

## Incorporating Traits in Aquatic Biomonitoring to Enhance Causal Diagnosis and Prediction

Joseph M Culp,<sup>†,‡,\*</sup> David G Armanini,<sup>‡</sup> Michael J Dunbar,<sup>§</sup> Jessica M Orlofske,<sup>‡</sup> N LeRoy Poff,<sup>||</sup>  
Amina I Pollard,<sup>#</sup> Adam G Yates,<sup>††</sup> and Grant C Hose<sup>‡‡</sup>

<sup>†</sup>Environment Canada, NWRI, University of New Brunswick, 10 Bailey Drive, Fredericton, NB, Canada E3B 5A3

<sup>‡</sup>Canadian Rivers Institute and Department of Biology, University of New Brunswick, Fredericton, Canada

<sup>§</sup>Centre for Ecology and Hydrology, Wallingford, United Kingdom

<sup>||</sup>Colorado State University, Fort Collins, Colorado, USA

<sup>#</sup>US Environmental Protection Agency, Office of Research and Development, Washington, District of Columbia, USA

<sup>††</sup>Environment Canada, CCIW, Burlington, Ontario, Canada

<sup>‡‡</sup>Macquarie University, Sydney, Australia

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### EDITOR'S NOTE

This is 1 of 5 papers reporting on the results of a SETAC technical workshop entitled “Traits-based Ecological Risk Assessment (TERA): Realizing the potential of ecoinformatics approaches in ecotoxicology,” held 7–11 September 2010, in the Canadian Centre for Inland Waters, Burlington, Ontario, Canada, to evaluate the potential of traits-based ecological risk assessment among experts of different fields of biomonitoring and environmental risk assessment.

### ABSTRACT

The linkage of trait responses to stressor gradients has potential to expand biomonitoring approaches beyond traditional taxonomically based assessments that identify ecological effect to provide a causal diagnosis. Traits-based information may have several advantages over taxonomically based methods. These include providing mechanistic linkages of biotic responses to environmental conditions, consistent descriptors or metrics across broad spatial scales, more seasonal stability compared with taxonomic measures, and seamless integration of traits-based analysis into assessment programs. A traits-based biomonitoring approach does not require a new biomonitoring framework, because contemporary biomonitoring programs gather the basic site-by-species composition matrices required to link community data to the traits database. Impediments to the adoption of traits-based biomonitoring relate to the availability, consistency, and applicability of existing trait data. For example, traits generalizations among taxa across biogeographical regions are rare, and no consensus exists relative to the required taxonomic resolution and methodology for traits assessment. Similarly, we must determine if traits form suites that are related to particular stressor effects, and whether significant variation of traits occurs among allopatric populations. Finally, to realize the potential of traits-based approaches in biomonitoring, a concerted effort to standardize terminology is required, along with the establishment of protocols to ease the sharing and merging of broad, geographical trait information. *Integr Environ Assess Manag* 2011;7:187–197. © 2010 SETAC

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### INTRODUCTION

Biomonitoring uses biota to assess the ecological condition of the environment and has traditionally incorporated the taxonomic composition of communities as an indicator of ecological change. Following this assessment process, samples are collected from potentially impacted and reference sites, identified, and enumerated. Differences in taxonomic composition among samples are then compared quantitatively using various multivariate and metric approaches to infer the level of impairment (Figure 1). Here, species identity serves as a surrogate for the suite of attributes that a species possesses, with these attributes influenced by environmental conditions and evolutionary processes. An unstated assumption of this approach is that the presence of a species (or more specifically, a population) indicates that it possesses the attributes or “traits” necessary to cope with environmental conditions at a site (Southwood 1977).

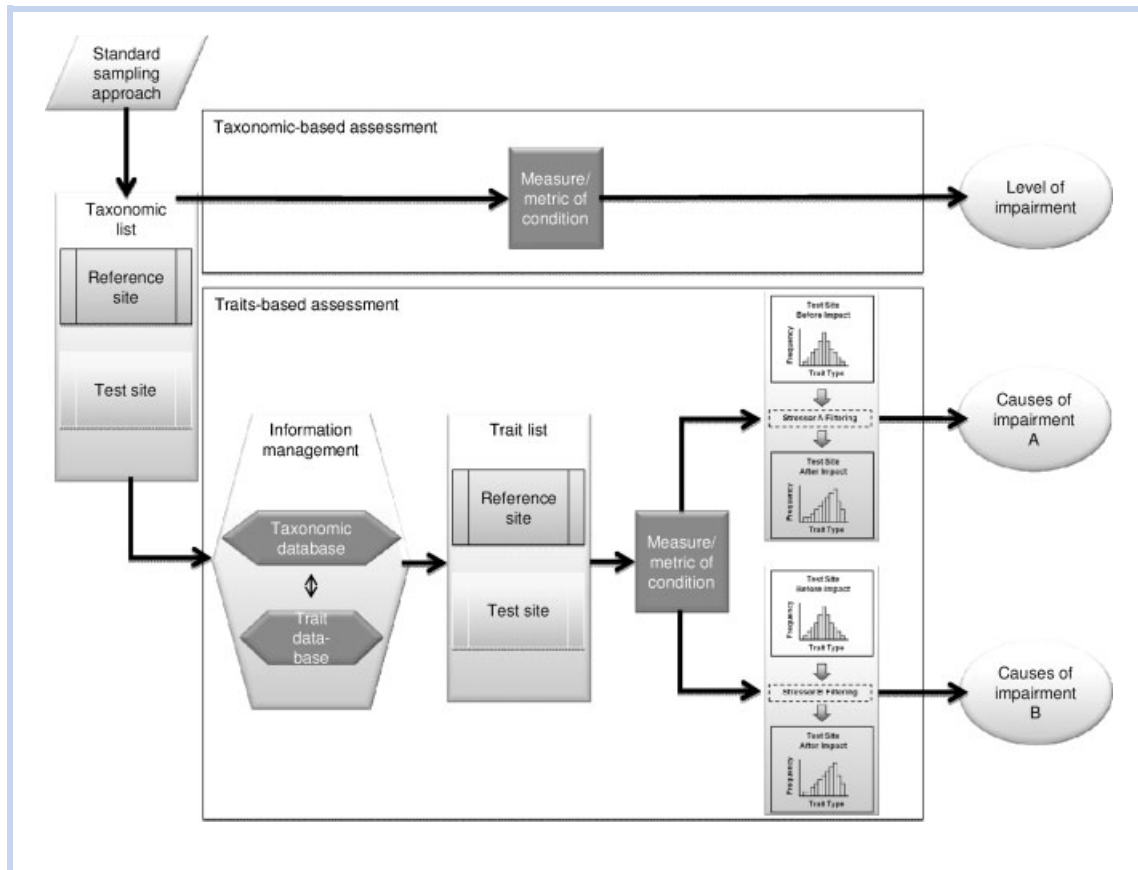
Alternatively, the traits of taxa present at a site can be used to indicate environmental conditions, and further, to infer mechanisms by which the community composition is shaped. In this article we use traits as defined by McGill et al. (2006), where traits are a measurable property of an organism, such as body size, longevity, or feeding guild (Table 1), usually measured in individuals and applied comparatively across species and at broad geographic scales. The use of traits to indicate causal mechanisms is possible because after stressor exposure, traits distribution at the impacted site is predicted to shift relative to the reference site (Figure 2); see Rubach et al. (2011) for a framework that links traits to toxic effects. Thus, traits that impart resistance or resilience to the stressor are conserved in a population. This filtering of traits by environmental stressors may allow biomonitoring approaches to yield mechanistic understanding rather than our current ability to observe only that ecological change has occurred. This novel approach allows improvement to the standard biomonitoring approach by linking the taxonomic data to the traits of the taxa identified. Differences in the traits of taxa in samples can then be used to generate traits-based (in addition to taxonomically based) metrics of the level of impairment,

\* To whom correspondence may be addressed: joseph.culp@ec.gc.ca

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**Figure 1.** Traditional taxonomically based bioassessment approaches involve collecting samples from potentially impacted and reference sites, identifying the organisms in those samples, and deriving a metric from the differences in the compositions. Linking traits databases to the taxonomic data allows comparison of reference and impacted sites on the basis of the traits of organisms in those samples. This approach not only provides additional metrics on the level of impairment but can also allow diagnosis of the cause of impairment.

and to diagnose the causes of impairment (Figure 1). Finally, the use of traits-based approaches in biomonitoring has the potential to strengthen causal weight-of-evidence approaches (Culp et al. 2000; Lowell et al. 2000; Suter et al. 2002) if specific traits or suites of traits can be linked to stressor effects through plausible cause and effect mechanisms.

The aim of this article is to highlight how including traits within existing biomonitoring programs can improve assessment sensitivity and prediction, and provide insight into the mechanisms causing that change. Specifically, the objectives are to:

1. Describe how traits have been used previously in biomonitoring
2. Outline the benefits of traits-based approaches in biomonitoring
3. Describe the challenges (opportunities and limitations) in incorporating trait information into biomonitoring
4. Describe the availability, consistency, and applicability of existing trait data

In addressing these objectives we focus on our experiences in stream biomonitoring applied to benthic macroinvertebrates, because these systems have been the basis for significant conceptual development related to biomonitoring (Rosenberg and Resh 1993). However, a robust method for bioassessment should integrate multiple levels of biological organization, so where appropriate, we provide examples and references to

other biological groups and ecosystems to demonstrate the broader applicability of these ideas.

This article is based on output from the SETAC Workshop, Traits-based Ecological Risk Assessment (TERA): Realizing the Potential of Ecoinformatics Approaches in Ecotoxicology, held 7–11 September 2009 in Burlington, ON, Canada. It is the third of 5 articles resulting from this workshop. We build upon the traits hypotheses developed by Rubach et al. (2011) for ecological risk assessment (ERA) of toxic chemical stressors by providing an evaluation of how traits approaches can benefit bioassessment of other environmental stressors (such as nutrients, sediments, and flow). The fourth article in this series, by van den Brink et al. (2011), discusses the application of these hypotheses for ERA and bioassessment, and further identifies challenges and benefits of traits-based approaches. Finally, Baird et al. (2011) discuss data needs and novel approaches for producing traits databases.

#### A BRIEF HISTORY OF TRAITS IN BIOMONITORING

The use of trait information in biomonitoring is not new. Attributes of the biota collected have long been used, usually post hoc, to explain patterns in biomonitoring metrics (for example, the absence of filter-feeding organisms following sedimentation of aquatic habitats). However, this application of traits information has not been articulated as a traits-based approach, but has been ad hoc, and often dependent on the biological knowledge of the analyst. Formalizing the use of traits in biomonitoring will provide guidance to all users and

**Table 1.** Selected freshwater examples of algae, aquatic plants, zooplankton, benthic invertebrates, and fish that demonstrate trait–stressor linkages to several common environmental stressors

Taxa group	Stressor	Trait	Trait–stressor linkage	Reference
Algae	Nutrients	Cell size	Cell size varies with trophic status	Seip and Reynolds (1995)
	Water movement	Development rate	Faster cell division in moving water	Reynolds (1994)
Aquatic plants	Nutrients	Growth rate	Species with highest relative growth rate most sensitive to nutrient stress	Shiple and Keddy (1988)
	Flood disturbance	Vegetative dispersal	Type of vegetative reproduction affects recolonization rate	Henry et al. (1996)
Zooplankton	Predation	Diapause stage	Copepods enter diapause to avoid fish	Hairston and Walton (1986)
	Predation	Body size	Zooplankton size decreases in presence of predators	Brooks and Dodson (1965)
Benthic invertebrates	Deposited sediments	Clinger habit	Decreased abundance with increased sediment	Pollard and Yuan (2010)
	Channel reconfiguration	Mobility and development	Higher mobility and more rapid development with channel disturbance	Tullos et al. (2009)
Fish	Hydrologic variability	Body shape	Abundance of deep-bodied fish increases with greater hydrological stability	Poff and Allan (1995)
	Habitat	Invertivores	Decreased abundance with reduced habitat quality	Goldstein and Meador (2005)

add greater sensitivity and diagnostic power for biomonitoring programs.

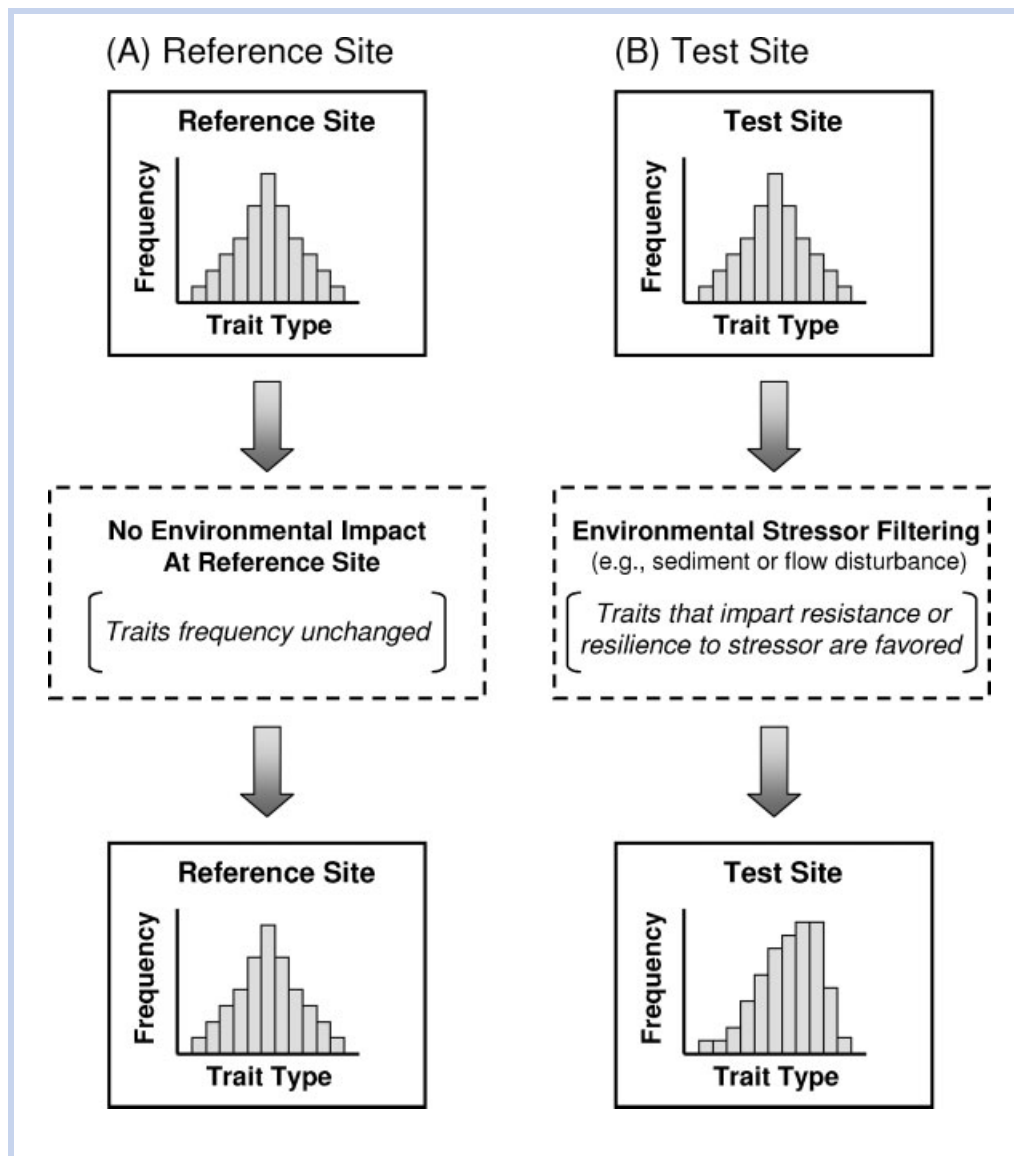
The concept of biomonitoring in rivers is attributed to Kolkwitz and Marsson (1909), whose Saprobien System assessed organic contamination in German rivers. Observations of taxa restricted to polluted or unpolluted locations led to the classification of taxa based on the empirically defined trait of pollution sensitivity, thereby providing the first trait-based assessment of stream condition. Although the Saprobien System is not used widely now (Friedrich 1990), the notion of using organism tolerance to assess environmental conditions underpins many current biomonitoring methodologies.

The science of biomonitoring was further developed by the groundbreaking work of Ruth Patrick, who in the 1930s began the practice of using biota, including diatoms, invertebrates, and fish, as indicators of environmental conditions, particularly those related to pollution effects (Patrick 1949). A subsequent shift in ecological thinking toward equilibrium theory and diversity saw diversity indices (Shannon 1948; Margalef 1958; Cairns and Dickson 1971; Washington 1984) emerging as a tool for ecosystem assessment. Thereafter, indices emerged combining the Saprobien style, tolerance of taxa, and the abundance and diversity of those taxa. This began with the Trent biotic index (Woodiwiss 1964) for macroinvertebrates in the United Kingdom, with similar indices subsequently developed for broader application in the United Kingdom (BMWP score,

Armitage et al. 1983), North America (Hilsenhoff's index, Hilsenhoff 1987, 1988), Australia (SIGNAL Index, Chessman 1995, 2003), and elsewhere, and for other taxonomic groups (protozoa, Jiang 2006; diatoms, Kelly and Whitton 1995). Like the earlier Saprobien System, these newer indices are principally based on the trait of taxa sensitivity or tolerance to particular stressors.

Growing interest in environmental assessment combined with increasing computational capacity led to the emergence of multimetric and multivariate predictive models for bioassessment. The development and formalization of multimetric approaches for fish (IBI, Karr 1981) and macroinvertebrates (RBP, Plafkin et al. 1989) encouraged the development of nontaxonomic traits-based metrics, particularly those relating to functional, trophic, or ecological characteristics of the biota (such as feeding guild or life history). In contrast, most multivariate models that predict a reference condition from environmental variables assess impairment through metrics derived from the taxonomic composition of assemblages (RIVPACS, Wright et al. 1993; AUSRIVAS, Simpson and Norris 2000). Although these methods remain focused on taxonomic composition of assemblages, they provide a simple platform for the inclusion of trait information, allowing comparisons of traits between predicted and observed assemblages.

Recognizing the influence of environmental conditions on the selection and expression of organism traits (Southwood



**Figure 2.** Conceptual diagram that compares the frequency distribution of species traits at reference (A) and test (B) sites. After exposure to a stressor, traits at the test site are modified, or filtered, such that traits that impart resistance or resilience to the stressor are favored. This results in a shift in the frequency distribution of species traits at the test site relative to the reference distribution.

1977; Townsend and Hildrew 1994; Poff 1997) led to the definition of a wider array of morphological, ecological, and life history traits. Research by Statzner and his colleagues (Dolédec and Statzner 1994; Dolédec et al. 1999; Statzner et al. 2001) has explored the relationships among this more diverse set of macroinvertebrate trait data and properties of stream systems on various spatial and temporal scales. This work provides ecological background and support for the adoption of trait information for biomonitoring (Statzner and Bêche 2010) and has also contributed to a broader ecological understanding, with traits-based models underpinning current paradigms in stream ecology (including the River Continuum Concept, Vannote et al. 1980).

Finally, the development of the SPEcies At Risk (SPEAR) method (Liess and Von der Ohe 2005; Beketov et al. 2009) represents an important development in traits-based biomonitoring because it incorporates various traits of macroinvertebrate taxa into a metric reflecting ecological condition. These traits combine sensitivity to toxicants,

generation time, migration ability, and presence of aquatic stages to produce a metric of the proportion of sensitive species (termed “species at risk”) at a test site (Liess and Von der Ohe 2005). The SPEAR method has benefited from the support of reasonably detailed toxicity databases, which has allowed it to be applied to a range of stressors and consequently to have stressor specificity. Rubach et al. (2011) further develop the framework of associating chemical-specific mode of action with trait sensitivity by using the population vulnerability conceptual model of Van Straalen (1994), in which vulnerability is determined by traits linked to external exposure, intrinsic sensitivity, and population sustainability.

#### BENEFITS OF USING TRAITS IN BIOMONITORING

The linkage of trait responses to stressor gradients has the potential to expand biomonitoring beyond traditional taxonomically based assessments that identify ecological effect to causal diagnosis assessments. Research to develop

an empirical framework for such diagnoses is under way and already suggests that traits-based information may have several advantages over taxonomically based methods. These advantages include:

- 1) The ability to provide mechanistic linkages of biotic responses to environmental condition and improve sensitivity
- 2) Consistent descriptors or metrics across broad spatial scales
- 3) More seasonal and interannual stability compared with taxonomic measures
- 4) The ability to seamlessly integrate traits-based analysis into current assessment programs
- 5) Greater utility of biomonitoring outputs in ecological risk assessment (van den Brink et al. 2011)

Incorporation of a traits-based approach in biomonitoring presents the possibility of developing a mechanistic framework linking the occurrence and distribution of traits in ecological communities to environmental or stressor gradients (Pollard and Yuan 2010). This approach is based on sound theoretical constructs developed over the past 30y by Southwood (1977), Townsend and Hildrew (1994), Statzner et al. (2001), and Poff et al. (2006), with trait information broadly available for both terrestrial and aquatic organisms (Poff 1997). In freshwater ecosystems, traits have been articulated for many taxonomic groups. Furthermore, traits of many aquatic organisms, ranging from algae to fish, have been mechanistically linked to environmental stressors, including nutrients, sediments, temperature, habitat restoration, and predation.

Table 1 provides selected examples of aquatic organisms to demonstrate several environmental stressor effects that may be diagnosed through the analysis of trait expression. For example, Henry et al. (1996) could predict the order of macrophyte species reestablishment following sediment-scouring floods by considering the trait modalities associated with vegetative dispersal (presence of nonsubterranean vegetative organs and stem fragment regeneration). Traits favored in disturbed habitats also were central to the argument of Tullos et al. (2009) that functional trait analysis may improve expectations for the duration and trajectory of macroinvertebrate recovery following stream channel restoration. Additionally, Poff and Allan (1995) found that among other fish traits, body shape was significantly related to hydrologic stability of streams in Minnesota and Wisconsin. While not an exhaustive listing of trait–stressor linkages, the summary in Table 1 supports the contention that trait responses to stressor gradients have the potential to move biomonitoring approaches beyond simple quantitative assessments that identify ecological effect, to a mechanistically based, conceptual framework that allows development of causal diagnostic tools for biomonitoring.

Traits-based approaches can provide mechanistic linkages between biotic pattern and environmental condition and may improve the sensitivity of bioassessments. Greater sensitivity is achieved because an assemblage's trait composition (sublethal changes and shifts in body size, age structure, or reproduction that occur without or prior to a loss of taxa) may demonstrate a substantive change before its taxonomic composition does. A corollary is that traits-based bioassessments may be able to detect changes in ecological condition at mildly impacted sites better than taxonomically based

assessments. Bady et al. (2005) concluded that functional diversity based on biological traits had greater accuracy and was more precise than diversity estimates based on taxonomic (genus) richness. Recent results from field studies also provide support for these hypotheses because traits were more strongly related to differences in land use (Dolédec et al. 2006) and other human-related disturbances (Dolédec et al. 1999) than was taxonomy. In these cases, the mechanistic link between traits and stressors may be useful for further interpretation of assessment results and may also provide insight regarding the causes of impairment (Figures 1 and 2). However, further refinement of trait characterization is required to better link traits to stressors in a causal manner (Carlisle and Hawkins 2008; Rubach et al. 2011; van den Brink et al. 2011).

Traits-based approaches may enhance biomonitoring by increasing the spatial applicability of reference conditions relative to taxonomic methods. This is possible because traits composition can exhibit stability across large spatial areas, such as ecoregions (Charvet et al. 2000; Statzner et al. 2005). Traits may also be more consistent than taxonomic measures in their response to individual stressor gradients across regions. Pollard and Yuan (2010) found that the percentage of aquatic invertebrates classified as clinging taxa exhibited a consistent and negative response to gradients of increasingly fine sediments across the conterminous United States. In sharp contrast, the response of the taxonomic metric, Ephemeroptera, Plecoptera and Trichoptera (EPT) richness, varied significantly among geographic regions. Similarly, biological traits appear to be more stable among seasons than taxonomic composition (Bêche et al. 2006), a quality that could potentially reduce biomonitoring sampling effort. Furthermore, using trait composition has the potential to reduce the regularity with which reference sites need to be sampled to maintain a current definition of reference condition. These temporal stability hypotheses need further testing across broader scales before final conclusions about sampling requirements can be made.

A traits-based biomonitoring approach does not require the formulation of a new biomonitoring framework; rather, traits-based approaches can be integrated into current assessment programs without additional data collection or sampling effort. This integration is possible because contemporary biomonitoring programs, using standard sampling and analytical protocols, gather the basic site-by-species composition matrices required to link community data to the traits database, and existing databases may provide the needed trait information (Figure 2). As a result, current study designs, sampling protocols, and laboratory procedures can still be used and perhaps, because of the wider geographical consistency of traits, more widely applied. Current reference condition models can also be used, because both multimetric and multivariate methods can readily incorporate traits-based information (Carlisle and Hawkins 2008). In fact, the primary addition to the framework prior to the analysis stage is the linking of the observed taxa to a database of taxa with their traits (Figure 2), a step that is already a part of some aquatic biomonitoring programs that include tolerance or functional group indices (Plafkin et al. 1989; Schmidt-Kloiber et al. 2006).

The development of traits databases will require considerable development by researchers, as discussed by Baird et al. (2011). Additionally, the use of traits may increase resource demands for biomonitoring, because taxonomic information

must be linked to functional databases to describe categorical traits (such as feeding group), and measurements of individual invertebrates may be necessary to quantitatively describe continuous traits (for example, body size). Despite the added sample processing time, the substantial advantages described above indicate that traits have the potential to be a more powerful and sensitive biomonitoring tool than taxonomic composition in all instances except programs aimed at conserving biodiversity. Finally, traits-based approaches have considerable potential to improve resource management decisions by the addition of improved diagnostic capabilities in ERA and biomonitoring (van den Brink et al. 2011).

### CHALLENGES OF INCORPORATING TRAIT INFORMATION INTO BIOMONITORING

Incorporating trait information into the existing biomonitoring framework offers several advantages as already discussed, but broad application of this approach is limited by several challenges (Statzner and Bêche 2010; van den Brink et al. 2011). These challenges reflect the character of trait data, including taxonomic and trait resolution, trait measurement, population variation of traits, and correlation among traits. In addition, we have little knowledge of how traits may be evolutionarily linked into suites related to particular stressor effects.

#### *Relationship of taxonomic and trait resolution*

Historically, most biomonitoring programs have used family (Hilsenhoff 1988; Metzeling and Miller 2001; Reynoldson et al. 2001) or genus level taxonomic resolution (Carter and Resh 2001; Jones 2008), and by extension, traits-based approaches should match this resolution. Some argue, however, that species level data may better detect ecological patterns and perturbations (Carter and Resh 2001; Lenat and Resh 2001; Jones 2008). Thus, the decision to include lower taxonomic identification and more detailed trait information in biomonitoring presents a difficult decision for practitioners. For example, increased effort and financial resources are often required to improve taxonomic resolution in biomonitoring programs (Bailey et al. 2001; Jones 2008), especially in areas where regional taxonomic knowledge is limited. Fortunately, this issue may not be a large concern for biomonitoring given that Gayraud et al. (2003) concluded that genus, and perhaps family, identifications for invertebrates may be adequate for traits-based approaches in river biomonitoring. Although it remains to be shown whether this trend holds for other taxonomic groups and ecosystems, we anticipate that increased traits resolution will improve the ability to detect a response to an environmental driver up to a threshold where higher resolution may not be cost-effective. A related discussion is whether to include or omit rare traits, but because traits composition is more temporally and spatially stable than taxonomically based analyses (Charvet et al. 2000; Statzner et al. 2005), making this decision may not be an important issue for traits-based analyses.

#### *Trait representation and measurement*

Biomonitoring programs may differ not only with respect to taxonomic resolution but also in the number of taxonomic groups they consider (Carter and Resh 2001). For traits-based approaches to be incorporated effectively into monitoring

programs, the effect of taxonomic bias toward a subset of taxa, such as easily identifiable taxa or known sensitive taxa (for example, Ephemeroptera, Plecoptera and Trichoptera) must be understood. The use of a narrow range of taxa for biomonitoring could restrict the suite of traits and accompanying trait modalities available for identifying the type and level of environmental impact (Table 1). Although some traits and trait modalities may be more indicative of certain types of impact, until these associations are identified, it is important for biomonitoring programs to incorporate adequate taxonomic diversity to provide the trait diversity needed for an effective traits-based approach. It is likely that a reduced range of traits may be needed for targeted monitoring once the trait–stressor connection is well established.

Biomonitoring practitioners must also determine the way in which traits are quantified, such as on a categorical or continuous scale, with some traits being naturally categorical (foraging mode) and others continuous but coded as categorical (body size). Given the coarse nature of biomonitoring data, categorical trait data may be adequate for environmental assessment (Dolédéc et al. 1999; Bonada et al. 2006). A particular trait can often be measured in a number of ways, especially across taxonomic groups, and it is essential for traits to be measured consistently (e.g., length, mass, or volume for body size). Thus, to improve causal diagnostic power of traits-based assessment, a detailed definition of each trait and its related modalities must be provided with metadata detailing how the information was quantified (Baird et al. 2011).

#### *Trait correlations and combinations*

The numerous traits used in biomonitoring can be correlated to one another (Resh et al. 1994; Poff et al. 2006), with at least 4 potential reasons for these relationships.

1. Multiple traits can be related mechanistically to similar underlying attributes, including the association of long adult lifespan with semivoltinism in lotic insects and the linkage between flow preferences and several traits including body shape, armor, and attachment (Poff et al. 2006).
2. Trait correlations can reflect phylogenetic relationships (evolutionary history) among taxa (Blomberg et al. 2003; Buchwalter et al. 2008).
3. Convergent evolution may create linkage (e.g., traits associated with limpet-like forms in freshwater mollusks).
4. Trait correlations can complicate the nature of environment–trait relationships when strong environmental selection for one trait causes other linked traits to respond as well (Poff et al. 2006).

The potential for traits to be correlated may confound causal inference in biomonitoring applications, and it suggests that a limited number of possible trait combinations or “syndromes” may exist (Poff et al. 2006; Horrigan and Baird 2008). Thus, the relative sensitivity of individual and correlated traits to different stressors needs to be evaluated more fully. In some cases correlated traits may be redundant (Poff et al. 2006). Conversely, recognition of phylogenetically correlated traits may provide a way to derive information for scarcely studied taxa, thereby allowing the identification of

taxa that respond similarly to a stressor (Buchwalter et al. 2008).

#### *Population variation in traits*

A common approach in traits-based biomonitoring studies is to report the traits of the taxa that occur in a sample based on a given trait dataset. Traits applied in this fashion are frequently treated as static values. In other words, the most common trait modality for a given taxon is assigned to all individuals of the taxon thereby ignoring variation that might occur among individuals due to growth, development, or other responses to environmental conditions. Assigning a static value for traits ignores potentially important variation displayed by a population (Brown 1995; Jones et al. 2009) that may be the result of phenotypic plasticity, a genotypic response to the environment, or ontogeny (Sagnes et al. 2008; Petchey et al. 2004). For example, larval stages may differ in their life history characteristics and change from one larval stage to another (Sagnes et al. 2008). In freshwater biomonitoring using insect larvae, traits are usually applied for selected taxa (insects) on the basis of the mature larval stages, because taxonomic knowledge is in most cases also restricted to identification of mature larvae (Merritt et al. 2008). Similarly, population variation could arise from sexual dimorphism and species showing multiple trait states depending on life cycle stages (e.g., sexual and asexual reproduction).

A better understanding of the sources and extent of trait variation as well as the role of trait variation in defining sensitivity to environmental stressors should lead to improved traits-based inferences. In some cases, however, variation in particular traits may be useful or diagnostic of particular environmental stressors (Hodkinson and Jackson 2005). For example, morphological variation and certain life history characteristics have been used to detect stressors, including chemical contamination (Lenat 1993) and thermal shifts (Hogg and Williams 1996).

#### *Trait–environment linkage*

Few traits were initially described with the intention of representing a clear mechanistic linkage or response to environmental stressors (Poff et al. 2006). In fact, some traits exist simply as a result of the types of information available for particular taxa (Statzner et al. 2004), yet a clear mechanistic linkage between environmental gradient and biological traits has been demonstrated for the primary biological elements used for biomonitoring: benthic invertebrates (Pollard and Yuan 2010), fish (Lamouroux et al. 2002), macrophytes (Thiebaut et al. 2002), and phytoplankton (Litchman et al. 2007).

Where a mechanistic linkage between traits and environmental stressors can be established (Figure 2), the relationship can become confounded if particular traits respond to multiple features of the environment. Thus, Statzner and Bêche (2010) argue that individual traits must not be used as indicators of many different stressors if reliable interpretations of trait responses are to be determined in multiple stressor environments. Using the trait modalities described by Poff et al. (2006), Horrigan and Baird (2008) demonstrated that in a multistressor environment, selected trait modalities were influenced exclusively by changes in flow conditions and were not responsive to thermal and oxygen stress. Other traits were simultaneously responsive to the multiple stressors, and consequently had reduced diagnostic power. Similarly, life

cycle strategies can provide a useful indicator of community condition, but their diagnostic power can be limited if taxa alter their life cycles in response to multiple stressor conditions (Richards et al. 1996; Dolédec et al. 2006; Füreder et al. 2007; Diaz et al. 2008). Thus, we emphasize that the identification of stressor-specific traits (trait suites) based on the understanding of the causal relationship between trait occurrence and stressor level should be the focus of future research into the use of traits in biomonitoring.

#### **AVAILABILITY, CONSISTENCY, AND APPLICABILITY OF TRAITS DATA**

Traits-based approaches necessitate the association of taxa and their traits (Figure 2), which usually requires the development of new databases or compilation of existing ones. Information is available for a variety of traits and taxonomic groups through published and online data, and this information also can be obtained from source authors. Table 2 provides a range of examples that illustrate the variety of available databases, traits, and approaches, and the variability of geographical and taxonomic coverage. We restrict our reporting to 1) trait databases that minimally apply to ecoregions, with the caveat that many other databases can be found for smaller geographical areas; and 2) trait databases that are of potential use in biomonitoring.

Consistency of trait description and classification is critical if the full potential of a traits-based approach is to be realized. Such consistency begins with a conceptual framework of trait definitions that is valid across different taxonomic groups and ecosystems (Baird et al. 2011). Such frameworks are evolving for individual taxonomic groups, and trait generalizations among taxa across biogeographical regions are rare except for a limited number of traits (body size, basal metabolic rate, and life duration). For biomonitoring purposes, consistency must be achieved for the taxonomic group and the resolution at which the assessment is undertaken. Here, consistency refers to the 1) applicability of trait modalities to all taxa (some physiological traits may not be compatible across higher taxonomic groups with very different physiologies), and 2) adequate knowledge of trait differences related to taxonomic resolution (trait states of insect families and genera are similar and well described; Beketov et al. 2009).

A first step toward building a comprehensive trait and environmental database as advocated by Statzner et al. (2007) is the use of a standard nomenclature (Baird et al. 2011). Although no standardized requirements and protocols exist for establishing traits databases, a taxonomic basis is essential because traits are associated with species. In addition, several researchers have grouped traits into broad categories, such as life history, mobility, morphology, and ecology (Lamouroux et al. 2002; Poff et al. 2006; Litchman and Klausmeier 2008; Stevenson et al. 2008), but a common categorization and vocabulary are lacking. A case in point is the broad list of traits categorized by several authors as “ecological,” even though these traits can be associated with multiple attributes including habitat preference, locomotion mode, and stressor tolerance (Poff et al. 2006; Carlisle and Hawkins 2008; Stevenson et al. 2008; Buffagni et al. 2009).

Finally, a number of analytical methods have been used to define traits, explore relationships among traits, and assess environment–trait relationships. Statistical methods used include cluster analysis (Poff et al. 2006), correlation (Horrigan and Baird 2008), ordination (Dray and Legendre

Table 2. Examples of trait databases for freshwater, marine, and selected terrestrial habitats summarized for different taxonomic groups<sup>a</sup>

Habitat	Group	Taxonomic resolution	Coding method	Distribution Format	Description of key aspects of database	Examples
Stream and river	Macroinvertebrates	Variable	Fuzzy	Spreadsheet	European coverage	Tachet et al. (2002); Usseglio-Polatera et al. (2000); Statzner et al. (2007)
	Macroinvertebrates, fish, diatoms	Species	Binary or 10-point assignment	Web database	Variable European and taxonomic coverage	Euro-limpacs Consortium (2008)
	Macroinvertebrates	Genus	Fuzzy or binary	Spreadsheet	North American lotic insect focus	Vieira et al. (2006); Poff et al. (2006)
Freshwater and marine	Fish	Species	Binary	Spreadsheet	North American and European coverage limited to six traits	Lamouroux et al. 2002
	Phytoplankton	NA	NA	NA	Defines a structural framework for work in progress	Litchman and Klausmeier (2008)
	Phytoplankton	Genus or Species	Descriptive data	NA	Traits-separated for freshwater functional groups	Reynolds et al. (2002)
Freshwater-terrestrial ecotone	Fish	Species	Descriptive data	Web database	Well-established web-based database	Froese and Pauly (2000)
	Riparian plants	NA	NA	NA	Conceptual approach focused on monitoring and management	Merritt et al. (2009)
	Primates	Species	Quantitative variables	Spreadsheet	Global coverage	Cowlshaw et al. (2009)
Terrestrial	Lepidoptera	Species	Binary and quantitative variables	NA	Global coverage limited to two families only	García-Barros (2008)
	Lepidoptera	Species	Quantitative variables	NA	Feeding habits of UK butterflies	Hardy et al. (2007)
	Frogs	Species	Quantitative and qualitative variables	Spreadsheet	Life-history and ecological traits of Australian frog fauna	Murray and Hose (2005a, 2005b)
Multiple habitats	Plants	Species	Quantitative variables	Web database	Well-established web-based database	Lavorel et al. (2007, 2009); Kattge et al. (in press)
	Mammals	Species	Quantitative variables	Spreadsheet and web database	Global coverage	Jones et al. (2009)

<sup>a</sup>For each database information is provided for level of taxonomic resolution, method of coding, format in which the information is distributed, and a brief description of key aspects of the database. NA = data not available.



2008), and regression (Cowlshaw et al. 2009). Because univariate correlations are unable to disentangle multiple stressor–trait relationships, these statistical tools may have limited applicability in establishing linkages between traits and environmental conditions. In contrast, multiple regression and multivariate (ordination, clustering) approaches have been widely used in traits analysis. A key difference is that regression models usually consider traits to be explanatory variables, while multivariate models treat traits as response variables. This distinction can be important when turning relationships into indices and management tools.

## CONCLUSIONS AND SUMMARY

Trait information has long been used in biomonitoring programs, but its full potential is yet to be realized. Traits-based approaches have the potential to expand the outputs of biomonitoring programs from the identification of impact to include a causal diagnosis. This expansion can be achieved with little change to existing monitoring programs, other than linking the observed taxa to a database of taxa with their traits, as described by Vieira et al. (2006). The exceptions to this generalization are traits that need to be quantified (like body size) and require more detailed data collection than normally included in standard biomonitoring approaches. Traits-based approaches have a number of desirable attributes, such as greater stability of assessment outcomes and broader applicability of reference conditions, which are likely to broaden their range of application and increase their sensitivity. Indeed, we have outlined many of the benefits that traits-based biomonitoring can provide, including the potential to develop consistent descriptors or metrics across broad spatial scales. However, a number of challenges must be met before the full potential of traits-based approaches can be realized. Chief among those challenges is the establishment of effective and accessible trait databases (Baird et al. 2011). While some databases already exist, there is still a paucity of traits data for many taxonomic groups and many types of traits, indicating a clear and immediate research need. A concerted effort to standardize terminology is required with the establishment of data-interoperability infrastructures to ease the sharing and merging of broad, geographical trait information. Research efforts must determine whether generalizations can be made among taxa and across biogeographical regions and must also produce a consensus on the required taxonomic resolution and methodology for traits assessment. Already a number of promising developments have occurred in traits-based biomonitoring approaches. It is our hope that the discussion provided here, and in other articles based on the workshop (Baird et al. 2011; Rubach et al. 2011; van den Brink et al. 2011), will provide the stimulus and direction for the development of traits-based approaches that improve diagnostic assessments of environmental stressor effects.

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## REFERENCES

- Armitage PD, Moss D, Wright JF, Furse MT. 1983. The performance of a new biological water quality system based on macroinvertebrates over a wide range of unpolluted running-water sites. *Water Res* 17:333–347.
- Bady P, Dolédec S, Fesl C, Gayraud S, Bacchi M, Schöll F. 2005. Use of invertebrate traits for the biomonitoring of European large rivers: the effects of sampling effort on genus richness and functional diversity. *Freshw Biol* 50:159–173.
- Bailey RC, Norris RH, Reynoldson TB. 2001. Taxonomic resolution of benthic macroinvertebrate communities in bioassessments. *Journal of the North American Benthological Society* 20:280–286.
- Baird DJ, Baker CJO, Brua R, Hajibabaei M, McNicol K, Pascoe TJ, de Zwart D. 2011. Towards a knowledge infrastructure for traits-based ecological risk assessment. *Integr Environ Assess Manag* 7:209–215.
- Bêche LA, McElravy EP, Resh VH. 2006. Long-term seasonal variation in the biological traits of benthic-macroinvertebrates in two Mediterranean-climate streams in California, USA. *Freshw Biol* 51:56–75.
- Beketov M, Foit K, Schäfer R, Schriever C, Sacchi A, Capri E, Biggs J, Wells C, Liess M. 2009. SPEAR indicates pesticide effects in streams—comparative use of species- and family-level biomonitoring data. *Environ Pollut* 157:1841–1848.
- Blomberg SP, Garland T, Ives A. 2003. Testing for phylogenetic signal in comparative data: behavioral traits are more labile. *Evolution* 54:717–745.
- Bonada N, Prat N, Resh VH, Statzner B. 2006. Developments in aquatic insect biomonitoring: a comparative analysis of recent approaches. *Annu Rev Entomol* 51:495–523.
- Brooks JL, Dodson SI. 1965. Predation, body size, and composition of plankton. *Science* 150:28–35.
- Brown JH. 1995. *Macroecology*. Chicago (IL): Univ Chicago. p 47–75.
- Buchwalter DB, Cain DJ, Martin CA, Xie L, Luoma SN, Garland T. 2008. Aquatic insect ecophysiological traits reveal phylogenetically based differences in dissolved cadmium susceptibility. *Proc Natl Acad Sci U S A* 105:8321–8326.
- Buffagni A, Cazzola M, Alba-Tercedor J, López Rodríguez MJ, Armanini DG. 2009. Vol. 3. Ephemeroptera. In: Schmidt-Kloiber A, Hering D, editors. *Distribution and ecological preferences of European freshwater organisms*. Sofia (BG): Pensoft. p 1–256.
- Cairns J Jr, Dickson KL. 1971. A simple method for the biological assessment of the effects of waste discharges on aquatic bottom dwelling organisms. *Journal Water Pollution Control Federation* 43:755–772.
- Carlisle DM, Hawkins CP. 2008. Land use and the structure of western US stream invertebrate assemblages: predictive models and ecological traits. *Journal of the North American Benthological Society* 27:986–999.
- Carter JL, Resh VH. 2001. After site selection and before data analysis: sampling, sorting, and laboratory procedures used in stream benthic macroinvertebrate monitoring programs by USA state agencies. *Journal of the North American Benthological Society* 20:658–682.
- Charvet S, Statzner B, Usseglio-Polatera P, Dumont B. 2000. Traits of benthic macroinvertebrates in semi-natural French streams: an initial application to biomonitoring in Europe. *Freshw Biol* 43:277–296.
- Chessman BC. 1995. Rapid assessment of rivers using macroinvertebrates: A procedure based on habitat-specific sampling, family level identification and a biotic index. *Austral J Ecology* 20:122–129.
- Chessman B. 2003. SIGNAL 2—A scoring system for macro-invertebrate ('water bugs') in Australian rivers. Monitoring river health initiative. Canberra (AU): Department of the Environment and Heritage. Technical report 31.
- Cowlshaw G, Pettifor RA, Isaac NJB. 2009. High variability in patterns of population decline: the importance of local processes in species extinctions. *Proc R Soc London B* 276:63–69.
- Culp JM, Lowell RB, Cash KJ. 2000. Integrating in situ community experiments with field studies to generate weight-of-evidence risk assessments for large rivers. *Environ Toxicol Chem* 19:1167–1173.
- Diaz AM, Alonso MLS, Gutierrez MSV. 2008. Biological traits of stream macroinvertebrates from a semi-arid catchment: patterns along complex environmental gradients. *Freshw Biol* 53:1–21.
- Dolédec S, Phillips N, Scarsbrook MR, Riley RH, Townsend CR. 2006. A comparison of structural and functional approaches to determining land-use effects on grassland stream invertebrate communities. *Journal of the North American Benthological Society* 25:44–60.

- Dolédéc S, Statzner B. 1994. Theoretical habitat templates, species traits, and species richness: 548 plant and animal species in the Upper Rhône River and its floodplain. *Freshw Biol* 31:523–538.
- Dolédéc S, Statzner B, Bournaud M. 1999. Species traits for future biomonitoring across ecoregions: patterns along a human-impacted river. *Freshw* 42:737–758.
- Dray S, Legendre P. 2008. Testing the species traits–environment relationships: the fourth-corner problem revisited. *Ecology* 89:3400–3412.
- Euro-limpacs Consortium. 2008. Freshwaterecology.info database: The taxa and autecology database for freshwater organisms. [Accessed 2008 March 2–8]. Available from: [www.freshwaterecology.info](http://www.freshwaterecology.info)
- Friedrich G. 1990. Eine revision des saprobiensystems. *Zeitschrift für Wasser und Abwasser Forschung* 23:141–152.
- Froese R, Pauly D. 2000. FishBase 2000: concepts, design and data sources. ICLARM, Los Baños, Laguna, Philippines 344 p.
- Füreder L. 2007. Life at the edge: Habitat condition and bottom fauna of alpine running waters. *International Review of Hydrobiology* 92:491–513.
- García-Barros E. 2008. Body size, egg size, and their interspecific relationships with ecological and life history traits in butterflies (Lepidoptera: Papilionoidea, Hesperioidea). *Biol J Linn Soc* 70:251–284.
- Gayraud S, Statzner B, Bady P, Haybach A, Schöll F, Usseglio-Polatera P, Bacchi M. 2003. Invertebrate traits for the biomonitoring of large European rivers: an initial assessment of alternative metrics. *Freshw Biol* 48:2045–2064.
- Goldstein RM, Meador MR. 2005. Multilevel assessment of fish species traits to evaluate habitat degradation in streams of the Upper Midwest. *North American Journal of Fish Management* 25:180–194.
- Hairton NG, Walton WE. 1986. Rapid evolution of a life-history trait. *Proc Natl Acad Sci U S A* 83:4831–4833.
- Hardy PB, Sparks TH, Isaac NJB, Dennis RLH. 2007. Specialism for larval and adult consumer resources among British butterflies: Implications for conservation. *Biol Conserv* 138:440–452.
- Henry CP, Amoros C, Bornette G. 1996. Species traits and recolonization processes after flood disturbances in riverine macrophytes. *Vegetation* 122:13–27.
- Hilsenhoff WL. 1987. An improved biotic index of organic stream pollution. *Gt Lakes Entomol* 20:31–39.
- Hilsenhoff WL. 1988. Rapid field assessment of organic pollution with a family-level biotic index. *Journal of the North American Benthological Society* 7:65–78.
- Hodkinson ID, Jackson JK. 2005. Terrestrial and aquatic invertebrates as bioindicators for environmental monitoring, with particular reference to mountain ecosystems. *J Environ Manage* 35:649–666.
- Hogg ID, Williams DD. 1996. Response of stream invertebrates to a global-warming thermal regime: an ecosystem-level manipulation. *Ecology* 77:395–407.
- Horrigan N, Baird DJ. 2008. Trait patterns of aquatic insects across gradients of flow-related factors: a multivariate analysis of Canadian national data. *Can J Fish Aquat Sci* 65:670–680.
- Jiang J-G. 2006. Development of a new biotic index to assess freshwater pollution. *Environ Pollut* 139:306–317.
- Jones CF. 2008. Taxonomic sufficiency: The influence of taxonomic resolution on freshwater bioassessments using benthic macroinvertebrates. *Environ Rev* 16:45–69.
- Jones KE, Bielby J, Cardillo M, Fritz SA, O'Dell J, Orme CDL, Safi K, Sechrest W, Boakes EH, Carbone C, Connolly C, Cutts MJ, Foster JK, Grenyer R, Habib M, Plaster CA, Price SA, Rigby EA, Rist J, Teacher A, Bininda-Emonds ORP, Gittleman JL, Mace GM, Purvis A. 2009. PanTHERIA: a species-level database of life history, ecology, and geography of extant and recently extinct mammals. *Ecology* 90:2648.
- Kattge J, Ogle K, Bonisch G, Diaz S, Lavorel S, Madin J, Nadrowski K, Nollert S, Sartor K, Wirth C. in press. A generic structure for plant trait databases. *Methods in Ecology and Evolution* DOI: 10.1111/j.2041-210X.2010.00067.x
- Karr JR. 1981. Assessment of biotic integrity using fish communities. *Fisheries* 6:21–27.
- Kelly MG, Whitton BA. 1995. The trophic diatom index: a new index for monitoring eutrophication in rivers. *J Appl Phycol* 7:433–444.
- Kolkwitz R, Marsson K. 1909. Ökologie der tierischen saprobien. Beiträge zur lehre von des biologischen gewasserbeurteilung. *Internationale Revue der Gesamten Hydrobiologie und Hydrographie* 2:126–152.
- Lamouroux N, Poff NL, Angermeier PL. 2002. Convergence of stream fish community traits in France and Virginia (USA) streams along hydraulic and geomorphic gradients. *Ecology* 83:1792–1807.
- Lavorel S, Prentice C, Diaz S, Leadley P. 2007. Refining plant functional classifications for earth system modeling. *Global Land Project Newsletter* 2:14.
- Lavorel S, Gachet S, Sahl A, Colace M-P, Gaucherand S, Burylo M, Bonet R. 2009. A plant functional traits database for the Alps – application to the understanding of functional effects of changed grassland management. In: Korner C, Spehn E, editors. Data Mining for Global Trends in Mountain Biodiversity. Boca Raton (FL): CRC Press, Taylor and Francis. p 106–123.
- Lenat DR. 1993. Using mentum deformities of chironomid larvae to evaluate the effects of toxicity and organic loading in streams. *Journal of the North American Benthological Society* 12:265–269.
- Lenat DR, Resh VH. 2001. Taxonomy and stream ecology: The benefits of genus- and species-level identifications. *Journal of the North American Benthological Society* 20:287–298.
- Liess M, Von der Ohe PC. 2005. Analyzing effects of pesticides on invertebrate communities in streams. *Environ Toxicol Chem* 24:954–965.
- Litchman E, Klausmeier CA. 2008. Trait-based community ecology of phytoplankton. *The Annual Review of Ecology, Evolution, and Systematics* 39:615–639.
- Litchman E, Klausmeier CA, Schofield OM, Falkowski PG. 2007. The role of functional traits and trade-offs in structuring phytoplankton communities: scaling from cellular to ecosystem level. *Ecol Lett* 10:1170–1181.
- Lowell RB, Culp JM, Dubé MG. 2000. A weight-of evidence approach for northern river risk assessment: integrating the effects of multiple stressors. *Environ Toxicol Chem* 19:1182–1190.
- Margalef JL. 1958. Information theory in ecology. *General Systems* 3:36–71.
- McGill BJ, Enquist B, Weiher E, Westoby M. 2006. Rebuilding ecology from functional traits. *Trends Ecol Evol* 21:178–185.
- Merritt DM, Scott ML, Poff L, Auble GT, Lytle DA. 2009. Theory, methods and tools for determining environmental flows for riparian vegetation: riparian vegetation-flow response guilds. *Freshw Biol* 55:206–225.
- Merritt RW, Cummins KW, Berg MB. 2008. An introduction to the aquatic insects of North America. Dubuque (IA): Kendall Hunt. p. 12–28.
- Metzeling L, Miller J. 2001. Evaluation of the sample size used for the rapid bioassessment of rivers using macroinvertebrates. *Hydrobiologia* 444:159–170.
- Murray BR, Hose GC. 2005a. The inter-specific range size–body size relationship in Australian frogs. *Glob Ecol Biogeogr* 14:339–345.
- Murray BR, Hose GC. 2005b. Life-history and ecological correlates of decline and extinction in the endemic Australian frog fauna. *Austral Ecology* 30:564–571.
- Patrick R. 1949. A proposed biological measure of stream conditions based on a survey of Conestoga Basin, Lancaster County, Pennsylvania. *Proceedings of the Academy of Natural Sciences of Philadelphia* 101:277–341.
- Petchey OL, Downing AL, Mittelbach GG, Persson L, Steiner CF, Warren PH, Woodward G. 2004. Species loss and the structure and functioning of multitrophic aquatic systems. *Oikos* 104:467–478.
- Plafkin JL, Barbour MT, Porter KD, Gross SK, Hughes RM. 1989. Rapid bioassessment protocols for use in streams and rivers: Benthic macroinvertebrates and fish. Washington DC: U.S. Environmental Protection Agency. EPA 444/4-89-001.
- Poff NL. 1997. Landscape filters and species traits: towards mechanistic understanding and prediction in stream ecology. *Journal of the North American Benthological Society* 16:391–409.
- Poff NL, Allan JD. 1995. Functional organization of stream fish assemblages in relation to hydrologic variability. *Ecology* 76:606–627.
- Poff NL, Olden JD, Vieira NKM, Finn DS, Simmons MP, Kondratieff BC. 2006. Functional trait niches of North American lotic insects: trait-based ecological applications in light of phylogenetic relationships. *Journal of the North American Benthological Society* 25:730–755.

- Pollard AI, Yuan LL. 2010. Assessing the consistency of response metrics of the invertebrate benthos: a comparison of trait- and identity-based measures. *Freshw Biol* 55:1420–1429.
- Resh VH, Hildrew AG, Statzner B, Townsend CR. 1994. Theoretical habitat templates, species traits, and species richness: A synthesis of long-term ecological research on the Upper Rhône River in the context of concurrently developed ecological theory. *Freshw Biol* 31:539–554.
- Reynolds CS. 1994. The long, the short and the stalled: On the attributes of phytoplankton selected by physical mixing in lakes and rivers. *Hydrobiologia* 289:9–21.
- Reynolds CS, Huszar V, Kruk C, Naselli-Flores L, Melo S. 2002. Towards a functional classification of the freshwater phytoplankton. *J Plankton Res* 24:417–428.
- Reynoldson TB, Logan C, Pascoe T, Thompson S, Sylvestre S. 2001. Invertebrate biomonitoring field and laboratory manual for running water habitats. Environment Canada, National Waters Research Institute, Canadian Aquatic Biomonitoring Network.
- Richards C, Johnson LB, Host GE. 1996. Landscape scale influences on stream habitats and biota. *Can J Fish Aquat Sci* 53:295–311.
- Rosenberg DM, Resh VH. 1993. Freshwater biomonitoring and benthic macroinvertebrates. New York (NY): Chapman and Hall. p. 1–9.
- Rubach MN, Ashauer R, Buchwalter DB, De Lange HJ, Hamer M, Preuss TG, Töpke K, Stephen J, Maund SJ. 2011. Framework for traits-based assessment in ecotoxicology. *Integr Environ Assess Manag* 7:172–186.
- Sagnes P, Méricoux S, Péru N. 2008. Hydraulic habitat use with respect to body size of aquatic insect larvae: Case of six species from a French Mediterranean type stream. *Limnologia* 38:23–33.
- Schmidt-Kloiber A, Graf W, Lorenz A, Moog O. 2006. The AQEM/STAR taxalist: A pan-European macro-invertebrate ecological database and taxa inventory. *Hydrobiologia* 566:325–342.
- Seip KL, Reynolds CS. 1995. Phytoplankton functional attributes along trophic gradient and season. *Limnol Oceanogr* 40:589–597.
- Shannon CE. 1948. A mathematical theory of communication. *Bell System Technical Journal* 27:379–423, 623–656.
- Shiple B, Keddy PA. 1988. The relationship between relative growth rate and sensitivity to nutrient stress in twenty-eight species of emergent macrophytes. *J Ecol* 76:1101–1110.
- Simpson JC, Norris RH. 2000. Biological assessment of river quality: Development of AUSRIVAS models and outputs. In: Wright JF, Sutcliffe DW, Furse MT, editors. Assessing the biological quality of fresh waters: RIVPACS and other techniques. Cumbria (UK): Freshwater Biological Association. p 143–163.
- Southwood TRE. 1977. Habitat, the templet for ecological strategies? *J Anim Ecol* 46:337–365.
- Statzner B, Bady P, Dolédec S, Schöll F. 2005. Invertebrate traits for the biomonitoring of large European rivers: An initial assessment of trait patterns in least impacted river reaches. *Freshw Biol* 50:2136–2161.
- Statzner B, Bêche LA. 2010. Can biological invertebrate traits resolve effects of multiple stressors on running water ecosystems? *Freshw Biol* 55:80–119.
- Statzner B, Bis B, Dolédec S, Usseglio-Polatera P. 2001. Perspectives for biomonitoring at large spatial scales: A unified measure for the functional composition of invertebrate communities in European running waters. *Basic and Applied Ecology* 2:73–85.
- Statzner B, Bonada N, Dolédec S. 2007. Conservation of taxonomic and biological trait diversity of European stream macroinvertebrate communities: a case for a collective public database. *Biodivers Conserv* 16:3609–3632.
- Statzner B, Dolédec S, Huguény B. 2004. Biological trait composition of European stream invertebrate communities: assessing the effects of various trait filter types. *Ecography* 27:470–488.
- Stevenson RJ, Pan Y, Manoylov KM, Parker CA, Larsen DP, Herlihy AT. 2008. Development of diatom indicators of ecological conditions for streams of the western US. *Journal of the North American Benthological Society* 27:1005–1021.
- Suter GW II, Norton SB, Cormier SM. 2002. A methodology for inferring the causes of observed impairments in aquatic ecosystems. *Environ Toxicol Chem* 21:1101–1111.
- Tachet H, Richoux P, Bournaud M, Usseglio-Polatera P. 2002. Invertébrés d'eau douce (2nd corrected impression). Paris (FR): CNRS Editions. p 587.
- Thiebaut G, Guérol F, Muller S. 2002. Are trophic and diversity indices based on macrophyte communities pertinent tools to monitor water quality? *Water Res* 36:3602–3610.
- Townsend C, Hildrew A. 1994. Species traits in relation to a habitat template for river systems. *Freshw Biol* 31:265–275.
- Tullos DD, Penrose DL, Jennings GD. 2009. Analysis of functional traits in reconfigured channels: Implications for the bioassessment and disturbance of river restoration. *Journal of the North American Benthological Society* 28:80–92.
- Usseglio-Polatera P, Bournaud M, Richoux P, Tachet H. 2000. Biological and ecological traits of benthic freshwater macroinvertebrates: Relationships and definition of groups with similar traits. *Freshw Biol* 43:175–205.
- van den Brink PJ, Alexander A, Desrosiers M, Goedkoop W, Goethals P, Liess M, Dyer S. 2011. Traits-based approaches in bioassessment and ecological risk assessment: strengths, weaknesses, opportunities and threats. *Integr Environ Assess Manag* 7:198–208.
- Van Straalen NM. 1994. Biodiversity of ecotoxicological responses in animals. *Netherlands Journal of Zoology* 44:112–129.
- Vannote RL, Minshall GW, Cummins KW, Sedell JR, Cushing CE. 1980. The river continuum concept. *Can J Fish Aquat Sci* 37:130–137.
- Vieira NKM, Poff NL, Carlisle DM, Moulton SR, Koski ML, Kondratieff BC. 2006. A database of lotic invertebrate traits for North America. U.S. Geological Survey Data Series 187. US Geological Survey, US Department of the Interior, Reston (VA). [Accessed 2009 November 27]. Available from: <http://pubs.usgs.gov/ds/ds187/>
- Washington HG. 1984. Diversity, biotic and similarity indices: A review with special relevance to aquatic ecosystems. *Water Res* 18:653–694.
- Woodiwiss F. 1964. The biological system of stream classification used by the Trent River Board. *Chemistry and Industry* 11:443–447.
- Wright JF, Furse MT, Armitage PD. 1993. RIVPACS: A technique for evaluating the biological quality of rivers in the UK. *European Water Pollution Control* 3:15–25.