



Allocation of effort and imbalances in biodiversity research

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ABSTRACT

Ecosystem transformation and depletion of natural resources by human activity with associated increase in species extinctions renders research to understand the consequences of these transformations and design strategies to conserve biological diversity a fundamental priority. Since the introduction of the term biodiversity, accumulated research in this field has expanded exponentially. An analysis of existing literature was conducted to examine patterns in the resulting research effort. The analysis, conducted using the Web of Science (WoS), identified 13336 published articles between 1987 and 2005 concerning biodiversity research. Research efforts are increasing, with 72% of the research effort addressing terrestrial ecosystems. Most of the research is experimental in nature, with few models developed, and focuses on species. Despite constant technical improvements, research on genetic diversity still represents a minor component. Research on different systems is disseminated through different publication outlets, fragmenting the community and derived knowledge. Reported results, here measured as strength of the correlation between biodiversity and ecosystem function, do not differ across ecosystems but are stronger when the study focused on functional groups instead of species level. Collaborative efforts remain limited, as the average number of authors per paper is not increasing with time, unlike patterns in other disciplines. The international distribution of research efforts is highly skewed, with the USA and the EU conducting nearly 90% of the research.

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1. Introduction

Recent global increases in species extinction (Ricciardi and Rasmussen, 1999; Thomas et al., 2004) and habitat deterioration (Vitousek et al., 1997; Achard et al., 2002; Gaston et al., 2003) have driven biodiversity research to become a prominent component of ecological sciences (Loreau et al., 2001). Examples of anthropogenic threats include habitat destruction, the increased pressure of fisheries; and pollution (Duffy and Stachowicz, 2006). Biodiversity is also threatened by niche changes due to global climate change and associated biological invasions, which are increasingly aided by human vectors like containerships (Occhipinti-Ambrogi and Savini, 2003).

Starting from the study of ecology over a century ago, increasing extinction rates caused biodiversity research to evolve from addressing academic issues to research aimed at preserving and conserving biological diversity (Tilman, 1999). Current biodiversity research aims at understanding the consequences of the ongoing transformation of ecosystems and biosphere processes by humans (Hillebrand and Blenckner, 2002), on the stability of communities and populations (Tilman and Downing, 1994; Tilman, 1996), as well as the importance of biodiversity on ecosystem function (Naeem et al., 1994; Humbert and Dorigo, 2005), as to ultimately design strategies to conserve biological diversity and use ecosystems in a sustainable manner.

Biodiversity research has evolved to include large-international concerted research programs (e.g. DIVERSITAS, <http://www.diversitas-international.org/>, Census of Marine Life <http://www.coml.org/>), which provide a new impulse to biodiversity research by providing ambitious goals, clear targets and helping articulate the necessary resources. Most importantly these concerted programs aim at engaging a true international contribution, which is particularly important for biodiversity research as there is often a mismatch between the geographic distribution of potential research effort and that of biodiversity richness and threats; which tend to be higher in the tropics (Gaston, 2000). The resulting recent growth of biodiversity research is so phenomenal that imbalances across topics, systems and scales of analysis may have developed (Hendriks et al., 2006). The examination of patterns in the resulting research effort is essential to identify gaps, improve the balance across various scales of analyses and habitats, and improve the international coordination of research to address these problems at a global scale.

Here we provide a study of patterns of effort in biodiversity research on the basis of a bibliometric analysis of publication rates and the origin, outlets, scale of analyses, systems and types of organisms addressed in the literature. We performed a meta-analysis on a randomly chosen subset of the dataset to test if the power of the relationship between biodiversity and functions investigated across system types and scales differs.

2. Methods

Constraining biodiversity research is an elusive task, as it encompasses a broad array of research programs, some of which

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explicitly identify themselves with this research agenda whereas many others do not, although their products may be relevant to biodiversity research. Indeed, the definition of biodiversity adopted in Article 2 of the Convention on Biological Diversity (CBD), ‘the variability among living organisms from all sources including, *inter alia*, terrestrial, marine and other aquatic ecosystems and the ecological complexes of which they are part; this includes diversity within species, between species, and of ecosystems’, is very broad. In one extreme it could be argued that all biological research at the organism level or above is relevant to biodiversity research. In practice, however, only a small subset addresses the quantification of the diversity of life, whether examined at genomic or taxonomical levels, and its importance for the structure and functioning of ecosystems, addressing directly biodiversity research.

Hence, in order to address recent growth of biodiversity research, we choose to concentrate on the keyword “biodiversity”. This renders the analysis provided here a conservative one, in that the number of papers relevant to biodiversity may be larger than that using this keyword. However, in doing so we avoid Type I error of including research irrelevant to biodiversity research in our analysis. The number of papers relevant to biodiversity that did not use this keyword was likely larger in the first years included in the analysis, but the use of this term as already well established in the early 1990’s. Hence, the earlier rise in number of published papers may represent both an increased research effort and a popularization of the term ‘biodiversity’ combined, whereas the trends since 1990 should represent increased research effort alone.

We searched the published literature on biodiversity to extract (1) the total rate of publication per year, as well as the partitioning of publication effort into ecosystem types, type of approach, biological level, and metabolic role of the organisms; (2) the geographical distribution of the first authors; and (3) output (journals) used. This allows us to identify the specific importance of the field as compared to general growth of publications, and to contrast the research effort of terrestrial, marine and freshwater systems as well as assess how strong the empirical basis of the field is and at which scale most research is done. Clarifying the geographical distribution of the research allows us to evaluate the contribution of countries with high initial biodiversity, currently suffering severe habitat and species losses. Overlap in journals publishing biodiversity research on specific systems would indicate a well-informed community, whereas a division signifies compartmentalization between the research communities working on different systems.

A bibliographic database was compiled from references obtained from the Web of Science 7.2 (WoS) published by Thomson ISI (<http://portal.isiknowledge.com/portal.cgi>). The database runs from 1945 to October 2005, although in early years coverage is poor and the first year of appearance of articles on the subject in fact is 1987.

The search carried out to collect references related to the search string ‘biodiversity’. The survey conducted is affected by two processes, the rate of publication in biodiversity research and the increasing use of the term ‘biodiversity’ reflecting the development of a core research program from previously loose research elements. Much research that would now be labeled ‘biodiversity’ research did not use this term in the past. To evaluate how many articles are not recovered, even when in fact they are investigating species diversity, we manually screened the 15 top journals of each field in two particular years (1993 and 2003) to identify what percent of articles of our search were missed by using the search string ‘biodiversity’ only. We found the error to be < 10%, indicating that the bibliometric search by keywords and subsequent screening provided a reliable estimate of the research effort in this field.

A bibliographic database consisting out of 13336 references (all types) was produced in Endnote 8.0.2 (Thomson ResearchSoft). The data set was still incomplete for 2005, which was, therefore, excluded from the analysis of growth rate. The country of affiliation of first authors was made consistent, and EU countries identified as such (EU25). Keywords (provided by the authors as well as by WoS) and biome of investigation were listed (marine, freshwater, terrestrial, general/theoretical). We also

classified the biological level of the research (species level, functional groups or genetic diversity), the approach (experimental/observational, model approach or conceptual/theoretical) and the metabolic role of the organisms (autotrophic, heterotrophic and both). Screening of the assembled database (n=100) revealed that 6% of organism classifications, 4% of habitat and 8% of the other classifications contained errors, so the error of the present analysis is approximately 5% for each analyzed metric reported.

From this initial database we selected articles on the topic of biodiversity and ecosystem function. From this subset 100 papers were selected randomly for in depth analysis. Since few aquatic papers were found, we continued sub-sampling while only adding the aquatic papers encountered until a better balance was reached. Effect of biodiversity changes on the studied ecosystem function was measured as a simple correlation coefficient, r (Balvanera et al., 2006), extracted from the literature where biodiversity was treated as an independent continuous variable or where a linear or log-linear contrast was made for the factor biodiversity. In this way we analyze differences in strength and direction of the link between biodiversity and ecosystem function in relation to habitat and community level studied.

3. Results

The number of papers using the term biodiversity increased from 25 in 1990 with almost two orders of magnitude to 1916 papers published

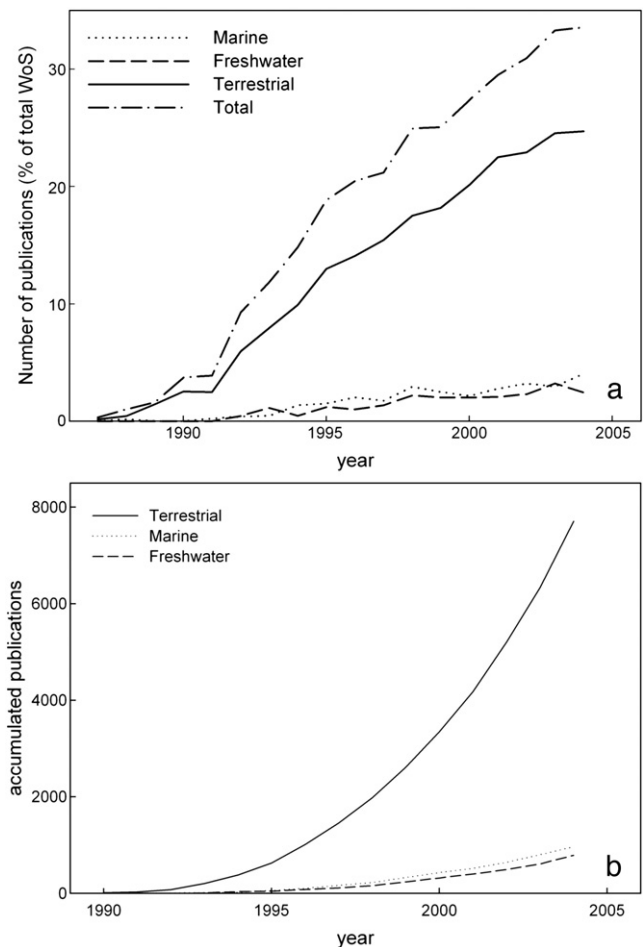


Fig. 1. Yearly rate of publication in biodiversity research for terrestrial (solid line), freshwater (dashed) and marine (dotted) habitats. (a) Biodiversity references expressed as a percent of the total number of records listing biodiversity and/or ecology archived in the Web of Science (WoS) database, total publications (dash dotted line) and percentages per habitat. (b) Accumulated number of publications listing biodiversity recovered from the Web of Science (WoS) database.

in 2004. This increase was largely driven by research on terrestrial environments, which represented 72.3% of the total papers published between 1990-2004 (n=9120), with aquatic research representing about 17.3% of the papers published, divided roughly equally between freshwater and marine. Normalizing the number of publications to the

total number of articles within the WoS retrieved with the more general search string 'ecology' OR 'biodiversity' showed that the share of biodiversity research over the general ecological research has increased tenfold since 1990 to encompass a third of all published papers in 2004 (Fig. 1a). By correcting our yearly results with more general research on

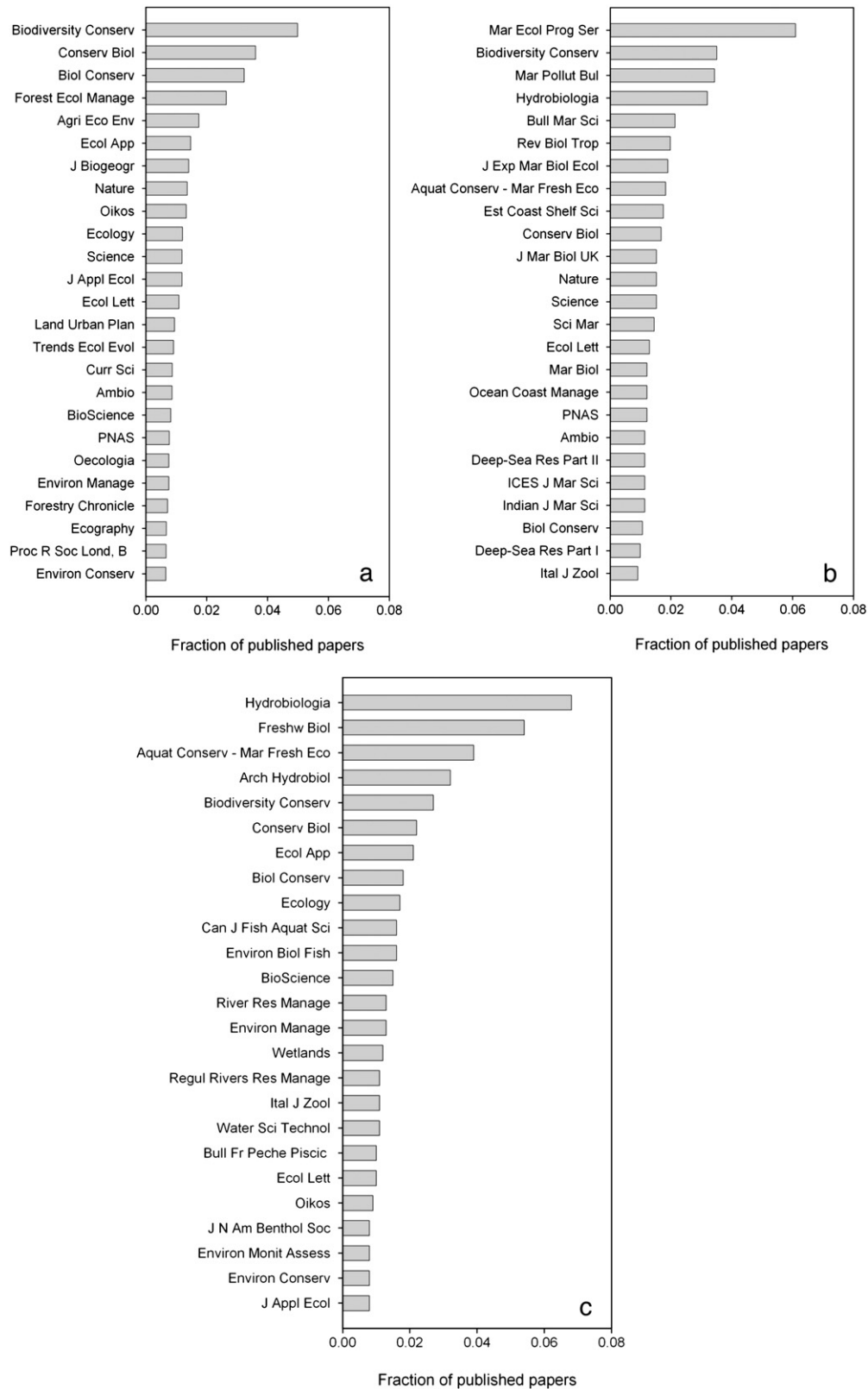


Fig. 2. Fraction of published papers, within (a) terrestrial, (b) marine and (c) freshwater habitats, published in the 25 journals with the highest publication rate on biodiversity research within that biome.

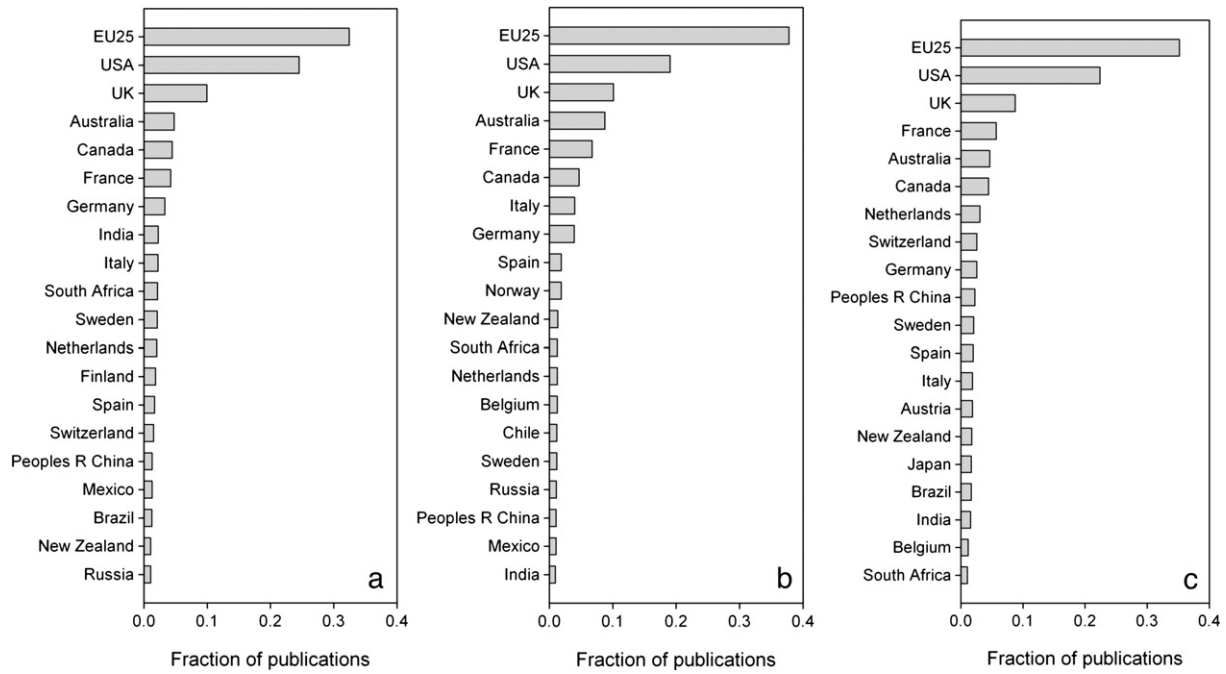


Fig. 3. Geographical distribution, expressed as fraction of publications within (a) terrestrial, (b) marine and (c) freshwater habitats, of the affiliation of first author.

ecology we show that this increase in publication effort is not due to the pressure to publish more small papers in recent decades since this pressure should be equal over all research areas.

To obtain the growth rate of publications per year until 2004 we fitted the accumulated number of publications (Fig. 1b) for the period 1990–2004 exponentially ($y = a \cdot e^{bx}$) in Statistica. We excluded the first year where biodiversity was mentioned (1987), since we know that since 1990 the use of the word biodiversity starts being common. Whereas the accumulated research on terrestrial biodiversity has been growing at 42.9 (± 3.6) % per year, publications on marine ecosystems have been growing slightly faster (50.1 (± 4.2) % annually), while publications on freshwater biodiversity research grew at 36.2 (± 2.9) % per year. However, this faster growth of marine research has been insufficient to balance research efforts across systems. Growth rates for biodiversity research are in general relatively high compared to e.g. the growth rate on ecology research, which is 18.0 (± 1.3) % annually.

The range of journals publishing research using the term biodiversity increased over time from 16 in 1990 to 532 in 2004. Biodiversity publication efforts are, however, differently allocated over journals; research on different systems is disseminated through different outlets

(Fig. 2). Only 3 journals among the top 25 journals for each biome are shared between terrestrial, marine and freshwater researchers (Conserv. Biol., Biodiversity Conserv. and Ecol. Letters), suggesting a sharp divide between authors, and most probably readers as well, primarily focusing in different systems. Average impact factor (SE) for the top 5 publication outlets are: terrestrial 9.76 (0.464), marine 1.28 (0.254), and freshwater 1.37 (0.275) research. Most impacting research on biodiversity is focused on comprehensive and theoretical issues for which the journal Nature is the primary outlet.

Biodiversity research attracts wide international interest, the major contributors concerning publications being the 25 EU countries, followed by the USA, with scientists from institutions in these two regions contributing nearly 90% of the research (Fig. 3). The United Kingdom (UK) is the major contributor to published research using the keyword biodiversity conducted in Europe. The skewed international distribution of research efforts signifies that authors from countries with highest initial diversity as well as most impacted by extinctions and ecosystem degradation recently only have a minor contribution to this research, with only India, Mexico and Brazil being significant contributors to biodiversity research amongst tropical countries with little resources.

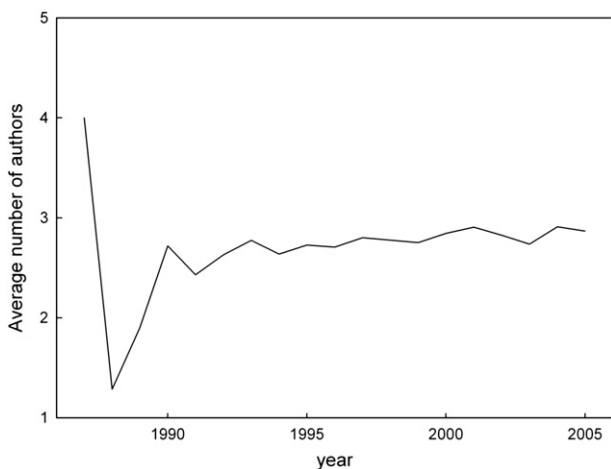


Fig. 4. The average numbers of authors signing articles that treat biodiversity.

Table 1

Percent of total research (1990–2004) efforts divided into: Biological level of the research, approach, and the metabolic role of the organisms focused on for terrestrial, marine and freshwater research

	Terrestrial	Marine	Freshwater
<i>Biological level</i>			
species	23.76	3.76	2.55
functional groups	18.16	2.63	2.09
genetic	9.10	1.04	0.67
<i>Approach</i>			
experimental/observational	42.01	6.14	9.64
model approach	6.65	0.51	0.46
conceptual/theoretical	15.63	2.45	1.92
<i>Metabolic role</i>			
Autotrophic	20.98	1.16	0.75
Heterotrophic	19.85	4.38	3.44
Both	22.95	3.20	2.40

Missing percentages are unclassified articles or general papers without a clear focus on specific biome.

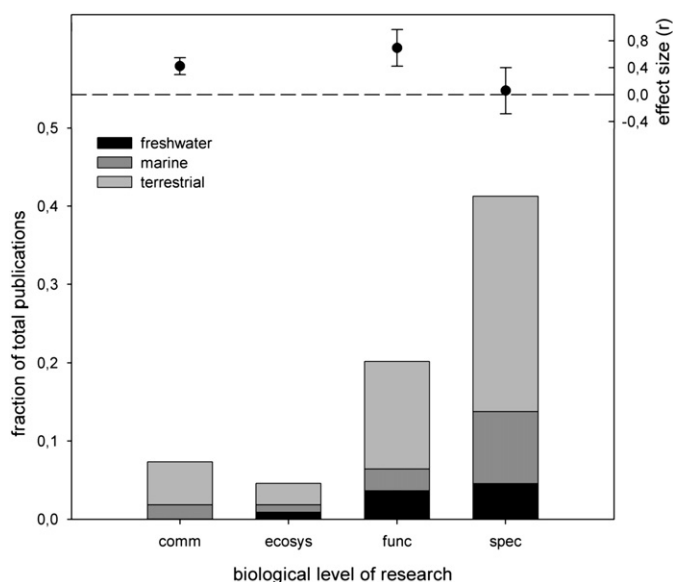


Fig. 5. Fraction of papers linking biodiversity and ecosystem function according to biological level of research for terrestrial, marine and freshwater habitats. Right y-axis: average (\pm stdev) effect size of studies addressing different biological levels.

Despite the interdisciplinary nature of biodiversity studies and the recent development of large international research programs the average number of authors (Fig. 4) has remained more or less stable around 2.7 ± 0.11 for all fields combined over 1987–2005 (linear regression slope = 0.25, $t_{17} = 1.07$, $p = 0.30$). This indicates that, as opposed to trends in other (Gattuso et al., 2005) as well as similar fields (Paine, 2005; Harrison, 2006) collaborative research is not increasing in this field.

Research identifying itself as work on biodiversity is still largely focused at the species level (Table 1), and, despite constant technical improvements, research on genetic diversity still represents a minor component of the research effort, particularly in freshwater ecosystems. The species addressed in biodiversity studies include both autotrophic and heterotrophic organisms, with no apparent bias in this partitioning in the terrestrial habitat, but a strong focus on studies targeting heterotrophic organisms or both in the aquatic habitats (Table 1). Most biodiversity research is experimental and observational, with more than three-quarters of these experiments being conducted on land. Modeling and synthesis studies do not exceed 13% of all research (Table 1).

GLM analysis of the sub-selection on articles relating biodiversity and ecosystem function showed no significant interaction between system and biological level of research ($p = 0.27$). Simplifying the model accordingly showed that there are no apparent differences in effect size r between systems ($F_{2,46} = 2.02$, $p = 0.145$), for aquatic systems (freshwater systems 0.07 ± 0.621 ; $n = 11$, marine systems 0.22 ± 0.427 ; $n = 8$) and terrestrial systems (0.31 ± 0.436 ; $n = 30$). While there is an effect of biological level of research ($F_{2,46} = 17.24$, $p < .001$) more specifically, articles focusing on species level consistently found lower effect sizes (0.06 ± 0.342 ; $n = 19$) compared to studies testing the functional role of biodiversity at community or functional group level (0.70 ± 0.264 ; $n = 14$, Fig. 5).

4. Discussion

The results presented clearly portray a rise of research using the keyword biodiversity from a marginal (3%) to a major component of the main ecological literature, currently representing a third of all papers published in ecological research. This growth undoubtedly responds to the alarming global deterioration of ecosystem and the erosion of biodiversity in land and the ocean (Balmford and Bond,

2005) and the consequences for ecosystem function. Biodiversity research is dominated by research efforts on land, whereas freshwater and marine ecosystems receive a small fraction of the effort. This contrast may reflect the higher biodiversity, in terms of numbers of species, on land compared to the sea, as reports estimate a total of between 2–10 million species (Diversity, 2006) and 5–15 million (Stork, 1993) compared to estimates of between 250,000 – 274,000 species for the marine habitat (Bouchet, 2006). Terrestrial ecosystems are also perceived as being more complex than marine ones, although this perception may simply reflect the fact that terrestrial ecosystems have been more extensively studied (Link, 2002). The most important driver of the dominant focus on terrestrial biodiversity is undoubtedly the much larger number of documented extinctions on land compared to the ocean (Carlton et al., 1999; IUCN, 2004) but also accessibility of the environment.

However, the relative effort of biodiversity research allocated to terrestrial and inland freshwater ecosystems compared to marine ones appears disproportionate when considering that the ocean occupies a much larger surface of the planet and, like land, is not free of threats (Balmford and Bond, 2005), which have already resulted in about a dozen documented extinctions (Lotke et al., 2006) as well as a widespread depletion of many species due to overfishing (Jackson et al., 2001). Coastal areas, often subject to over population and pollution (Suman et al., 2005), are under particular pressure, as evidenced by rapid loss of many important habitats, and their associated communities, including mangrove forests (Murray et al., 2003), coral reefs (Roberts et al., 2002) and seagrass meadows (Duarte, 2002). Novel global threats to marine biodiversity, such as global warming and ocean acidification, are emerging (Kleypas et al., 1999). A major increase in research efforts, to approach those on land, is required to better understand the causes of these declines and formulate effective remediation strategies, as well as to understand the consequences of changes in marine biodiversity on the functioning of the ecosystem and eventually the biosphere (Duffy and Stachowicz, 2006). Increased networking and collaborative efforts, including international programs and sharing of technological resources, such as deep-sea submarine and RoVs, can achieve a better-balanced research effort across taxonomic groups, ecosystem types and regions.

Research should be integrated on different scales of biological levels (species, functional groups, communities) as relationships with biodiversity may change over different biological levels. For instance studies linking biodiversity to ecosystem functioning will benefit from a focus change to functional groups rather than on individual member species since across all systems studies on functional groups demonstrate stronger correlations with the functioning of the ecosystem. The minor component of research on genetic diversity, particularly in aquatic ecosystems confirms a similar conclusion by an in-depth study on aquatic sciences only that found that molecular and genetic approaches changed little and ranged between 4 and 10% of total study approaches up to the year 2000 (Moustakas and Karakassis, 2005). Molecular tools could examine marine genetic biodiversity to resolve phylogenetic and taxonomic issues (Costello et al., 2006), and to resolve genetic diversity within species and develop genomic and environmental genomic approaches to understand the role of genes in the marine ecosystem.

Biodiversity research is still largely occupied with deriving an empirical basis, as most of the research is experimental and observational. Modeling and synthesis studies do not exceed 13% of all research, suggesting that the development of synthesis and theory is still ongoing. Also, collaborative efforts are still underdeveloped in biodiversity research, as indicated by authorships typically involving <3 authors, with no indication of increase. Collaborations should develop between systems as well as within a single research domain since there is a need to create an additional forum to facilitate the communication of results across the communities to resolve the split across research domains, a result of the broader compartmentalization

between the research communities working on different systems. Increased cooperation between marine, terrestrial and freshwater researchers to develop theoretical and conceptual frameworks applicable and testable across all biomes should be a research priority.

Manual screening does not essentially retrieve more articles than through a search on the web of science. This is arguably due to the subjectivity of the searcher, and inevitably errors will be made when manually going through more or less 396 (33 x 12) tables of contents. But on the other hand, we could argue that the Web of Science's use of added keywords and search through abstracts, titles, keywords and subject group effectively captures the content of the classified articles. Their search system, even when using limited keywords, is a rapid and efficient way to screen a huge database for articles of interest. We argue that even if our search was limited to a buzzword, we retrieved most articles on the subject of biodiversity, even when this popular word was not listed as key word, nor mentioned in the title. The < 10% discrepancy between the database driven and the manual bibliography search are reasonable and the results presented here are a reliable portrayal of research effort in this field.

5. Conclusions

Increased collaborative efforts to develop theoretical and conceptual frameworks applicable and testable across all biomes would help both increase the scope and ambition of the research and provide a new impetus to biodiversity research. Marine biodiversity research needs a particular incentive, as it is currently underdeveloped relative to the size, complexity and threats acting upon ocean ecosystems and requires collaborative efforts to be able to face the logistic and technological challenges of ecosystem-level research in the ocean. Research should also be aimed at developing effective models to conserve marine biodiversity through concerted efforts including physical oceanographers, fisheries scientists and marine ecologists.

Across all systems, research should integrate different scales of biological levels (species, functional groups and communities) and the use of molecular tools to resolve genetic diversity within species, and develop environmental genomic approaches to understand the role of genes in ecosystems should be promoted. Re-structuring biodiversity research to address these challenges is of paramount importance to effectively respond to the mounting threats for the conservation of biodiversity.

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