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REVIEW

Temporal patterns in ecosystem services research: A review and three recommendations

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Abstract Temporal aspects of ecosystem services have gained surprisingly little attention given that ecosystem service flows are not static but change over time. We present the first systematic review to describe and establish how studies have assessed temporal patterns in supply and demand of ecosystem services. 295 studies, 2% of all studies engaging with the ecosystem service concept, considered changes in ecosystem services over time. Changes were mainly characterised as monotonic and linear (81%), rather than non-linear or through system shocks. Further, a lack of focus of changing ecosystem service demand (rather than supply) hampers our understanding of the temporal patterns of ecosystem services provision and use. Future studies on changes in ecosystem services over time should (1) more explicitly study temporal patterns, (2) analyse trade-offs and synergies between services over time, and (3) integrate changes in supply and demand and involve and empower stakeholders in temporal ecosystem services research.

Keywords Ecosystem service dynamics · Ecosystem service supply · Linear change · Periodic change · Stakeholder involvement

INTRODUCTION

Ecosystem services are commonly defined as the benefits people obtain from ecosystems (Millennium Ecosystem Assessment 2003). During the last two decades, the field of ecosystem service research has rapidly diversified (Chaudhary et al. 2015). Research has to date focused on biophysical structures and functions, and the spatial supply of ecosystem services (Abson and Termansen 2011; Luederitz et al. 2015). Temporal aspects of ecosystem service flows have received far less attention (Kremen 2005; Abson and Termansen 2011; Birkhofer et al. 2015), with potentially far reaching consequences for the sustainable management of the ecosystem services on which humanity is ultimately dependent for its survival. Analyses based on snapshots in time do not necessarily correctly represent the way in which ecosystem services are supplied as ecosystem services are not static but change over time (Fisher et al. 2009; de Groot et al. 2010). Indeed, neglecting temporal variability in individual ecosystem services (Martín-López et al. 2009) and ecosystem service bundles (Renard et al. 2015) may yield misleading results. Maximising a service, such as current yields in agriculture, may risk long-term provision of underlying ecosystem services, such as soil quality in intensively managed systems, because benefits of maintaining high soil organic carbon for agriculture occur in a distant future (Baveye et al. 2016). As a more extreme example, monitoring increases in potato yields as such in the early 19th century in Ireland, without considering the capacity of the environment to sustain high yields, would have underestimated the sudden, large-scale crop failure that occurred in the 1840s because of late blight, which ultimately led to the death and displacement of 25% of the Irish population (Fraser 2003).

Both cases illustrate the importance of considering the management of ecosystem services over long time periods and accounting for temporal dynamics, including non-linear events, of all aspects of service supply and demand.

Changes in the *supply* of ecosystem services over time can take many forms. For example, Bullock et al. (2011)

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provided an overview on the rate of recovery of ecosystem services or biodiversity in restored ecosystems, and grouped changes over time into the categories asymptotic, linear, unimodal and stochastic, whereas Bastian et al. (2012) distinguished between ecosystem services that are provided periodically, episodically or permanently. As perceived benefits of ecosystem services can strongly differ between different stakeholder groups, benefits cannot simply be assumed by scientists but need to be elicited by involving stakeholders (Reed 2008; Hicks et al. 2013). Therefore, it is important to include stakeholder perceptions in studies on temporal aspects of ecosystem services. Particularly, supply of, and demand for, ecosystem services can change in different ways over time (Rau et al. 2018a), which can lead to mismatches in the appropriation of ecosystem services if supply and demand are analysed in isolation.

Despite insights about the impact of temporal aspects on ecosystem services, there are no comprehensive reviews that systematically assess how changes in ecosystem services over time have been studied. In this review, we systematically appraise the literature on ecosystem services to investigate how changes in the supply and demand for ecosystem services have been analysed and characterised over time.

Here we would note that one potential reason for the lack of focus on temporal patterns in the ecosystem services literature might be due to the multiple ways in which such dynamics may be conceptualised in the operationalization of the ecosystem services concept. For example, the ‘provision’ of timber from a forest may be quantified either in terms of the amount of timber harvested at a given point in time (specific ecosystem service flows), or the amount of timber that the forest will theoretically produce over a defined management cycle (potential ecosystem service provision). The former is more likely to capture periodic changes in ecosystem supply/demand than the latter. There remains the possibility of systematic artefacts/bias depending on the way in which the ecosystem services have been operationalized in the literature (for example, actual appropriation over short time periods versus long-term assessment of potential provision). However, the objective of this paper is not to accurately describe the (actual or potential) dynamics for given ecosystem services, but rather map how such temporal patterns have been described in the literature. Specifically, we addressed the following questions:

- Where and with which methods have changes in ecosystem services been quantified?
- Which ecosystem services have been assessed over time and at which temporal scales?
- To what extent has research on changes in ecosystem services over time described linear, periodical or non-linear (events) temporal patterns in ecosystem services?
- To what extent has research on temporal patterns in ecosystem services focused on supply and demand of services across temporal scales?
- To what extent have stakeholders been integrated or accounted for in the research?

METHODS

Review procedure

This quantitative review is based on the method described by Luederitz et al. (2016), which combines quantitative statistical analyses with qualitative content analyses.

We first developed a search string (see Appendix S1) to identify studies (i.e. individual peer-reviewed journal studies) in the Web of Science Core Collection and in Scopus in October 2016. The search returned 5601 unique studies published in English (Fig. 1). We thereafter screened studies based on the titles and abstracts. To increase objectivity (see Luederitz et al. 2016), every article was screened independently by two out of 14 reviewers. The cohort of reviewers covered a broad range of academic backgrounds, including ecology, environmental science, sustainability science and physical geography. Studies were included if they actively engaged with the ecosystem services concept and explicitly sought to quantify changes in ecosystem services over time (Fig. 1). To reduce selection bias, both reviewers had to agree on whether to exclude or include individual studies. We note that a certain degree of selection bias cannot be avoided as we focussed our review on studies that actively deal with the ecosystem service concept, which may disproportionally exclude studies on some services that have not commonly been studied under this framework.

After assessing titles and abstracts, 911 potentially relevant studies that matched all three criteria were included in a full-text review. To increase the coherence between reviewers and, as far as possible, avoid selection bias, we first compared the review results of the first five studies in the full-text review amongst the whole group of 14 reviewers (following Luederitz et al. 2016). Where there were inconsistencies, we discussed how to resolve these until we agreed on a solution with all 14 reviewers. Based on this procedure we compiled a review manual for the full-text review that was distributed to, and approved by, all reviewers (see Appendix S2).

Out of the 911 studies identified as potentially relevant, 893 PDF files (98%) could be accessed and were downloaded (Fig. 1). The obtained full texts were assessed using

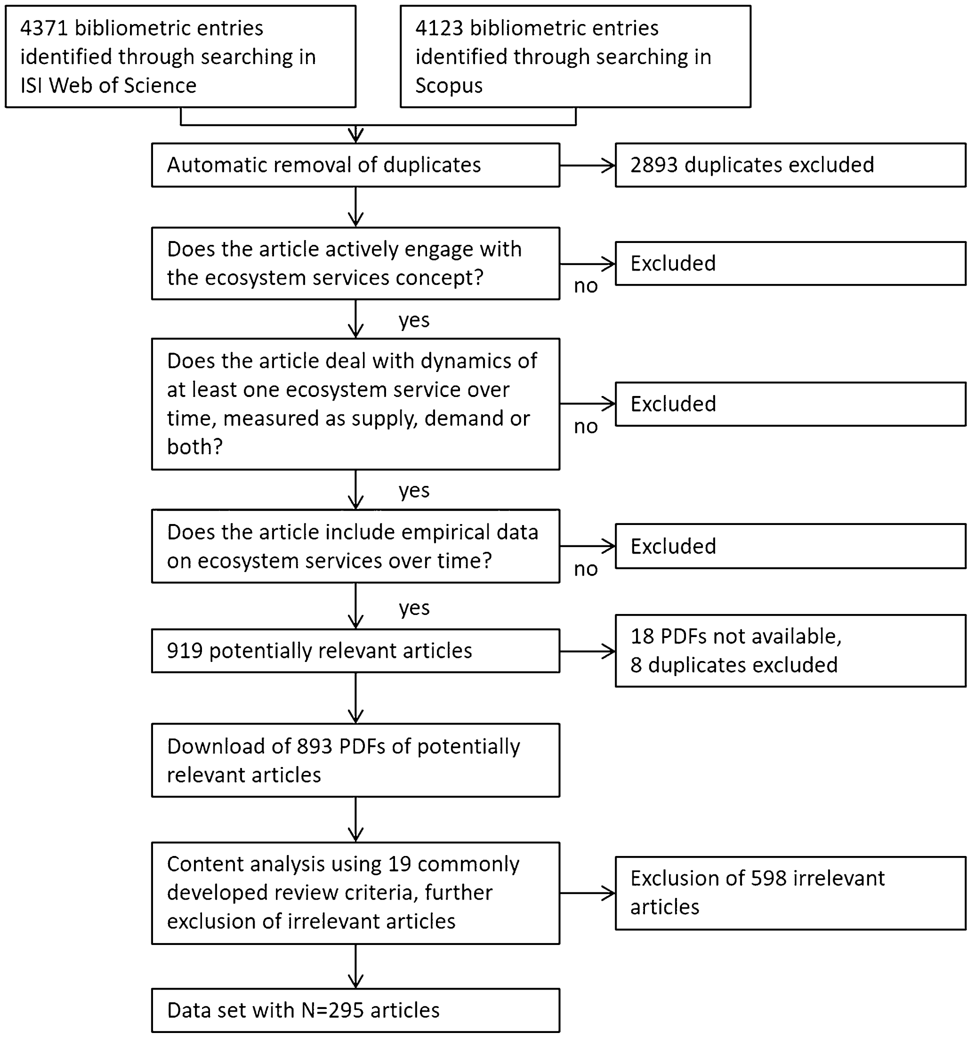

Fig. 1 Review procedure

19 commonly developed review categories, divided into 68 sub-categories (see below and Appendix S3). All reviewers agreed on these categories in consensus. The research categories were developed in an iterative process involving two test-reviews after which review categories were fixed to provide consistent reporting across all reviewed papers. During the final in-depth review, many studies were found not to meet the inclusion criteria, and hence our final data set consisted of 295 studies (see Fig. S1).

Description of data, coding and analyses

In this review, our aim was to analyse how temporal patterns in ecosystem services have been described in the literature. To this end, we coded the data into a format that allowed descriptive statistical analyses. We used numerical expressions (study location coordinates), words, or presence-absence dummy coding.

We used word coding to describe study characteristics with multiple choices, such as type of data (e.g. observational, experimental, remote sensing; see Appendix S3 for details), type of ecosystem service or temporal scale of the study (see below), human dependency of ecosystem services and stakeholder involvement, and ecosystem services cascade level (see below for details). Presence-absence dummy codes were used to characterise binary classifications, e.g. whether a study measured changes in supply or demand over time, and whether these changes were characterised as linear or not (see Table 1).

Our review categorised the studies/cases based on variables including temporal patterns, type of service, type of human dependence on the services, whether the study focused on supply or demand, stakeholder engagement and methods employed in the study. The temporal patterns are summarised in Table 1 and further described below, together with some of the other key variables.

Table 1 Definitions and examples for the different types of temporal patterns

Type of temporal patterns	Definition	Example
Linear	Continuous, monotonic changes in ecosystem service supply or demand	Linear increase of global yields over the last couple of decades (Millennium Ecosystem Assessment 2005)
Periodic	Oscillations around a linear trend (a special case of non-monotonic linear dynamic)	Crop failure due to droughts occurring every 10 years in semi-arid regions of Eastern and Southern Africa (Rockström and Falkenmark 2000)
Non-linear	Events caused by a sudden perturbation in the supply or demand of ecosystem services, occurring without steady repetitions	Afforestation causing a sudden increase in carbon uptake by the soil (Smith 2004)

First, regarding *temporal patterns* in change over time, we distinguished between linear and non-linear dynamics. We treated periodic change over time as a special case of linear dynamics and events as non-linear dynamics. We classified temporal patterns in ecosystem services as they were reported in the literature in relation to three different temporal patterns described by Rau et al. (2018a), broadly falling under three categories: monotonic linear changes, periodic change, and non-linear change (summarised in Table 1).

As previously noted, inevitably, change over time may appear as linear, periodic or as an abrupt event depending on the temporal grain of the study. A periodic dynamic may appear monotonically linear if measurements are aggregated across a longer time frame. In our categorization, we classified changes over time as they were described by the authors. In cases where such a classification was lacking, we interpreted the data points that were reported in the study. We characterised studies according to their *temporal resolution* by distinguishing between ecosystem service measurements taken during seven time scales (duration of less than or up to 1 year; 2 to 4 years; 5 to 10 years; 11 to 20 years; 21 to 50 years; 51 to 100 years; and more than 100 years). For full details of the coding scheme and coding categories, see Appendix S2.

Second, to categorise the ecosystem services types we used the four ecosystem services categories, presented in the MEA (Millennium Ecosystem Assessment 2003). The MEA distinguishes the following categories of ecosystem services (Millennium Ecosystem Assessment 2003, p. 5):

- Provisioning services: Products obtained from ecosystems
- Regulating services: Benefits obtained from regulation of ecosystem processes
- Cultural services: Nonmaterial benefits obtained from ecosystems
- Supporting services: Services necessary for the production of all other ecosystem services

Because many studies named ecosystem services differently, we unified the names of ecosystem services using a comprehensive list and typology of ecosystem services presented in Wilkinson et al. (2013).

To categorise the intensity of stakeholder involvement in studies involving ecosystem service demand, we followed the classification by Krütli et al. (2010) that differentiates between *information* (communication from academia to stakeholders from practice), *consultation* (information flow from stakeholders to academia, e.g. in the form of interviews and questionnaires), *collaboration* (a higher degree of involvement from both sides) and *empowerment* (where decision authority is given to stakeholders).

We also assessed how strongly people depended on the studied ecosystem services, and if so, in which way (through their livelihood, income, or life quality; see Appendix S3 for details and a full list of review criteria). Livelihood-related dependencies include ecosystem services that provide basic necessities such as food, fuel or shelter (Jha et al. 2011), whereas income-related dependencies include ecosystem services that contribute to income but not explicitly to people's subsistence, such as pollination of cash crops (e.g. Winfree et al. 2011). Life quality in turn includes ecosystem services that affect non-monetary values that are not seen as basic necessities, such as health, or recreation benefits (Nijkamp et al. 2008).

Third, we used the cascade model (Haines-Young and Potschin 2010) to distinguish between quantification of ecosystem services demand and supply (Fig. 2). The cascade identifies five facets of ecosystem services appropriation and management: biophysical structure/processes, ecosystem functions, ecosystem service appropriation, value ascription and management. We related the structure/processes and function facets to the supply side aspects of ecosystem service provision. Ecosystem service appropriation and value ascription were considered to relate to the demand side, and management to address both ecosystem service supply and demand. Here we note that the notion of the ecosystem service cascade (Haines-Young and Poschin 2010, Fig. 2), tends to frame management of ecosystem services as primarily about managing physical supply, with the assumption that this shapes ecosystem service appropriation and value ascription. In practice, there may be

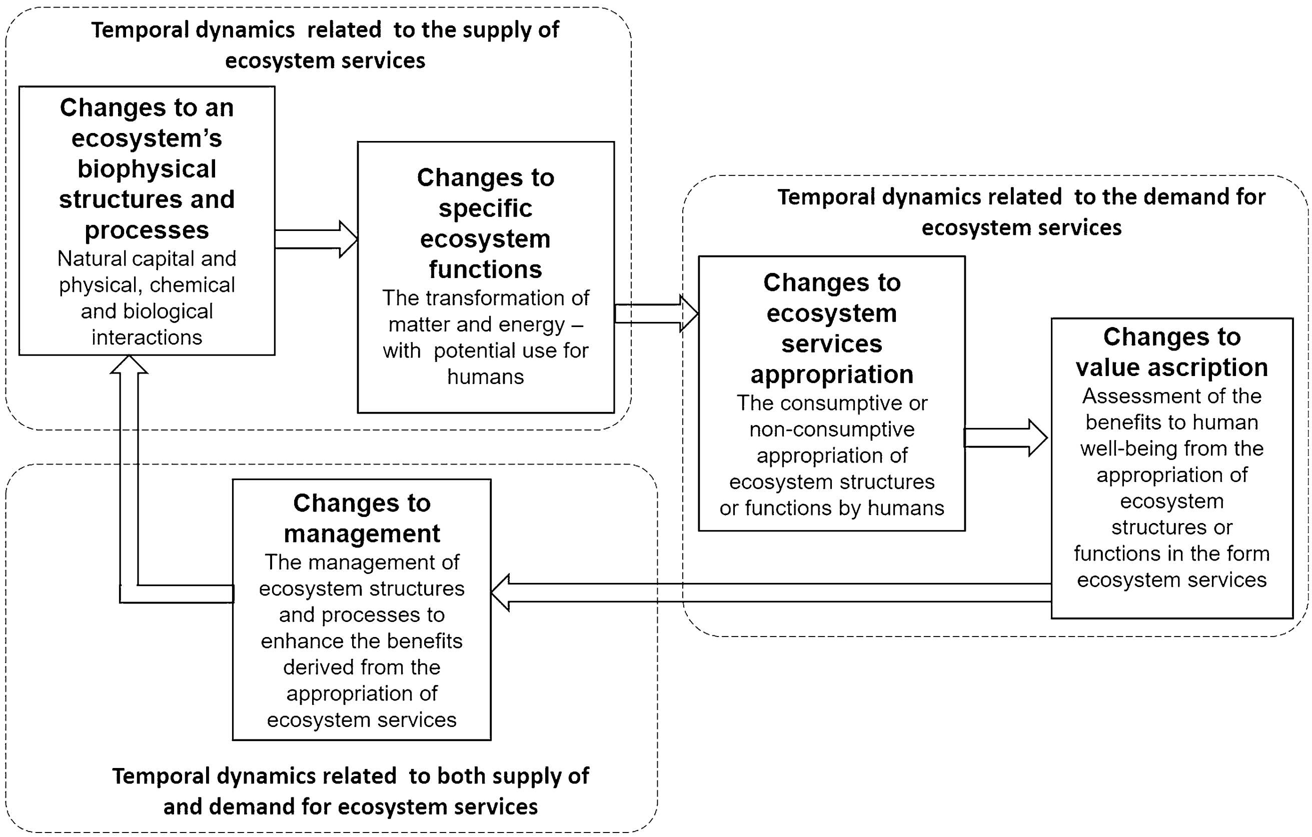

Fig. 2 Supply and demand in the ecosystem services cascade Adapted from Haines-Young and Potschin (2010)

attempts to directly manage the demand for ecosystem services. Considering temporal dynamics in both supply and demand of ecosystem services may help highlight the disconnect between supply and demand-side management.

To analyse how temporal dynamics of ecosystem services are measured, we noted which methods were used in each study. Therefore, we categorised the data types into experimental data, field samples/observations, remote sensing, secondary data and simulated data. *Experimental data* include field experiments and experiments under controlled conditions, whereas *field samples and observations* include data that were collected without manipulations by the researcher (for discussion of these distinctions see Caniglia et al. 2017). *Remote sensing* consists of aerial photography and satellite data. *Secondary data* are data that were not collected by the researchers themselves, e.g. yield data from national governments or international organisations. *Simulated data* include all results of simulations and models.

Individual studies frequently studied more than one ecosystem service (i.e. either multiple different services or the same service in different locations). Therefore, we distinguish between 'studies' (i.e. an article) and the individual 'cases' of ecosystem services dynamics researched in those studies.

To help visualise and characterise the different literature strands of research on temporal patterns in ecosystem services on a quantitative basis we conducted a cluster analysis dividing the body of literature into clusters based on 25 sub-categories that were coded using a binary classification (e.g. if an event was mentioned in the study or not) dividing the studies rather than individual cases into clusters. To this end, we used the package labdsv (Roberts 2016) in R version 3.4.2 (R Core Team 2017). First, we created a dissimilarity matrix using the method "binary", and then we performed hierarchical clustering. Therefore, we used the function "hclust" with the method "ward.D2" which is a minimum variance method that aims at finding compact, spherical clusters while maximising within-group similarity and minimising among-group similarity (Legendre and Legendre 2012). The strength of the clustering had an agglomerative coefficient of 0.89 (with 1 being the highest). This is a measure for the strength of the clustering based on the means of the normalised lengths of the dendrogram's branches (Kaufman and Rousseeuw 1990). The cluster analysis was not intended to provide a definitive typology for ecosystem services temporal patterns research, but rather to provide a descriptive overview of the different approaches to studying temporal patterns in the ecosystem services literature that have emerged since the year 2000.

RESULTS

General trends in the research on temporal patterns of ecosystem services

The 295 studies contained a total of 1231 individual cases assessing temporal patterns in ecosystem services. Research on temporal patterns using the concept of ecosystem services started in 2000 and has increased in parallel with the increasing number of studies on ecosystem services in general (see Figure S2). In the year 2000, one in 32 publications (3.1%) dealt with temporal aspects of ecosystem services, whereas in 2015, 57 of 1830 publications (3.1%) published in this year focused on this topic. In total, only 2.0% of all research (295 of 14 931 studies—published before October 2016—see Figure S2) actively engaging with the ecosystem services concept considered changes in ecosystem services over time.

Most of the studies on temporal aspects of ecosystem services were conducted in Europe (83 studies), North America (73 studies) and Asia (72 studies), the latter of which was strongly dominated by China (60 studies) (Fig. 3).

Research on temporal aspects of ecosystem services most often involved regulating ecosystem services (426 cases), followed by provisioning services (331 cases) and supporting services (317 cases). Cultural ecosystem services were least often studied (180 cases).

In total 291 studies out of 295 specified the time spans that were analysed (Fig. 4). Studies based on field samples and observations (409 cases in total) predominantly considered short time scales, whereas the share of cases based on secondary data (601 cases) and simulated data (355 cases) increased with increasing time spans that were studied (Fig. 4). Remote sensing methods (539 cases) were most frequently used in studies considering intermediate time spans. Experimental data and other methods (e.g. interviews) were rarely used (29 and 6 cases, respectively). The different temporal patterns were relatively evenly distributed across the time spans (see Fig. S1).

Literature strands

As it is likely that the types of temporal patterns in ecosystem services are dependent on the approaches used to analyse those patterns, we used our review categories to quantify how dynamics of ecosystem services have been

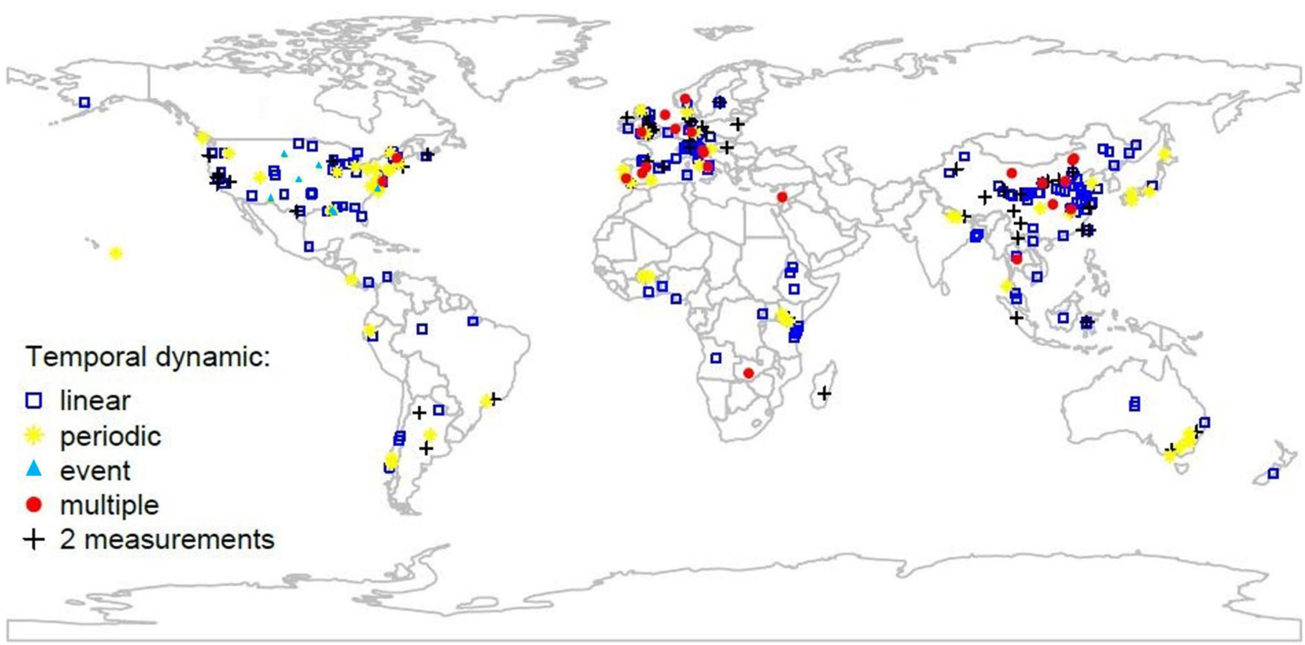

Fig. 3 Global distribution of locations where temporal aspects of ecosystem services were studied. Some studies report a combination of modes in which ecosystem services have changed over time ("multiple"), whereas some studies measured changes over time using two points in time ("2 measurements"). In cases where there were different locations reported for one study, all locations ($N = 312$) are displayed in the map. Global ($N = 8$), continental ($N = 10$) and national ($N = 5$) studies are not displayed. Of the continental studies, eight took place in Europe, and one each in Asia and North America. Of the national studies, one per country was conducted in Angola, Chile, Italy, Switzerland and China, respectively

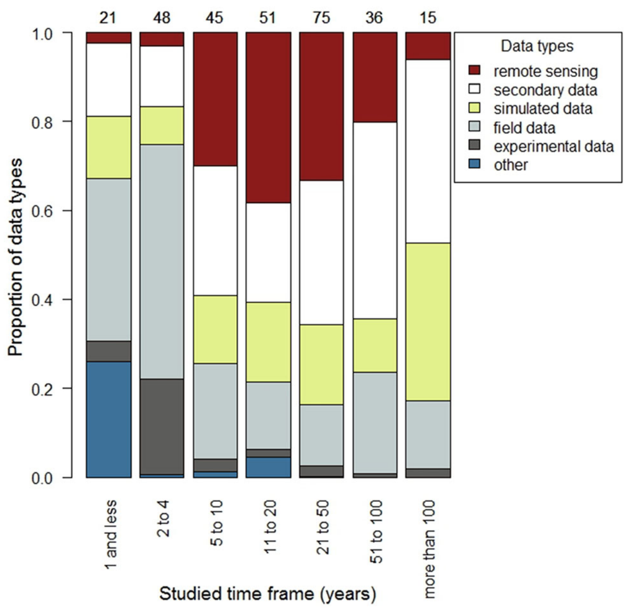

Fig. 4 Research methods (data types) used in research on temporal aspects in ecosystem services in relation to time frames of the studies, i.e. the span of years that was analysed in a study. Proportions are given for frequencies in which different data types were used (note that one study might be based on several data types). The category "other" refers mostly to questionnaires and interviews. Numbers of studies per time frame are given on top of the bars

studied using a cluster analysis. Our cluster analysis identified nine distinct types of studies on temporal patterns in ecosystem services, based on research focus and choice of methods (Table 2; Appendix S4; Figure S3).

Three of the clusters (clusters 2, 5 and 8) were significantly explained by the type of temporal pattern, and studies in these clusters considered only a few individual ecosystem services. First, studies in cluster 2 were based on field samples and observations, and described *periodic dynamics of ecosystem services*. Most studies in this group considered regulating services (every fifth study considered pest regulation). Second, cluster 5 was comprised of studies that all described *linear dynamics of ecosystem services*. The most studied ecosystem services were provisioning, supporting and regulating services. Third, studies in cluster 8 had in common that they were based on *two points in time* and covered a *time span of one year or less*, focused on ecosystem structure and function and the studies did not specify if and how people depend on ecosystem services. The dominating services in this group were supporting and provisioning services.

Three of the research clusters (clusters 1, 4 and 7) had specific methodological approaches focused on ecosystem service supply (quantification of spatial pattern of ecological structures underpinning service supply; experimental research; and simulations) that did not appear to be correlated to a specific type of temporal pattern.

The final three clusters (clusters 3, 6 and 9) were broadly defined by their social/demand focus. Studies in cluster 3 were based on secondary data and explicitly mentioned *people's dependency on ecosystem services for their livelihood and life quality*. In contrast to the groups characterised by a temporal dimension, studies in this group typically considered multiple ecosystem services (seven on average). Studies in cluster 6 were characterised by a focus on *human demand for ecosystem services*. These studies considered ecosystem service benefits and related to people's dependency on ecosystem services for their income. A typical study in this group included three ecosystem services. Finally, studies in cluster 9 focused on regulating and provisioning services and the *valuation stage of the ecosystem services cascade*, using remote sensing methods. The typical study included eight to nine individual ecosystem services.

Temporal patterns of ecosystem services

General patterns

Research describing linear dynamics over time (733 cases, 81%) strongly dominated the literature on temporal patterns in ecosystem services, followed by research describing periodic dynamics (142 cases, 16%). Research describing event (non-linear) dynamics in ecosystem services was only found in 35 cases (3%).

The most commonly assessed ecosystem services were similar across the different categories describing temporal patterns, and therefore only linear trends are described in the following (for a description on periodic and non-linear dynamics, see Appendix S5). In this analysis, we did not include the 321 cases of ecosystem services which were only assessed over two points in time, since these could not be classified according to the above typology of temporal patterns.

Trends in linear changes in ecosystem services over time

Almost half of the cases described declines in ecosystem services (326 cases), whereas the rest either described positive trends (227 cases) or services showing no distinct trend over time (neutral, 160 cases). In some cases, more than one trend was described for one ecosystem service, depending on the location (mixed, 20 cases). Ecosystem services from all categories were mainly decreasing over time (Fig. 5 and Appendix S6).

Linear trends in *provisioning services* were documented in 205 cases. The most commonly described trend was negative (91 cases), whereas fewer provisioning services were described as positive (68 cases) or neutral (41 cases). Most cases described changes in food production (97

Table 2 Characteristics of groups identified by the cluster analysis. For the number of ecosystem services, the total number, the mean per paper and standard deviation are given. Dominating ecosystem services are given in percent of the whole cluster

Cluster	Number of ES included	Dominating ES studied
Cluster group 1: studies characterised by specific relation to temporal patterns, focus on few ecosystem services (groups 2 and 8)		
2 Field samples/observations, periodic dynamics	19, 2.68 ± 2.58	Pest regulation (20%), water regulation (14%), climate regulation—local (12%), erosion regulation/soil retention (10%), water purification/waste treatment (8%)
5 Linear dynamics	29, 3.41 ± 2.46	Biodiversity (10%), food—agriculture (9%), fresh water (8%), water regulation (5%), water purification/waste treatment (5%)
8 Human dependency not specified, cascade levels 'function' and 'structure', two measurements over time, time frame 1 year or less	24, 1.92 ± 2.15	Nutrient cycling—nitrogen (22%), nutrient cycling—carbon (13%), biodiversity (11%), primary production (4%), food—wild (4%)
Cluster group 2: no specific relation to temporal patterns, focus on ecosystem service supply		
1 Cascade level' biophysical structures and functions', supply side	22, 2.64 ± 2.08	Biodiversity (17%), erosion regulation/soil retention (7%), food—agriculture (7%), food—commercial fishing (7%), recreation and eco-tourism (7%)
4 Experimental data, supporting services	31, 3.39 ± 3.38	Biodiversity (13%), nutrient cycling—carbon (10%), nutrient cycling—nitrogen (10%), water purification/waste treatment (7%), nutrient cycling—phosphorus (6%)
7 Simulated data	34, 5.91 ± 4.81	Water regulation (9%), erosion regulation/soil retention (8%), biodiversity (7%) food—agriculture (6%), water—fresh water (5%)
Cluster group 3: no specific relation to temporal patterns, focus on valuation/demand of (multiple) ecosystem services		
3 ES for livelihood and life quality, secondary data	35, 7.00 ± 4.58	Food—agriculture (7%), biodiversity (7%), recreation and eco-tourism (6%), water regulation (5%), nutrient cycling—carbon (5%)
6 Human demand, cascade level 'benefit', income	26, 3.38 ± 2.52	Recreation and eco-tourism (11%), fuel (9%), food—commercial fishing (8%), biodiversity (8%), food—agriculture (7%)
9 Remote sensing, provisioning services, cascade level 'valuation', regulating services	37, 8.54 ± 8.73	Recreation and eco-tourism (9%), biodiversity (8%), climate regulation—local (8%), water purification/waste treatment (8%), food—agriculture (8%)

cases), with equally many positive and negative trends over time. The majority of cases on food production concerned agricultural production, followed by commercial fishing.

Linear trends in *regulating services* (239 cases in total) were most often described as being in decline (117 cases). Fewer regulating services were described as increasing (71 cases) or remaining constant (43 cases). Climate regulation (57 cases), and erosion regulation (44 cases) were the most frequently studied regulating ecosystem services. Most cases dealing with climate regulation measured local-scale regulation (39 cases) rather than global-scale regulation (18 cases), and most cases described negative trends.

Of the *supporting services* (192 cases in total) 41% were described as decreasing (79 cases), rather than increasing (59 cases) or remaining constant over time (49 cases). However, the higher prevalence of negative trends was conditional on biodiversity being considered an ecosystem service. Nutrient cycling dominated amongst studied supporting services (65 cases), with equally many positive (26 cases) and negative (20 cases) trends over time.

Cultural ecosystem services (97 cases in total) were relatively evenly described as decreasing (39 cases), increasing (29 cases) or remaining constant over time (27 cases). The vast majority of cases considered recreation and eco-tourism (52 cases). Other cultural services were rarely considered.

Supply and demand in research on temporal aspects of ecosystem services

In total, 235 studies focused on the supply of ecosystem services over time, whereas 46 studies considered changes in both supply and demand over time. Only 14 studies exclusively considered demand of ecosystem services over time.

The largest share of research on supply of ecosystem services over time focused on regulating services (355 cases), followed by supporting services (261 cases) (Fig. 6, upper panel). In cases focusing on the supply of ecosystem services over time, human dependency on ecosystem

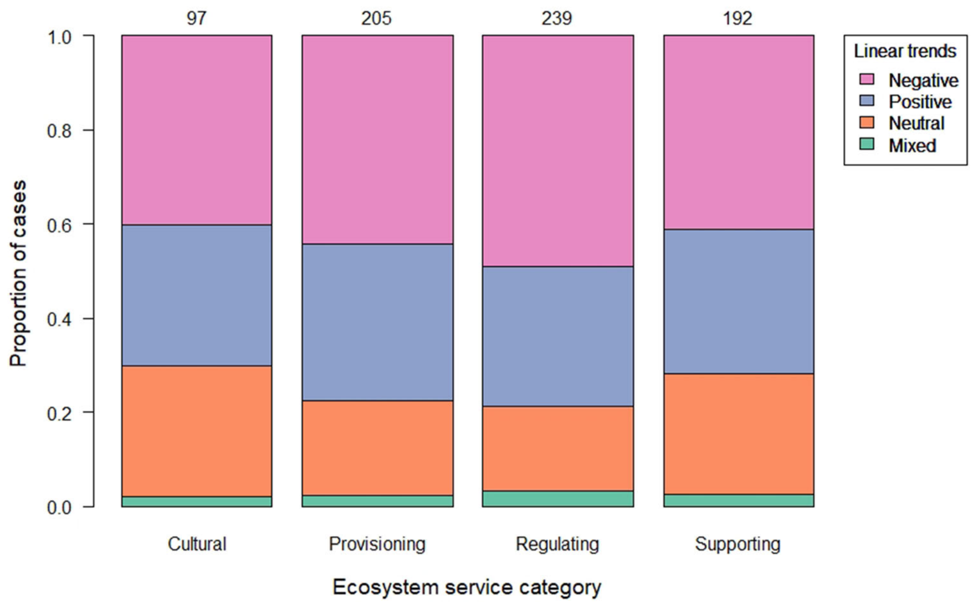

Fig. 5 Linear trends in ecosystem services divided into MEA categories. "Mixed" means that more than one type of linear trend is given per case. Numbers of cases per category are given on top of the bars

services was rarely mentioned (Fig. 6, lower panel), and the majority of cases considering ecosystem service supply alluded to the function-level in the ecosystem services cascade model (Figure S4). In contrast, cases focusing on changes in ecosystem service demand over time mostly focused on provisioning (15 cases) and cultural services (13 cases). Cases involving both supply and demand mostly considered provisioning (87 cases) and regulating services (62 cases). When the changes in ecosystem service demand over time were studied, human dependency of ecosystem services was explicitly mentioned in the majority of cases (162 cases), and the majority of ecosystem services concerned the benefit level of the ecosystem services cascade model (Figure S4). The demanded ecosystem services were most often reported to affect people's livelihood (25 cases), followed by life quality (8 cases).

Stakeholder involvement generally played a minor role in research on temporal patterns in ecosystem services, as non-academic actors were only involved in 21% (62) of studies. Research on changes in cultural services over time had the highest share of stakeholder involvement (43%, 67 cases), whereas research on changes in regulating services over time had the lowest share (19%, 426 cases, Figure S5). In relative terms, stakeholders were more frequently involved in research focusing on changes in ecosystem service demand (71%) than research on changes in ecosystem service supply (18%). In general, consultation was the most often used form of stakeholder involvement (172 cases), whereas collaboration (5 cases) and empowerment (14 cases) were only rarely integrated in research on changes in ecosystem services over time.

DISCUSSION

While the research on ecosystem services that address temporal patterns has increased over time, our review shows that it still makes up a minor share (2.0%) of the entire literature on ecosystem services. The reasons for this might be higher costs of maintaining long-term research projects and the higher workload for the researchers involved. The geographic distribution of studies showed very little coverage apart from Europe, North America and China. Studies were lacking especially in parts of Central Asia and North Africa, and to some extent Latin America, although this is where much of the current and future pressure on ecosystem services is emerging (IPBES 2019). Moreover, these understudied regions are often characterised as containing non-equilibrium systems with higher annual and decadal environmental variance than more stable temperate regions (von Wehrden et al. 2012). Similarly, there were a lack of studies in the arctic and tundra biomes despite the rapid environmental changes occurring in these regions. This suggests that ecosystem service research needs to ensure a broad spatial coverage to avoid systematic bias related to clustered research locations.

Changes in ecosystem services over time were mainly characterised as monotonic and linear (81%), rather than nonlinear or through system shocks. However, it remains unclear if this is because there are less nonlinear dynamics

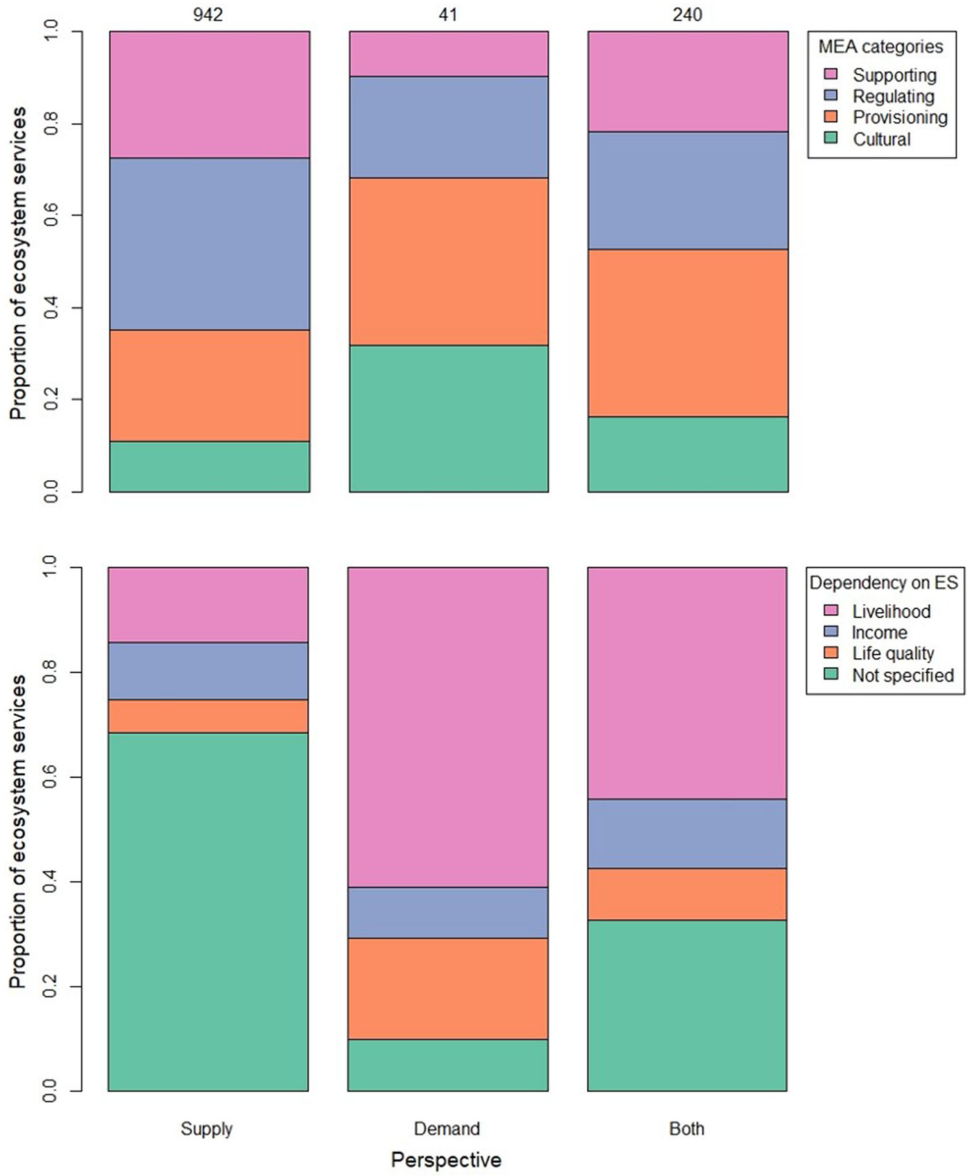

Fig. 6 The distribution of ecosystem services included in studies on temporal patterns in ecosystem services in relation to supply and demand, separated according to MEA categories (upper panel), and human dependency on ecosystem services in relation to supply and demand (lower panel). Numbers of cases per category are given on top of the bars

and system shocks than linear change in ecosystem services, or if such system shocks are masked by the temporal grain and methods employed in ecosystem service research. Historically ecosystem service research has focused on aggregate well-being and while there are calls to disaggregate the value of ecosystem services between stakeholders (Daw et al. 2011) it is equally important to understand temporal distributions of such services. It is often short-term shocks to ecosystem supply rather than long-term trends that are most problematic for maintaining human well-being (Chapin et al. 2010), because of the increased possibility of crossing ecological and socio-economic thresholds that lead to dramatic system shifts (Horan et al. 2011).

Further, a lack of focus of changing ecosystem service demand (rather than supply) hampers our understanding of the temporal patterns of ecosystem services provision and use. The focus on the current literature reinforces the idea that ecosystem services research is fundamentally a 'supply side issue'. It is likely that a sustainable ecosystem service management regime cannot be achieved solely by focusing on matching supply to demand (Burkhard et al. 2012), but must actively focus on managing demand to meet bio-physically sustainable supply.

Temporal trends in ecosystem services: Focus on interdependencies

We found that provisioning services were more often described as increasing than services belonging to the other categories. A possible explanation is that provisioning services such as food or timber production increase at the expense of other services such as supporting and regulating services that are needed to secure ecosystem services provision in the long term (Rodríguez et al. 2006). Provisioning ecosystem services can be viewed as consumer goods/services (i.e. the end product that the individual consumer demands and values). Supporting and regulating services are 'the common capital' (i.e. the 'machinery' needed to produce the end product), but are largely hidden costs for directly consumed services. Thus, a greater focus on temporal dynamics of interdependent services is important for ensuring long-term sustainable provision. This suggests a shift from studying temporal dynamics of co-occurring bundles of ecosystem service provision (e.g. Renard et al. 2015) towards a greater focus on temporal interdependencies between the regulating and supporting services and directly consumed provisioning and cultural services.

Moreover, one can expect heterogeneous trends in particular ecosystem services, depending on study system, spatial scale and temporal resolution of individual studies. For example, pollination was found to have a positive trend over three to 4 years, in response to sown flower plantings on farms with insect-pollinated crops (Blaauw and Isaacs 2014), but no clear trend (i.e. a neutral trend) in a study focusing on modelling effects of an invasive species on pollination (Cook et al. 2007), and a negative trend in response to increasing urban sprawl spanning some decades (Dupras and Alam 2015). Yet all of these dynamics may co-occur in a given system suggesting a need to carefully define system boundaries and dynamics in temporal ecosystem services research.

A higher share of declining trends overall could to some extent be explained by a publishing bias encouraged by a potentially higher impact of reports on declining ecosystem services, or a desire from researchers to highlight pressing problems regarding ecosystem exploitation. This might also reflect that there is more demand for research where there is greater perceived pressure on ecosystem services. Prominent declines have been documented for some ecosystem services, including soil fertility and erosion prevention, freshwater availability, wastewater treatment and food provision from marine ecosystems (Schroter 2005; Worm et al. 2006). Because our review is based on studies explicitly using the ecosystem services concept, studies on single ecosystem functions or services that did not use this concept were not included. Whereas our review could to some extent be biased we note that the distribution between negative, positive and neutral trends in our study is remarkably similar to recent comprehensive assessments of trends in ecosystem services (see, e.g. IPBES 2018).

Supply and demand of ecosystem services over time

Fundamentally, ecosystem service provision is only of concern when there is a mismatch between supply and demand. Food shortages, insufficient carbon sequestration to maintain climate stability, the loss of desired cultural services etc., are what drive the desire to better understand ecosystem services and their relation to human well-being. However, the majority of all studies focused on the supply side of ecosystem services. We found that studies focusing on the supply of ecosystem services rarely considered how people depend on ecosystem services (for their income, livelihood or well-being). Research considering only the supply side does not cover the full potential of the ecosystem services concept, particularly in the context of decision-making (Egoh et al. 2007).

Studies involving the demand side additionally to the supply side were underrepresented in the research on changes in ecosystem services over time (16% of all studies). We identified some studies that only focused on demand for ecosystem services. These focused on provisioning and cultural services, and often considered the value ascription stage in the cascade model. As regulating and supporting services are often challenging to value in monetary terms, they become invisible in planning and management processes for ecosystem services (Chan et al. 2012). Linking the demand-side approaches that were identified in the clusters 3 and 6 of the cluster analysis to the supply side approaches is crucial for avoiding potential temporal mismatches in ecosystem services supply and demand, hindering the sustainable provisioning of services.

Here we note that the focus of this review was not to explicitly study how the supply and demand-side dynamics are related temporally to the drivers of change in ecosystem services provision or appropriation (e.g. changing economics, demography, climate or technologies etc.). Unpacking these driver-change dynamics would be an important further step in understanding temporal patterns in ecosystem services.

Sources of bias in temporal ecosystem services dynamics research

We found strong patterns in methodological approaches and the time spans studied. Particularly, studies over time spans of several decades relied on remotely sensed data, secondary data or simulations, while experimental data and field samples/observations strongly dominated short-term studies. This creates a knowledge gap between these two approaches. Long-term experiments and monitoring of ecosystem services are necessary as these methods yield results that are less reliant on theoretical assumptions compared with simulations. In addition to such methodological considerations, we found that the number of individual ecosystem services considered in a study is generally low (in particular concerning studies on ecosystem service supply), which limits our understanding of trade-offs and synergies between ecosystem services over time. The fact that most studies focussed on provisioning services suggests that short-term provisioning services are exploited at the expense of regulating services that are required to sustain ecosystem service provision in the long term.

Furthermore, we found that provisioning and regulating services are overrepresented compared to supporting and cultural services in the research on temporal aspects of ecosystem services. This unbalance might be related to the choice of method and framing of the research. Research on temporal dynamics was dominated largely by mapping, field measurements and modelling, which are the same methods that were listed as dominating in ecosystem services research in general in an earlier review (Seppelt et al. 2011). Choice of method may be strongly driven by data availability, which could explain the dominance of provisioning services over other types of services. Secondary data for provisioning services such as food production are in many cases collected routinely, as they are often used in national and international reports, and as a foundation for decision-making (Martínez-Harms and Balvanera 2012).

Moreover, supporting ecosystem services might be underrepresented because many studies, e.g. on biogeochemical cycles or biodiversity, might not be framed around the concept of ecosystem services. In particular, there is a rich and abundant literature on the relationship between biodiversity and ecosystem functions (Loreau et al. 2002) that is not captured by an explicit focus on ecosystem services. Strong disciplinary traditions may also mean that other potentially relevant strands of the literature might not have been captured by our review. For instance, the literature on ecosystem consequences of climate change is in many cases not placed in the ecosystem services framework (cf. Bhattacharyya et al. 2016; cf. Thornton et al. 2014).

Because of differences in conceptual frameworks, studies considering ecosystem integrity and stability at longer time scales, such as those involving planetary boundaries (see, e.g. Steffen et al. 2015) may also be underrepresented in this review. For similar reasons the concepts of regime shifts, transformations and transitions, which are not clearly distinguished from each other, are often not explicitly connected to ecosystem services research (Rau et al. 2018b). This review suggests that in terms of temporal dynamics there is considerable knowledge that has not yet been integrated into the ecosystem services literature. To do so may provide valuable insights to the field. In particular, a focus on potential future nonlinear changes to ecosystem service supply and demand is a crucial knowledge gap in ecosystem service research. For demand-side dynamics, this will require greater stakeholder engagement regarding how to evaluate and manage ecosystem service demand.

Recommendations for future research

Our quantitative review shows that temporal aspects are underrepresented in ecosystem services research, despite its significance for the concept and for the practical need to balance between supply and demand of ecosystem services. We found that the vast majority of studies focusing on the temporal aspects studied the supply of ecosystem services without considering changes in human demand. Therefore, it will be challenging to determine to which extent supply meets demand, or if there is increasing pressure to supply more services from already heavily appropriated ecosystems (e.g. Scholes and Biggs 2005). Moreover, the number of studies that involved stakeholders was relatively low which resonates with the systematic review conducted by Luederitz et al. (2015) stating that only 20% of studies on urban ecosystem services involved stakeholders. Almost half of the studies involving stakeholders were restricted to cultural ecosystem services (Luederitz et al. 2015), which corresponds with our findings. This raises issues regarding potential changes to the value humans ascribe to the services that are being demanded. Based on our literature review, we offer three recommendations to integrate temporal aspects into future research on ecosystem services.

Recommendation one: conduct more long-term research and increase the temporal resolution of observations of ecosystem services supply and demand. We found that long-term studies spanning over 5 years were rarely based on experiments and field observations. Conducting long-term research projects with regular measurements is the most obvious way to integrate temporal aspects into ecosystem services research, such as those conducted in the Biodiversity Exploratories in Germany (Fischer et al. 2010). It may also be critical in order to enable the detection and understanding of the mechanistic reasons to sudden, non-linear changes. Ideally, long-term projects would also consider both the supply and the demand of ecosystem services. As an example, Guerra et al. (2016) analysed a data set covering 60 years of land use change in a silvo-pastoral system in southern Portugal, focusing on soil erosion prevention. They found that soil erosion prevention declined during the last four decades following a decrease in tree cover which was most likely caused by agricultural policies aimed at increasing the productive capacity of farms (e.g. increase in number of grazing cows) (Guerra et al. 2016). This example shows that long-term data sets on ecosystem services play an important role in detecting changes in ecosystem services provision, finding the reasons for these changes and learning for the future to improve ecosystem services management towards sustainability.

Recommendation two: more explicit temporal analyses of ecosystem service interdependencies, trade-offs and synergies. Our analysis showed that the number of ecosystem services included in a study differs strongly between the literature clusters. In particular, short-term studies that focus on the supply of ecosystem services (structure and function levels of the cascade), tend to focus on very few ecosystem services (less than three per study). As a consequence, we may lack insights on relationships between the supply (and demand) of multiple ecosystem services over time, and in particular whether multiple services change over time because of a common driver, or because of a causal link between ecosystem services (Birkhofer et al. 2015; Cord et al. 2017; Lautenbach et al. 2019).

To foster sustainable management of ecosystem services, it is necessary to understand trade-offs and synergies between different ecosystem services (Howe et al. 2014). Trade-offs occur when one ecosystem service increases at the expense of other ecosystem services, whereas synergies arise when two ecosystem services increase or decrease in tandem (Bennett et al. 2009; Raudsepp-Hearne et al. 2010). Maximising single provisioning services without considering negative externalities may inadvertently lead to a simultaneous decline of the supply of a range of regulating, cultural and supporting services (e.g. Rodríguez et al. 2006; Raudsepp-Hearne et al. 2010; Maes et al. 2012). As an example, Haase et al. (2012) found unintentional trade-offs between decreasing recreational potential and increasing supply of local climate regulation, carbon mitigation, biodiversity potential and food production between 1990 and 2006 in urban regions of Halle and Leipzig, Germany. As recreation in (semi-)natural areas plays an important role for urban residents, trade-offs diminishing this ecosystem service should be avoided (Jim and Chen 2006).

To enable informed decisions on ecosystem services management and prevent unintentional trade-offs, we urge researchers to consider the interaction between ecosystem services over time at an ecosystem-scale, whilst also considering that different ecosystem services might respond differently depending on the strength of anthropogenic pressures (IPBES 2018), and exhibit different temporal patterns within the same geographical location (Rau et al. 2018a).

Recommendation three: include the demand side and human dependency in a meaningful way by involving stakeholders. To better include the demand side into ecosystem services research, stakeholder involvement is crucial. A good example we found in the literature for a combined study of supply of and demand for ecosystem services is from Huxham et al. (2015) who combined ecosystem services supply data from fish catches, a mangrove carbon sequestration project and published accounts with demand data from household surveys, focus groups and interviews, to develop scenarios for Kenya‘s mangrove forests. With the help of stakeholders from the region they modelled values and costs associated with the forest for 20 years into the future for a business as usual and a sustainable forest management scenario (Huxham et al. 2015). Matching supply with demand-side data helps to identify mismatches between supply and demand, which in turn enables a more sustainable approach of managing ecosystem services over time.

CONCLUSIONS

Our review showed that temporal aspects of ecosystem services constitute a consistently minor share (2.0%) of the entire literature on ecosystem services, i.e. most studies on ecosystem services present a static ‘snap-shot’ view based on measurements that were only conducted once. Research on temporal patterns in ecosystem services has mainly described linear changes, rather than abrupt non-linear, or periodic changes, over time. However, many studies were based on only two points in time, which precludes assessing how selected ecosystem services have changed over time. Future research on fine grain, non-linear changes in ecosystem services over time, including system shocks and events, is needed if we are to ensure sustainable ecosystem service provision in rapidly changing socio-ecological systems.

The dominant approach of assessing the supply of ecosystem services without explicitly considering human demand or dependency represents a considerable challenge for the sustainable management of ecosystem services. Supply and demand are fundamentally interdependent, and we need to understand not just how they relate to each other, but also how both sides of the ecosystem services concept can be proactively managed in the face of rapid ecological and societal change.

Therefore, to take temporal aspects of ecosystem services better into account, future research on ecosystem services should include a wide variety of services and more measurements over time to explicitly (1) study fine grain temporal patterns of ecosystem services, (2) study trade-offs and synergies between interdependent ecosystem services, and (3) meaningfully integrate ecosystem supply and demand in modelling and understanding ecosystem services dynamics. In applying these methods, we believe that ecosystem services research will increase its ability to support the sustainable management of ecosystems and their services in the future.

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