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Review

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

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ABSTRACT

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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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