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How do ecologists select and use indicator species to monitor ecological change? Insights from 14 years of publication in *Ecological Indicators*

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Abstract

Indicator species (IS) are used to monitor environmental changes, assess the efficacy of management, and provide warning signals for impending ecological shifts. Though widely adopted in recent years by ecologists, conservation biologists, and environmental practitioners, the use of IS has been criticized for several reasons, notably the lack of justification behind the choice of any given indicator. In this review, we assess how ecologists have selected, used, and evaluated the performance of the indicator species. We reviewed all articles published in *Ecological Indicators* (EI) between January 2001 and December 2014, focusing on the number of indicators used (one or more); common taxa employed; terminology, application, and rationale behind selection criteria; and performance assessment methods. Over the last 14 years, 1914 scientific papers were published in EI, describing studies conducted in 53 countries on six continents; of these, 817 (43%) used biological organisms as indicators. Terms used to describe organisms in IS research included "ecological index", "environmental index", "indicator species", "bioindicator", and "biomonitor," but these and other terms often were not clearly defined. Twenty percent of IS publications used only a single species as an indicator; the remainder used groups of species as indicators. Nearly 50% of the taxa used as indicators were animals, 70% of which were invertebrates. The most common applications behind the use of IS were to: monitor ecosystem or environmental health and integrity (42%); assess habitat restoration (18%); and assess effects of pollution and contamination (18%). Indicators were chosen most frequently based on previously cited research (40%), local abundance (5%), ecological significance and/or conservation status (13%), or a combination of two or more of these reasons (25%). Surprisingly, 17% of the reviewed papers cited no clear justification for their choice of indicator. The vast majority (99%) of publications used statistical methods to assess the performance of the selected

indicators. This review not only improves our understanding of the current uses and applications of IS, but will also inform practitioners about how to better select and evaluate ecological indicators when conducting future IS research.

Keywords:
Indicator species, ecological indicators, ecological monitoring, environmental changes, review

1. Introduction

Many ecologists and environmental scientists are striving to find management solutions to urgent global environmental issues, including climatic change, habitat loss and fragmentation, pollution and contamination, disease outbreaks, and the spread of invasive species. Among many suggested strategies, one of the most popular has been to adopt monitoring techniques that can detect ecological changes both at an early stage and over the long term. Such *biological monitoring* allows for better-informed and more cost-effective management decisions (Landress, 1988; Spellerberg, 2005).

Indicator Species (IS) are living organisms that are easily monitored and whose status reflects or predicts the condition(s) of the environment where they are found (Landress, 1988; Cairns and Pratt, 1993; Bartell, 2006; Burger, 2006). The strategy of using IS is derived from the hypothesis that cumulative effects of environmental changes are integrated over, or reflected by, the current status or trends (short- or long-term patterns of change) in the diversity, abundance, reproductive success, or growth rate of one or more species living in that environment (Cairns and Pratt, 1993; Bartell, 2006; Burger, 2006).

Typically, the dynamics of a single population or a group of populations of one or more taxa are monitored as IS. Because the demographic parameters of a single population (e.g. abundance, density, age/size structure, reproduction rate and growth rate) are easy to measure and thought to be sensitive to environmental changes (e.g. drought), monitoring single population dynamics is considered to be a relatively cost-effective and reliable way to detect ecosystem change (Spellerberg, 2005). Identifying changes in IS also may reflect effects either of short-term severe stress events or of long-term changes, thus allowing scientists to react to unforeseen variation and to predict future conditions (Cairns and Pratt, 1993). These perceived advantages of IS not only have motivated the environmental research community to use them, but also have led to a large number of publications about IS in a range of technical journals (Burger, 2006). Further, as the use of IS has increased rapidly in recent decades, specialized journals focusing on IS have been established, including *Ecological Indicators* (est. 2001) and *Environmental Indicators* (formerly *Environmental Bioindicators*; est. 2005). This heightened focus is reflected in a recent survey by Borrett et al. (2014) of the most important ecological concepts and methods described in the literature, which listed the term "indicator organism" (or "indicator species") as among the top 15 concepts, a rapid increase relative to its 29th-ranking in 1986 (Cherret et al., 1989).

Despite the increasing popularity of using IS, several limitations of IS have been described (e.g. Lindenmayer et al, 2000; Lindenmayer and Fisher, 2003; U.S. EPA, 2008; Morrison, 2009; Lindenmayer and Likens, 2011). Primary limitations include: a single population rarely reflects the complexity of the environment; selection criteria for indicators are subjective; terminology is ambiguous (e.g. ecological indicator, indicator species, bioindicator, biomonitor); association between the indicator and the environmental contexts (i.e. monitoring goals) are vague; the influences of other biological interactions at the community level (e.g. predation/parasitism) often are ignored; methodological difficulties (e.g. indicator detectability, sampling protocols) may bias results; and finally the effects of future climatic changes on effectiveness of indicator species are unclear. Although these limitations have not slowed the increasing use of IS, research is needed to evaluate how ecologists and environmental scientists have employed them.

To help make progress towards the goal of developing a comprehensive understanding of the use of IS in their role as a tool for monitoring ecosystems, we reviewed all of the nearly 2000 papers published in *Ecological Indicators* between its founding in 2001 and the end of 2014. This focused review of the literature of this journal allowed us to narrow our scope to a single body of literature that focuses on the application of IS to monitoring and management that we could examine in detail. Our goal was to address the following questions:

- How many publications explicitly describe the use of IS, and how has this number changed through time?
- What determines terminology choice, and is terminology used in a manner consistent with accepted definitions (Box 1)?
- What are the motivations and criteria used to select indicators, and from which taxa are indicators most commonly selected?
- What are the varying methodologies by which IS are used?

Given the pressing need to monitor community and ecosystem dynamics, answering these questions will aid the development of effective tools for monitoring environmental change; therefore we end with a discussion of an updated protocol for selecting and using IS in ecological monitoring.

2. Methods

We reviewed and analyzed all 1914 articles published in *Ecological Indicators* between January 2001 and December 2014. This particular journal was chosen for three reasons. First, it is specialized in scope, with an exclusive concentration on the ecological and environmental indicators that are the focus of the current study. Second, the journal is representative of IS research; it has published ~30% of all articles published in the ecological literature that address indicator species (Borrett et al. 2014), and that cover ecological applications including biodiversity and population dynamics, ecological integrity, environmental disturbances, risk assessment, and ecosystem restoration. Third, the journal has existed for 14 years, a timescale we believe is both short enough to reflect current trends in the use of IS, while also long enough to allow for assessment of trends in the usage of the IS concept.

We conducted the literature analysis in two phases. First, we conducted a *preliminary survey* of 40 randomly selected articles to establish analytical questions and a corresponding coding system to classify IS use, and to test the validity of the coding system and troubleshoot analysis techniques (Box 2). Then, we performed the *actual analysis*, in which we used the title, abstract and keywords of each article to answer each analytical question. If necessary, we also looked at the rest of the text. We first classified IS-related articles (i.e. any article that used biological organisms as an indicator or monitor of ecological patterns or processes) by the keyword used (e.g. indicator species, bioindicator, biomonitor) and rejected articles that used abiotic ecological indicators. We determined indicator taxa, type, and selection criteria, and research area, and the objective of the IS study. We also noted country or geographic region of study and whether the research involved using indicators to assess the impacts of climatic change.

3. Results

3.1. Use of indicators species as ecological indicators

Research articles using IS comprised 43% of all research articles published in EI between January 2001 and December 2014. IS research has increased substantially from 8 papers in 2001, to 149 papers in 2014. On average, 58 papers per year explicitly dealt with IS during the last 14 years (Fig. 1). The use of IS has been widely adopted around the world; publications described studies from more than 53 countries and on six continents. Approximately 50% of the studies described by these articles were done in Europe, 30% in North America, and the rest (20%) conducted in Africa, Asia, Australia and South America.

3.2. Indicator species terminology, application and usage in climate change

Generally, four terms were used interchangeably to describe the use of biological organisms as ecological indicators in research or management (Table 1). Most papers (345; 40%) used the term “ecological index” or “environmental index” to describe the use of a broad number of indicators species. More specific terms, such as “indicator species” (group of species) were used in many publications (28%), especially for those focused on early warning applications and ecosystem management and restoration. Other terms, including “biomonitor” and “bioindicator”, were used in 15% and 17% of publications respectively.

Indicator species have been adopted for a wide range of ecological and environmental applications (Table 1). Their most frequent use (42%) was for the assessment of environmental integrity and health, but only 4% of publications focused on monitoring for early warnings of environmental change. Use of IS relating to biodiversity and ecosystem management comprised

18% of publications; use for monitoring the changes in the chemistry of the environment (e.g. pollution and contamination) comprised 18%; use for risk assessment and natural and human disturbances monitoring comprised 16%. Despite the importance of climatic changes, we found that only 6% of the IS discussed in these papers were focused on monitoring for climatic change.

Fewer than 2% of the papers we reviewed were classified as synthesis research. These few papers reviewed use of IS by only focusing on one aspect such as selection criteria, effectiveness and applications, evaluation of different taxa as IS, and suitability of indicators in different media (e.g. Fry et al. 2009, Vo et al. 2012).

3.3. Types of taxa and numbers of indicators commonly used as indicator species

Overall, nearly 80% of IS publications used a group of multiple species within the same taxa or a cross-taxa index as indicators, whereas only 20% used a single species as an indicator. Indicator species have been identified in virtually all taxa, including plants, vertebrates, invertebrates, and microorganisms (Fig. 2). Animals were used as indicators in 46%, plants in 30%, and microorganisms in 10% of the IS-related papers. Among animals used as indicators, nearly 70% were invertebrates, which were particularly common indicators of aquatic and wetland health. Although only 4% of publications described studies using mammals in ecological monitoring, fish (16%) and birds (10%) were used more frequently, particularly for assessing pollution and radionuclide contamination, water quality, and marine stock changes. Amphibians and reptiles ("herpetofauna") were only used in about 1% of IS studies.

Temporal trends in type of IS also were apparent (Fig. 3A). Plants and invertebrates have showed a steady increase in their use as IS relative to the other taxa. The percent of publications of these two taxa have increased from less than 10% in 2001 to 40% in 2014. The percent of other taxa used as IS show little trend in the last 15 years; fish, microbes, birds, mammals, and herpetofauna ranged from 1-10% in any given year. Although the use of multiple IS initially were used more frequently than single IS, the use of the former has been declining in the last 5 years (Fig. 3B).

3.4. Habitats of interest

More than 50% of IS were used to assess marine or wetland ecosystems, 35% for terrestrial ecosystems, 13% in more than one habitat (including review papers) and only 2% for atmospheric conditions (Fig. 4). After 2001, when all the IS papers were focused on terrestrial habitats, the relative proportions of different habitats assessed with IS has remained raltively constant (Fig. 3C). The use of IS in wetland systems has remained close to 60% (declining to < 50% in 2014), approximately 40% in terrestrial systems (increasing to just over 50% in 2014). The remaining 10% has been split between the atmosphere and "multiple" habitats.

3.5. Basis for selecting indicator species and evaluating their performance

Overall, nearly all IS research has used quantitative and statistical methods to assess the validity and performance of the selected IS. Indicator species were chosen for four primary reasons (Fig. 5). The greatest number (40%) of choices was based on previously published research that established the success of certain indicators. In contrast, only 13% was based on the ecological importance or conservation status of the species, and 5% used the indicator species because it had a locally abundant population. One-quarter of the publications used combinations of these rationales for selecting indicator species for monitoring ecological changes. Surprisingly, 17% of IS research failed to clearly justify why the indicator was chosen, likely reflecting personal interest of the authors or other subjective judgment. As research on IS has increased, the importance of prior research as a rationale for choosing an IS also has increased, from less than 5% in 2001 to 35% in 2014 (Fig. 4D). Other rationales have fluctuated widely throughout the 14-year period.

4. Discussion

In our study, we uncovered interesting patterns in how ecological indicators have been studied and developed as tools for assessing and monitoring community and ecosystem responses to environmental change, particularly from anthropogenic sources. In particular, we found that IS research comprises 43% of EI research during the last 14 years with notable annual increase. Although researchers tend to use terms such as “ecological index” to describe IS, other terms, including “indicator species,” “bioindicator,” or “biomonitor” were used consistently with the different environmental applications (Table 1 and Box 1). Approximately 40% of IS research used success of previous studies as the primary motivation for choosing one or more indicator species, Invertebrates were the most frequent taxa used as IS and 50% of IS research was conducted in marine and wetlands habitats.

There also are revealing trends in the literature (Fig. 3) that suggest ways to improve how indicator species are studied and developed. For example, there has been a steady increase in the use of single species in the last nine years and a continued emphasis on invertebrates and plants. Future studies could ask whether researchers favor single species, and particular types of species, because of ease of sampling, wide distribution, or other logistical concerns. Wetlands have been the primary focus of IS, but after a 13-year run in second place, the number of terrestrial ecosystems studied exceeded wetlands again in 2014. Finally, the acknowledgement of the ecological importance of IS as main reason for selecting indicators was highest between 2001 and 2005, but thereafter received little attention until the last 4 years.

4.1 ***Possible reasons for rise in use of indicator species***

The substantial increase in the use of IS in part reflects the overall increase in the number of articles published annually in *Ecological Indicators,* but it also illustrates the broad adoption of IS. Indicators are widely used because environmental practitioners need cost-effective tools that are easy to measure and that provide results that can be communicated clearly to decision makers and the broader public. Indicators also can be used to meet regulatory mandates by, for example, the United States Environmental Protection Agency (U.S. EPA, 2002 and 2008) and the European Environment Agency (e.g., EU Water Framework Directive).

Lindenmayer and Likens (2011) observed that no single species can reflect the complexity of the total environment, and our analysis revealing a diversity of IS supported their assertion. Nonetheless, 20% of the papers used only a single species to monitor ecosystem changes, and this proportion is increasing through time (Fig. 3B; see also Godet et al. 2012, Hurme et al. 2008). As there is not a lot of evidence that assesses the efficacy of any particular IS, and 40% of papers justified their selection and use of a specific IS on success of previous studies, it seems imprudent to rely on only a single IS in most studies. Furthermore, a considerable number of articles selected and used IS only because they were locally abundant, ecologically significant, endangered, or charismatic, and some did not provide any justification at all. The reliability of data derived from IS and the success of monitoring programs using IS depend on the quality and justification of the selected indicators (Cairns and Pratt, 1993).

4.2. *Selection and use of indicator species in ecological monitoring:*

We suggest a 5-step process (Fig. 6) by which indicator species or a group of IS should be selected and used in monitoring environmental changes (see also EPA 2002, 2008, EU directive, Carignan and Villard 2002; Welsh et al. 2008; Lindenmayer and Likens 2011).

1) Set clear monitoring goals that can be reflected by the selected IS.
2) Identify the ecological setting (forest, watershed, wetland, desert, etc.) and spatial extent of the study site (i.e. scope of inference).
3) Select the candidate IS and demographic parameters based on criteria given by Cairns and Pratt (1993), Dale and Beyeler (2001) or Carignan and Villard (2002).
4) Select ecological covariates / predictors (e.g. habitat types, climatic factors, soil properties, water chemistry) to which the IS is particularly responsive.
5) Simultaneously sample species abundance and ecosystem covariates then conduct the indicator species analysis to get the indicator value (IndVal) for each species following the method of Dufrêne and Legendre (1997).

5. Conclusions

The use of IS as ecological indicators for monitoring environmental changes is reliable and cost-effective, but selection of specific indicator(s) and identification of the relationship between these indicators and their specific applications remains challenging. The future utility of IS will depend on rigorously selected groups of indicators that reflect the environment in realistic ways and also reflect cause-effect relationships between the IS and underlying processes of interest. Recent discussions about the statistical validity of metrics evaluating the performance of IS (e.g.

Dufrêne and Legendre (1997)), inclusion of additional (or multi-) metrics (e.g. detection ability, variability, demographic stability) should be applied regularly (De Cáceres and Legendre 2009; Quinn et al. 2011, Urban et al. 2012).

Overall, our review and analysis of papers published in *Ecological Indicators* suggest several lessons for ecologists and environmental professionals. The significant increase in the number of publications of indicator species implies widespread and continued growth in the use of indicator species in environmental monitoring and management. Our analysis suggests that IS are effective in some applications such as environmental quality and ecosystem integrity and restoration, and that IS are used rarely in others, such as early warnings of environmental change and assessment of climate change (Table 1). Future work could focus on identifying IS for these areas.

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Table 1. The proportion of papers using different terms for indicator species varies among the applications of them.

Applications/Monitoring objectives	Total No. of IS Publications	Eco/Env. Index	Indicator species	Bioindicator	Biomonitor	% of IS publications
Environmental quality and integrity	345	44	25	15	16	42
Pollution and contamination	149	26	23	27	24	18
Ecosystem Management and Restoration	144	40	36	16	8	18
Risk assessment and disturbances	128	44	29	16	11	16
Early warning	32	38	50	6	6	4
Synthesis and reviews	18	83	17	0	0	2
Total	816	40	28	17	15	100

Box 1: Terms related to the Indicator Species (IS) concept.

Indicator species: One or more taxa selected based on its sensitivity to a particular environmental attribute, and then assessed to make inferences about that attribute. Commonly used in the context of wildlife conservation, habitat management and ecosystem restoration (Simberloff, 1998; Morrison, 2009; Caro, 2010).

Bioindicator / Biomonitor: One or more living organisms used as an indicator of the quality of the environment it is living in and the biological component associated with it. Bioindicators or biomonitors are used most commonly to monitor chemical changes in the environment in fields such as ecotoxicology (Burger, 2006).

Umbrella species: A species that requires a large area of suitable habitat to maintain a viable population, and whose requirements for persistence are believed to encapsulate those of an array of associated species. Umbrella species usually have very large home ranges. As indicator species, umbrella species are used most commonly for conservation applications and management of protected areas (Simberloff, 1998 and Morrison, 2009; Caro, 2010).

Keystone species: A species on which the health of the ecosystem depends, due to its strong interactions with other species in that ecosystem. As indicator species, keystone species are used most commonly for monitoring habitat quality, restoration success and protected areas management (Simberloff, 1998; Ellison et al., 2005; Morrison, 2009; Caro, 2010).

Flagship species: A species that can easily attract public support based on its charismatic qualities and its conservation status. As indicator species, flagship species are used most commonly for identifying and monitoring conservation status of the species (Simberloff, 1998; Morrison, 2009; Caro, 2010).

Ecosystem engineer: A species that causes physical changes in biotic or abiotic materials, thereby modulating the availability of resources to other species. As indicator species, ecosystem engineers are used most commonly for ecosystem restorations and conservation (Jones et al., 1994; Morrison, 2009).

Foundation species: A species that defines much of the structure of a community by creating locally stable conditions for other species, and by modulating and stabilizing fundamental ecosystem processes. As indicator species, foundation species are used most commonly for monitoring ecosystem changes (Ellison et al. 2005).

Box 2: Analytical methods and specific search questions addressed during literature analysis of publications of the Journal of Ecological Indicators.

Box 2. Analytical questions and coding

I. **Keyword:** Which of the following keywords is used to describe the indicator?
  1. Indicator species
  2. Biomonitor
  3. Bioindicator
  4. Ecological or environmental indicator/index

II. **Indicator Taxa:** What taxon of organism is used as an indicator?
  1. Plants (including algae and photosynthetic microorganisms)
  2. Animals
     1. Vertebrates (Fish, Amphibians, Reptiles, Mammals, Birds)
     2. Invertebrates
  3. Microbes/microorganisms
  4. More than one(i.e. combinations of 1-3)

III. **Indicator Type:** What category does the article focus on as an indicator?
  1. Single species (e.g. Monarch, *Danaus plexippus*)
  2. Group of closely related species (e.g. Butterflies, Order *Lepidoptera*)
  3. Cross-taxa (e.g. Insects, Class *Insecta*)

IV. **Indicator Selection:** Which of the following was most influential to the author's choice of indicator species initially, prior to statistical work?
  1. Past published research
  2. Indicator is abundant
  3. Indicator is charismatic/endangered/invasive
  4. Any combination of 1-3
  5. Not clear in the publication

V. **Media:** What habitat does the article focus on?
  1. Water/wetlands
  2. Terrestrial
  3. Soil and land resources
  4. Air
  5. None (synthesis)
  6. Multiple

VI. **Applications:** What was the purpose of using the IS method?
  1. Pollution/contamination assessment
  2. Environmental/ecosystem health assessment
  3. Management oriented
  4. Risk/disturbance assessment
  5. Early warning of environmental change

VII. **Climate Change:** What is the proportion of IS publications that used for monitoring climate change related issues?

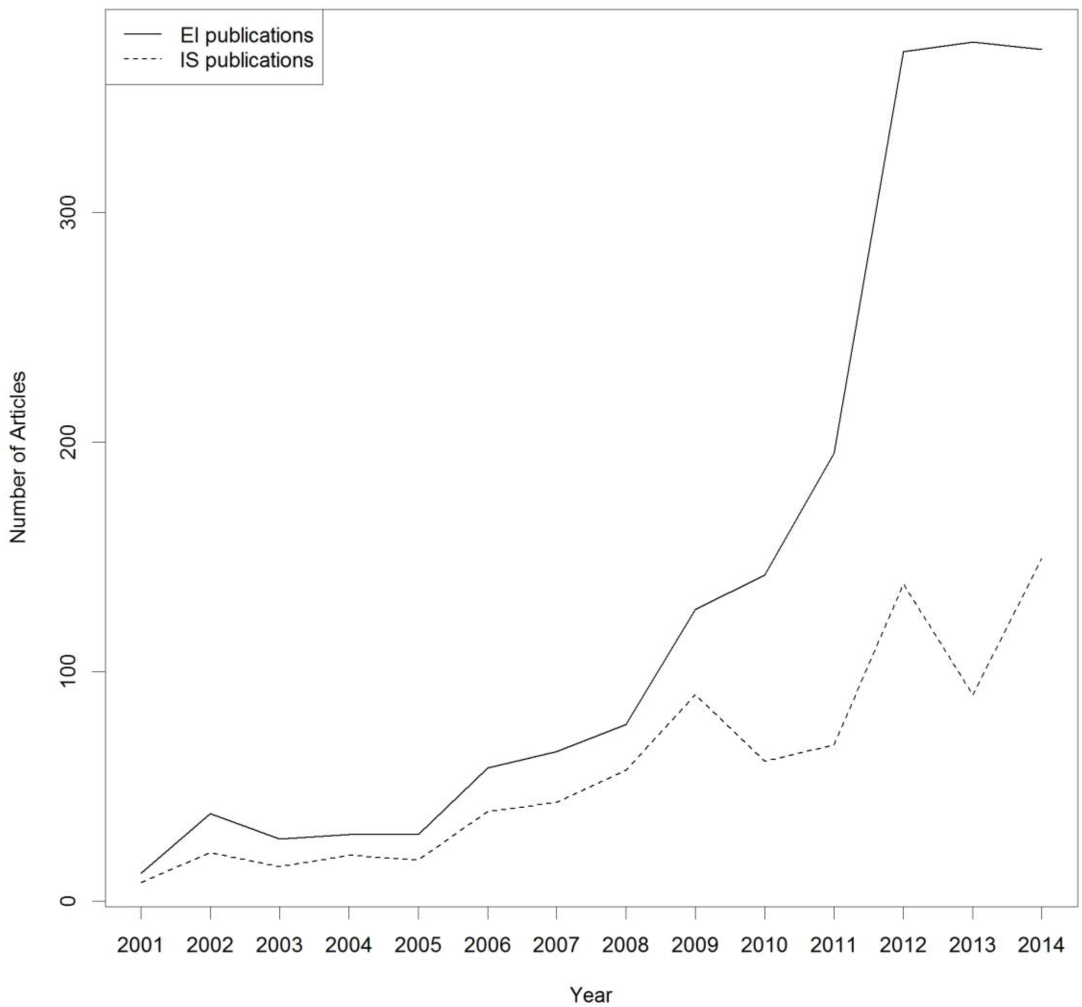


Figure 1.The total number of papers published annually in *Ecological Indicators*, and the number of those publications that discussed indicator species.

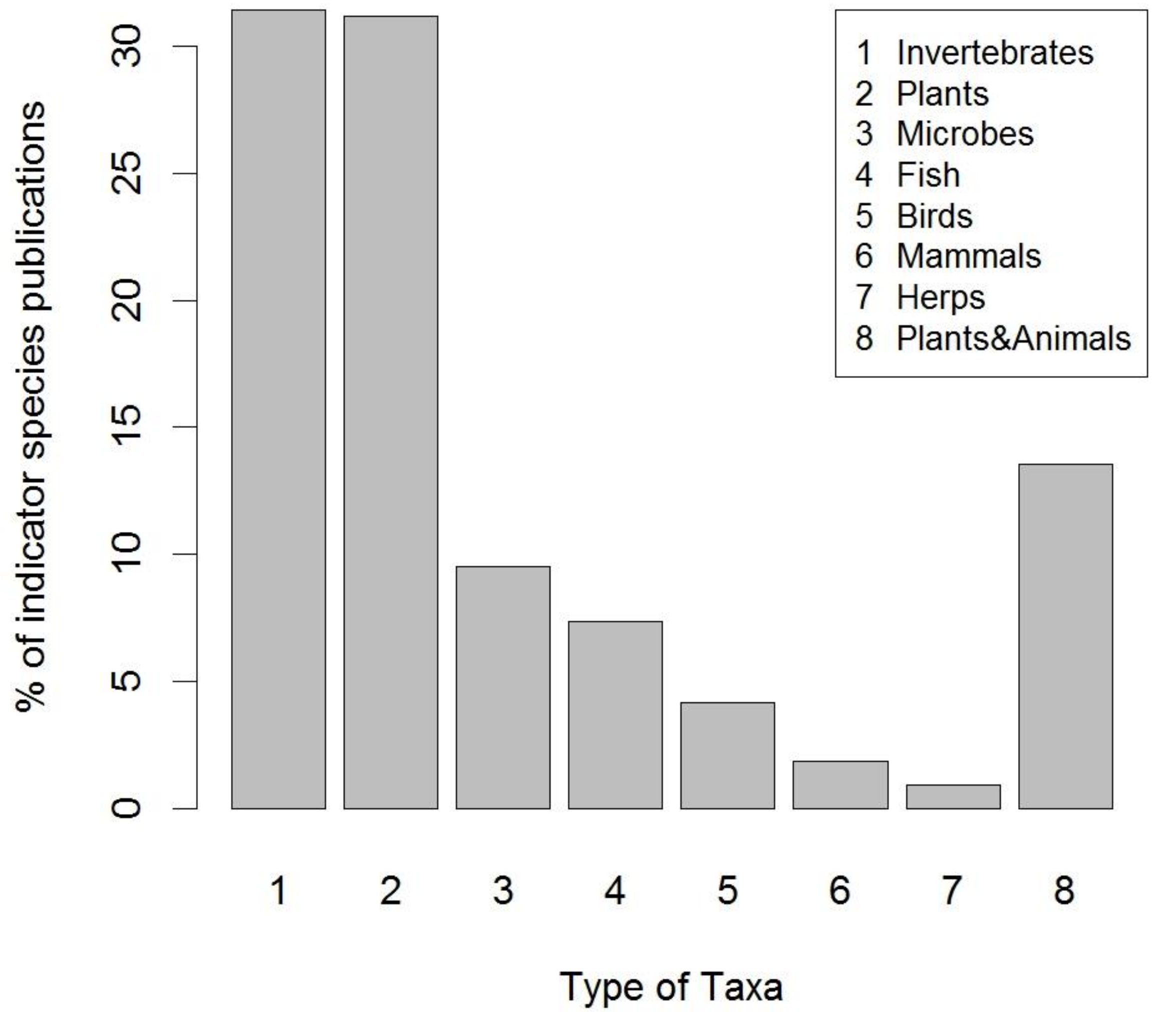


Figure 2. Type of taxa used in indicator species research in *Ecological Indicators*.

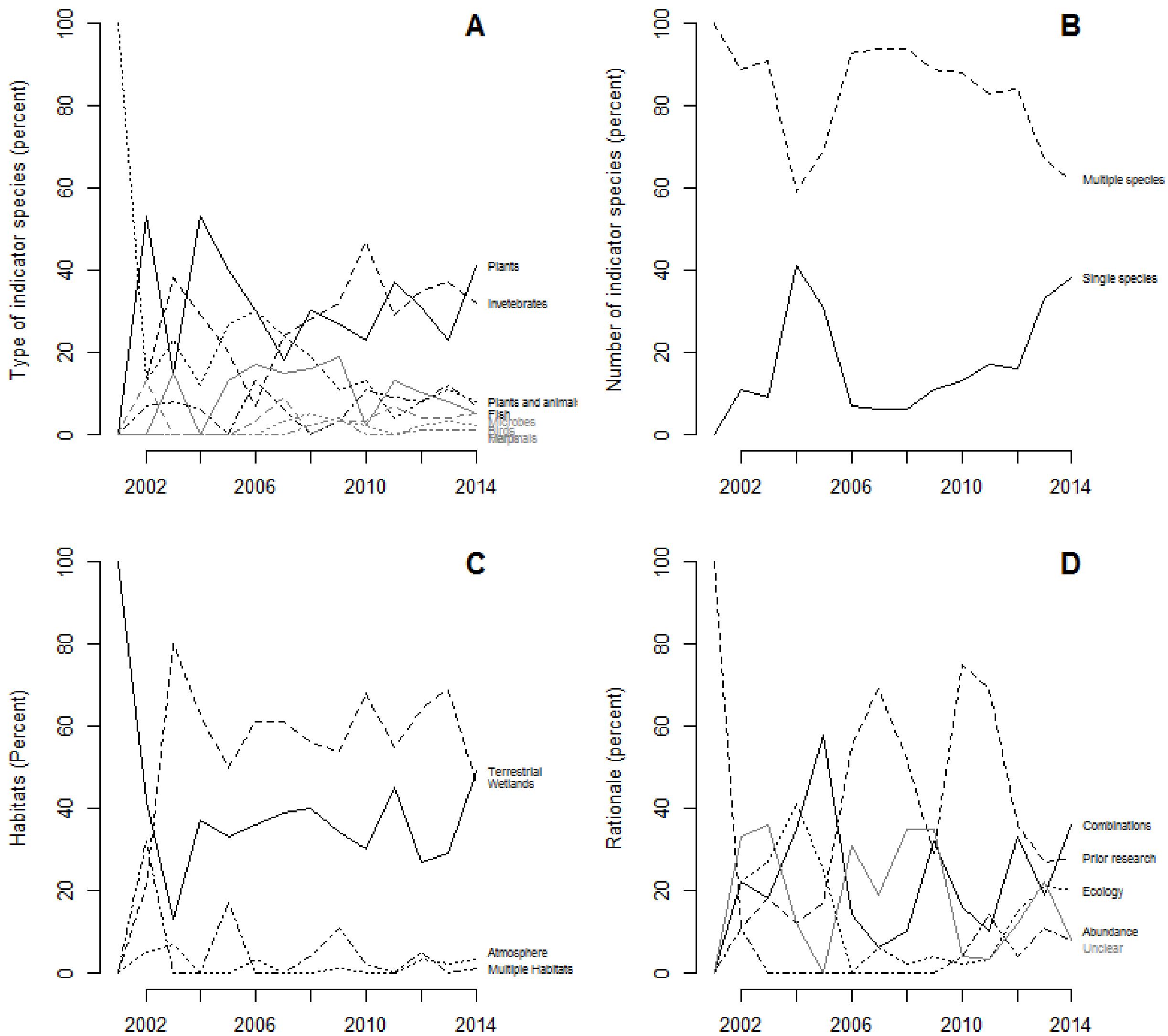
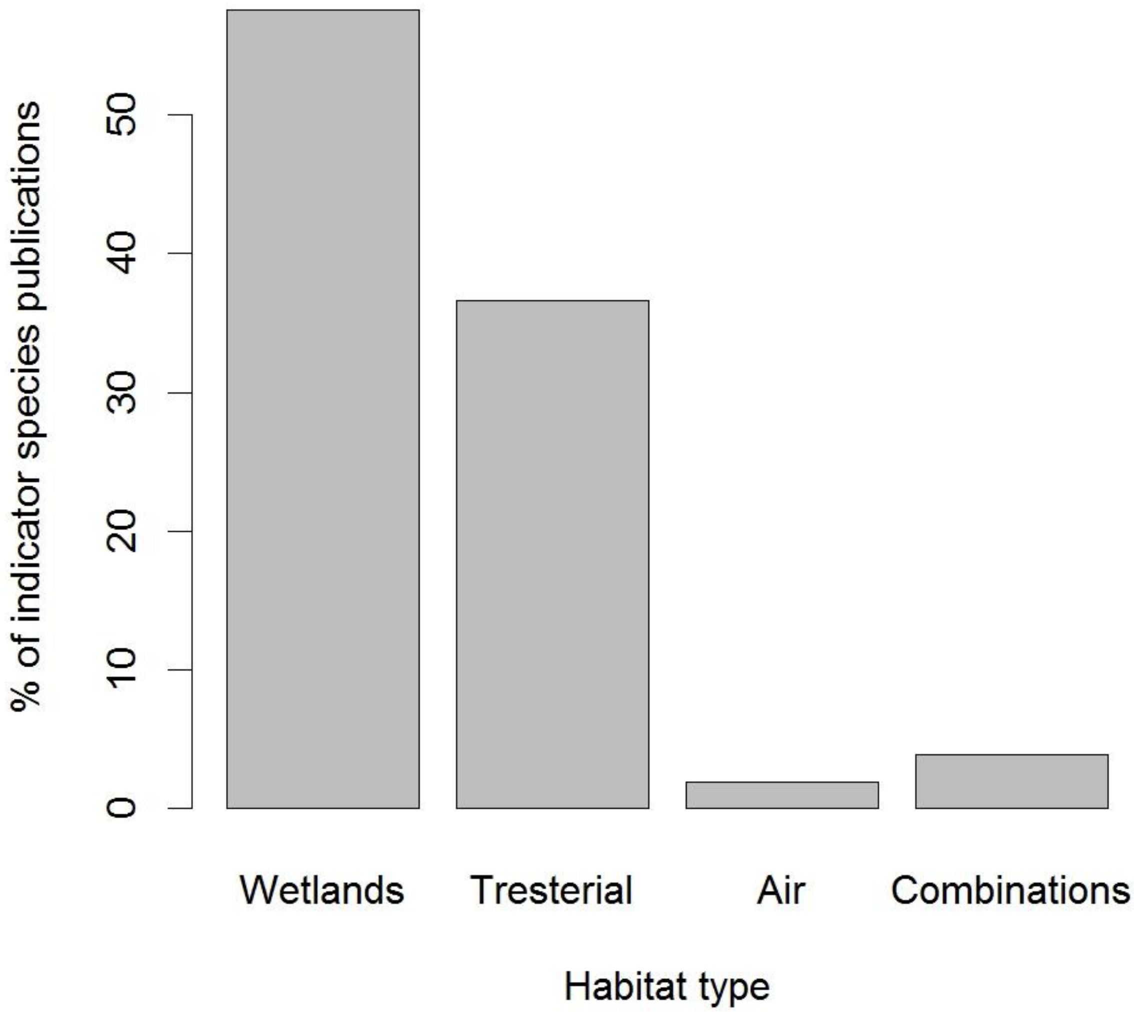


Figure 3. Trends in types if IS (A), number of IS (B), habitats (C), and rationale for selecting IS (D) in papers published in *Ecological Indicators* between 2001 and 2014.



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385 Figure 4. Relative proportion of different habitats used in research on indicators species.

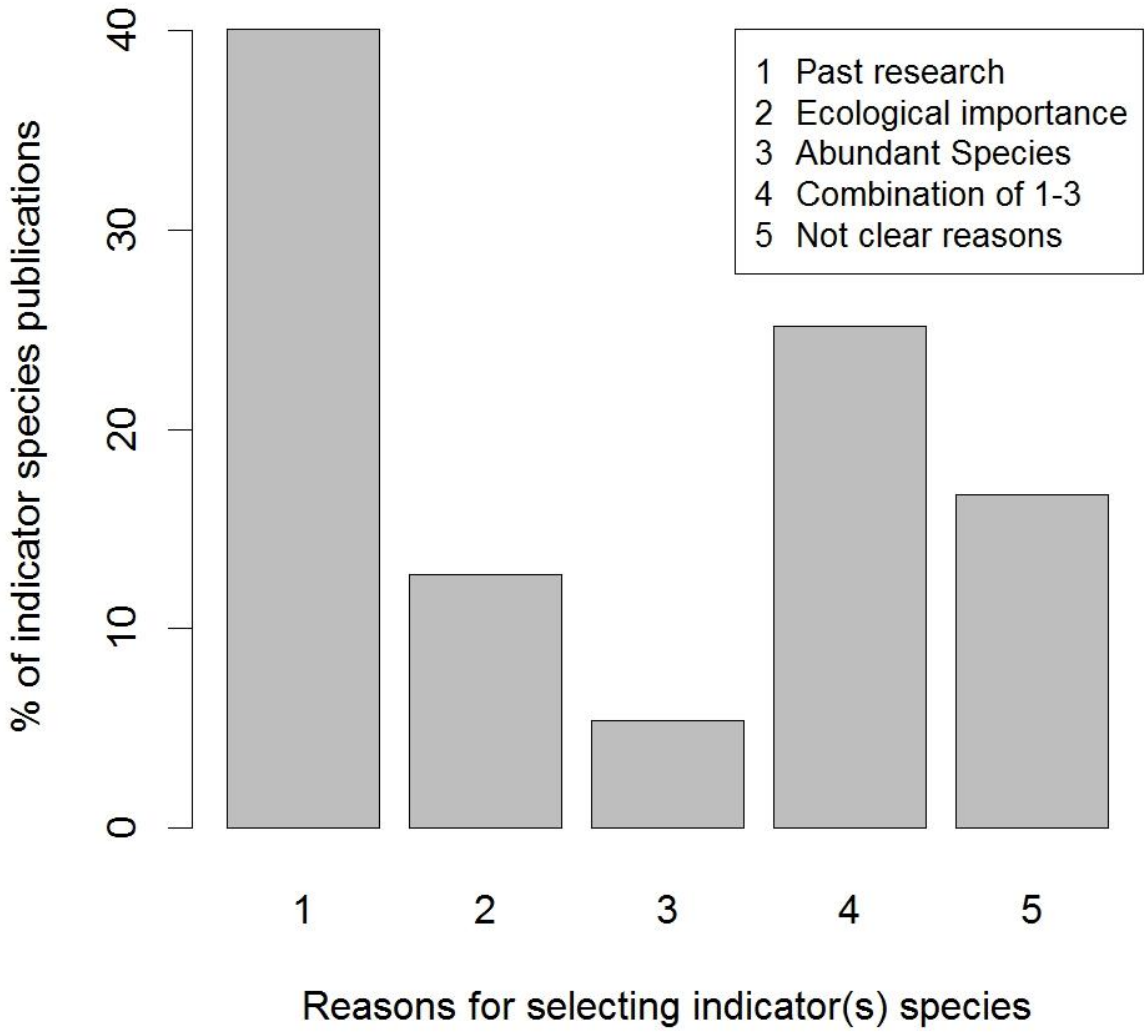

Figure 5. Most common rationales for selecting and using indicator species as ecological indicators

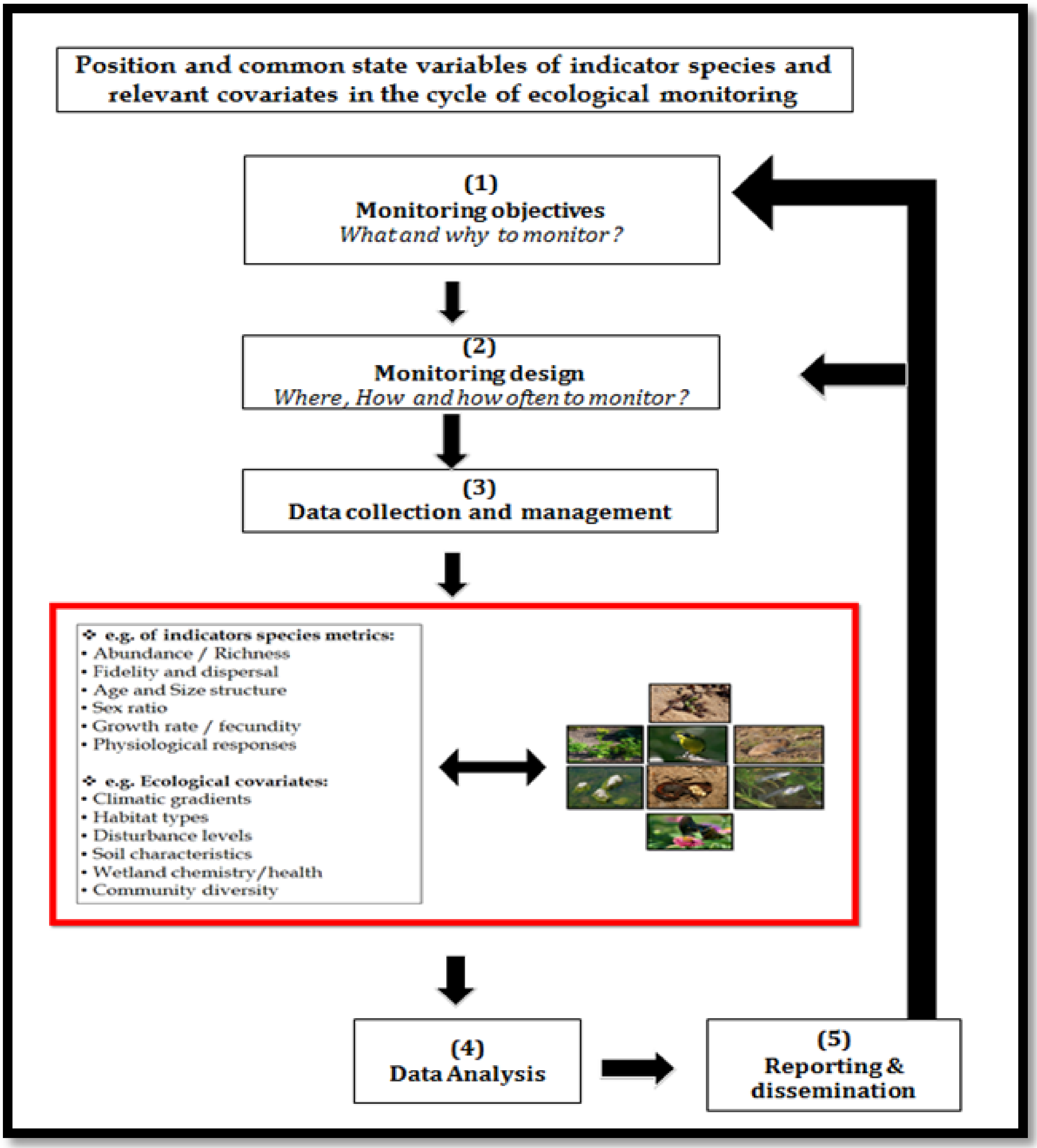

Figure 6. The necessary processes of ecological monitoring and the position of indicators species and common related state covariates within the monitoring cycle.