, approximately equal to; >, greater than; <, less than; µg/L, micrograms per liter; µS/cm, microsiemens per centimeter; meq/L, milliequivalents per liter; mg/L, milligrams per liter; ppt, parts per thousand; +, plus]

Attribute (number of taxa classified)	Metric Label	Reference	Metric Code	Metric Name	Metric Description
pH (936)	PH_AB	van Dam and others (1994)	1	Acidobiontic diatoms	pH < 7, optimum pH < 5.5
	PH_AP		2	Acidophilous diatoms	pH < 7, optimum pH < 7
	PH_CN		3	Circumneutral diatoms	pH around 7
	PH_LP		4	Alkaliphilous diatoms	pH > 7, optimum pH ~ 7
	PH_LB		5	Alkalibiontic diatoms	pH > 7, optimum pH > 7
	PH_IN		6	Indifferent diatoms	indifferent; wide range of tolerance to pH
SOFT_PH (229)	SPH_AB	Potapova (2005)	1	Acidobiontic (soft algae)	pH optima < 6.5
	SPH_AP		2	Acidophilous (soft algae)	6.5 > pH optimum > 7.0
	SPH_CN		3	Circumneutral (soft algae)	7.1 > pH optimum > 7.5
	SPH_LP		4	Alkaliphilous (soft algae)	7.6 > pH optimum > 8.0
	SPH_LB		5	Alkalibiontic (soft algae)	pH optima > 8.0
SALINITY (880) [new combination of codes]	SL_FR	van Dam and others (1994)	1	Freshwater diatoms	< 100 mg/L chloride; < 0.2 ppt salinity
	SL_FB		2	Fresh-brackish water diatoms	< 500 mg/L chloride; < 0.9 ppt salinity
	SL_BF		3	Brackish-freshwater diatoms	500 - 1000 mg/L chloride; 0.9 - 1.8 ppt salinity
	SL_BR		4	Brackish water diatoms	1000 - 5000 mg/L chloride; 1.8 - 9.0 ppt salinity
	SL_HB		3 + 4	Halobiontic diatoms	Tolerance or requirements for dissolved salts

Table 4. Algal-metric indicators of pH, salinity, specific conductance, and chloride concentrations.—Continued

[~, approximately equal to; >, greater than; <, less than; µg/L, micrograms per liter; µS/cm, microsiemens per centimeter; meq/L, milliequivalents per liter; mg/L, milligrams per liter; ppt, parts per thousand; +, plus]

Attribute (number of taxa classified)	Metric Label	Reference	Metric Code	Metric Name	Metric Description
DIATCOND (327)	DCOND_HI	Potapova and Charles (2003)	1	Specific conductance optimum: high (diatoms)	Specific conductance optima > 500 µS/cm
	DCOND_LO		2	Specific conductance optimum: low (diatoms)	Specific conductance optima < 200 µS/cm
SOFTCOND (106)	SCOND_HI	Potapova (2005)	1	Specific conductance optimum: high (soft algae)	Specific conductance optima > 500 µS/cm
	SCOND_LO		2	Specific conductance optimum: low (soft algae)	Specific conductance optima < 200 µS/cm
NAWQA_COND (431) [new combination of codes]	NCOND_HI		1	Specific conductance optimum: high (diatoms + soft algae)	Specific conductance optima > 500 µS/cm
	NCOND_LO		2	Specific conductance optimum: low (diatoms + soft algae)	Specific conductance optima < 200 µS/cm
DIAT_CL (497)	DCL_HI	Potapova and Charles (2003)	1	Chloride optimum: high (diatoms)	Chloride optima > 35 mg/L [0.987 meq/L]
	DCL_LO		2	Chloride optimum: low (diatoms)	chloride optima < 15 mg/L [0.423 meq/L]
SOFT_CL (97)	SCL_HI	Potapova (2005)	1	Chloride optimum: high (soft algae)	Chloride optima > 35 mg/L [0.987 meq/L]
	SCL_LO		2	Chloride optimum: low (soft algae)	Chloride optima < 15 mg/L [0.423 meq/L]
NAWQA_CL (593) [new combination of codes]	NCL_HI		1	Chloride optimum: high (diatoms + soft algae)	Chloride optima > 35 mg/L [0.987 meq/L]
	NCL_LO		2	Chloride optimum: low (diatoms + soft algae)	Chloride optima < 15 mg/L [0.423 meq/L]

Table 5. Algal-metric indicators of microhabitat traits, suspended-sediment, and calcium concentrations.

[>, greater than; <, less than; mg/L, milligrams per liter; meq/L, milliequivalents per liter; TSS, total suspended sediment]

Attribute (number of taxa classified)	Metric Label	Reference	Metric Code	Metric Name	Metric Description
BEN_SES (5,023) [various codes]	BS-BE		1	Benthic alge	Primarily or exclusively associated with benthic substrates
	BS-SE		2	Sestonic algae	Primarily or exclusively sestonic (planktonic taxa)
MOTILITY (5,694) [various codes]	MT_YS		1	Motile algae	Taxa capable of movement in water or on submerged surfaces
	MT_NO		2	Non-motile algae	Taxa without capability of movement
SOFT_TSS (97)	STSS_HI	Potapova (2005)	1	Suspended-sediment optimum: high (soft algae)	TSS optima > 70 mg/L
	STSS_LO		2	Suspended-sediment optimum: low (soft algae)	TSS optima < 15 mg/L
DIAT_CA (340)	DCA_HI	Potapova and Charles (2003)	1	Calcium optimum: high (diatoms)	Calcium optima > 40 mg/L [2.0 meq/L]
	DCA_LO		2	Calcium optimum: low (diatoms)	Calcium optima < 12 mg/L [0.6 meq/L]