



## Review

# Are indicator groups and cross-taxon congruence useful for predicting biodiversity in aquatic ecosystems?

Jani Heino<sup>a,b,\*</sup><sup>a</sup> Finnish Environment Institute, Research Programme for Biodiversity, University of Oulu, P.O. Box 413, FI-90014, Finland<sup>b</sup> Department of Biology, University of Oulu, P.O. Box 3000, FI-90014 Oulu, Finland

## ARTICLE INFO

## Article history:

Received 22 December 2008

Received in revised form 21 April 2009

Accepted 28 April 2009

## Keywords:

Congruence  
Indicator groups  
Lentic  
Lotic  
Spatial patterns  
Surrogates

## ABSTRACT

Resources for biodiversity surveys and conservation planning are limited, and conservation biologists and environmental managers are thus striving to find suitable surrogates for mapping and predicting biodiversity. Among popular surrogates are indicator groups that could be used for predicting variation in the biodiversity of other taxonomic groups. Despite some success at large scales, surveys of multiple taxonomic groups across ecosystems have suggested that no single group can be used effectively to predict variation in the biodiversity of other taxonomic groups. This paper concentrates on indicator groups and cross-taxon congruence in species richness and assemblage composition patterns in inland aquatic ecosystems. As has been found in studies of terrestrial ecosystems, there is low utility for indicator groups in predicting the biodiversity of other taxa in aquatic ecosystems. Even when statistically highly significant correlations between taxonomic groups have been detected, these correlations have been too weak to provide reliable predictions of biodiversity among various taxonomic groups or biodiversity in general. Indicator groups and, more generally, cross-taxon congruence thus do not appear to be particularly relevant for conservation in the freshwater realm.

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## 1. Introduction

Biodiversity is complexly distributed across ecosystems. This complexity has proved to be difficult to describe and predict, and typically a proper characterisation of the biodiversity of multiple taxonomic groups necessitates much effort, expertise, and money. There is thus a need for suitable surrogates of biodiversity. These surrogates include environmental features, higher taxa, indicator species, and indicator groups (Gaston, 1996; Faith and Walker, 1996;

McGeogh, 1998; Howard et al., 1998). An indicator group should at least be taxonomically and ecologically well-understood, easily monitored, occur in various environmental conditions, and show strong relationships with other target groups in biodiversity value (Noss, 1990; Pearson, 1994). Studies testing the utility of indicator groups have generally been based on the description of biodiversity across large-scale grids, countries, and regions (Ricketts et al., 1999; Myers et al., 2000), while studies describing cross-taxon congruence across ecosystems have appeared more recently (Heino et al., 2003; Su et al., 2004). In this paper, cross-taxon congruence refers to the strength and significance of correlation in assemblage-level biodiversity measures between taxonomic groups across a set of localities. In terms of strong congruence, correlations among taxonomic groups should preferably be positive and high to be effective in guiding conservation planning.

\* Correspondence address: Finnish Environment Institute, Research Programme for Biodiversity, University of Oulu, P.O. Box 413, FI-90014, Finland.  
Tel.: +358 50 5845977; fax: +358 20 4902985.

E-mail address: [jani.heino@ymparisto.fi](mailto:jani.heino@ymparisto.fi).

**Table 1**

Study regions and taxonomic groups considered in the aquatic congruence studies. LO = lotic study and LE = lentic study.

Study	Country	Organism groups
Allen et al. (1999a) <sup>LE</sup>	USA	Sedimentary diatoms, planktonic crustaceans, planktonic rotifers, macroinvertebrates, fish, birds
Allen et al. (1999b) <sup>LE</sup>	USA	Sedimentary diatoms, zooplankton, macroinvertebrates, fish, riparian birds
Bilton et al. (2006) <sup>LE</sup>	UK	Snails, beetles, caddisflies, non-biting midges
Bini et al. (2007) <sup>LE</sup>	Brazil	Testate amoebae, rotifers, copepods, cladocerans
Bini et al. (2008) <sup>LE</sup>	Brazil	Rotifers, copepods, cladocerans
Bowman et al. (2008) <sup>LE</sup>	Canada	Phytoplankton, zooplankton, macroinvertebrates, crayfish, fish
Grenouillet et al. (2008) <sup>LO</sup>	France	Diatoms, macroinvertebrates, fish
Heino et al. (2003) <sup>LO</sup>	Finland	Mayflies, stoneflies, caddisflies, non-biting midges
Heino et al. (2005) <sup>LO</sup>	Finland	Bryophytes, macroinvertebrates, fish
Heino and Mykrä (in press) <sup>LO</sup>	Finland	Mayflies, stoneflies, caddisflies, non-biting midges
Heino et al. (2009) <sup>LO</sup>	Finland	Diatoms, macrophytes, macroinvertebrates
Infante et al. (2009) <sup>LO</sup>	USA	Macroinvertebrates, fish
Jackson and Harvey (1993) <sup>LE</sup>	Canada	Macroinvertebrates, fish
Johnson and Hering (2009) <sup>LO</sup>	Europe	Diatoms, macrophytes, macroinvertebrates, fish
Kilgour and Barton (1999) <sup>LO</sup>	Canada	Macroinvertebrates, fish
Longmuir et al. (2007) <sup>LE</sup>	Canada	Bacteria, phytoplankton, zooplankton
Mykrä et al. (2008) <sup>LO</sup>	Finland	Macrophytes, macroinvertebrates
Paavola et al. (2006) <sup>LO</sup>	Finland	Bryophytes, macroinvertebrates, fish
Paszkowski and Tonn (2000) <sup>LE</sup>	Canada	Fish, birds
Sánchez-Fernández et al. (2006) <sup>LO</sup>	Spain	Molluscs, mayflies, stoneflies, true bugs, beetles, caddisflies
Sánchez-Fernández et al. (2006) <sup>LE</sup>	Spain	Molluscs, mayflies, true bugs, beetles, caddisflies
Soininen et al. (2007) <sup>LE</sup>	Finland	Phytoplankton, zooplankton
Soininen et al. (2009) <sup>LO</sup>	Finland	Diatoms, macroalgae
Tolonen et al. (2005) <sup>LE</sup>	Finland	Phytoplankton, macrophytes, zooplankton, macroinvertebrates, fish

The findings from the large-scale versus ecosystem-level congruence studies could be expected to differ, yet findings from both types of studies have been ambiguous. This ambiguousness is seen in the fact that, despite many studies show significant cross-taxon congruence in biodiversity measures, the strength of these correlations is typically rather weak (Flather et al., 1997; Gaston, 2000). Studies spanning large-scale grids (e.g. 2500–10,000 km<sup>2</sup>) and very large spatial extents (e.g. countries to continents) have typically reported strongest cross-taxon congruence in species richness patterns (Reid, 1998; Ricketts et al., 1999; Myers et al., 2000). However, exceptions to such findings have also emerged in large-scale studies (Flather et al., 1997). Studies examining local assemblages within smaller regional extents have reported variable (Pharo et al., 1999; Sauberer et al., 2004), but often low degrees of congruence in species richness among multiple taxonomic groups (Allen et al., 1999a,b; Kati et al., 2004). There are a number of reasons why congruence is often weak.

The mechanisms responsible for strong cross-taxon congruence can be divided in five general groups (Gaston and Williams, 1996). Strong congruence may be generated by (i) random draw of species from the regional species pool; (ii) similar responses of different taxonomic groups to the same environmental gradient(s); (iii) responses to different, but correlated environmental gradients; and (iv) biotic interactions. Furthermore, (v) inconsistent sampling effort, with some sites being sampled more efficiently for multiple organism groups, may affect congruence, species richness patterns in particular (Gaston, 2000). Although disentangling between these mechanisms may be challenging due to the large spatial scales associated with congruence studies, examining simultaneously the responses of multiple taxonomic groups to the same ecological gradients may shed light into this issue.

The aim of this paper is to review studies that have simultaneously compared variation in the biodiversity of multiple taxonomic groups along ecological gradients. Understanding the influences of ecological gradients on species richness and assemblage composition of multiple taxonomic groups would help not only in understanding the degree of cross-taxon congruence, but also have potential implications for conservation. The relevance of congruence and indicator groups for conservation will be given specific attention after patterns in lotic (i.e. streams

and rivers) and lentic (i.e. ponds and lakes) have been considered. The objective of this paper is to examine patterns across inland aquatic systems, and thus those across terrestrial ecosystems and large-scale grids will not be considered. The reader should refer to the previous reviews that have considered mainly terrestrial organisms and large spatial scales (Gaston, 1996; Reid, 1998). The present review is narrative, rather than based on a formal meta-analysis. This approach was followed, because the scarcity of data and various measures of congruence used in the studies prevented conducting a meaningful meta-analysis. Nevertheless, there were a relatively large number of aquatic congruence studies that had considered either species richness, assemblage composition, or both (Table 1).

## 2. Patterns in lotic ecosystems

A number of studies have examined cross-taxon congruence of biodiversity patterns in streams and rivers in the last decade. A general finding in these studies has been that species richness is typically relatively weakly correlated ( $r < 0.7$ ) among different taxonomic groups (Table 2). This means that less than half of the variation in the biodiversity of a target group is explained by another taxonomic group. Such findings have emerged from studies of mayflies, stoneflies, caddisflies, and midges of boreal streams (Heino et al., 2003; Heino and Mykrä, in press). Similarly weak relationships have been found in studies of diatoms, macrophytes, macroinvertebrates, and fish in boreal streams (Heino et al., 2005, 2009). By contrast, Sánchez-Fernández et al. (2006) found that aquatic beetles were relatively good indicators of species richness of some other stream taxa, with correlations ranging from non-significant for molluscs and mayflies to significant and rather strong for true bugs, stoneflies, caddisflies, and total richness of the studied taxonomic groups in a Mediterranean drainage basin. The correlations between the species richness of mayflies, stoneflies, and caddisflies were also among the highest ones ( $r > 0.7$ ) reported from lotic systems (Sánchez-Fernández et al., 2006).

Similarly to species richness, a number of recent lotic studies have compared patterns in species compositional variation among different taxonomic groups (Table 2). These studies have been

**Table 2**

Characteristics of congruence studies conducted in aquatic ecosystems. Strong correlations refer to those with  $r$ -values  $>0.7$  in correlation or Mantel test. LO = lotic study and LE = lentic study.

Study	Measure of congruence and method of analysis	No. taxonomic groups	No. significant correlations	No. strong correlations	Range of $r$ -values	Source	Notes
Allen et al. (1999a) <sup>LE</sup>	Species richness, correlation	6	2	0	−0.07 to 0.37	Table 4	Measurement variability not accounted for
Allen et al. (1999b) <sup>LE</sup>	DCA site scores, correlation	5	7	1	0.03–0.76	Figure 3	Across the whole study region
Bilton et al. (2006) <sup>LE</sup>	Species richness, correlation	4	4	0	−0.07 to 0.64	Table 2	Both regions included
Bini et al. (2007) <sup>LE</sup>	Ordination scores, Procrustes analysis	4	1	?	?	Table 5	No $r$ -value available
Bini et al. (2008) <sup>LE</sup>	Mantel test, Procrustes analysis	3	6	0	0.36–0.67	Table 2	Both seasons included
Bowman et al. (2008) <sup>LE</sup>	Dissimilarity matrix, Mantel test	5	6	2	0.28–0.85	Table 3	Overall spatial concordance only
Grenouillet et al. (2008) <sup>LO</sup>	Dissimilarity matrix, Mantel test	3	2	0	0.28–0.59	Table 1	
Heino et al. (2003) <sup>LO</sup>	Species richness, correlation	4	3	0	0.13–0.28	Figure 1	Across the whole study region
Heino et al. (2003) <sup>LO</sup>	DCA site scores, correlation	4	4	0	0.16–0.53	Figure 2	Across the whole study region
Heino et al. (2003) <sup>LO</sup>	Dissimilarity matrix, Mantel test	4	6	0	0.09–0.23	Table 7	Across the whole study region
Heino et al. (2005) <sup>LO</sup>	Species richness, correlation	3	3	0	0.22–0.43	Page 424	
Heino and Mykrä (in press) <sup>LO</sup>	Species richness, correlation	4	2	0	−0.08 to 0.52	Table 3	All 3 years included
Heino and Mykrä (in press) <sup>LO</sup>	Dissimilarity matrix, Mantel test	4	6	0	0.07–0.35	Table 4	All 3 years included
Heino et al. (2009) <sup>LO</sup>	Species richness, correlation	3	1	0	−0.28 to 0.51		
Heino et al. (2009) <sup>LO</sup>	Dissimilarity matrix, Mantel test	3	2	0	0.14–0.43		
Infante et al. (2009) <sup>LO</sup>	Dissimilarity matrix, Mantel test	2	0	0	0.08		
Jackson and Harvey (1993) <sup>LE</sup>	Ordination scores, Procrustes analysis	2	1	?	?	Page 2646	No $r$ -value available
Johnson and Hering (2009) <sup>LO</sup>	Dissimilarity matrix, Mantel test	4	6	0	0.18–0.38	Table 2	Lowland streams, presence–absence data
Johnson and Hering (2009) <sup>LO</sup>	Dissimilarity matrix, Mantel test	4	6	0	0.19–0.55	Table 2	Mountain streams, presence–absence data
Kilgour and Barton (1999) <sup>LO</sup>	Dissimilarity matrix, Mantel test	2	4	0	?	Figure 2	Species data for macroinvertebrates
Longmuir et al. (2007) <sup>LE</sup>	Species richness, correlation	3	0	?	?	Page 1668	No $r$ -value available
Mykrä et al. (2008) <sup>LO</sup>	Species richness, correlation	2	1	0	0.31	Page 195	Both reference and test sites included
Mykrä et al. (2008) <sup>LO</sup>	Dissimilarity matrix, Mantel test	2	1	0	0.22	Page 195	Both references and test sites included
Paavola et al. (2006) <sup>LO</sup>	Ordination scores, Procrustes analysis	3	3	?	?	Table 1	Across the whole study region
Paszkowski and Tonn (2000) <sup>LE</sup>	Dissimilarity matrix, Mantel test	2	1	?	?	Page 431	No $r$ -value available
Paszkowski and Tonn (2000) <sup>LE</sup>	Ordination scores, Procrustes analysis	2	1	?	?	Page 431	No $r$ -value available
Sánchez-Fernández et al. (2006) <sup>LO</sup>	Species richness, correlation	6	6	4	−0.07 to 0.88	Table 4	Lotic freshwater sites
Sánchez-Fernández et al. (2006) <sup>LE</sup>	Species richness, correlation	5	0	0	−0.53 to 0.62	Table 4	Lentic freshwater sites
Soininen et al. (2007) <sup>LE</sup>	Dissimilarity matrix, Mantel test	2	0	0	0.07	Page 150	
Soininen et al. (2009) <sup>LO</sup>	Species richness, correlation	2	0	0	−0.20	Page 84	
Soininen et al. (2009) <sup>LO</sup>	Dissimilarity matrix, Mantel test	2	1	0	0.24	Page 84	
Tolonen et al. (2005) <sup>LE</sup>	Species richness, correlation	5	1	0	−0.28 to 0.50	Table 5	
Tolonen et al. (2005) <sup>LE</sup>	Evenness, correlation	4	1	0	−0.40 to 0.34	Table 5	

based on various means to examine congruence, including correlations between major ordination axes (Heino et al., 2003), Procrustes rotation of multiple ordination axes (Paavola et al., 2006), and Mantel tests of dissimilarity matrices (Kilgour and Barton, 1999). Despite these multiple types of analyses, the

findings in these studies have been remarkably similar. Although pairwise comparisons between different taxonomic groups have typically been highly significant, the strength of these relationships has been low ( $r < 0.5$  assessed based on correlation coefficients in correlation analyses and Mantel test;  $m^2 > 0.5$  in

Procrustes analysis). Such findings have been detected across a wide range of geographical regions (Kilgour and Barton, 1999; Heino et al., 2003; Paavola et al., 2006; Johnson and Hering, 2009). Thus, different taxonomic groups do not show particularly similar variation in assemblage composition across a set of localities.

What might be the explanations for low degrees of congruence in species richness or assemblage composition in lotic ecosystems? Differential response to environmental gradients is the most plausible explanation to differing patterns among taxonomic groups. For example, the responses of species richness and assemblage composition to local environmental gradients and geographical location vary among different stream insect groups (Heino et al., 2003; Heino and Mykrä, in press). Similarly, assemblage–environment relationships show some differences between bryophytes, macroinvertebrates, and fish in boreal streams (Paavola et al., 2003; Mykrä et al., 2008). A further explanation for weak congruence may be due to the fact that different-sized organisms, such as diatoms, macroinvertebrates, and fish, perceive their environment at such disparate scales that co-variation in biodiversity patterns remains inevitably weak (Heino et al., 2005; Grenouillet et al., 2008; Infante et al., 2009). However, a study on stream fish and macroinvertebrates suggested that both groups responded similarly to environmental gradients (Kilgour and Barton, 1999), and other studies have shown that diatoms, macrophytes, macroinvertebrates, and fish show relatively similar relationships to ecological variables at different scales (Passy et al., 2004; Johnson et al., 2007). However, the latter two studies did not consider congruence *per se*, so it is difficult to judge the degree to which these taxonomic groups actually showed similar variation across the studied stream sites.

### 3. Patterns in lentic ecosystems

The patterns of cross-taxon congruence in lentic ecosystems are closely similar to those in lotic ecosystems (Table 2). For example, Allen et al. (1999a) found that species richness correlations were low among benthic invertebrates, fish, riparian birds, diatoms, crustaceans, and rotifers. Similar findings have emerged from other studies of various taxa, comprising macroinvertebrates, fish, zooplankton, phytoplankton, and macrophytes in lakes (Tolonen et al., 2005; Longmuir et al., 2007) and different groups of invertebrates in ponds (Briers and Biggs, 2003; Bilton et al., 2006; Sánchez-Fernández et al., 2006).

Despite low species richness correlations among taxonomic groups, some relationships in assemblage composition have been found to be stronger (Table 2). For example, Bilton et al. (2006) found that various macroinvertebrate groups in ponds showed rather strong congruence in assemblage similarity, Allen et al. (1999b) detected some relatively strong correlations between the assemblage patterns of lake fish and riparian birds, and Bini et al. (2008) suggested that major zooplankton groups show similar assemblage variation across a set of reservoirs. Paszkowski and Tonn (2000) also found significantly congruent assemblage patterns between lake fish and birds. These studies suggest that lentic organisms with closely similar body size may show stronger congruence in assemblage composition than organisms with disparate body size (Allen et al., 1999b). However, opposite findings have also been emerged, indicating that also different groups of small organisms may exhibit weak congruence (Bini et al., 2007; Soininen et al., 2007).

When strong congruence has been detected between lentic taxa, the most likely reason behind the observed patterns has again been similar responses to environmental gradients. This is what was suggested by Bilton et al. (2006) for pond invertebrate assemblages and Allen et al. (1999b) for riparian birds and lake fish. Similar-sized organisms may thus show more similar

responses to the environment than species differing in size. In general, large-sized organisms may be presumed to respond more strongly to large-scale environmental variation (e.g. land use, climate) than small-sized organisms that may perceive environmental variation at smaller scales (e.g. water chemistry, habitat heterogeneity). This reasoning is supported by some studies that have shown fish to be more closely associated with lake morphometry and invertebrates with water chemistry (Jackson and Harvey, 1993). Findings of different environmental drivers of biodiversity among taxonomic groups have been provided by other studies of lentic organisms (Declerck et al., 2005; Beisner et al., 2006; Longmuir et al., 2007). However, Allen et al. (1999a) found that species richness in five of the six taxonomic groups studied was primarily determined by lake area, while diatoms showed strongest responses to water acidity.

### 4. Implications for conservation

Strong correlations ( $r > 0.7$ ; see also Flather et al., 1997; Vellend et al., 2008) in species richness or assemblage composition patterns between taxonomic groups might be considered as evidence that indicator groups are relevant for biodiversity surveys and conservation planning. Strong correlations would facilitate that surveys were restricted to a single taxonomic group, given that it mirrors well variation in the biodiversity of other taxa and can be used in predictive purposes. However, based on the present literature review, very few cross-taxon correlations are high enough to aid the accurate prediction of biodiversity in other taxa by a presumed indicator group. Although some studies have reported highly significant correlations, suggesting that different taxonomic groups often show more similar patterns than could be expected by chance, such significance is not enough if the aim is to predict variation in the biodiversity of multiple taxonomic groups (Flather et al., 1997; Gaston, 2000). Significant congruence is likely to emerge in analyses where significance testing is based on randomisation tests, which may lead to highly significant results even if the strength of correlations is very low. Thus, one should separate highly significant correlations from strong correlations, as the latter are necessary for biodiversity surveys and effective conservation planning.

It should be emphasised, however, that simple correlations between taxonomic groups may not be the only option in assessing the utility of cross-taxon congruence in the conservation context. Rather, also complementarity between different taxonomic groups in biodiversity patterns should be considered (Pressey et al., 1993; Margules and Pressey, 2000). Complementary cross-taxon surrogacy refers to the extent to which conservation planning based on complementary representation of species surrogates effectively represents target species (Rodrigues and Brooks, 2007). Studies on cross-taxon complementarity have sometimes found that patterns in complementarity networks may be rather strongly related among taxonomic groups (Howard et al., 1998; Kati et al., 2004). Thus, there is clearly a need to examine patterns in the cross-taxon complementarity of biodiversity patterns in the freshwater realm. For freshwater ecosystems, a study on macroinvertebrates suggested that the use of complementarity networks is a promising approach (Sánchez-Fernández et al., 2006). It may well be that complementarity is the best option to assess where conservation efforts should be directed in the freshwater realm (see also Brooks et al., 2001; Kati et al., 2004).

A further limitation of simple correlations in assessing the usefulness of indicator groups and cross-taxon congruence may be related to the fact that high levels of biodiversity in multiple taxonomic groups only coincide in exceptionally “good” environmental conditions. For freshwater ecosystems, slightly alkaline water (e.g. Giller and Malmqvist, 1998), relatively low natural and



anthropogenic disturbance (e.g. Huston, 1994), and high habitat heterogeneity (e.g. Eadie and Keast, 1984) may enhance biodiversity, and thus sites having such characteristics may harbour high levels of biodiversity in various taxonomic groups. Identification of such exceptionally diverse “hotspots” should be a prerequisite in the conservation planning of freshwater ecosystems, and these sites may not be easily separated using simple correlations across entire ranges of environmental conditions. Similarly, exceptionally “bad” environmental conditions, such as acid, anthropogenically disturbed, and low-heterogeneity aquatic ecosystems, may harbour low diversity of multiple taxonomic groups, being “coldspots” of biodiversity. Again, despite the coincidence of low diversity of multiple taxonomic groups, overall correlations do not necessarily show evidence of their existence. Thus, multiple approaches of examining cross-taxon congruence should be used in future studies of biodiversity surveys and conservation planning in the freshwater realm.

## 5. Conclusions

Cross-taxon congruence in the species richness and assemblage composition patterns of aquatic organisms is typically weak. Although one could envisage that similar-sized organisms (e.g. different groups of aquatic insects) show strong congruence, the evidence suggests that even such groups are often ecologically so different (e.g. in their responses to the environment) that congruence remains weak. Congruence between different-sized organisms that perceive their environment at highly disparate scales may be even weaker. Weak congruence, although often significant, offers poor utility for indicator group-based assessments of biodiversity patterns and conservation planning. At best, indicator groups are highly region- and system-specific, and the transferability of an indicator group to other ecological contexts beyond the focal system is likely to be limited. Indicator groups and, more generally, cross-taxon congruence thus do not appear to be relevant for practical conservation work in the freshwater realm. However, if the aim is to monitor environmental degradation, one should carefully select a group of organisms that is supposed to respond to a specific stressor (Allen et al., 1999b; Bini et al., 2007; Johnson and Hering, 2009). Given that various taxonomic groups respond differently to ecological gradients, all groups are not likely to respond similarly to anthropogenic changes in aquatic ecosystems. Thus, when possible, researchers should rely on information provided by multiple taxonomic groups in both environmental assessment and conservation planning.

## Acknowledgments

Financial support during the writing of this paper was provided by Maj and Tor Nessling Foundation and Kone Foundation. I would like to thank Timo Muotka, Heikki Mykrä, Riku Paavola and Janne Soininen for discussions about the topic over the years, as well as anonymous referees for constructive comments.

## References

- Allen, A.P., Whittier, T.R., Larsen, D.P., Kaufman, P.R., O'Connor, R.J., Hughes, R.M., Stemberger, R.S., Dixit, S.S., Brinkhurst, R.O., Herlihy, A.T., Paulsen, R.G., 1999a. Concordance of taxonomic richness patterns across multiple assemblages: effects of scale, body size and land use. *Canadian Journal of Fisheries and Aquatic Sciences* 56, 2029–2040.
- Allen, A.P., Whittier, T.R., Larsen, D.P., Kaufman, P.R., O'Connor, R.J., Hughes, R.M., Stemberger, R.S., Dixit, S.S., Brinkhurst, R.O., Herlihy, A.T., Paulsen, R.G., 1999b. Concordance of taxonomic composition patterns across multiple lake assemblages: effects of scale, body size, and land use. *Canadian Journal of Fisheries and Aquatic Sciences* 56, 2029–2040.
- Beisner, B.E., Peres-Neto, P.R., Lindström, E.S., Barnett, A., Longhi, M.L., 2006. The role of environmental and spatial processes in structuring lake communities from bacteria to fish. *Ecology* 87, 2985–2991.
- Bilton, D.T., MacAbendroth, L., Bedford, A., Ramsay, P.M., 2006. How wide to cast the net? Cross-taxon congruence of species richness, community similarity and indicator taxa in ponds. *Freshwater Biology* 51, 578–590.
- Bini, L.M., da Silva, L.C.F., Velho, L.F.M., Bonecker, C.C., Lansac-Tôha, F.A., 2008. Zooplankton assemblage concordance patterns in Brazilian reservoirs. *Hydrobiologia* 598, 247–255.
- Bini, L.M., Vieira, L.C.G., Machado, J., Velho, L.F.M., 2007. Concordance of species composition patterns among microcrustaceans, rotifers and testate amoebae in a shallow pond. *International Review of Hydrobiology* 92, 9–22.
- Bowman, M.F., Ingram, R., Reid, R.A., Somers, K.M., Yan, N.D., Paterson, A.M., Morgan, G.E., Gunn, J.M., 2008. Temporal and spatial concordance in community composition of phytoplankton, zooplankton, macroinvertebrate, crayfish, and fish on the Precambrian Shield. *Canadian Journal of Fisheries and Aquatic Sciences* 65, 919–932.
- Briers, R.A., Biggs, B.J., 2003. Indicator taxa for the conservation of pond invertebrate diversity. *Aquatic Conservation: Marine and Freshwater Ecosystems* 13, 323–330.
- Brooks, M., Balmford, A., Burgess, N., Fjeldså, J., Hansen, L.A., Moore, J., Rahbek, C., Williams, P., 2001. Toward a blueprint for conservation in Africa. *Bioscience* 51, 613–624.
- Declerck, S., Vandekerckhove, J., Johansson, L., et al., 2005. Multi-group biodiversity in shallow lakes along gradients of phosphorus and water plant cover. *Ecology* 86, 1905–1915.
- Eadie, J.A., Keast, A., 1984. Resource heterogeneity and fish species diversity in lakes. *Canadian Journal of Zoology* 62, 1689–1695.
- Faith, D.P., Walker, P.A., 1996. How do indicator groups provide information about the relative biodiversity of different sets of areas? On hotspots, complementarity and pattern-based approaches. *Biodiversity Letters* 3, 18–25.
- Flather, C.H., Wilson, K.R., Dean, D.J., McComb, W.C., 1997. Identifying gaps in conservation networks: of indicators and uncertainty in geographic-based analyses. *Ecological Applications* 7, 531–542.
- Gaston, K.J., 1996. Biodiversity—congruence. *Progress in Physical Geography* 20, 105–112.
- Gaston, K.J., 2000. Global patterns of biodiversity. *Nature* 405, 220–227.
- Gaston, K.J., Williams, P.H., 1996. Spatial patterns in taxonomic diversity. In: Gaston, K.J. (Ed.), *Biodiversity. A Biology of Numbers and Difference*. Blackwell Science, Oxford, pp. 202–229.
- Giller, P.S., Malmqvist, B., 1998. *The Biology of Streams and Rivers*. Oxford University Press, Oxford.
- Grenouillet, G., Brosse, S., Tudeque, L., Lek, S., Baraillat, Y., Loo, G., 2008. Concordance among stream assemblages and spatial autocorrelation along a fragmented gradient. *Diversity and Distributions* 14, 592–603.
- Heino, J., Ilmonen, J., Kotanen, J., Mykrä, H., Paasivirta, L., Soininen, J., Virtanen, R., 2009. Surveying biodiversity in protected and managed areas: algae, macrophytes and macroinvertebrates in boreal forest streams. *Ecological Indicators* 9, 1179–1187.
- Heino, J., Muotka, T., Paavola, R., Paasivirta, L., 2003. Among-taxon congruence in biodiversity patterns: can stream insect diversity be predicted using single taxonomic groups? *Canadian Journal of Fisheries and Aquatic Sciences* 60, 1039–1049.
- Heino, J., Mykrä, H., in press. Among-taxon congruence and species richness–environment relationships in stream insects: implications for conservation planning. In: Fattorini S. (Ed.), *Insect Ecology and Conservation*. Research Signpost, Kerala.
- Heino, J., Paavola, R., Virtanen, R., Muotka, T., 2005. Searching for biodiversity indicators in running waters: do bryophytes, macroinvertebrates, and fish show congruent diversity patterns? *Biodiversity and Conservation* 14, 415–428.
- Huston, M.A., 1994. *Biological Diversity: The Coexistence of Species on Changing Landscapes*. Cambridge University Press, Cambridge.
- Jackson, D.A., Harvey, H.H., 1993. Fish and benthic invertebrates: community concordance and community–environment relationships. *Canadian Journal of Fisheries and Aquatic Sciences* 50, 2641–2651.
- Howard, P.C., Viskanic, P., Davenport, T.R.B., Kigenyi, F.W., Baltzer, M., Dickinson, C.J., Swanga, S.L., Matthews, R.A., Bamford, A., 1998. Complementarity and the use of indicator groups for reserve selection in Uganda. *Nature* 394, 472–475.
- Infante, D.M., Allan, J.D., Linke, S., Norris, R.H., 2009. Relationship of fish and macroinvertebrate assemblages to environmental factors: implications for community concordance. *Hydrobiologia* 623, 87–103.
- Johnson, R.K., Furse, M.T., Hering, D., Sandin, L., 2007. Ecological relationships between stream communities and spatial scale: implications for designing catchment-level monitoring programs. *Freshwater Biology* 52, 939–958.
- Johnson, R.K., Hering, D., 2009. Response of taxonomic groups in streams to gradients in resource and habitat characteristics. *Journal of Applied Ecology* 46, 175–186.
- Kati, V., Devillers, P., Dufrene, M., Legakis, A., Vokou, D., Lebrun, P., 2004. Testing the value of six taxonomic groups as biodiversity indicators at a local scale. *Conservation Biology* 18, 667–675.
- Kilgour, B.W., Barton, D.R., 1999. Associations between stream fish and benthos across environmental gradients in southern Ontario, Canada. *Freshwater Biology* 41, 553–566.
- Longmuir, A., Shurin, J.B., Clasen, J.L., 2007. Independent gradients of producer, consumer, and microbial diversity in lake plankton. *Ecology* 88, 1663–1674.
- Margules, C.R., Pressey, R.L., 2000. Systematic conservation planning. *Nature* 405, 243–253.
- McGeogh, M.A., 1998. The selection, testing and application of terrestrial insects as bioindicators. *Biological Reviews* 73, 181–201.

- Myers, N., Mittermeier, R., Mittermeier, C., da Fonseca, G., Kent, J., 2000. Biodiversity hotspots for conservation planning. *Nature* 403, 853–858.
- Mykrä, H., Aroviita, J., Hämäläinen, H., Kotanen, J., Vuori, K.-M., Muotka, T., 2008. Assessing stream condition using macroinvertebrates and macrophytes: concordance of community responses to human impact. *Fundamental and Applied Limnology* 172, 191–203.
- Noss, R.F., 1990. Indicators for monitoring biodiversity: a hierarchical approach. *Conservation Biology* 12, 822–835.
- Paavola, R., Muotka, T., Virtanen, R., Heino, J., Jackson, D., Mäki-Petäys, A., 2006. Spatial scale affects community concordance among fishes, benthic macroinvertebrates, and bryophytes in streams. *Ecological Applications* 16, 368–379.
- Paavola, R., Muotka, T., Virtanen, R., Heino, J., Kreivi, P., 2003. Are biological classifications of headwater streams concordant across multiple taxonomic groups? *Freshwater Biology* 48, 1912–1923.
- Paszkowski, C.A., Tonn, W.M., 2000. Community concordance between the fish and aquatic birds of lakes in northern Alberta, Canada: the relative importance of environmental and biotic factors. *Freshwater Biology* 43, 421–437.
- Passy, S.I., Bode, R.W., Carlson, D.M., Novak, M.A., 2004. Comparative environmental assessment in the studies of benthic diatom, macroinvertebrate, and fish communities. *International Review of Hydrobiology* 89, 121–138.
- Pearson, D.L., 1994. Selecting indicator taxa for the quantitative assessment of biodiversity. *Philosophical Transactions of the Royal Society of London Series B* 345, 75–79.
- Pharo, E.J., Beattie, A.J., Binns, D., 1999. Vascular plant diversity as a surrogate for bryophyte and lichen diversity. *Conservation Biology* 13, 282–292.
- Pressey, R.L., Humphries, C.J., Margules, C.R., Vane-Wright, R.I., Williams, P.H., 1993. Beyond opportunism: key principles for systematic reserve selection. *Trends in Ecology and Evolution* 8, 124–128.
- Reid, W.V., 1998. Biodiversity hotspots. *Trends in Ecology and Evolution* 13, 275–280.
- Ricketts, T.H., Dinerstein, E., Olson, D.M., Loucks, C., 1999. Who's where in North America. *Bioscience* 49, 369–381.
- Rodrigues, A.S.L., Brooks, T.M., 2007. Shortcuts for biodiversity conservation planning: the effectiveness of surrogates. *Annual Review of Ecology, Evolution and Systematics* 38, 713–737.
- Sánchez-Fernández, D., Abellán, P., Mellado, A., Velasco, J., Millán, A., 2006. Are water beetles good indicators of biodiversity in Mediterranean aquatic systems? The case of the Segura river basin (Spain). *Biodiversity and Conservation* 15, 4507–4520.
- Sauberer, N., Zulka, K.P., Abensperg-Traun, M., Berg, H.-M., Bieringer, G., Milasowszky, N., Moser, D., Plutzar, C., Pollheimer, M., Storch, C., Tröstl, R., Zechmeister, H., Grabherr, G., 2004. Surrogate taxa for biodiversity in agricultural landscapes of eastern Austria. *Biological Conservation* 117, 181–190.
- Soininen, J., Kokocinski, M., Estlander, S., Kotanen, J., Heino, J., 2007. Neutrality, niches, and determinants of plankton metacommunity structure across boreal wetland ponds. *Ecoscience* 14, 146–154.
- Soininen, J., Paavola, R., Kwadrans, J., Muotka, T., 2009. Diatoms: unicellular surrogates for macroalgal community structure in streams? *Biodiversity and Conservation* 18, 79–89.
- Su, J.C., Debinski, D.M., Jakubasukas, M.E., Kindscher, K., 2004. Beyond species richness: community similarity as a measure of cross-taxon congruence for coarse-filter conservation. *Conservation Biology* 18, 167–173.
- Tolonen, K.T., Holopainen, I.J., Hämäläinen, H., Rahkola-Sorsa, M., Ylöstalo, P., Mikkonen, K., Karjalainen, J., 2005. Littoral species diversity and biomass: concordance among organismal groups and the effects of environmental variables. *Biodiversity and Conservation* 14, 961–980.
- Vellend, M., Lilley, P.L., Starzomski, B.M., 2008. Using subsets of species in biodiversity surveys. *Journal of Applied Ecology* 45, 161–169.