Where communities intermingle: outlining the evolution of topics in ecosystem service research

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Abstract

We analyze how the content of ecosystem service research has evolved since the early 1990s. Conducting a computational bibliometric content analysis we process a corpus of 14,118 peer-reviewed scientific article abstracts on ecosystem services (ES) from Web of Science records. To provide a comprehensive content analysis of ES research literature, we employ a latent Dirichlet allocation algorithm. For three different time periods (1990-2000, 2001-2010, 2011-2016), we derive nine main ES topics arising from content analysis and elaborate on how they are related over time. The results show that natural science-based ES research analyzes oceanic, freshwater, agricultural, forest, and soil ecosystems. Pollination and land cover emerge as traceable stand alone topics around 2001. Social science ES literature demonstrates a reflexive and critical lens on the role of ES research including critiques of market oriented perspectives. Economic valuation is thus part of but not a dominant focus of ES research as determined in previous reviews. The area where social and natural science merge most is about land use systems such as agriculture. Overall, we provide evidence of the strong natural science foundation, the highly interdisciplinary nature of ES research, and a shift in social ES research towards integrated assessments and governance approaches.

Keywords: ecosystem services, latent dirichlet allocation, content analysis, research policy

Highlights:

- quantitative content analysis of Web of Science article abstracts on ES since 1990
- employing an unsupervised machine learning algorithm: latent Dirichlet allocation
- showing that ES research is largely natural science based
- providing evidence that social science ES research is reflexive and critical
- most cross-disciplinary research happens in land use system analyses

1 Introduction

The ecosystem services (ES) concept was developed in the 1970s and 1980s by conservation biologists and ecological economists to foster recognition among decision-makers of socio-ecological connections (Westman, 1977; Ehrlich and Mooney, 1983), and the field has grown exponentially since the late 1990s (Abson et al., 2014; Braat and de Groot, 2012; Chaudary et al., 2015; Gómez-Baggethun et al., 2010). As a metaphor linking environmental sustainability and economic development, the concept was quickly adopted as a research frontier and boundary object for evaluating social-ecological systems and as a basis for managing environmental change (Norgaard 2010; Raymond et al., 2013, Abson et al. 2014).

The ES concept encompasses and bridges several disciplines in sustainability science ranging from natural to social sciences and humanities, thus reflecting a myriad of interpretations and applications of the ES concept (Bennett et al., 2015; Gómez-Baggethun et al., 2010). Previous reviews indicate that the ES literature remains dominated by ecology and economics, but that the research is growing increasingly diverse and multidisciplinary (Chaudhary et al. 2015; Abson et. al 2014). The concept has furthermore been actively promoted at science-policy

51 interfaces (Díaz et al., 2015; MA, 2005; TEEB, 2011) and in grey literature supporting research
52 and practice outside of academia (e.g. GRI, 2011; NCC, 2015; Waage and Kester, 2014).

53 Today's ES research is largely occupied with conceptual and methodological
54 development, refining applications and tools for ES mapping, valuation and policy
55 implementation (Balmford, et al., 2011; Burkhard et al., 2012, Fisher et al., 2008; Heink et al.,
56 2015; Maes et al., 2012, Spangenberg et al., 2014; Wunder, 2015). Critiques of ES research have
57 focused on theoretical and practical implications and limitations of the concept, mainly revolving
58 around monetary valuation and a potential danger of commodifying ES (e.g. Gomez-Baggethun
59 and Ruiz-Perez, 2011; Naeem, 2013; Silvertown, 2015; Spash, 2015). Partially in response to
60 these critiques, several authors have identified gaps and potential avenues for ES research. For
61 example, La Notte et al. (2017) pointed out that the traditional research approach to ecosystem
62 services cascade framework highlights the end-use benefits of ecosystem services, while more
63 emphasis on the underlying complexity of ecological systems would be beneficial. Reyers et. al
64 (2013) highlight this complexity as a challenge to the ES concept and argue for ES research
65 engage more with the social-ecological systems approach, which encompasses ecological
66 processes, ES interactions, human well being, and feedback loops. Abson et. al's (2014) review
67 of the sustainability vernacular within academic ES research relatedly identified an emphasis on
68 descriptive (as opposed to normative or transformative) research. Chaudhary et al. (2015)
69 highlighted emerging opportunities for the interdisciplinary ES research to engage more with
70 topics such as poverty and justice.

71 The aim of this study is to capture the internal diversity of ES research. Our research
72 question is: *What are the main topics in ES research and how have the topics changed over time,*

from 1995 to 2016? Previous studies have only evaluated a subset of the ES literature (Abson et al., 2014; Chaudhary et al. 2015; Fisher et al., 2008, Gómez-Baggethun et al., 2010; Mooney and Ehrlich, 1997; van den Belt and Stevens, 2016). This study, instead, explores the entire Web of Science literature on ES. Given the magnitude of scientific literature dealing with the topic, we employ an unsupervised machine learning algorithm, latent Dirichlet allocation (LDA), which allows us to process an unprecedented volume of ES research articles (Blei et al. 2003, see for a notable exception in sustainability research D'Amato et al., 2017). Deriving clusters of documents belonging to topics through an occurrence probability matrix of words in documents, we analyze the literature without predefined topics and let the corpus "speak for itself." Both the most representative terms for each of the topics and the topics' relative size are generated from the literature corpus across three time periods between 1990-2016. The quantitative approach adds methodological rigor to the process of capturing content due to its reproducibility. Based on the LDA-determined topic areas, we interpret the results to describe 1) the relative importance in the overall ES narrative based on their share of the overall corpus for each period and 2) the link of topics within the ES literature across periods .

The structure of the article is the following. We present our methodology in section 2, provide the results in section 3 and discuss our interpretations in section 4. In section 5, we conclude briefly.

2 Related literature

Given the extraordinary effort observed in advancing ES literature, some reviews have already attempted to synthesise the evolution and current status of research.

Gomez-Baggethún et al. (2010) articulated four stages of ES research, practice, and economic theory: utilitarian framing (1960s - 1990s), monetization (begun 1960s - accelerating in 1990s), appropriation, and exchange (both began in the 1970s - accelerating in 2000s). They find that the utilitarian framing of the initially rather communicatively used ES metaphor could open up the way for "market logics in the field of nature conservation" (Gomez-Baggethun et al., 2010: 1215). In line with this historical analysis, Dempsey and Robertson (2012) criticize research on ES exchange values and market-based instruments for opening the way to commodification and privatization of ES that should remain public and thus associate it with a neoliberal agenda.

Abson et al. (2014) summarised the state of ES research and examined its contribution to sustainability knowledge based on a review of 1,388 top cited ES scientific articles. They found nine main discourse topics in the literature: valuation, conservation, management, carbon, diversity, water, pollination, forests, biomass. Abson et al. (2014) focused their analysis on the cohesiveness of the ES literature and the extent to which ES research develops knowledge for sustainability goals. They categorized each paper's descriptive, normative, and transformative focus. They identified that most research in their sample is descriptive in nature, rarely explicit in its normative position, and under-developed with respect to transformative knowledge essential to sustainability. This is perhaps related to findings from Seppelt et. al (2011). They aimed to

quantitatively review the methods and approaches found in 153 regional case studies of ecosystem services between 1980 - 2010 and identified a lack of methodological consistency across studies.

Chaudhary et al. (2015) focused their review on the evolution of ES research through time with a quantitative analysis of ES research disciplines coupled with a qualitative assessment of "discursive-institutional spirals" – or the relationships between people, institutions, and discourses – over time. They grouped five periods according to important events and identified each period's main actors, institutions, and disciplines. While they conclude that both ecology and economics are the most important disciplines they also identified that boundary organizations played a critical role to the institutionalization of the ES discourse. Both Abson et al. (2014) and Chaudhary et al. (2015) found that ES research is increasingly represented across social and natural science disciplines, but that research topics remain relatively siloed.

Amidst often polarized scholarly perspectives on ES research, a recent review of the first four years of the Ecosystem Services Journal (van den Belt and Stevens, 2016) found that by now, different value frameworks ranging from utilitarian to intrinsic values are employed and that a discourse evolves between these spheres. Chan et al. (2016) furthermore include relational values that bridge and link instrumental and intrinsic values in human-nature relationships. Correspondingly, Jacobs et al. (2016) show the diversity of valuation methods and call for an integrative valuation school that includes the diversity of values. In a conceptual analysis, Schröter et al. (2017) recently suggested a strategy to refocus the ecosystem services concept towards the normative goal of sustainability, with the particular call to refocus research on inter and intra-generational justice. From an overarching perspective, the Intergovernmental Science-

Policy Platform on Biodiversity and Ecosystem Services (IPBES) community produced a conceptual framework that incorporates "diverse conceptualizations of multiple values of nature and its benefits" (IPBES 2015). The IPBES framework incorporates and articulates various sources and concepts of values regarding nature's contribution to people and society such as anthropocentric values like instrumental, socio-ecological relational values, and ecocentric intrinsic values (Díaz et al., 2015; IPBES 2015; Pascual et al., 2017). One might argue that the various disciplines and perspectives on how nature constitutes and contributes to human well-being in the form of ES have considerably broadened the scope of an initially communicative, then instrumentalized concept. Calls to assess ES with regard to the underlying complexity of socio-ecological systems and principles of sustainability, and the breadth of the IPBES values guide suggest a research and science-policy agenda that strives towards more inclusive and holistic understanding of the role and potential for ES work (Costanza et al., 2017).

This complexity of meaning and connotations within the ES debate provides impetus to our analysis. We aim to provide both a descriptive picture and highlight the linkages between different types of topics within ES research in order to clarify where and around what topics different research communities have evolved.

3 Methods

3.1 Data collection

This study is based on a bibliometric analysis of the scientific literature dealing with the concept of ES. To retrieve the body of literature, we mined the Web of Science (WoS) core collection (all

years, by topic) using the string “ecosystem service*”. This string collects all articles mentioning the word “ecosystem service” or “ecosystem services” in the title and/or abstract. The search resulted in over 15,000 records, which we saved in a tab delimited text file format. These records include authors’ names and affiliations, title, abstract, full record and cited references.

In order to outline the evolution of the ES literature, we downloaded all the WoS entries on published articles for three time periods 1990-2000, 2001-2010, and 2011-2016 - which corresponds roughly to phases from Chaudary et al. (2015). From the original data set we removed double entries and those records that did not provide an abstract. This collection of records, represented the corpus of text for our analysis (Table 1). It is important to note that the bibliometric content analysis has not been conducted on full texts but on the abstracts provided within the WoS database.

Table 1. Dataset record counts from initial pull and final dataset by time period

Years	**Records available**	**Final dataset ***
1990-2000	136	108
2001-2010	2,719	2,521
2011-2016	12,183	11,489
All years	15,038	14,118

*Excluding records with empty abstracts and double entries. Source: Author’s representation based on WoS.

3.2 Content analysis

The following analyses were performed within the **R** Environment (R Development Core Team, 2017). The respective code can be found on a public github repository*:* https://github.com/NilsDroste/ES-LDA.

Descriptive statistics include the geographical origin of the articles, and the most frequent authors' keywords. The geographical provenience of the articles is elaborated based on the authors' affiliations and then represented graphically on a map. It is important to note that the map shows where the articles are written, and it is not indicative of the geographical location of data or study sites. It should be noted that the number of keywords attributed by the authors may vary across documents, from 1 to 6. We use authors' keywords to identify the domain of research interest.

The computational content analysis of the abstracts, representing the main analysis, was performed using the latent Dirichlet allocation (LDA) method (Blei et al. 2003; cf. Pritchard et al., 2000). The software implementation was provided by the ***lda*** package (Chang, 2015), ***tm*** (Feinerer and Hornik, 2015) and ***SnowballC*** (Bouchet-Valat, 2014). For visualizations we used ***LDAvis*** (Sievert and Shirley, 2014), ***ggplot2*** (Wickham, 2009), ***rworldmap*** (South, 2011), and the ***sankey*** (Csardi and Weiner, 2015). The overall text processing procedure is an adaptation of the **R** source code provide by Knutas et al. (2015). The abstracts required specific preprocessing for analysis (cf. Bouchet-Valat., 2014; Feinerer and Hornik, 2015). Spaces, punctuation, acronyms, numbers and symbols were removed. Words were stemmed, meaning they are reduced to their underlying root form, and terms which occur fewer than 5 times have been removed. This resulted in a "bag" of words for each of the abstracts retrieved (cf. Weinberger et al., 2010; Harris, 1954). The most salient terms were identified based on overall word frequency in the abstracts. The LDA method has been developed in computational sciences as a form of natural language processing. The underlying assumption is that text documents are composed of several topics, and these can be revealed based on the likelihood of word co-occurrence. Basically, in

LDA each document can semantically be described by its mixture of latent or unobserved topics where each topic is a distribution over words (Blei et al., 2003). Every document consists of a particular set of words. Each topic is in turn characterized by a dirichlet distribution over a set of words where words may thus occur in the distribution of several topics. The probability that word w_i is contained in document d_k is given by

$$P(w_i|d_k) = \sum_{z=1}^{Z} P(w_i|z) P(z|d_k) \quad (1)$$

where z is the latent topic, $P(w_i|z)$ is the probability of word given topic, and $P(z|d_k)$ is the probability of topic z given the document d_k (cf. Blei et al. 2003; Polyakov et al. 2017).

In the unsupervised process of learning the set of topics, their word probability distributions and the topic mixture of the documents, LDA employs a multinomial dirichlet distribution and infers a posterior distribution through a variational Bayes approximation (Blei et al. 2003). Every document is being repeatedly assigned a topic. The posterior topic distribution $P(z|d_k)$ allows for multiple topic assignments of each document. From there it is possible to identify the most probable topic for each document and the most probable documents for each topic. The number Z of topics to be identified can be optimized in terms different measures, such as accuracy (Arun et al., 2010), density (Cao et al., 2009), latent concept modeling (Deveaud et al., 2014) or Bayesian Markov chain Monte Carlo algorithm (Griffiths and Steyvers). Since all these different optimizations computed through the ***ldatuning*** package provided by (Murzintcev, 2016) resulted in over 400 topics, we have chosen to limit topics to an

interpretable number which we hold constant over time in order to ensure comparability across periods and display (dis-)continuities in the development of topics over time. [1]

The results of the LDA analysis, can be explored interactively with a web-based visualization (http://nils.droste.io/2017/10/05/ES_LDA/). In the interactive figures, the keyword frequencies are represented in a histogram, while the topics are positioned on a principle component plot based on their semantic relationship. The topics are represented as circles, where the size signifies the relative topic share. The browser-based display provides the option to identify the keywords that are most relevant for each topic. The relevance of a word for a topic is defined as $\lambda \times p(word|topic) + (1-\lambda) \times p(word|topic)/p(word)$ for values of $0 \leq \lambda \leq 1$ (Sievert and Shirley, 2014). A lower λ corresponds to more exclusively relevant keywords, while higher values of λ retain more frequent keywords.

The interpretative derivation of topic development and linkages over time. The topics identified by the models for each time period were labelled by the authors. The interpretation process was conducted based on the keywords originating from the LDA analysis using various λ values. Each topic was attributed a tentative name, aimed at being descriptive in its meaning. In order to map the evolution of the topics in time (see sankey diagram in Figure 4), the authors compared the topics found across the four time periods according representative keywords occurring in several topics and to inter-topic distances. Through iterative discussions and

1 This required us to chose a sufficient, but not excessive number of topics to reveal the literature's internal variability without hampering its interpretation with information overload for the sake of model accuracy. We chose the total number of topics in an iterative and literature driven process. First, we set the model to extrapolate six topics, which is the default option proposed by Knutas et al. (2015). Based on the results, we agreed to increase the number of topics to nine to allow for more diversity to emerge from the literature. This number is also in line with the number of topics outlined in a content analysis of the most cited literature on ES by Abson et al. (2014). In this way, we can provide some comparability across reviews.

graphical refinements of how and where content can be found in another period's LDA derived topics we reached an agreement on topic linkages across periods. Topic descriptions (see section 4.2) were also derived from LDA generated salient keywords at different λ in addition to the abstracts of the top 20 most representative articles (see online appendix for a list of the most representative articles for each topic, link).

4 Results

4.1 Descriptive statistics plots

The descriptive statistics plots in this section are based on an analysis of the entire data set.

Figure 1 shows the exponential growth in ES literature.

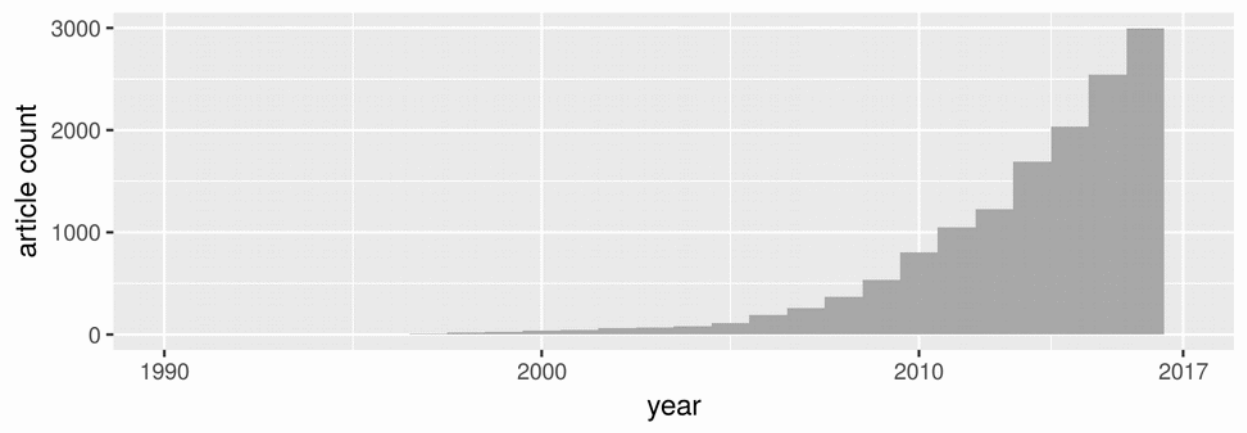

Figure 1: The growth in ES research. Source: authors' representation based on WOS data.

Figure 2 displays that the early ES research originated mainly originated from OECD countries. During later periods, the concept dispersed globally such that in the last period there is a much more equally distributed location of authors home institutions - with a gap in ES research authorship remaining in some African countries.

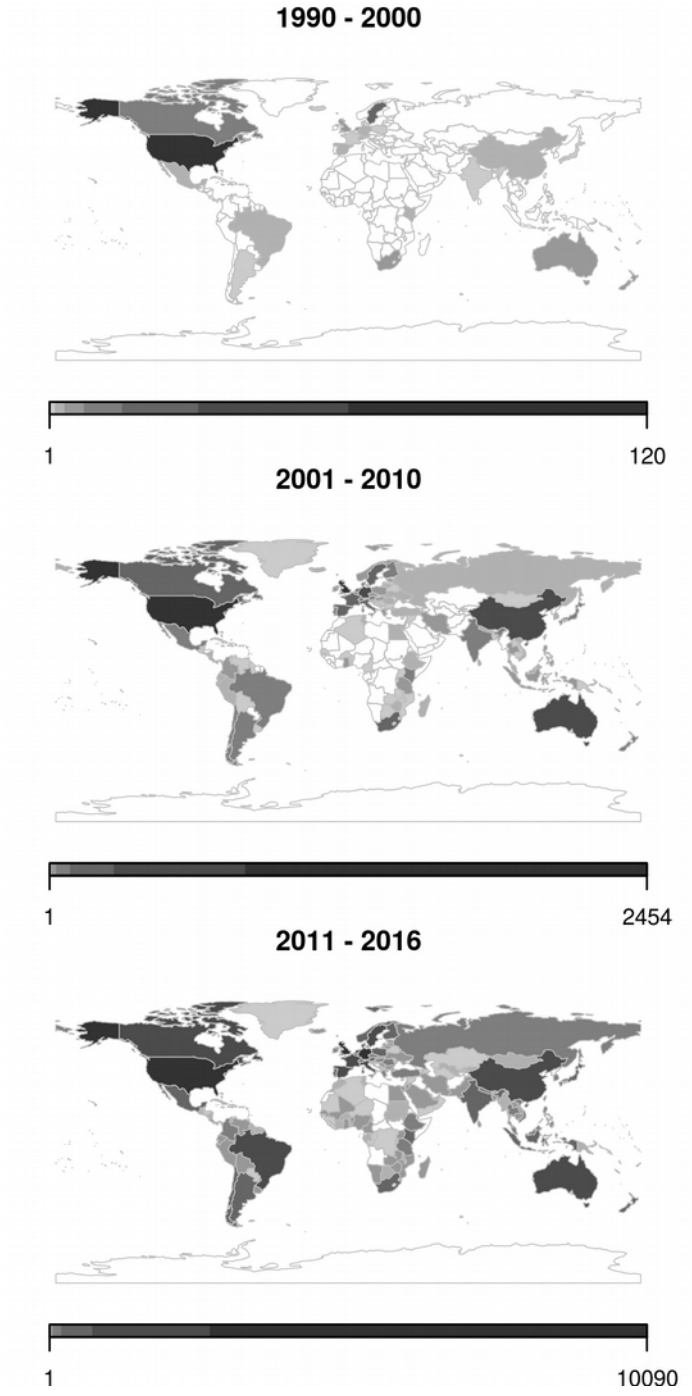

Figure 2: The geographical distribution of ES research. Note the different fixed width logarithmic colour scales. Source: author's own representation based on WoS. Colour scales represent the count of author affiliation locations.

Figure 3 shows the top 10 author supplied keywords except “ecosystem” and “ecosystem services”. The graph shows that overall biodiversity is essential to ES research. While “sustainability” was ranked second during the first two periods, “climate change” and “conservation” became more frequent keywords in the third and fourth period. While “resilience” drops in its relative frequency across time, “agriculture” is on the rise. Both “restoration” and “remote sensing” only become prominent during the last two periods.

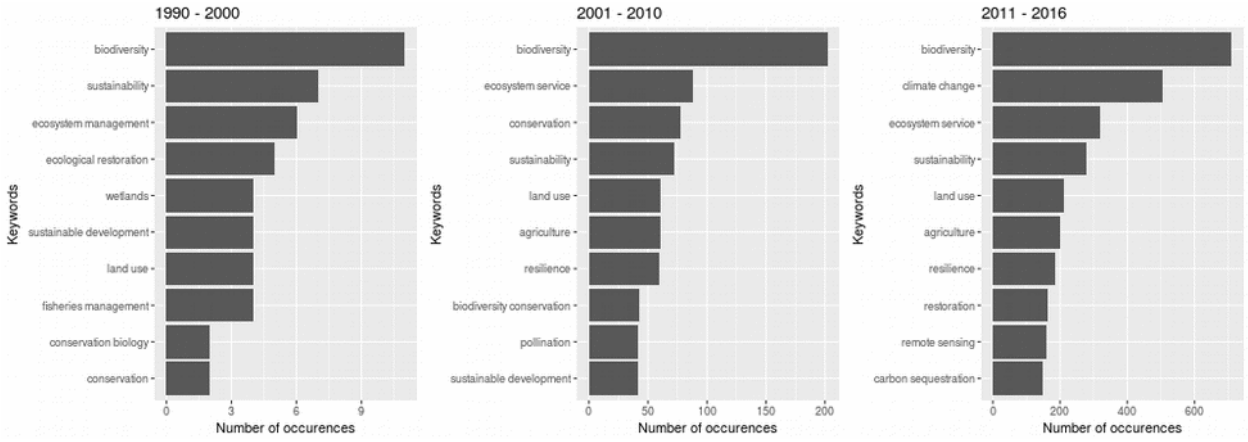

Figure 3: Top author keywords for the research corpi in four periods. Note the different x-axis-scale of the plots for each period. Source: author’s own representation based on WoS data.

4.2 Content analysis

For each of the periods, the LDA algorithm provides nine topics with a probability distribution over words. Here, we describe the topics in more generic terms and highlight the topic development over time. A graphical overview of the topics for each period and their development can be found in Figure 4. References to the 20 most representative articles for each of the topics and a table of the assigned topics for all articles per period can be found in the supplementary

material. Due to word limitations we limit descriptions to the last period of topic clustering (2010-2016) but highlight inputs from former topics (indicated with a forward arrow, →). The online interactive results provide far greater detail (see http://nils.droste.io/2017/04/20/ES_LDA/). In the discussion (section 5), we draw conclusions based on the entire body of analyses. For each of the topics we elaborate on what kind of ecosystems are assessed, and, as far as possible, what kind of ES are addressed. Following, we describe the topics emerging from the analysis of the most recent literature (2011-2016), with a perspective on their historical development. We ordered the topic descriptions according to their position within the figure's last period.

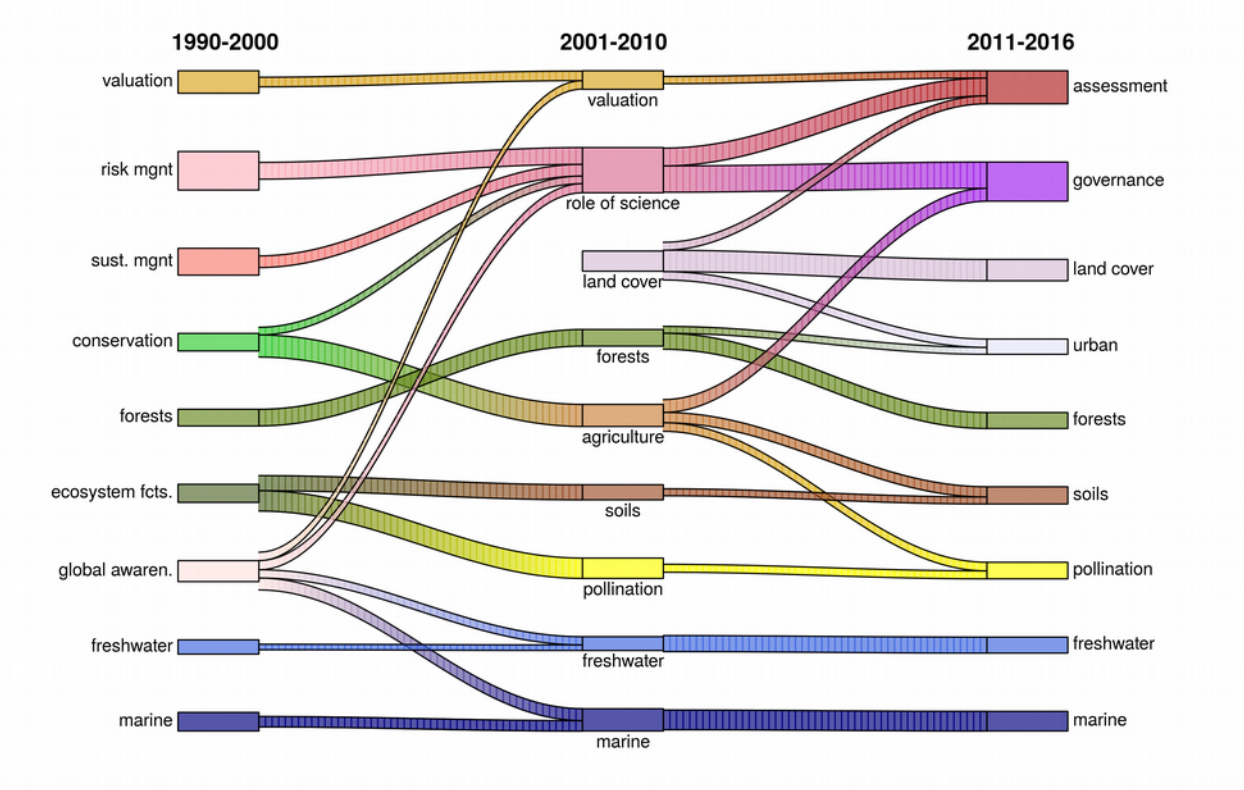

Figure 4: The development of ES topic clusters over time. The height of the topic boxes represent the relative topic proportion within each period. Note that the number of assessed articles increases over time (1990-2000: N=108, 2001-2010: N=2,521, and 2011-2016: N=11,489). The links between periods have interpretatively been deducted from LDA results. Source: Authors elaboration based on WoS data.

Assessment: This topic focuses on ecosystem services assessments, for example through mapping techniques, (spatially explicit) ecological models for ecosystem service flows, participatory (scenario) planning methods, and Bayesian belief networks. Although the main focus lies in methodology of assessment approaches, a strong link to science-policy interfaces of national ecosystem service assessments and planning procedures is given in the most relevant works. Both economic values and biophysical indicators can be found. The topic accounts for inputs from economic research (→ valuation), transdisciplinary participation in research (→ role of science), and satellite imagery for mapping exercises (→ land cover).

Governance: This topic focuses on policy instruments for land use systems. It includes research on i) limits and potential of payments for ecosystem services approaches, ii) socio-ecological interactions in conservation management and food systems, and iii) self-organized governance networks in terms of accountability and effectiveness. A general focus centers on how to steer and govern such systems with respect to adaptive, resilient and sustainable ecosystem management. Corresponding to inputs from past periods, the governance topic includes research on agricultural food system with respect to provisioning ecosystem services (→ agriculture) and on participatory, transdisciplinary methods and sustainability science research agendas, including critiques of neoliberal perspectives (→role of science).

Land cover: This topic deals with land use (change), land cover and vegetation types and is mainly based on GIS approaches and remote sensing imagery. From resulting maps and data, ES are assessed and sometimes monetarily valued. Analyses are often large scale and many top papers focus on Chinese regions. Spatially explicit models and analyses are used to compare

294 trade-offs and land use practices, e.g. in relation to climate change and biodiversity. The topic
295 only emerges as a stand-alone topic during the second period from 2001-2010.

296 **Urban**: This topic is mainly about green space ES in urban areas and settlements.
297 Preferences and perceptions of urban green spaces for recreational uses and cultural ecosystem
298 services are at the core of the respective analyses. Greenbelts, parks, and urban conservation are
299 (spatially) analyzed in terms of outcomes on health, preference satisfaction and access equality.
300 The ES perspective serves as a conceptual framework in this regard. Statistical analysis,
301 (contingent) valuation and qualitative methods are the most common methods. As parks and
302 green spaces are such a central theme, we see a linkage from the (→forest) topic. Spatial
303 analyses are interpreted as a link from (→land cover).

304 **Soils**: Literature dealing with this topic during 2011-2016 focuses on the role of land
305 management, microbial communities and soil invertebrates in plant productivity, especially in
306 agricultural systems and with a perspective on soil biochemical properties. In previous years
307 (2001-2010), the topic is slightly different, with research on pedofauna related to pollutant
308 degradation, effects by fertilizers, and carbon and nitrogen fixation. The ecosystems under
309 analysis during this period go beyond agricultural systems to include, for instance, grasslands
310 and forests. Research on soils stems from 1990-2001 literature on the links between biodiversity
311 and ecosystem functions.

312 **Forests**: This topic deals with the influence of management and restoration on (especially
313 tropical) forests and related biodiversity conservation, ecological dynamics, and ecosystem
314 services. In particular, carbon storage processes in forests are examined with respect to climate
315 change mitigation. The role of plantations, both for productive and restoration purposes is also

316 part of this topic. The topic remains somewhat isolated from the others throughout 1990-2016,
317 but an internal evolution of the content examined in the literature takes place. In addition to
318 forest ecology and related restoration and management practices, research during 1990-2010 also
319 deals with urban woods and parks which is later seen in the (→urban topic). Correspondingly,
320 the urban dimension disappears in recent literature on forests.

321 **Pollination and pest control**: Research emerging in this topic deals with the functional
322 role of pollination and pest control for the integrity of agr-environmental systems. Research
323 themes include the effects of habitat structure and land management on pollinators. Furthermore,
324 the role of biological control of pests in agricultural systems is also investigated. The topic stems
325 from 1990-2001 research on the links between biodiversity and ecosystem functions. During
326 2001-2016, research seems to focus mostly on bees, but it also examines the role of other
327 pollinating and pest control agents, such as birds, bats and various arthropods. From 2011 to
328 2016, the topic takes up input from agriculture (→), by incorporating analyses of particular land
329 management patterns and practices.

330 **Freshwater:** In this topic, freshwater dynamics in rivers, streams, and coasts are
331 examined. Dominant topics include managed wetlands, sediment control, nutrient fluctuation,
332 pollution attenuation, and the impact of flow dynamics on ecosystem services. A broader theme
333 of water management encompasses sub-foci on nutrient dynamics (e.g. Nitrogen fixation), which
334 draws on similar literature topics found within the (→global awareness) topic. The impact of
335 human activities (e.g. dams, stream burial, hydropower) is present throughout all time periods. A
336 technical foci on hydrology and ecological engineering dominant in relevant topic papers

perhaps explains its topical distance from the ecology and social science focus of other topic areas overtime.

Marine: This topic deals with the role of marine and coastal habitats for ecosystem functions and services from both an ecological and a socio-ecological perspective. A central focus lies on reduced resilience of coral reef research, examining how local (e.g. fisheries) or global (e.g. climate change) human impacts impact reef biodiversity, species assemblages, reef structure, post-disaster species community recovery, and ecosystem functioning. In the earliest time period, 1990-2000, the marine topic encompassed several key areas, including: debates over the goals and science of coastal restoration projects; conservation and management strategies; and the role of ecological and environmental economics in coastal and marine management. In the subsequent time period, 2001-2010, impacts of global warming, overfishing, and habitat disturbance on biodiversity and coral reef habitat are in focus.

5 Discussion

This article is based on a reproducible quantitative analysis of the abstracts of ES literature available in the Web of Science, from which we qualitatively evaluate the evolution of research topics over time. We focus our discussion on both the content and development of topics in ES research and the value and limitations of the LDA method.

5.1 Topic development

Overall, we find that a large share of the ecosystem services literature deals with the ecological functioning and biodiversity of key natural and managed systems such as freshwater, marine, and forest ecosystems, as well as agricultural ecosystems and urban green spaces. Though represented, the literature addressing social issues and social aspects of ecosystem engagement remains underdeveloped and tends to focus on management and conservation practices such as risk and sustainability management, valuation, the role of science and, governance. We find that the distribution of research investigating social versus ecological dimensions of ecosystem services varies over time. In the first period, from 1990-2000, five out of nine topics mainly deal with ecology and land use (conservation, forests, ecosystem functioning, freshwater, and marine) while four topics at address social issues and practices (valuation, global awareness, risk management, and sustainability management). A core topic in this time period clustered research papers dedicated to larger-scale societal impacts on ecosystems and economies, which we labeled (→global awareness). Concepts in the global awareness topic branch into different topics in later periods, such as valuation, the role of science, and freshwater ecosystems. The second time period (2001 to 2010) shows an increase in the share of natural science-related topics, with foci on forests, soils, pollination, freshwater and marine ecosystems. Land cover and agriculture research areas address topics at the interface of land use practices and ecosystem functioning. Valuation topics emerge with more detailed economic analyses relative to the larger-scale claims on the role of economics in ecosystem services from the first period. The role of science topic demonstrates a reflexive and critical focus emergent in ES research wherein researchers inquire about the potential to contribute to sustainability transformations. In the third period from 2011

376 to 2016, the ratio between natural and social science-related topics rather remains constant, but
377 the composition changes. There are five natural science topics (forests, soils, pollination,
378 freshwater, and marine) and one mainly social science topics (governance), and three at an
379 interdisciplinary interface: assessments (including biophysical and societal valuations), land
380 cover and urban analyses, and land use. The natural sciences-orientation of the ES literature is
381 not surprising, given that the concept was originally coined in the context of ecology (Westman,
382 1977; Ehrlich and Mooney, 1983). Yet, the composition of topics within each period changes
383 over time. The share of water related ES remain rather stable over time which means its
384 publication numbers are increasing at the same rate as overall ES literature such that the relative
385 share remains constant. Pollination occurs as an individual topic in the second period and
386 becomes an important (policy) issue globally, as reflected by the recent assessment by the IPBES
387 (IPBES, 2016). The relative research share of terrestrial biodiversity and ecosystem functioning
388 (agriculture, forests and soils) topics is stable over time. Land cover occurs in the second period
389 as a stand-alone topic and links to the urban ES topic that emerges in the last period. We
390 furthermore find that the stream of research with a focus on sustainability, risk management and
391 global awareness are predecessors to the reflective role of science for sustainability
392 transformations topic cluster. This topic then relates to ES governance research and integrated
393 assessments. The occurrence of the topic indicates a reflexive community within ES research,
394 which analyze their own (transdisciplinary) methodology and transformative potential. The
395 agriculture topic links with governance approaches, soil research and pollination and thus
396 submerges into various topic clusters that then include agricultural issues.

We find that most of the topics emerging from our LDA analysis of ES literature since 1990 are in line with the topics identified by Abson et al. (2014) and Chaudhary et al. (2015) despite some differences in framing and labelling. For example, Abson et al. (2014) identified nine research topics, including valuation, conservation, management, carbon, diversity, pollination, forests and biomass. However, from a quantitative perspective, we found that the topics' relative share in the overall literature (i.e. a corpus of 14,118 papers) is not in line with the topics' share found among the most relevant (i.e. highly cited) articles analyzed by Abson et al. 2014. According to the authors, valuation is by far the largest topic (N=606), followed by conservation (N=232) and by management (N=140). This analysis indicates a heavy social science orientation within the ES research community. Thus, our findings about the relation of social and natural science-based research interestingly contradict previous reviews' claims that the ES concept has been "hijacked" towards monetization and commodification arguments (e.g. Silvertown, 2015; Spash, 2015; van den Belt and Stevens, 2016). Even though the most influential literature could indeed be more oriented towards market-based thinking or economic valuation (cf. Costanza et al., 1997, 2014), such an argument cannot be supported from a quantitative evaluation of the overall literature. In other words, when considering the relative share of economic valuation topics related to the entire ES literature, we find natural-science and ecologically-focused research dominates the ES publication list. Additionally, our analysis demonstrates that even within the economic-oriented ecosystem services topics, some critical perspectives on ES valuation emerge (e.g. "neoliberal" is among the topic-specific keywords). This suggests that critical research on ES valuation plays an important role in shaping the overall valuation topic. What is perhaps more interesting is the disappearance of a core valuation topic in

419 the third period; instead, sub themes of ecosystem valuation get submerged into the integrated
420 assessment topic in the third period.

421 ***5.2 Methodological considerations***

422 The main value added of the LDA technique is that keywords and topics within a literature's
423 entire corpus emerge based on the data itself rather than the a priori postulations formulated by
424 researcher(s) through their analytical processes. The unsupervised learning algorithm that
425 clusters documents among topics based on their conditional distribution of words allows the data
426 to "speak". While highly effective, qualitative analysis performed by one or more researchers
427 would inevitably incur in some (pre-)formulated bias due to individual values and beliefs about,
428 and understanding and categorization of, the literature. This is not to say that such an approach is
429 invalid – indeed this paper hopes to demonstrate an approach to combine interpretive analysis
430 with a quantitative literature assessment. The LDA is a powerful tool for describing topics of a
431 research body in terms of how often words occur jointly. Our own contribution beyond applying
432 the method to ES research has been to track topic development over time though interpretative
433 linkages while holding the number of topics constant. We are the first to provide a fully
434 reproducible unsupervised machine learning algorithm analysis on ES research and link this to
435 an interpretive time series analysis.

436 Previous review papers summarizing the state or evolution of ecosystem service literature
437 have focused primarily on either top cited publications, e.g. papers with > 15 publications
438 (Chaudhary et al. 2015) or papers cited at least one time per year (Abson et al. 2014) or
439 publications within a leading impact factor journal, i.e. Ecosystem Services (van den Belt and

Stevens 2016). The value of this approach is its focus on the academic productivity of a given journal or paper. It's ability to capture the full landscape of knowledge production and academic activity, however, is limited. By including the expansive corpus of literature on ecosystem services, our approach does not bias topic development against influential articles in terms of citation count. While there may be drawbacks to leaving out academic influence (such as limitations on the ability to demonstrate which topics are *most influential*), we are the first to evaluate the entire spectrum of ES research up to date and evaluate the proportion of contributions from various topics to the evolution of ES research over time.

There are, of course, limits to our strategy and possible future extensions. Our data collection strategy is limited in some ways. It only includes scientific literature published in English, thus excluding, for instance, grey literature and policy documents, or publications written in languages other than English. Furthermore, we were unable to perform any preliminary screening of the collected articles given the size of the dataset to verify for relevance and adherence with the ES concept. It is thus possible that an undefined portion of the literature mentions "ecosystem service(s)" as a buzzword or post-hoc justification for research, as suggested by Abson et al. (2014). But we cover all scientific ES literature from WoS from 1990 onwards, which has not been accomplished before.

The linkages across periods were developed through interpretative analysis by all three authors. While the LDA analysis of topics for each period is fully reproducible, the interpretation of how these topics link and develop over time is not. We took an iterative approach to interpretation of topic development over time. Firstly, we conducted independent analysis of LDA results and the top 20 papers contributing to topic clusters. Secondly, we shared and

462 debated among the group regarding topic content and development. We made available citations
463 and abstracts for the top 20 papers for each of the topics across all three periods in the
464 supplementary material and an online interactive LDA visualization
465 (http://nils.droste.io/2017/10/05/ES_LDA/).

466 A next step in topic modelling regarding ES research would be the application of
467 dynamic topic models and the influence model (Blei and Lafferty, 2006a), which allows for
468 tracking the development and content of a singular topic over time algorithmically, instead of the
469 interpretation and linkage creation conducted by the authors. Another step could be the
470 application of hierarchical topic models which allows for topics to be correlated with each other
471 across time periods (Blei and Lafferty, 2006b).

472 ## 6 Conclusions

473 We have analyzed the Web of Science core collection for the search term “ecosystem service*”,
474 resulting in a final dataset of over 14,000 articles - which constitutes the most complete data set
475 for such an analysis to date. We used a computational science method, latent Dirichlet allocation
476 (LDA) analysis to derive main topics from the articles’ abstracts. We analyzed three periods of
477 ES research, from 1990 to 2016 and qualitatively linked the topics between the periods in order
478 to display research (dis-)continuities. Our results show that a majority of topics can be
479 characterized as natural science research on different ecosystems such as oceans, freshwater, soil,
480 pollination or forests. A smaller share of topics is based on social science based approaches such
481 as sustainable management, role of science, valuation, and governance. Some topics are at the

junction of socio-ecological land use systems (land cover, urban spaces). This finding provides a counterpoint to former analysis who find a stronger dominance of economic and social science research, at least in the most cited literature (Abson et. al., 2014; Chaudary et al., 2015). Particularly interesting is the shift from the sustainable management topic towards a more self-reflective topic on the role of science for sustainability transformations. Yet, this reflexive and critical role of science topic feeds into the governance topic which approaches the practice and policy side of ES. Also worth noting is that the (monetary) valuation topic submerges into the assessment topics that include biophysical assessments and non-monetary valuation approaches; such research develops more integrative and comprehensive analyses of ES research beyond monetary valuation exercises. We cannot deny the possibility that economic research may be more influential in the policy sphere. However, our results do not show a strong dominance of economic approaches, at least in terms of relative shares of topics. To the contrary, we find that natural science topics such as pollination and land use data based on satellite imagery rise over time, while social science research becomes reflexive and critical in terms of analyzing how it may contribute to socio-ecological transformations. Even the economic instruments topic contains words that display a certain degree of critical self-reflection such as “justice”, “perceptions” or “neoliberal”. This indicates that the need for discussion on justice and more inclusive governance called for by Chaudhary et al. (2015) and by Schröter et al., (2017) is a shared view among others and has least partly been addressed by existing research.

LDA analysis afforded us a broad and reproducible exploration into evaluating the question: what are the most dominantly researched topics in ES over time? Our analysis demonstrates that the ES research community remains dominated by natural science approaches,

but that integration across social and natural research agendas takes place particularly in the realm of land use practices topics such as agriculture. Our interpretive process led to several interesting observations unattended to in former reviews, including insight into the (fiercely) debated topic of monetary valuation. We conclude therein that while concerns about an ongoing neoliberalisation of ES research are an essential part of its reflexive and critical nature, we do not empirically observe a rise in the relative share of monetary and valuation-based research. We find that ecosystem services science partly contributed to a process of monetary valuation, i.e. during the first decade of the new millennium, as also observed by Gomez-Baggethun (2010). Yet, a new ES research direction is emerging towards a more comprehensive and transdisciplinary approach to assessments (Jacobs et al. 2016) and governance approaches for institution building for integrative ecosystem (service) management (Costanza et al., 2017; Saarikoski et al. 2017). Whether ES policy influenced by academic ES research follows this trend is an open question.

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