Ecological Indicators 81 (2017) 124–131

Contents lists available at ScienceDirect

Ecological Indicators

journal homepage: www.elsevier.com/locate/ecolind

Review

Using river microalgae as indicators for freshwater biomonitoring: Review of published research and future directions

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A R T I C L E I N F O

Keywords:
Riverine microalgae
Lotic ecosystem functions
Trait-based biomonitoring
Multiple stressors
Global change

A B S T R A C T

Trait-based approaches may give insights into underlying mechanisms of relationships between biological communities and environmental stressors, and are increasingly used in ecological studies, but are only very recently considered for freshwater riverine microalgae. Here, we i) review the research trend in riverine microalgae during the past 26 years in order to conduct a quantitative and qualitative analysis for global trends in the research field, ii) summarize the use of algae traits in riverine biomonitoring and iii) propose future research perspectives. The bibliometric analysis showed that the annual number of publications on microalgae increased significantly from 1991 to 2016, although their proportions to total numbers of scientific articles remained steady. The studies have become increasingly concerned on issues arisen from global environmental changes such as "eutrophication", "pollution", "land use", "biomonitoring", "biodiversity", "functional group", etc. The use of algae traits in biomonitoring has become popular and includes e.g. functional diversity, cell size, guild, life form, eco-morphology, spore formation as well as algal quality. Here we collate all relevant algal traits, their different categories and propose their responses to resource supply and disturbance frequency in a conceptual model, which should be validated in future studies. In order to expand the knowledge and future use of microalgae in biomonitoring research efforts should also include: i) description of relationships between algal traits and ecosystem functions (e.g., nutrient uptake, metabolism, energy transfer across the food web) and underlying mechanisms; ii) selection of robust traits reflecting and disentangling the effects of multiple stressors; iii) water resource management in an interdisciplinary manner linking risk assessment and management scenarios by an integrated modelling system using microalgae.

1. Introduction

Algae (both eukaryotics and cyanobacteria) occupy nearly every aquatic environment including fresh and marine waters, moist terrestrial habitats, such as soils and rock surfaces, and they also live on living surfaces such as plants and animals (Hoffmann, 1989; Round et al., 1990). While algae were known by the ancient Greeks and Romans, records as far back as 3000 BC indicated that algae already at that time were used by the emperor of China as food (Huisman, 2000; Porterfield, 1922). Since the late 18th century with the description and naming of *Ecklonia maxima* (Pehr Osbeck) in 1757, phycology (i.e. scientific study of algae) as a research field has undergone several stages. The first stage was from late 18th to late 19th century with descriptive work of scholars, such as Carl Adolph Agardh (1785–1859), who firstly emphasized the importance of the reproductive characters of algae and the use of these to distinguish different genera and families (Papenfuss, 1976). The second stage started from the late 19th century, when phycology became a recognized research field of its own. Scholars such as Friedrich Traugott Kützing (1807–1893) continued the descriptive work with systematic recordings, extensive distribution mapping and the development of identification keys. The third stage was from the early 20th century up to now. In this stage a rapid progress has

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http://dx.doi.org/10.1016/j.ecolind.2017.05.066
Received 2 March 2017; Received in revised form 22 May 2017; Accepted 25 May 2017
Available online 03 June 2017
1470-160X/

been made and numerous key books have been published. Two important new research areas were also initiated during this last stage including investigations of freshwater algae (most previous work was done with marine algae) and the use of algae in bio-assessments, warranted by decreased water quality of freshwater ecosystems due to intensive human disturbances. During the last decades the concepts and tools for assessing ecosystem health and diagnosing causes of impairment in streams and rivers have developed rapidly (Stevenson et al., 2010).

Algae (benthic and pelagic) are increasingly being used as reliable environmental indicators in streams and rivers globally (Lange et al., 2016; Wu et al., 2012) because they strongly respond to environmental changes (Dong et al., 2016; Stevenson et al., 2010). Especially three major properties merit their use in ecosystem monitoring (Hötzel and Croome, 1999): (i) they have a high sensitivity to environmental changes, (ii) they are easy to sample, and (iii) most species are cosmopolitan with well-known autecology (Porter, 2008; van Dam et al., 1994). As a consequence, many assessment methods based on microalgae (especially diatoms, a key component of stream benthic and pelagic algae) have been developed in several countries and regions (Siddig et al., 2016). Generally, the assessment methods build on one of three different approaches. The first approach is based on community composition and the ecological preferences and/or tolerances of species or taxa within the community (Kolkwitz and Marsson, 1908), for instance, the Pollution Sensitivity Index (PSI) (Kelly et al., 1995), the Trophic Diatom Index (TDI) (Kelly and Whitton, 1995), the Pollution Tolerance Index (PTI) (Kentucky Department for Environmental Protection Division, 2002), the Q index (Borics et al., 2007) and the Trophic Index of Potamoplankton (TIP) (Mischke and Behrendt, 2007). The second approach relies on algal diversity as a general indicator of river health (i.e. ecological integrity). The third approach can be seen as a mixture of the previous two approaches combining the different indices in multimetric indices, like for instance the Index of Biotic Integrity (IBI) (Karr, 1981). The third approach is preferred by more and more researchers for purposes of risk assessment and management of freshwater ecosystems and has been developed for different types of impairments in various regions (Bae et al., 2010; Birk et al., 2012; Dong et al., 2015; Zalack et al., 2010; Zhu and Chang, 2008).

Despite the increasing popularity of using these three approaches, some studies have shown that the first two approaches have not always been successful (Tang et al., 2006). For instance, nonlinear relationship between anthropogenic impacts and response of indices (Allan, 2004) resulted in potential bias for assessment. Moreover, if we look at the most used indices, summarized in a previous review (Wu et al., 2014), in research papers (Dong et al., 2015; Tang et al., 2006; van Dam et al., 1994; Wang et al., 2005) and in books (Mischke and Behrendt, 2007; Stevenson et al., 2010), it becomes obvious that the algorithm of many of these (e.g., TDI, PSI, PTI, TIP) is highly complex with a low degree of transparency. Furthermore, these approaches largely ignore that freshwater environments are exposed to a complex mixture of stressors arising from global change including water abstraction, intensive farming land use and climate change (Dudgeon et al., 2006; Hering et al., 2015; Vörösmarty et al., 2010). Consequently, the use of indices developed to target single stressors is inadequate and new approaches are needed to deal with this complexity.

Recent studies have shown the advantages of applying traits for biomonitoring of freshwater ecosystems and for biodiversity conservation (Di Battista et al., 2016; Lange et al., 2011; Litchman and Klausmeier, 2008; McGill et al., 2006; Menezes et al., 2010; Soininen et al., 2016). A trait is defined as a characteristic that reflects a species adaption to its environment (Menezes et al., 2010). Usually traits are divided into two types: ecological traits (related to habitat preferences, like pH, oxygen and temperature tolerance, tolerance to organic pollution, etc.) and biological traits (e.g., life history, physiological, behavioural and morphological characteristics, such as reproductive strategies, motility, cell size, life form, etc.). In comparison with traditional taxonomic indices, traits possess many merits: 1) most traits need only assignment to different categories and do not need complex algorithm, 2) traits show greater consistency in their responses across temporal and spatial scales (Menezes et al., 2010; Soininen et al., 2016), 3) traits can potentially be transferrable across geographic regions since different geographic regions are likely to contain similar complements of traits although they might be characterized by distinct taxonomic composition (Van den Brink et al., 2011), 4) traits can serve to tackle with complex mixture of stressors, e.g., disentanglement of multiple interacting influential factors (Baattrup-Pedersen et al., 2016), 5) they can give important insights into the mechanisms driving the community and ecosystem processes along the gradients of influential factors including responses to global change (Litchman and Klausmeier, 2008). In fact, functional traits have been used for different purposes in terrestrial plants (Grime, 1979; Tilman, 1980) and macroinvertebrate (Menezes et al., 2010), but have only very recently been considered for freshwater algae (Lange et al., 2016; McGill et al., 2006; Tapolczai et al., 2016), in particular in phytoplankton studies (Colina et al., 2016; Padisák et al., 2009; Reynolds et al., 2002; Thomas et al., 2016), and a growing number of investigations in benthic algae have also adopted a trait-based approach. A broadly accepted trait nowadays is guilds (i.e., low profile, high profile, motile) of diatoms (Berthon et al., 2011; Dong et al., 2016; Lange et al., 2011; Soininen et al., 2016; Tang et al., 2013), which can reflect not only the difference of dispersal ability, but also the environmental adaptability (Passy, 2007). Meanwhile, other biological traits based on cell sizes, life history, physiology, behaviour and morphology have been proposed recently (Lange et al., 2016).

In this paper we describe research trends in past years, and by collecting the latest trait-based approaches and existing attempts, we aim to identify future research gaps in order to progress the use of algal traits in biomonitoring. Specifically, the goals of this review are to 1) describe research trends of river microalgae in the past 26 years by conducting a bibliometric analysis, 2) summarize the current algal traits used in riverine biomonitoring, and 3) propose future research directions and applications.

2. Methods

2.1. Terminology of river microalgae

River microalgae can be divided into two main categories: pelagic algae and benthic algae. Pelagic algae are algae suspended in the water column and most previous studies have been carried out in lowland rivers or streams with long retention time and low flow current (Abonyi et al., 2014; Basu and Pick, 1996; Piirsoo et al., 2008; Sabater et al., 2008). In the literature, more popularly used terms are "phytoplankton", "potamoplankton", "phytoseston" or "riverine algae". In contrast to the pelagic algae, benthic algae grow on the surfaces of bottom sediments and are most commonly filamentous or colonial forms, but may also be microscopic single celled organisms. Former investigations have been conducted mostly in mountainous streams with short retention time and high flow velocity (Birk et al., 2012; Soininen et al., 2016; Wang et al., 2005). Except for "benthic algae", other widely used terms are "periphyton", "benthic diatom", "diatom", "eplithic algae/diatom", "epiphytic algae/diatom", "epipelic algae/diatom", etc. In this study, however, to unify the terminology, we confine to either "pelagic algae" or "benthic algae" (but for the publication searching, we used all keywords referred above).

2.2. Data sources, methods and results

We used a bibliometric analysis similar to a previous study (Wang et al., 2015) with a minor modification of the keywords used. All articles containing the keyword "river microalgae"; "pelagic algae"; "phytoplankton"; "potamoplankton"; "phytoseston"; "benthic algae"; "periphyton"; "benthic diatom"; "diatom"; "eplithic algae"; "eplithic

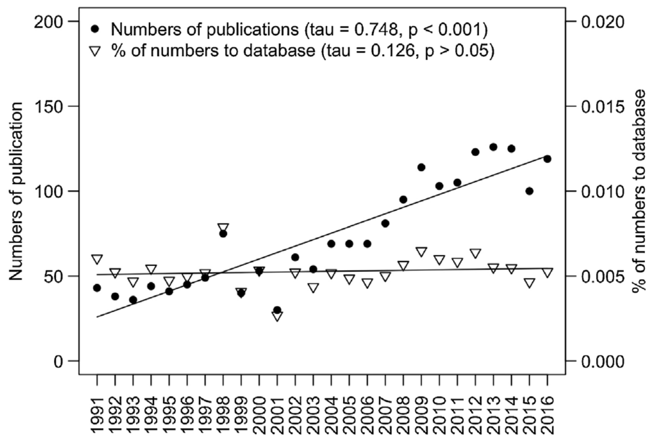

Fig. 1. Temporal trend of the research articles and its proportion in total databases from 1991 to 2016.

diatom"; "epiphytic algae"; "epiphytic diatom"; "epipelic algae" and "epipelic diatom" in the title published between 1991 and 2016; were queried from all citation indexes on Web of Science (Thomson Reuters). An XML file containing titles; keywords; abstracts; year of publication; authors' names and authors' affiliations; cited times and cited reference counts was generated. The search query was constructed as: TI = (river OR stream) AND TI = (microalgae OR pelagic algae OR algae OR algal OR phytoplankton OR potamoplankton OR phytoseston OR benthic algae OR periphyton OR benthic diatom OR diatom OR epilithic algae OR epilithic diatom OR epiphytic algae OR epiphytic diatom OR epipelic algae OR epipelic diatom).

A total of 1907 articles were found based on the keywords defined, and the annual numbers of publication demonstrated a linear increasing tendency ($p < 0.001$) from 1991 to 2016 (Fig. 1), although the proportion to the total numbers of scientific articles remained steady (around 0.005%).

Then, we extracted the keywords following the procedures of Wang et al. (2015) and top 30 keywords were visualized (Fig. 2). First, the yearly percentages of occurrence of each keyword was calculated as the yearly frequency divided by total frequency during a specified period of time, and then adjusted (divided) by the numbers of yearly total publications to compensate for the general increase of total amount of publications. Second, Mann–Kendal (MK) trend test, by a self-composed R code, was performed thereafter on each keyword in order to test whether the temporal change (from 1991 to 2016) is significant (increasing or decreasing). Third, we show 30 keywords with significant increasing trend from 1991 to 2016 in Fig. 2.

The temporal trends of the top 30 keywords showed an obvious increasing trend from 1991 to 2016 (Fig. 2). The popular keywords used were algae terms (e.g., "diatom", "phytoplankton", "periphyton", "algae", "benthic algae", "benthic diatom" "biofilm", "cyanobacteria", "bacillariophyceae" etc.) in relation to abiotic factors (e.g., "nutrient", "phosphorus", "nitrogen", "nutrient limit", etc.) and biotic interaction (i.e., "macroinvertebrate") at different research locations (e.g., "stream", "river"). Water problem related keywords (e.g., "eutrophication", "pollution", "land use") and its related fields (e.g., "monitoring", "biomonitoring", "indicator", "bioindicator", "biodiversity", "diversity", etc.) also showed an increasing trend. Impressively, new keywords as "functional group" and "framework directive" were also included in more studies.

3. Traits used in river microalgae biomonitoring

In addition to species composition, ecologists have recently started investigating trait composition since it reflects the functional responses of communities to environmental gradients (McGill et al., 2006). In this section, we summarize the latest proposed traits of river microalgae, which would be valid for both pelagic and benthic algae (Table 1), as complementary to traditional taxonomic based indices that have been summarized previously (Mischke and Behrendt, 2007; Wu et al., 2014). A total of 12 algal traits, which belong to 79 categories (for details see Table 1) have been widely used recently (Berthon et al., 2011; Centis et al., 2010; Ferragut and Campos Bicudo, 2010; Guo et al., 2016a; Passy, 2007; Rimet and Bouchez, 2012), but some obvious and concerning constrains exist:

(i) Trait categories are continuously being updated and taxa assignments to different categories are still controversial and a more complete and reliable assignment system for all algal taxa is therefore of high priority to advance the use of trait-based approaches in the future. Classification of diatom guilds, for instance, has mostly been based on the study of Passy (2007) with three guilds (i.e., low profile, high profile and motile taxa), but Rimet and Bouchez (2012) proposed modifications by adding a fourth ecological guild (i.e., planktonic taxa) and furthermore suggested some revisions. For example, planktonic species were excluded from the low profile guild (e.g., *Cyclotella* spp., *Stephanodiscus* spp., Supplementary Table S1) and all taxa presenting the largest size class (> 1500 μm^3, e.g., *Cymbella lanceolata*, *Eucocconeis flexella*, *Achnanthes brevipes*, etc.) were moved from the low profile guild to the high profile guild (Rimet and Bouchez, 2012). Nevertheless, the assignment of *Frustulia* spp. was still unclear: some regarded it as high profile guild (Passy, 2007; Rimet and Bouchez, 2012) while others regarded it as a motile taxa (Dong et al., 2016; Passy and Larson, 2011; Stenger-Kovács et al., 2013; Tang et al., 2013). These updates and modifications will improve the precision of assignments into distinct trait categories, but at the same time restrict the comparisons with other studies applying different assignment systems.

(ii) Responses of different traits to environmental stressors are still debated and some studies have concluded contradictory responses to a single stressor. For example, both positive (B-Béres et al., 2014; Lange et al., 2016; Passy, 2007B-Béres et al., 2014) and negative (Stenger-Kovács et al., 2013) relationships between motile taxa and nitrogen concentrations have been found. Besides, most previous studies have focused on single or a few traits and were conducted in mesocosms (Hill et al., 2011; Lange et al., 2011; Piggott et al., 2012; Piggott et al., 2015) or in the field (Berthon et al., 2011; Guo et al., 2016a; Passy, 2007; Soininen et al., 2016; Thomas et al., 2016). Very few have investigated the combined effects of multiple, simultaneously operating stressors on a comprehensive set of algal traits (Lange et al., 2016; Piggott et al., 2012), although it is quite clear that multiple stressors often interact on the algal community (i.e., synergism or antagonism) (Guo et al., 2016a; Hill et al., 2011; Lange et al., 2011; Lange et al., 2016; Piggott et al., 2012).

(iii) Trait distribution has been investigated at a comparatively small scale and their underlying environmental and historical drivers at larger scales are still poorly understood (Soininen et al., 2016). Furthermore, most of the previous studies have been conducted on a spatial scale (Berthon et al., 2011; Dong et al., 2016; Passy, 2007, 2009; Soininen et al., 2016) while studies based on a temporal scale are rare (B-Béres et al., 2014; Stenger-Kovács et al., 2013B-Béres et al., 2014).

4. Conceptual framework of algal traits in relation to resources and disturbance

Based on the existing knowledge, we here propose a number of conceptual models to describe the responses of different algae traits to resource supply (mainly nutrient enrichment) and disturbance intensity (e.g., flow regulation and grazing) (Fig. 3). Six response patterns (A-F) are shown in Fig. 3. Most traits are co-regulated by disturbance intensity and resource supply (e.g., Fig. 3A–D). For example large cell size, high profile and functional diversity decrease with increasing disturbance frequency and decreasing resource supply. On the contrary small cell size and low profile species are expected to increase from high resource and low disturbance towards low resources and high

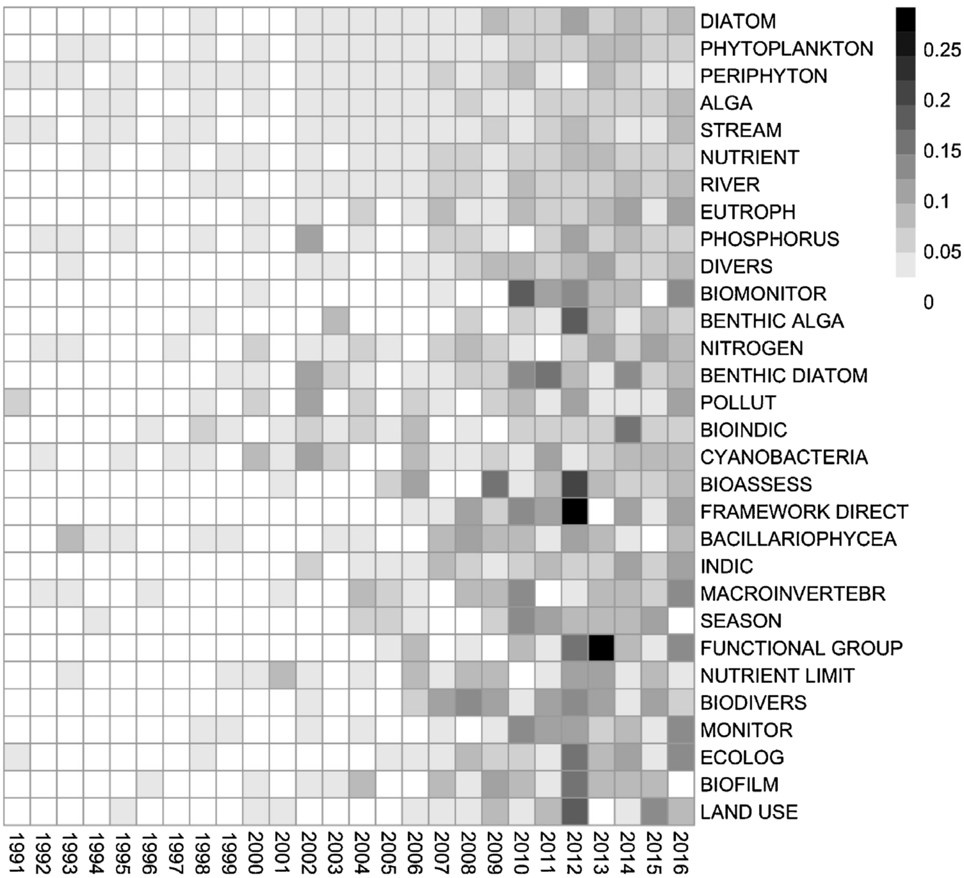

Fig. 2. The yearly percentages of occurrence of top 30 keywords with significant increasing trend in the articles found from 1991 to 2016. The significance was tested by Mann–Kendal (MK) trend test (see text for details). ALGA = algae, EUTROPH = eutrophication, DIVERS = diversity, POLLUT = pollution, DIOINDIC = bioindicator, INDIC = indicator, ECOLOG = ecology.

disturbance frequency. Some traits are supposed to respond to solely a single stressor (Fig. 3E, F) and may be suitable to disentangle the effects of multiple stressors (e.g., nitrogen fixation to detect nutrient enrichment, attachment to substrate to detect hydrological disturbance). Nevertheless, the relationship between traits and the complex mixture of stressors existing in freshwater habitats is still poorly documented and understood. We thus advocate that 1) further sampling of trait data to build up an updated database, 2) linkages between traits and environmental stressors should be further studied, and 3) validations of the hypotheses over larger spatial and temporal scale in the future studies, which may greatly benefit the trait-based environmental assessment, biodiversity conservation and integrated water resource management.

5. Future research directions and applications

5.1. The role of microalgae in ecosystem functions

There is an increasing interest in ecology to understand linkages between microalgae community composition and ecosystem functions (Reisinger et al., 2015; Reiss et al., 2009; Taylor et al., 2002), especially across the longitudinal gradient. Streams and rivers regulate resource (such as nutrients, sediments, organic matters, etc.) transport from terrestrial to marine ecosystems making them extremely important for understanding and protecting downstream ecosystems (Alexander et al., 2008; Reisinger et al., 2015). Nutrients entering the streams are partially used by benthic and pelagic biota (e.g., assimilation, dissimilation, sorption, etc.) with a portion being removed permanently via denitrification or deposited at the bottom, and the rest is transported to downstream waters. Assimilatory uptake by biota in streams has proved to constitute the majority of nutrient removal from the water column (Mulholland et al., 2008), however, the ultimate fate of assimilated nutrients still remains unknown (Reisinger et al., 2015). Understanding the role of benthic and pelagic microalgae in nutrient removal in streams is therefore particularly important for managing stream ecosystems given the fact that anthropogenic point and diffuse sources have increased nitrogen and phosphorus loads to river ecosystem globally (Guse et al., 2015; Hering et al., 2015; Seitzinger et al., 2005).

Experiments, reviews and meta-analyses have shown that biological traits, which can inform the contributions of species to ecosystem function through differences in nutrient use and storage (Cadotte et al., 2011), are one of the best predictors of ecosystem function available (Griffin et al., 2009; Hooper et al., 2005; Petchey and Gaston, 2006). However, to our knowledge, the role of different functional traits in maintaining stream ecosystem function is still not well documented. Therefore, the relationships between algal traits and ecosystem functions (e.g., nutrient uptake, metabolism) and their underlying mechanisms along stream size gradients are greatly needed. In addition, the majority of previous studies have focused only on algal traits lacking investigations of interaction with higher consumers (e.g., zooplankton, macroinvertebrates and fish) and energy transfer in ecosystem functions. Thus, impacts of human mediated stressors on algal traits and their consequent effect in stream food webs warrant further scientific attentions.

5.2. Trait-based approach for biomonitoring under multiple stressors

As mentioned above, freshwater resources are globally affected by multiple stressors such as water abstraction, intensive farming land use and climate change (Dudgeon et al., 2006; Hering et al., 2015; Vörösmarty et al., 2010), and the importance of assessing the potential risks on stream ecosystems is becoming ever more urgent. The traditional taxonomic based indices, however, do not fully meet these urgent demands and new approaches for biomonitoring purposes are required (see details above). Although the developments of the algal trait approach in biomonitoring are promising, one issue arises: how to select

Table 1
Algal indices, traits, their descriptions, and expected responses to different environmental stressors e.g., nutrient enrichment, light, flow regulation and grazing.

Traits	Categories	Abbreviations	Expected responses to stressors	
			Resource	Disturbance
1. Functional diversity (Bruno et al., 2016; Cadotte et al., 2011; Schleuter et al., 2010)	Functional richness Functional evenness Functional divergence Functional attribute diversity Functional dispersion Functional redundancy	FR_{ic} FE_{ve} FD_{iv} FAD FD_{is} FR_{ed}	Disturbances will reduce while high resource supply will increase functional diversity	
2. Cell size (Berthon et al., 2011; Rimet and Bouchez, 2012)	Nano (5–100 μm^3) Micro (100–300 μm^3) Meso (300–600 μm^3) Macro (600–1500 μm^3) Very large (> 1500 μm^3)	BioVol_c1 BioVol_c2 BioVol_c3 BioVol_c4 BioVol_c5	Smaller cells have higher nutrient uptake rates and growth rates that allow greater resilience to disturbance making them advantage under nutrient-limiting and high disturbance conditions; Larger cells show converse trend	
3. Diatom guild (Passy, 2007; Rimet and Bouchez, 2012)	Low profile High profile Motile taxa Planktonic taxa	LowPro HigPro MotTax PlaTax	Advantage at lower resources and high disturbance; Favor higher resources and low disturbance; Advantage in resource gathering and low-flow depositional condition (MotTax and PlaTax)	
4. Life form (Ferragut and Campos Bicudo, 2010)	Colonial Filamentous Flagellate Unicellular	LifFor_col LifFor_fil LifFor_fla LifFor_uni	LifFor_fil has advantage in resource gathering but susceptible to high disturbance regimes LifFor_uni has advantage in under depositional and high resource conditions	
5. Eco-morphology (B-Béres et al., 2016)	Guild + Cell size[a] Life form + Cell size[b]	– –	Combination between diatom guilds and cell size classes Combination between life forms and cell size classes	
6. Nitrogen fixation (Stancheva et al., 2013)	Yes (1) or no (0)	NitFix_1	N-fixer algae has advantage under nutrient-limiting condition but their relation to disturbances varies	
7. Attachment to substratum (Biggs et al., 1998)	Non attached Medium attached Tightly attached	AttSub_non AttSub_med AttSub_hig	Algae with stronger attachment are more likely to retain under high disturbance condition	
8. Motility (Round, 1984)	Motile attached Motile gliding Motile drift	Motile_att Motile_gli Motile_dri	Actively motile algae have advantage in resource gathering and low-flow depositional condition	
9. Reproductive strategies (Biggs et al., 1998)	Fission Fragmentation	RepStr_fis RepStr_fra	RepStr_fis has advantage for dispersal and recolonization after disturbance	
10. Spore formation (Agrawal, 2009; Lange et al., 2016)	No spore formation Zoospores Akinetes Oospores and zygospores	SpoFor_non SpoFor_zoo SpoFor_aki SpoFor_oos.zyg	SpoFor_aki and SpoFor_oos.zyg have advantage in unfavourable conditions	
11.Temperature traits (Thomas et al., 2016)	Optimum temperature for growth Maximum persistence temperature Minimum persistence temperature	T_{opt} T_{max} T_{min}	T_{opt} T_{max} T_{min} decline with latitude increasing	
12. Algal quality (Guo et al., 2016a,b; Hill et al., 2011)	Saturated fatty acids Monounsaturated fatty acids Polyunsaturated fatty acids Highly unsaturated fatty acid	SAFA MUFA FUFA HUFA	Nutrient enrichment, low light and low temperature increases PUFA%, which in turn affect growth and PUFA composition in stream grazers	

Note: Resource acquisition includes nutrient enrichment (e.g., global land use change) and light (global warming); disturbance includes flow regulation and grazing. Seven traits (i.e., cell size, life form, nitrogen fixation, attachment to substratum, motility, reproductive strategies and spore formation) were adapted from Lange et al. (2016). Although some traits are overlapped, we retained them in order to gather all potential traits. Except for temperature traits, which are ecological traits, all these traits are biological traits (for definitions see Supplementary Table S2).

[a] A simple combination between 4 guilds and 5 cell size classes, resulting in 20 combinations (B-Béres et al., 2016).

[b] A simple combination between 4 life forms and 5 cell size classes, resulting in 20 combinations.

robust traits that can disentangle the effects of multiple stressors in a catchment?

One of the main objectives of the trait-based research approach is relating traits to environmental factors (McGill et al., 2006). Although the relationships between environmental conditions (e.g., resources, disturbances, grazing, etc.) and many aspects of river microalgae community structure and dynamics are well known, trait − environment linkages are still poorly documented. Robust (unlinked, uncorrelated) traits should supply a quick assessment of the stressor and provide insight into the environmental gradients in question (Poff et al., 2006). Further field surveys and manipulative studies are needed to address how algal traits vary across gradients of environmental variables in streams and their consequent impacts on ecosystem functions. In fact, trade-offs and trait syndromes are two major challenges during the trait selection. A standard approach to diminish these two problems is to relate traits to each other by regression (McGill et al., 2006). One example was relating nutrient uptake rates and growth rates to cell size (Biggs et al., 1998; Lange et al., 2016; Litchman and Klausmeier, 2008). Similarly, Menezes et al. (2010) also suggested a formal analysis accounting for phylogenetic relationships and potential confounding

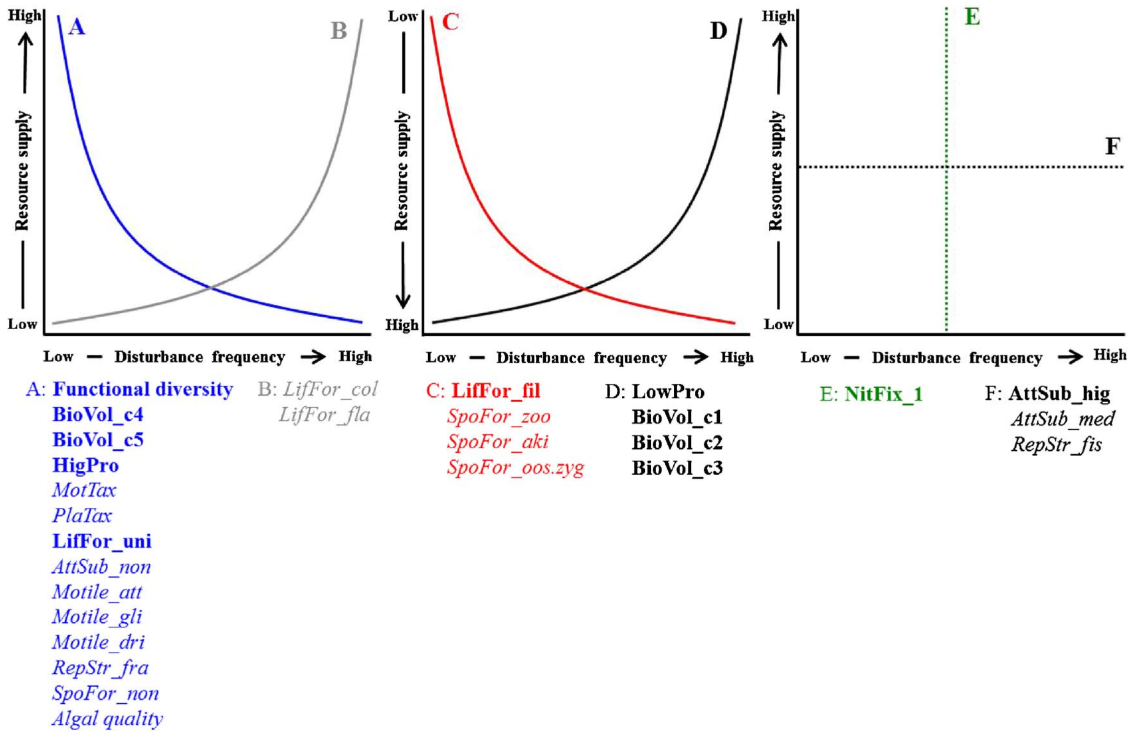

Fig. 3. Conceptual models showing six response patterns of different traits to resource supply and disturbance frequency. Traits categories are designated to different response patterns and given below the diagrams. Some of these patterns have been validated (**bold**) and others remain to be tested (*italic*). The pattern E and F show the potential traits, which relate solely to a single stressor and may be suitable for disentangling the effects of multiple stressors (e.g., nitrogen fixation to detect nutrient enrichment, attachment to substrate to detect hydrological disturbance). Temperature traits, which are supposed to relate solely to temperature changes, and eco-morphology traits were not shown here. Abbreviations are as in Table 1.

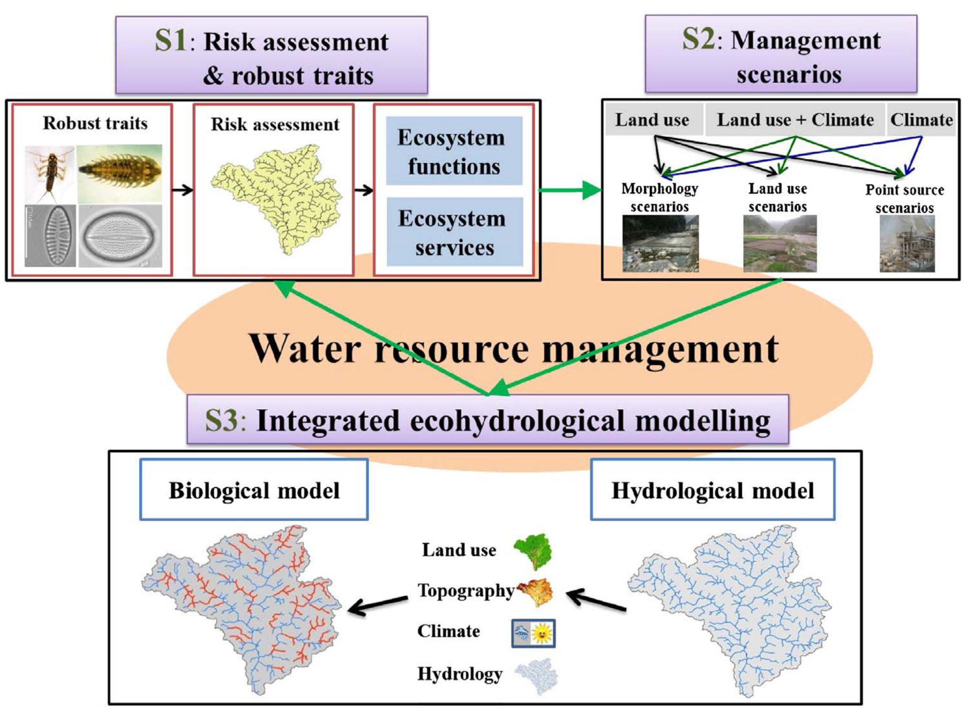

Fig. 4. A conceptual framework following a rigorous step-by-step process (S1-S3). S1 is risk assessment of different stressors and identifying robust traits of microalgae; S2 is predicting the future global change scenarios (including global land use and climate change) and developing management strategies with regard to global change and socio-economic development; S3 is the implementation and evaluation of distinct management scenarios in integrated modelling system. Definitions of different terms are shown at Supplementary Table S2.

effects on trait measures, which will be used to provide information on future trait selection for biomonitoring purposes.

5.3. Trait-based approach for water resource management in an interdisciplinary manner

Apart from biomonitoring and risk assessment, one of the great potential applications of trait-based approaches is to improve our ability to predict community composition, dynamics and ecosystem functions under rapidly environmental changes or management scenarios. To develop adaptive strategies and manage water resources in a sustainable way, we suggest to develop an integrated interdisciplinary approach with a sound understanding of potential risks, catchment processes and feedback mechanisms of stream organisms. Models could be especially promising to achieve this goal and researchers have started using integrated models (e.g., biological model + regional climate model, biological model + hydrological model, etc.) to predict community reorganization under different global change scenarios (Elliott et al., 2005; Jähnig et al., 2012; Kuemmerlen et al., 2015; Schmalz et al., 2015).

Here we propose a novel integrated framework that links trait-based risk assessment and management scenarios by an integrated ecohydrological modelling (Fig. 4). In a first step (S1), potential risks of different stressors should be evaluated statistically and robust traits of microalgae should be identified (the same processes as above). The selected traits are linked to benefits for human well-being by ecosystem functions and services (e.g. regulating, provisioning and cultural services). The second step (S2) is to generate different management strategies (scenarios) under global change (i.e. climate change, land use change, and both climate + land use change at the same time) based on socio-economic developments in the region. Numerous candidate management strategies should be generated by the combinations between future global change and management scenarios. The third step (S3) is the calibration and validation by an integrated modelling system which comprises hydrological and biological models (Fig. 4). Environmental predictors (e.g., land use, topography, climate and hydrology) are the bridge linking these two models. The effect of each management strategy on ecosystem services should be tested by the application of the interdisciplinary modelling system. The process circle should then continue until the best management strategy is successfully defined.

Acknowledgements

This study is financially supported by an AIAS-COFUND Marie Curie fellowship (N.W. and X.D.), the National Science Foundation of China (Grant No: 41530753 and 41472314) (X.D.), Carlsberg Foundation (CF16-0325) and the European Union Seventh Framework Project MARS (603378).

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.ecolind.2017.05.066.

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