The representation of temporal aspects in ecosystem services research:

Current state and recommendations for future research

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The representation of temporal aspects in ecosystem services research: Current state and recommendations for future research

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Summary

Since the early 2000s, ecosystem services strongly gained significance as a research topic. While the number of papers strongly increased, the concept was further developed which changed the way it was applied. From highlighting the value of ecosystems by viewing them not only from an ecological, but also from an economic perspective in the beginning, it is nowadays, among others, used to map and calculate the monetary value of ecosystem services. Lately, the International Panel on Biodiversity and Ecosystem Services (IPBES) further developed the concept into Nature's contributions to people (NCP) which puts a stronger emphasis on stakeholders and indigenous knowledge.

However, so far none of the conceptual developments managed to integrate the temporal dimension of ecosystem services into this concept, although this should be the basis for a sustainable long-term management of ecosystems and their services.

Therefore, I present three articles in this thesis that deal with temporal aspects of ecosystem services. In two of them I also present a proposal for a framework for the classification of ecosystem services based on their temporal dynamics.

In this dissertation I differentiate between two types of temporal aspects, both of which have in common that change takes place over a certain period of time. The concepts of transformation, transition and regime shift are used to describe changes in social or ecological systems as a whole, for example the transformation towards a more sustainable society. The temporal dynamics that I present, on the other hand, relate to the temporal changes in ecosystem services themselves.

The first article focuses on how the literature on ecosystem services incorporates social and ecological change, illustrated by the concepts of transformation, transition, and regime shift. The second and third articles deal with the temporal dynamics of ecosystem services. While the second article presents a preliminary framework for categorizing the temporal dynamics of ecosystem services, the third article uses this framework to test how the temporal dynamics of ecosystem services are represented in the literature.

Based on the insights from the three articles, I conclude that most of the studies on ecosystem services only focus on one point in time. One reason for this is that most studies are conducted

over a maximum of a four-year time span which does not allow to monitor dynamics over longer time spans. In most articles that do account for temporal aspects, the focus is strongly on the side of ecological supply of ecosystem services rather than on the demand-side which leads to the exclusion of stakeholder perceptions and therefore, makes it impossible to connect ecosystem service demand and supply over time. Moreover, the concept of change that is used most often in the literature is that of regime shifts which comes from a purely ecological background and focuses mostly on changes that happened in the past. This neglects the possibility of change towards a positive outcome in the future. In general, there is a strong disciplinary divide in the concepts and terminology used. This leads to a lack of exchange between different scientific disciplines and non-academic stakeholders. Approaches that are needed to solve problems of ecosystem service management are therefore impeded.

To enable future research to better account for temporal aspects and connect supply and demand sides of ecosystem services with each other, I give four recommendations for future research. These are (I) take temporal dynamics into account by conducting long-term research, (II) ensure conceptual clarity, (III) create a solution-oriented agenda and (IV) take the demand side into account by involving stakeholders' perceptions over time.

By following these recommendations, future research could help to support the sustainable management of ecosystem services as dynamics will be better known and targeted measures can be implemented.

Zusammenfassung

Seit Anfang der 2000er Jahre haben Ökosystemleistungen als Forschungsthema stark an Bedeutung gewonnen. Während die Anzahl der wissenschaftlichen Artikel stark zunahm, wurde das Konzept weiterentwickelt, was die Art und Weise seiner Anwendung veränderte. Diente es zunächst dazu, den Wert von Ökosystemen durch Betrachtung nicht nur aus ökologischer, sondern auch aus wirtschaftlicher Sicht, hervorzuheben, wird es heutzutage unter anderem verwendet, um den monetären Wert von Ökosystemleistungen auf Landkarten darzustellen und zu berechnen. In letzter Zeit hat der Weltbiodiversitätsrat (Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services, IPBES) das Konzept zu „Beiträge der Natur zum Menschen" (Nature's Contributions to People, NCP) weiterentwickelt, wobei unter anderem regionale Stakeholder und das Wissen indigener Völker stärker berücksichtigt werden sollen.

Trotz der konzeptionellen Weiterentwicklungen ist es bisher noch nicht gelungen, die zeitliche Dimension in das Konzept der Ökosystemdienstleistungen zu integrieren, obwohl dies die Grundlage für ein nachhaltiges und langfristiges Management der Ökosysteme und ihrer Dienstleistungen wäre.

Daher stelle ich in dieser Arbeit drei Artikel vor, die sich mit zeitlichen Aspekten von Ökosystemleistungen befassen. In zweien davon präsentiere ich zudem einen Vorschlag für ein Rahmenkonzept für die Klassifizierung von Ökosystemleistungen basierend auf ihrer zeitlichen Dynamik.

In dieser Dissertation unterscheide ich zwischen zwei Arten von zeitlichen Aspekten, die beide gemeinsam haben, dass Veränderungen über einen bestimmten Zeitraum stattfinden. Die Konzepte Transformation, Transition und Regime Shift werden angewendet, um Veränderungen sozialer oder ökologischer Systeme als Ganzes zu beschreiben, beispielsweise die Transformation hin zu einer nachhaltigeren Gesellschaft. Die zeitlichen Dynamiken, die ich vorstelle, beziehen sich hingegen auf die zeitlichen Veränderungen der Ökosystemleistungen an sich.

Der erste Artikel konzentriert sich darauf, wie die Literatur zu Ökosystemleistungen den sozialen und ökologischen Wandel einbezieht, der durch die Konzepte Transformation, Transition und Regime Shift veranschaulicht wird. Der zweite und dritte Artikel befassen sich mit der zeitlichen Dynamik von Ökosystemleistungen. Während der zweite Artikel ein vorläufiges Konzept

für die Kategorisierung der zeitlichen Dynamik von Ökosystemleistungen darstellt, verwendet der dritte Artikel diesen Rahmen, um zu testen, wie die zeitliche Dynamik von Ökosystemleistungen in der Literatur dargestellt wird.

Aufgrund der Erkenntnisse aus den drei Artikeln komme ich zu dem Schluss, dass zeitliche Aspekte in der Literatur zu Ökosystemleistungen immer noch unterrepräsentiert sind. Ein Grund dafür ist, dass die meisten Studien nur über einen Zeitraum von höchstens vier Jahren durchgeführt werden, sodass die Dynamik nicht über längere Zeiträume beobachtet werden kann. In den meisten Artikeln, die zeitliche Aspekte berücksichtigen, liegt der Schwerpunkt eher auf der Seite des ökologischen Angebots von Ökosystemleistungen als auf der Nachfrageseite, was dazu führt, dass die Wahrnehmung der Stakeholder nicht berücksichtigt wird. Somit wird es unmöglich, Nachfrage und Angebot von Ökosystemleistungen über die Zeit miteinander zu verbinden.

Darüber hinaus ist das in der Literatur am häufigsten verwendete Konzept der zeitlichen Veränderung das des Regime Shifts, das aus der ökologischen Forschung stammt und sich hauptsächlich auf Veränderungen konzentriert, die in der Vergangenheit stattgefunden haben. Die Möglichkeit einer positiven Veränderung in der Zukunft wird dadurch ausgeschlossen. Im Allgemeinen gibt es eine starke disziplinäre Kluft zwischen den verwendeten Konzepten und Begriffen. In Verbindung mit der mangelnden Nutzung von Definitionen für diese Konzepte und Begriffe werden inter- und transdisziplinäre Ansätze, die zur Lösung von Problemen des Managements von Ökosystemleistungen erforderlich sind, verhindert.

Um die zukünftige Forschung in die Lage zu versetzen, zeitliche Aspekte besser zu berücksichtigen und die Angebots- und Nachfrageseite von Ökosystemleistungen miteinander zu verbinden, gebe ich vier Empfehlungen für die zukünftige Forschung. Dies sind (I) stärkere Berücksichtigung der zeitlichen Dynamik durch Langzeitforschung, (II) Gewährleistung der konzeptionellen Klarheit, (III) Erstellung einer lösungsorientierten Agenda und (IV) Berücksichtigung der Nachfrageseite durch Einbeziehung der Wahrnehmungen der Stakeholder über die Zeit.

Indem die zukünftige Forschung diese Empfehlungen befolgt, könnte sie dazu beitragen, das nachhaltige Management von Ökosystemleistungen zu unterstützen, da die zeitlichen Dynamiken besser erforscht und somit gezielte Maßnahmen umgesetzt werden können.

Chapter 1: Introduction

1 Introduction

Interactions between people and nature have been a strongly debated topic already for decades. Therefore, several concepts for shaping these interactions were developed since the 1960s, ranging from strict protection of nature to more anthropocentric approaches such as the ecosystem services concept. In the late 1990s, ecosystem services were defined as the "range of conditions and processes through which natural ecosystems, and the species that are part of them, help sustain and fulfil human life" (Daily 1997, p. 2).

Since the beginning of research on human-nature connections, knowledge on how anthropogenic impacts influence nature has strongly increased, especially in the field of ecosystem services (Abson et al. 2014). However, implementation of this knowledge to enable a sustainable usage of ecosystems and their services is so far not sufficient (Brunet et al. 2018, Posner et al. 2016).

One of the reasons why it is still problematic to integrate scientific knowledge on the sustainable usage of ecosystem services into practice is that the temporal dimension of ecosystem services is still not sufficiently taken into account by researchers (Birkhofer et al. 2015, Kremen et al. 2005). By contrast, considering the spatial distribution of ecosystem services by mapping them has already become a widely applied method (see Kareiva et al. 2011; Syrbe & Waltz 2012). The neglect of the temporal scale might lead to static "snapshot" representations of ecosystem services that do not allow predictions of ecosystem services development in the future (Abson & Termansen 2011). This means that it is not possible to plan the future management of ecosystems and their services without knowledge on their past development.

Therefore, the goal of this dissertation is to enable future-oriented research on temporal aspects of ecosystem services. In the following, I present new definitions for the concepts transformation, transition and regime shift based on a systematic review on the usage of these terms in the ecosystem services literature, I propose a tentative framework for the classification of temporal dynamics of ecosystem services and test it against the literature. Finally, I give recommendations for better accounting for temporal aspects of ecosystem services.

1.1 Background

The development of concepts for shaping human-nature-interactions started with nature conservation. Its main goal developed over time from prioritizing intact habitats by creating protected areas in the 1960s over protecting species and habitats specifically from anthropogenic threats in the 1970s to recognizing that nature provides goods and services that cannot be replaced in the 1990s (Mace 2014). Out of the idea to connect ecology and economics to provide better guidelines for practitioners in ecosystem management, the concept of ecosystem services was established in the late 1990s (cf. Daily 1997). Costanza's (1997) study on the monetary valuation of the world's ecosystem services was later on criticized for its methodological approach but raised awareness for the value of ecosystem services and the way humans depend on them. However, this study operated at a purely spatial and global scale and did not take temporal dynamics into account as the valuation of the world's ecosystem services was only conducted for one point in time.

The usage of the term "ecosystem services" strongly gained momentum after the Millennium Ecosystem Assessment was published in 2003 (cf. Millennium Ecosystem Assessment 2003). The concept based on the four categories of regulating, supporting, provisioning and cultural services was broadly applied by scientists which lead to a strongly increasing number of papers until today, covering a wide range of topics such as conservation, pollination, biomass, water, and carbon (Abson et al. 2014). Although the MEA mentions sudden drastic changes in ecosystems, e.g. from coral-dominated to algae-dominated coral reefs, it does not include temporal dynamics in its framework (cf. Millennium Ecosystem Assessment 2005).

Even 17 years after the MEA report was published, there is still a strong division between different fields of research that look at ecosystem services from their own perspectives (Abson et al. 2014, Luederitz 2015). On the one hand, economists conduct studies focusing on calculating financial stocks and flows of ecosystem services, on the other hand, nature conservationists stress the importance of biodiversity for ecosystem services, but mostly do not value it in economic terms. As an example for the disciplinary divide, a review on the benefits of ecosystem services provided by wild bees showed that most studies were written from the disciplinary background of ecology (Matias et al. 2017). However, it is disadvantageous to neglect the relations between society and bees as most of the drivers of wild bee decline such as land-use change, pesticide use, and climate change are anthropogenic (Bodin & Tengö 2012).

Recently, research on ecosystem services and biodiversity is combined in the International Panel on Biodiversity and Ecosystem Services (cf. IPBES 2019a). IPBES introduced a new conceptual framework for conducting assessments at global and regional scales, and a new approach for working with indigenous and local knowledge. Moreover, it summarizes all negative and positive contributions of living nature, including ecosystem services, under the term "Nature's Contributions to People" (NCP) (Díaz et al. 2018).

Although the latest report by IPBES acknowledges that "interactions between spatial and temporal scales are relevant for future pathways", it does not put emphasis on temporal aspects of ecosystem services or nature's contributions to people (IPBES 2019b, p. 48). Mastrángelo et al. (2019) point out that "temporal dynamics of ecological change" represent one of the major knowledge gaps across the IPBES conceptual framework getting in the way of reaching the Aichi Biodiversity Targets (ABTs) and Sustainable Development Goals (SDGs).

1.2 Importance of taking temporal dynamics of ecosystem services into account

Temporal aspects gain increasingly in importance in the face of climate change which is a temporal development over a long time scale itself, but also causes other types of patterns on shorter time scales such as extreme weather events that are predicted to occur more often in the future (IPCC 2014).

These temporal aspects are already acknowledged amongst practitioners but are still not represented in the literature. Neglecting temporal aspects by only analysing an ecosystem service or a bundle of services at one point in time might lead to wrong assumptions about the future development of those services (Rodríguez et al. 2006). For instance, climate change leads to a serious problem with late frosts for fruit farmers in Germany. This is because apple blossom on average started almost 13 days earlier in 2005 than in 1961 and this trend is observed to continue over the last years (Chmielewski & Blümel 2013; Hartwich & Gandorfer 2014). Apple blossoms are very susceptible to frost, so farmers need to constantly sprinkle their trees with water as long as the temperatures are lower than 0°C during the flowering period. This leads to a strong increase in costs for labor, machines, and electricity. Moreover, still not all the flowers can be protected, so that there are still less fruits than if there was no frost. In total, this leads to a shortage of profit for fruit farmers (Chmielewski & Blümel 2013). This development is well-documented by fruit farmers as they need to have this knowledge about temporal aspects to better adapt to climate change. If this were not the case, however, people could assume that water spraying is unnecessary by just looking at data from one year without late frosts and not regarding the long-term trend. By doing so, farmers could come to wrong assumptions for ecosystem management, e.g. by not planning an overhead sprinkling system in a newly planted fruit orchard.

Additionally, supply of and demand for ecosystem services can have different temporal patterns which may lead to a mismatch of ecosystem service demand and supply if they are analysed separately. A prominent mismatch between the supply of an ecosystem service and the demand of customers is the production of fruits such as apples in Germany. As the provision of apples only takes place in the months between beginning of August and end of October, the supply side of this ecosystem service follows a seasonal (periodic) pattern (Blanke & Burdick 2005). However, the demand for apples is less seasonal and mostly stays on the same level during the year. This creates a mismatch between supply and demand as there are excessive apples during harvest and too little apples during the rest of the year, especially in spring.

To balance apple provision during the whole year, German apples are stored for about half a year and a share is exported. Additionally, apples are imported from other countries such as New Zealand where apple harvest takes place in March/ April (Bundesinformationszentrum Landwirtschaft 2020). In both cases, satisfying customer demand for apples half a year after harvest needs additional energy input. Transporting an apple in a refrigerating ship from New Zealand increases primary energy input by 37% whereas storing a regionally grown apple for six months increases primary energy input only by 22% (Blanke & Burdick 2005). Therefore, it is important to raise awareness for seasonal patterns of ecosystem service provision amongst customers.

In the UK, moorland landscapes are under pressure of change by several different drivers including increasing sheep numbers between 1970 and 1990, changing burning practices, atmospheric deposition of fertilizing substances, and climate change (Holden et al. 2007). This drives the long-term erosion of peatlands which leads to sudden decreases in ecosystem services provision. This includes a loss of water storing capacity leading to floods or sudden release of toxic chemicals that were stored in the peat since the industrial revolution (Holden et al. 2007). As in the example above, an anthropogenic long-term dynamic is causing other dynamics in the form of events.

These examples show that temporal dynamics already play a major role in ecosystem service management. Still, in the scientific literature, this is only included to a very limited degree. So far, a framework and coherent definitions for better including temporal patterns into ecosystem services research are lacking. To enable future-oriented research on temporal aspects of ecosystem services, I will answer the following research questions in this thesis:

- How are temporal aspects of ecosystem services conceptualized in the literature?
- Where are gaps and shortcomings in the recent scientific discourse on temporal aspects of ecosystem services?
- How can temporal aspects be better taken into account by future research?

1.3 Theoretical framework

1.3.1 The ecosystem services concept

Already in the 1970s the idea that ecosystems provide welfare benefits for humans started to develop (see Westman 1977). The term "ecosystem services" was first mentioned in 1981 with the intention to highlight humanity's dependence on nature (see Ehrlich & Ehrlich 1981). Therefore, the main question was how ecosystems and human well-being are connected (Daily et al. 1997; Millennium Ecosystem Assessment 2005). Nowadays, the concept is more often used to analyse how ecosystems and their functions are used by humans to increase their well-being (e.g. Abson et al. 2014; Gómez-Baggethun et al. 2010; Seppelt et al. 2011). Moreover, it is also applied as a tool for managing ecosystems (e.g. Vihervaara et al. 2010).

The concept of valuing nature (usually in monetary terms) for the services it provides and not purely for its intrinsic value was strongly contested, especially amongst nature conservationists as they criticized the anthropocentric focus (Schroeter et al. 2014). However, proponents of the concept argue that protecting nature for itself by excluding people from it did not help to protect ecosystems and the species they contain as decisions are often based on costs and benefits. If ecosystems are not assigned with any value, they are treated as having no value and therefore ignored in decision making (Mace 2014).

Since the term "ecosystem services" emerged, several typologies were developed. Based on the MEA (2003) typology with the categories provisioning, regulating, supporting and cultural services, The Economics of Ecosystems and Biodiversity (TEEB) initiative proposed a typology in which supporting services are replaced by "habitat services" (cf. TEEB 2010). To clarify which steps are needed to transform ecosystem structures and processes to human well-being, Haines-Young and Potschin (2010) developed the ecosystem services cascade which distinguished the levels "biophysical structure or process", "ecosystem function", "ecosystem service", "benefits" and "value". This typology later was further developed and adapted to specific purposes (cf. Brink et al. 2016; cf. Spangenberg et al. 2014).

Additionally, several different definitions for ecosystem services were developed since the 1990s. In the following, I define ecosystem services as goods or services co-produced via human-environmental interactions (Kumar and Kumar 2008). This definition is well-suited to the purpose of this dissertation as it stresses the fact that both human and environmental inputs are needed to obtain an ecosystem service.

1.3.2 Concepts that are used to describe temporal aspects of ecosystem services

The term "temporal aspects" comprises very different kinds of concepts. They all have in common that change happens over a certain period of time. In this thesis, I distinguish between:

(I) Concepts that are applied to describe changes of social or ecological systems as a whole such as transformation towards a more sustainable society in the sense that it was proposed by the German Advisory Council on Global Change (WBGU) in Germany in 2011 (cf. German Advisory Council on Global Change 2011).

(II) Concepts that are specifically used to describe temporal aspects of ecosystem services (in the following called "temporal dynamics" or "temporal patterns"[1])

In the first chapter, I will focus on the concepts of transformation, transition and regime shift. The last two evolved in parallel and also describe a drastic change in a system. However, both terms are mostly used by different research communities.

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[1] In chapter 3.3, the term "dynamics" had to be replaced by "patterns" in response to a reviewer. The meaning remains the same.

In the following, I will sum up the three concepts transformation, transition and regime shift under the term “concepts of change”. As the ecosystem services concept works as a boundary object for sustainability (Abson et al. 2014), it overlaps with the concepts of change. These concepts are used in different ways by their initial research communities which leads to confusion on the meaning of these terms. This inhibits the research on drastic change in ecosystem services.

The other two chapters will focus on temporal dynamics of ecosystem services. Some conceptualizations for temporal dynamics were already proposed in addition to the general ecosystem services categories provisioning, regulating, supporting and cultural services by the MEA (2003). For instance, Fisher et al. (2009) suggest differentiating between services where the benefit is obtained at the same time and place the service is provided (e.g. soil formation) and between services whose benefits are appropriated at another space and time. One example is water regulation that is provided on top of a mountain for a population living in the lowland. However, this framework does not help to describe temporal variance of supply of and demand for ecosystem services. Moreover, socio-ecological heuristics such as panarchy and resilience also include temporal patterns, especially cyclical dynamics (Holling 2001; Walker et al. 2006) and non-linear dynamics (Scheffer et al. 2001). However, none of these frameworks help to meaningfully integrate temporal dynamics into the ecosystem services concept.

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Chapter 2: Research design

2 Research design

This thesis aims to highlight shortcomings and gaps in the current literature on temporal patterns of ecosystem services and to give empirically based recommendations on how to better account for temporal dynamics of ecosystem services in the future. This should enable researchers to plan their studies on ecosystem services and transformation from the beginning in a way that makes it possible to detect changes over time. In the long run, this would enable better estimations on how management interventions in ecosystems impact the future development of ecosystem services provision and demand. This knowledge makes a more sustainable usage of ecosystem services possible. Building on what was said before, I am also investigating in how far stakeholders are involved in the research.

2.1 Structure of this dissertation

To start with a general view and take a more precise focus in the following steps, this thesis has a pyramidal structure (Figure 1). It starts at its basis with the chapter "Linking concepts of change and ecosystem services research: A systematic review" to gain an overview of the literature on transformation, transition, regime shift and ecosystem services.

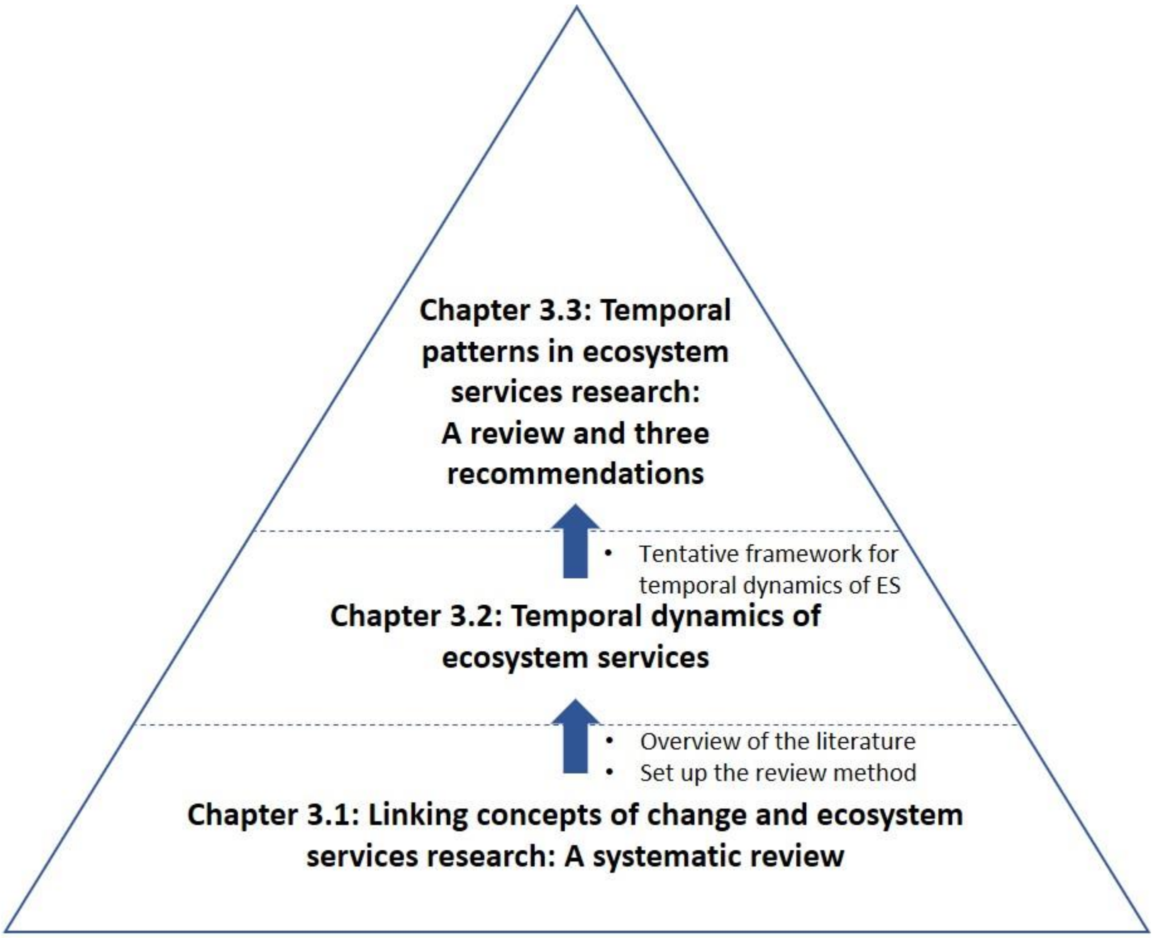

Figure 1. Structure of this thesis. The blue arrows represent the knowledge gain that is carried on to the next chapter(s).

As already mentioned in the previous chapter, there is a strong confusion of the usage of the concepts of transformation, transition and regime shifts as they have different meanings in different research fields. Therefore, in chapter 3.1,

- I present a general perspective on how the concepts of change transformation, transition and regime shift are applied in the ecosystem services literature.
- I show how these concepts integrate temporal dimensions of change within the ecosystem services literature
- and how research on ecosystem services and concepts of transformation, transition and regime shift link to real-world sustainability challenges.

In chapter 3.2, "Temporal dynamics of ecosystem services",

- I present a tentative framework for conceptualizing temporal patterns of ecosystem service provision and appropriation. Based on this framework,
- I propose steps for better integrating temporal patterns into ecosystem services research,
- and give a summary of decision-making tools and frameworks for more adaptive management that can account for such temporal patterns.

Chapter 3.3, named "Temporal patterns in ecosystem services research: a review and three recommendations", is a follow-up of the conceptual paper. In this chapter, I test the tentative framework by applying it to the literature. By doing this, I show:

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

2.2 Methodological approaches

To answer the overarching research questions of this thesis, I conducted a conceptual study based on an extensive literature search and two systematic literature reviews based on the method by Luederitz et al. (2016) which, in turn, is based on the approach by Newig & Fritsch (2009). With this approach, the literature on a specific topic is systematically searched for and analysed. Therefore, a search string is adjusted to the research question and applied to literature databases such as Web of Science and/or Scopus. By applying commonly defined exclusion criteria, the literature basis is then restricted to articles that are suited to answer the research questions. The selected articles are analysed using a set of review categories that help to answer the research questions. This results in a data sheet that is the basis for graphs and statistical analyses.

For the chapters 3.1 and 3.3, I conducted systematic literature reviews with groups of students and researchers as part of a project combining teaching and research. Therefore, I split the literature into smaller work packages which were distributed among the authors. For each of the literature reviews, I conducted a cluster analysis of the analysed literature. The cluster analyses were performed using all the articles that gave information on a set of selected research categories that were coded using a binary classification. In the resulting dendrogram, articles that are more similar to each other appear closer to each other. Additionally, it is possible to show which research categories significantly distinguish the different literature strands from each other. As displayed in Figure 1, I gained a first overview on the literature of temporal aspects of ecosystem services in chapter 3.1. Moreover, working on this chapter also helped me to set up the review procedure for chapter 3.3. Based on the experiences made during the systematic literature review for chapter 3.1, I improved the review procedure for chapter 3.3.

For chapter 3.2, however, I conducted an extensive search in the ecosystem services literature to see which kinds of temporal dynamics are presented. To exemplify these dynamics, I chose the important, well-studied ecosystem services food production and carbon sequestration. In the face of two of the most important challenges for humanity, food security and climate change, these two ecosystem services are vitally important for human well-being (Bellarby et al. 2014).

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Chapter 3: Scientific research articles

3 Scientific research articles

In this chapter, I present three peer-reviewed research articles dealing with temporal aspects of ecosystem services. In chapter 3.1, I identify the key elements of and differences between the concepts transformation, transition and regime shift in the literature on ecosystem services. I present new definitions for these concepts to facilitate their usage in the future research on ecosystem services. Moreover, I link these new definitions to the levels of the ecosystem services cascade by Haines-Young and Potschin (2010).

In chapter 3.2, I present a tentative framework for temporal dynamics of ecosystem services. I distinguish between linear dynamics, periodic dynamics, and events. As ecosystem services have a supply and a demand side, these dynamics can be found for both sides. Moreover, I give definitions for these dynamics and exemplify how these dynamics can occur on the supply as well as the demand side of the ecosystem services food production and carbon sequestration.

In the systematic literature review in chapter 3.3, I test the framework presented in chapter 3.2 against the ecosystem services literature. Moreover, I analyse the different literature strands using a cluster analysis. Based on this, I give three recommendations on how to better represent temporal dynamics in ecosystem services research (Table 1).

Table 1: Overview of the chapters that the results section comprises. All the chapters are already published as scientific research articles in peer-reviewed journals.

	Chapter 3.1	**Chapter 3.2**	**Chapter 3.3**
Topic	Ecosystem services and concepts of change	Ecosystem services and temporal dynamics	Ecosystem services and temporal dynamics
Citation	Rau, A.-L., Bickel, M.W., Hilser, S., Jenkins, S., McCrory, G., Pfefferle, N., Rathgens, J., Roitsch, D., Schroth, T.N., Stålhammar, S., Villada, D., Weiser, A., Wamsler, C., Krause, T., von Wehrden, H., 2018. **Linking concepts of change and ecosystem services research: A systematic review.** *Change and Adaptation in Socio-Ecological Systems* 4, 33–45.	Rau, A.-L., von Wehrden, H., Abson, D.J., 2018. **Temporal Dynamics of Ecosystem Services.** *Ecological Economics* 151, 122-130.	Rau, A.-L., Burkhardt, V., Dorninger, C., Hjort, C., Ibe, K., Keßler, L., Kristensen, J.A., McRobert, A., Sidemo-Holm, W., Zimmermann, H., Abson, D.J., von Wehrden, H., Ekroos, J., 2020. **Temporal patterns in ecosystem services research: A review and three recommendations.** *Ambio* 49, 1377–1393.
Research questions	1, 2, 3	3	1, 2, 3
Approach	Systematic literature review	Conceptual study based on literature search	Systematic literature review
Results	- terms transformation, transition and regime shift are rarely defined - concepts overlap - little stakeholder involvement - most articles focus on the past instead of the future	- presentation of tentative framework based on differentiation between linear and non-linear dynamics in both the provision and appropriation of ecosystem services - linear: continuous, but not necessarily monotonic increases or decreases - periodic: special type of linear dynamics, oscillating around a fixed or varying mean - non-linear dynamics: event-driven dynamics, irregular perturbations of the	- temporal patterns make up a minor share of research on ecosystem services - dynamics mostly described as linear - most studies only cover short time spans - lack of focus on changing demand (rather than supply) for ecosystem services

		provision or demand of ecosystem services	
Recommendations	- better differentiate the concepts of transformation, transition, and regime shift by using the suggested definitions - include stakeholder knowledge - focus on the future-oriented transformation instead of only tracking the past	- Recognize that there are different types of temporal dynamics across all ecosystem services. - Recognize the difference between the supply and demand sides of ecosystem services. - Recognize temporal grain. - Recognize that the drivers of ecosystem service dynamics occur at multiple spatial scales.	- Conduct more long-term research and increase the temporal resolution of observations of ecosystem services supply and demand. - Conduct more explicit temporal analyses of ecosystem service interdependencies, trade-offs, and synergies - Include the demand side and human dependency in a meaningful way by involving stakeholders.

3.1 Linking concepts of change and ecosystem services research: A systematic review

Rau, A.-L., Bickel, M.W., Hilser, S., Jenkins, S., McCrory, G., Pfefferle, N., Rathgens, J., Roitsch, D., Schroth, T.N., Stålhammar, S., Villada, D., Weiser, A., Wamsler, C., Krause, T., von Wehrden, H., 2018. Linking concepts of change and ecosystem services research: A systematic review. Chang. Adapt. Soc. Syst. 4, 33–45. https://doi.org/10.1515/cass-2018-0004

Abstract

Transformation, transition and regime shift are increasingly applied concepts in the academic literature to describe changes in society and the environment. Ecosystem services represent one framework that includes the implicit aim of supporting transformation towards a more sustainable system. Nevertheless, knowledge and systematic reviews on the use of these concepts within ecosystem services research are so far lacking. Therefore, we present a systematic literature review to analyse the interlinkages between these concepts and ecosystem services.

Using a search string we identified 258 papers that we analysed based on 40 review criteria. Our results show that transformation was mentioned most often (197 articles), followed by transition (183 articles) and regime shifts (43 articles). Moreover, there is no consolidation of these concepts. Only 13% of all articles gave definitions for the three concepts. These definitions strongly overlapped in their use. Furthermore, most papers described changes that happened in the past (73%). We conclude that research would benefit from being directed towards the future rather than evaluating what has happened in the past.

Based on our results, we present: i) clear definitions for the three concepts; and ii) a framework highlighting the interlinkages between the ecosystem services cascade and the concepts of change.

1. Introduction

Since the early 2000s, the concept of transformation has become increasingly important in academic literature to describe changes in society and the environment, with the aim of informing a more sustainable future [1–3]. In parallel, other concepts have evolved to conceptualize change, namely transition and regime shift. These three concepts partially overlap, yet also differ in terms of their particular lenses through which the world is viewed [2,4–6].

What unites all three concepts is the focus on continuous change characterising human societies and ecosystems. Early research dealing with ecosystem services already highlighted the relevance of sustaining human well-being over time, and therefore implemented an understanding of ecological change in the provision of ecosystem services into the original concept [7]. While the ecosystem service concept was initially developed to highlight the importance of nature's benefits or services for human well-being, it has increasingly evolved into an interdisciplinary framework that integrates policies and management strategies for ecosystems as well as societal change [8–10]. More recent research increasingly recognizes the capacity of the framework to aid transformation and change[11], though other approaches recognise the capacity to link ecosystem services to sustainability [12]. The ecosystem services concept could play a major role in engaging different disciplines and stakeholders from various backgrounds in shaping and achieving societal goals. It could therefore be an instrument for implementing transformative processes for creating more sustainable relations between humans and nature [11]. Moreover, transformative knowledge is needed to shape the management of ecosystems and their services towards societal goals [11,13,14].

However, knowledge and systematic reviews on the use and conceptualization of transformation, transition and regime shift within ecosystem services research is so far lacking. Increasing such knowledge is crucial as ecosystem services and human well-being are strongly vulnerable to fundamental changes of ecosystems caused by anthropogenic interventions [8], while transformation towards sustainability is an implicit goal in terms of the concept of ecosystem services [11]. The lack of coherence in defining and applying the different concepts is also creating dissonance or even contradictions within the literature [4]. Against this backdrop, this paper investigates the interlinkages between the concepts of transformation, transition, regime shift and ecosystem services by asking the following questions:

- How are transformation, transition and regime shift conceptualized within the ecosystem services literature?;
- How do these concepts integrate temporal dimensions of change within the ecosystem services literature?; and

- How does research on ecosystem services and concepts of transformation, transition and regime shift link to real-world sustainability challenges?

We use ecosystem services as a boundary object to better understand how transformation, transition and regime shift are applied and conceptualized in the scientific literature. By restricting ourselves to the ecosystem services literature, we seek to gain a better understanding both from a conceptual as well as an applied perspective. Furthermore, we elaborate an agenda for future research and highlight ways forward toward integrating the concepts of transformation, transition and regime shift within ecosystem services research. This permits us to advance the ecosystem services concept and associated cascade model [15] by matching it with the concepts of transformation, transition and regime shift. Ultimately, this will allow us to clarify the different concepts and enhance related research.

2. Methods

This paper is based on a systematic literature review, which combines quantitative statistical analyses with qualitative content analyses. To conduct the quantitative literature review, we followed the approach for systematic student-driven literature reviews in sustainability science described by Luederitz et al. [16].

2.1 Data collection

Using a jointly-defined search string (see Supplementary Material A), which was employed to search within the Scopus and ISI Web of Science databases in October 2015, we identified 1034 potentially relevant bibliometric entries. By following the review procedure portrayed in Figure 1, we identified 258 relevant case studies and conceptual papers with the earliest publication dating back to 1993 (see Supplementary Material B for the list of articles). Those publications were analysed using 40 review criteria (Supplementary Material C).

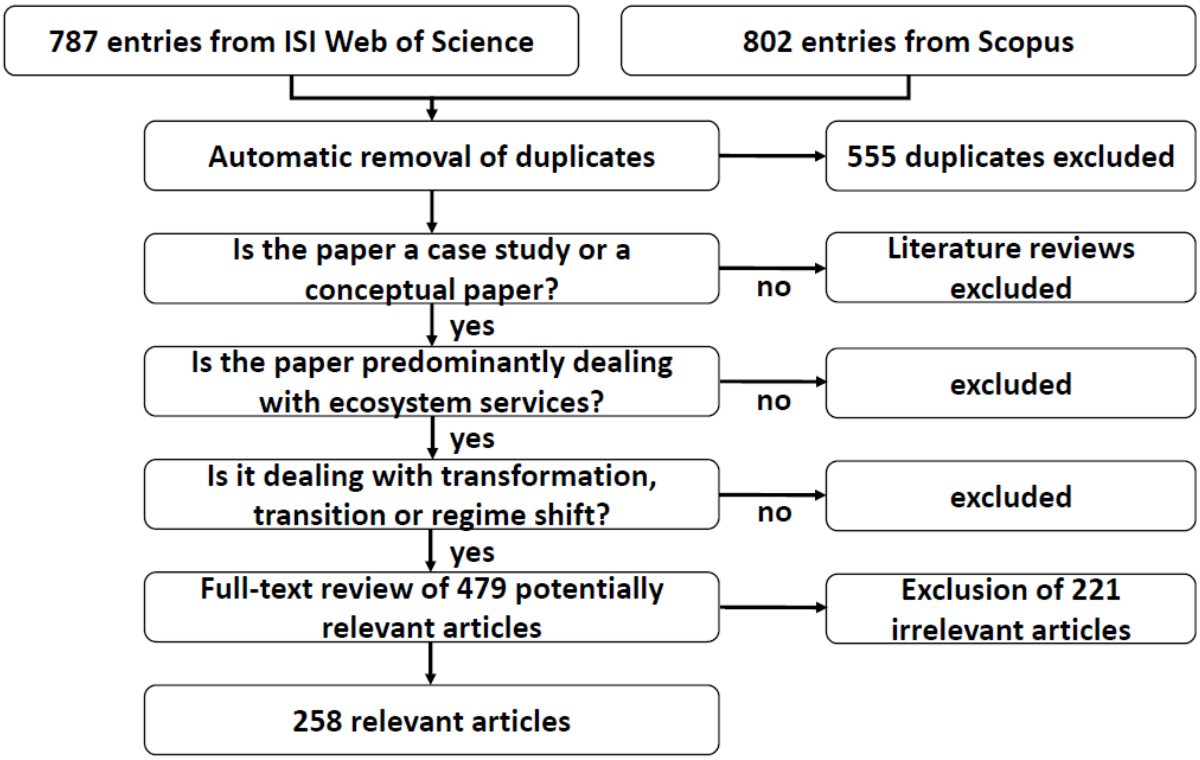

Figure 1. Review procedure.

2.2 Data analysis

We conducted a systematic qualitative and quantitative analysis of each article [17]. The resultant data were either words that were copied from the original texts, such as definitions and implications for future research, decision-makers or practitioners, or figures like how often a specific term was mentioned in the text.

To analyse and compare the results retrieved from our review categories, we clustered articles into ones that describe: i) change processes in the ecological system: ii) change processes in the social system; iii) change processes in the social-ecological system; and iv) change processes from a meta-perspective. Additionally, we noted for each paper which stages of the ecosystem services cascade (structure, function, benefit, value, management) were mentioned, and if the paper was based on data from the past or offered an outlook on the future (e.g., by simulations or modelling). Moreover, we noted if an article included system knowledge, target knowledge or transformative knowledge following the definitions presented by Brandt et al. (2013) [18]. System knowledge represents the analysis of a system as it is at the moment. Target knowledge describes how the system should be and transformation knowledge includes how to reach the target, e.g., by problem solving strategies [18].

Moreover, we categorized the intensity of stakeholder involvement by using the classification by Krütli et al. (2010) [19], distinguishing between information, consultation, collaboration and empowerment. Information is defined as communication from academia to stakeholders from practice. Consultation is the information flow from stakeholders to academia, e.g. in the sense of surveys and interviews. Collaboration between stakeholders and academia, however, requires a higher degree of involvement, e.g. rules for both sides. Empowerment is the highest level of involvement as the stakeholders are given decision authority [19].

All statistical analyses were performed in R (version 3.1.3; R Core Team Vienna, Austria; http://www.R-project.org/). To display our results, we used the package ggplot2 (Wickham, 2016).

Qualitative analysis of definitions for the terms transformation, transition and regime shift was conducted by collecting all definitions for these terms from our data set and systematizing them in relation to their main differences and similarities. To develop the criteria, we read through all definitions looking for items that were present in most of them and helped to characterize the most important aspects of change. This process resulted in the following criteria:

- What is driving the change?
- Which system is supposed to be changed (social, socio-ecological, ecological)?
- What is the temporal dynamic of change (incremental/ abrupt)
- What is the outcome of change (e.g., more sustainable system)?
- Did the change occur intentionally or unintentionally?
- Is the change reversible?
- Are stakeholders involved?

To visualize the different literature strands of research on ecosystem services as well as transformation, transition and regime shift on a quantitative basis, we conducted a cluster analysis using the R package mclust (Scrucca et al., 2017). Based on 13 of our 40 research categories that were coded using a binary classification according to the approach of Milcu et al. [20] we clustered all papers that gave information on these categories (N=204) into three groups. The strength of the clustering had an agglomerative coefficient of 0.97 (with 1 being the highest).

3. Results

3.1 Characteristics of the analysed literature

3.1.1 Authors and Definitions

For the ecosystem services concept, three authors were mainly cited: The Millennium Ecosystem Assessment (MEA) was cited 61 times [21–23], Robert Costanza 25 times [24–27] and Gretchen Daily 22 times [28-29]. For the terms transformation, transition and regime shift, there was great diversity with regards to how these terms were presented. Within the total amount of articles analysed, transformation was the most frequently mentioned term (197 articles), followed by transition (183 articles) and regime shift (43 articles) (Figure 2). The majority of these articles did not give a clear definition of the mentioned concepts (regime shift, transition, transformation). Out of a total of 258 articles, 34 (13%) articles clearly defined transformation, transition or regime shift. None of the papers defined more than one of the terms. Within this sub-sample of 34 articles, the term regime shift was defined in 18 (53%), transformation in nine (26%) and transition in seven (21%) articles. Of the articles including a definition for one of the terms, the same term is mentioned as the research object in the title in 18 cases (53%). In detail, this is the case for 13 articles defining the term regime shift and three articles defining the term transformation. Transitions were only stated as the main research objects in the titles of two papers giving definitions for this term.

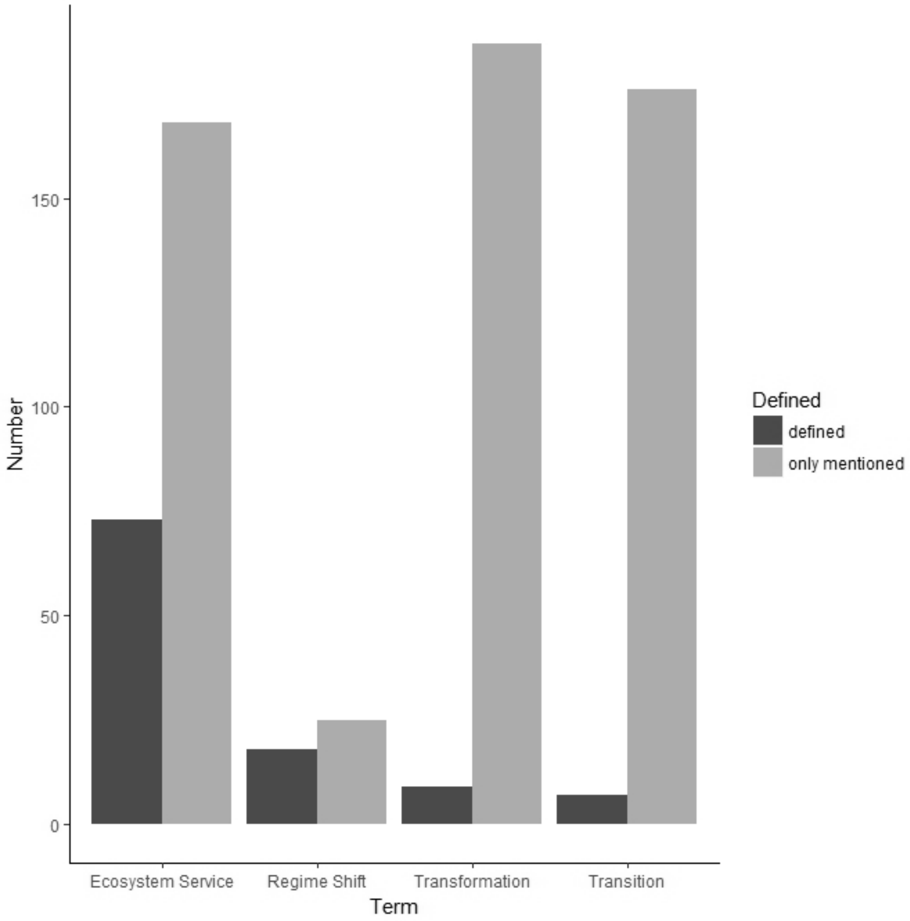

Figure 2. Number of papers defining the terms ecosystem service, regime shift, transformation and transition and those only mentioning the terms.

The use of specific definitions for the term regime shift began to emerge in 2004. A definition for transition appeared first in 2007 and for transformation in 2009. Definitions for all three terms were found in the papers during the years 2012 to 2014. The number of papers giving a definition for one of the terms increased from one in 2004 to six in 2014 and 2015 (Figure 3).

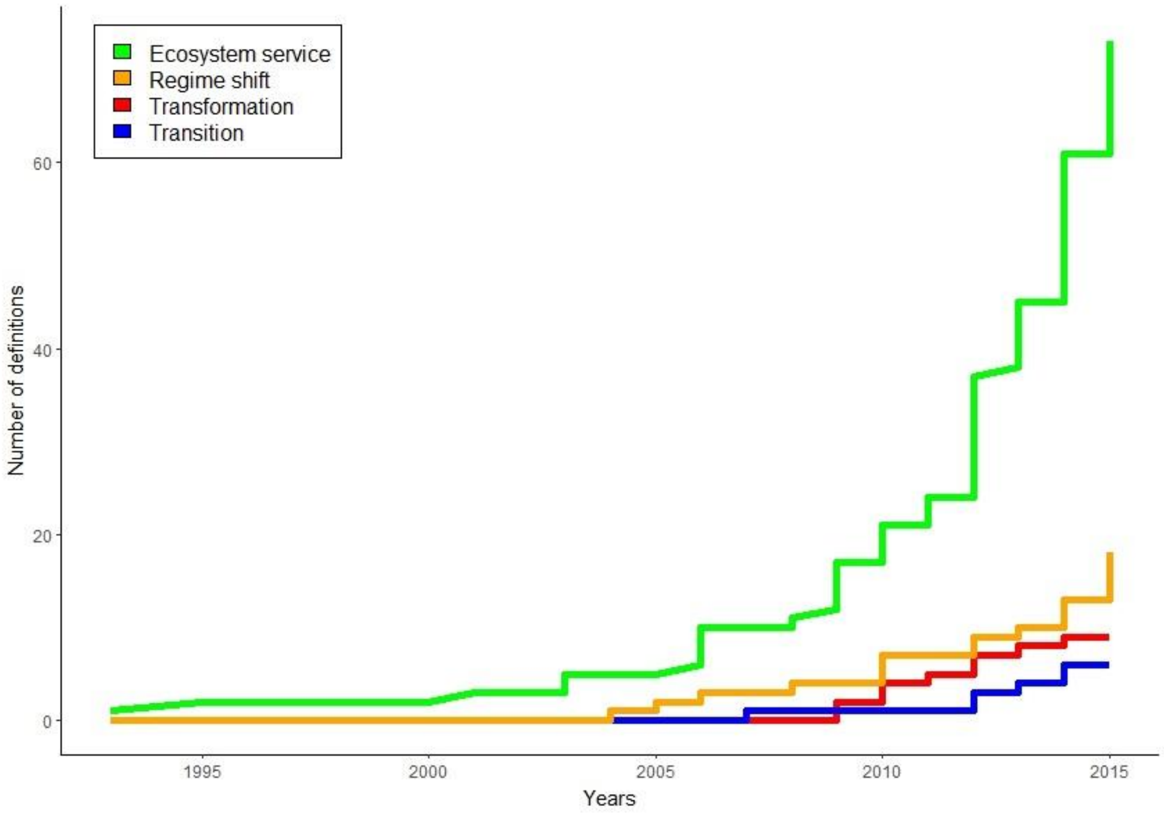

Figure 3. Number of definitions for the terms regime shift, transformation and transition over time in the articles evaluated.

Interestingly, papers giving definitions for the terms were cited more often and appeared in journals with higher impact factors. Papers not defining one of the terms received up to 73 citations whereas papers giving definitions were cited up to 127 times with one outlier at 1045 times (Figure 4a). Papers defining none of the terms appeared in journals with impact factors ranging between one and two whereas papers defining one of the terms appeared in journals with impact factors of up to seven (Figure 4b).

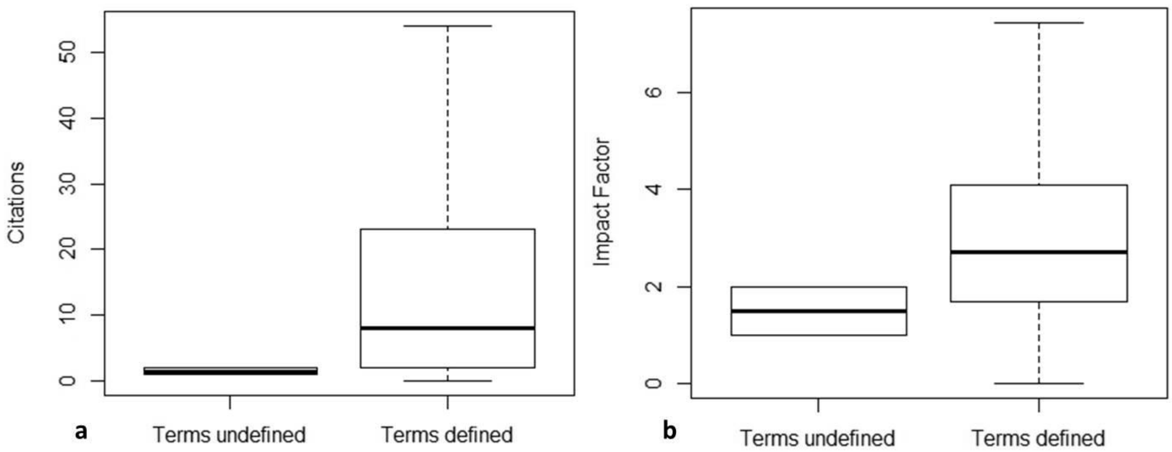

Figure 4. a) Citations for papers defining one of the terms vs. papers not giving definitions (one outlier at 1045 for terms defined). b) Impact factors in 2014 for papers defining one of the terms vs. papers not giving definitions.

No specific sources for the given definitions of the concepts of transformation, transition and regime shift emerged in the literature. In the nine articles defining transformation, no authors are cited with any predominance, with only Chapin [30,31] being cited more than once (four times). Three of the articles giving a definition presented transformation simply as a shift from one kind of system to another, while three other articles equated it to land-use change and the remaining three as a fundamental change in socio-ecological systems.

Within the sub-sample of eight articles defining transition, no authors were cited with any predominance - three authors were cited for more than one definition: Mather was cited by four papers [32,33] while Meyfroidt and Lambin were cited three times [34,35]. One article defined the word transition with a focus on land-use transition, five articles with a focus on forest transition and only one article with a focus on the radical, structural change of a societal (sub)system.

Of the 18 articles defining regime shift, the authors Scheffer (12 citations) and Carpenter (7 citations) were cited most often [36–41]. Folke was cited by four articles [8] and Hughes by three articles [42,43].

While many articles do not clearly define the term they use for describing change, some articles still referred to certain literature sources. Yet, no clear baseline articles were evident from our analysis. In total, the analysed articles referred to 213 authors (first author only) when using the term transformation, transition or regime shift. Out of these, six authors were referred to at least five times: Scheffer (N=17), Carpenter (N=10), Lambin (N=8), Folke (N=9), Walker (N=9) and Mather (N=5).

Table 1 depicts the results of the qualitative analysis of the 34 definitions for transformation, transition and regime shift we found in the literature. It shows the similarities and differences of the three concepts as they are used within the ecosystem services literature.

Table 1. Key elements and differences of the concepts of transformation, transition and regime shift in the ecosystem services literature.

	TRANSFORMATION	**TRANSITION**	**REGIME SHIFT**
Driver of change	Human-induced	Human-induced	Loss of ecological resilience (often human-induced)
Changed/targeted system	Social/socio-ecological, economic, political/institutional	Social/ecological	Ecological system
Speed of change	Gradual	Incremental or gradual (?)	Abrupt
Outcome	More beneficial system (e.g., more sustainable)	Depending on the system, e.g., forest cover gain for forest transition	Less desired ecological state
Solution-oriented/ problem-oriented	Solution-oriented	Problem-oriented	Problem-oriented
Reversibility	Hardly possible (?)	Possible (?)	Not or hardly reversible
Stakeholder involvement	Yes	Yes	No

As illustrated in Table 1, most of the reviewed articles describe a human-induced change that influenced a natural or socio-ecological system. Examples are land-use transformations that are human-induced and forest transitions that are driven by reforestation and afforestation [44]. Regime shifts are also described as the outcomes of human activity, but often in a more indirect sense, e.g., regime shifts caused by climate change or ocean acidification (e.g., Beaugrand 2015; Conversi et al. 2014) [45,46]. The systems that are being changed are social or socio-ecological systems in those articles dealing with transformation, social or ecological systems in articles dealing with transition, and ecosystems such as lakes [36,39], coastal [47,48] and marine ecosystems [49–51] as well as forests [52] in articles focusing on regime shifts. The speed of change is mainly stated as gradual or incremental for transformations and transitions whereas regime shifts are clearly described as abrupt changes in a system (e.g., Satake & Rudel, 2007; Zhang, 2015; Crepin et al., 2012; Guttal & Jayaprakash, 2008) [48,53–55]. The outcomes of the fundamental change in a system are strongly different for the three concepts (Table 1). For transformation, the outcome is viewed as a more beneficial system (e.g., Gelcich et al., 2010)

[56], whereas for regime shifts, it is a less beneficial system, like a less desired ecological state in which the ecosystem is less capable of providing ecosystem services [54]. In addition, papers dealing with transformation processes often mention that these are intentional, for instance, creating a more sustainable society (e.g., Chapin et al. 2012; Gelcich et al. 2010) [56,57]. In many articles dealing with transformations, authors do not only concentrate on a specific development, but also make qualified statements about transformation being beneficial in one way or the other. This stands in contrast to regime shifts which are described as caused by unintentional and unnoticed gradual changes in a system, leading to an abrupt change when a certain threshold is crossed (cf. Ernstson et al., 2010) [58]. For transformations, there is no clear pattern as this term is used for various systems. In the case of forest transitions, the outcome is positive in the sense of net reforestation [59] whereas it can also be negative in the sense of land use transition causing lower ecosystem services values [60]. Hardly any study on transformations and transitions supplies information on the reversibility of the changes it presents. In contrast, for regime shifts, it is commonly stated that these are hardly or not reversible [54]. In Table 1, we also highlight stakeholder involvement in the articles, although only a few mention these. Stakeholders were, amongst others, tourists, residents, farmers, governmental and non-governmental organizations. However, those few studies that did mention stakeholders investigated transformations and transitions. In the evaluation of regime shifts, stakeholder involvement plays just a minor role (e.g., Burkhard & Gee, 2012; Conversi et al., 2014; Troell et al., 2005) [46,47,61].

3.1.2 Focus on social and ecological systems

Our results reveal the great variety of social and ecological systems in which change is described. The largest share of articles (38%, N=99) deals with change in social-ecological systems, followed by 28% (N=71) of the articles that concentrated on change in the ecological system.

Only 18% (N=47) of the articles defined change as occurring in the social system, and interestingly, those articles did not mention any explicit connection to the natural system or specific ecosystems.

An even smaller share of 13% of studies (N=33) defined transformation as a change from a system’s perspective and on a “meta-level” (Table 2).

Table 2. Perspectives of identified articles on ecosystem services, transformation, transition and regime shift.

PERSPECTIVE	FOCUS	ABSOLUTE NUMBER	SHARE OF ARTICLES [%]
SOCIO-ECOLOGICAL SYSTEM	Change caused by humans affecting the natural system and change in the natural system affecting humans	99	38
ECOLOGICAL SYSTEM	Change of land, forest, fresh water and salt water ecosystems	71	28
SOCIAL SYSTEM	Change in economy, values, the legislative system and cultural transformation	47	18
SYSTEM'S PERSPECTIVE/ META-LEVEL	Event of (substantial) change itself No specific system Articles referring to the "Great Transformation" by Haberl and colleagues [62] and transition theory according to Grin and colleagues [9]	33	13

Of the 88 (34%) articles that gave a clear definition for the term ecosystem services, only a comparatively small share of 11 articles (13%) applied concepts of transformation, transition and regime shift in the context of the ecological system. Out of the 47 articles referring to change in the social system, 64% (N=30) concentrated on the "service" stage within the ecosystem services cascade.

Only a small share of papers (N=22, 8.5%) investigated all levels of the ecosystem services cascade from structures to policy interventions. Out of these, 81% (N=18) of papers evaluated all levels from structure to valuation. In contrast, with 84%, the largest number of papers (N=218) focused on a set of stages of the cascade, partially with gaps in between.

3.2 Conceptualization of change within ecosystem services research

Based on the results of the cluster analysis, we divided the literature into three groups (Figure 5). Each group is characterized by at least one review category that applies to all articles within this group. From each group, we chose the most-cited articles to present as examples. This helps highlight the main topics of each literature strand we identified. The first group contains 60 articles focusing on change in the ecological system. The field covers a variety of ecosystems and mostly assesses the resilience of ecosystems and regime shifts. The second group consists of 40 scientific publications. This group is characterized by a focus on socio-ecological topics with a diverse range of research with different foci. Human behaviour and its impact on ecosystems are investigated in this strand of literature. Group 3 comprises 104 papers focusing on transformation as change in the social system, socio-economic and socio-cultural changes and providing target knowledge as well as transformative knowledge.

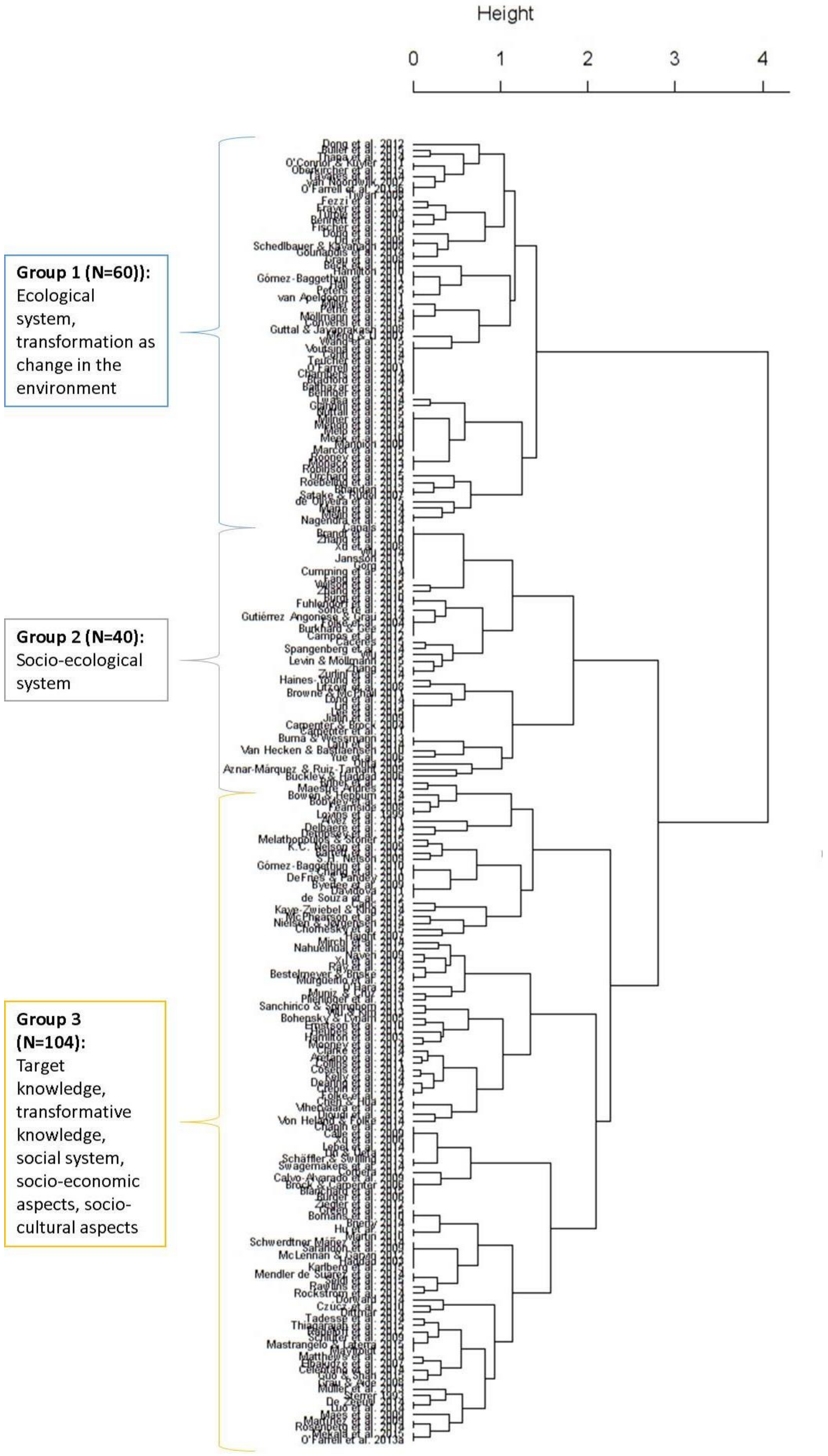

Figure 5. Dendrogram of all articles analysed in this review. Articles that appear more closely to each other are more similar in the way the columns of the review categories were filled out. A list of all articles per group can be found in Supplementary material D.

3.3 Integration of temporal dimensions

Of the 206 papers that provided information on whether they were building upon data from the past or predicting change in the future, 177 (86%) were case studies and 18 (9%) were conceptual papers. Articles building on data from the past (N=150, 73%) were the most prevalent in our data set. Future changes were predicted in 23% of papers (N=47) whereas only nine dealt with changes both in the past and future

Information on the velocity of change is rarely given. In total, 52 of 258 papers provided this information by characterising change as abrupt (N=24, 46%), incremental (N=18, 35%) or describing both patterns (N=10, 19%). Of the 34 papers that give definitions for one of the three terms, only those defining regime shift supplied information on the velocity of change by describing it either as abrupt or incremental. Of those eight papers, four mentioned abrupt dynamics, one incremental dynamics and three both types.

Although dealing with change, long-term research was rarely conducted in the papers we reviewed. Out of all papers, just 11% (N=28) described their data as deriving from a longer-term study. Of the 34 papers giving definitions of one of the three concepts, only in two papers did the authors state they conducted long-term research.

3.4 Consideration of real-world sustainability challenges

In the literature on ecosystem services and concepts of transformation, transition and regime shift, real-world sustainability challenges were present to different degrees and partly addressed by involving various stakeholders affected by the problem and offering recommendations or solutions to problems, e.g., in the discussion or conclusion. Stakeholder involvement and participation were only reported by a small share of articles. From a total of 258 articles, 52 (20%) mentioned some form of stakeholder involvement. About half of these articles mentioned the term participation. Out of the 52 articles involving stakeholders, 27 (51%) were related to transformation, 22 (42%) to transition and three (6%) to regime shifts. Stakeholders were informed in 10 cases, consultation was conducted in 43 cases and collaboration in 10 cases. Interviews were applied in 32 cases whereas questionnaires and workshops were each only used in 16 cases.

Of all analysed papers, 39% (N=101 of N=258) had clear recommendations for solutions, with just 27% (N=69 of N=258) offering a detailed intervention strategy transgressing the academic system. A comparable number of articles suggested a change in methods for future research or a change in academic institutions (N=51, 20%).

4. Discussion

Research on ecosystem services and transformation, transition and regime shift has strongly gained momentum over the last decades. Most of these studies were conducted on the continent of the first author’s affiliation. Both these patterns have also been observed for ecosystem services research in relation to other topics, such as urban environments and climate adaptation [63,64].

Most papers were written by first authors who are affiliated with European research institutions. This is in line with other reviews on ecosystem services that have shown that related research is primarily dominated by authors from the northern hemisphere, although this study displayed a lesser dominance of China and the United States [63]. Our study further showed that research on ecosystem services has been consolidated over the last years, indicated by the fact that a larger share of studies refers to the same three definitions for ecosystem services.

On the contrary, concepts of transformation, transition and regime shift are hardly consolidated within the scientific literature on ecosystem services. The different emphases of the three groups within the cluster diagram as well as the fact that each paper only defined one of the three terms show that there are separate research communities applying these concepts in different ways. Ecological analyses featuring descriptive knowledge still comprise the largest share of the literature. Only a small proportion addresses the meaning of change in social-ecological systems. In fact, the terms transformation, transition and regime shift were employed referring to various descriptions and contexts. In addition, just a few articles included specific definitions referring to several authors/papers. Actually, a wide array of literature was cited regarding transformation, transition and regime shift, indicating that there is no standard reference for these concepts. Interestingly, those papers that provided definitions had on average more citations and were published in journals with higher impact factors.

The author that was cited most often in the reviewed papers was Scheffer, who refers to regime shifts as “sudden drastic switches to a contrasting state” caused by a loss of ecological resilience, and states that these shifts have been specifically reported for ecosystems including lakes, coral reefs, oceans and arid lands (Scheffer et al., 2001: 591) [41]. The reason why the term regime shift was used relatively consistently might be based on the fact that the concept has a longer history and originated from ecology [65].

For the other two concepts (i.e., transformation and transition), several definitions were identified, of which some are more abundantly used than others. In our review, the most-cited author on transformation, Chapin, defines transformation as “a fundamental change in a social-ecological system resulting in different controls over system properties, often mediated by changes in feedbacks that govern the state of the system” (Chapin et al., 2012: 3) [57]. Interestingly, this definition and approach does not consider whether the fundamental change is intentional or unintentional and does not describe the outcome of the transformation.

In contrast, outside of ecosystem services research, the transformation concept is often defined by providing specific outcomes and goals, such as the “Great Transformation” that was proclaimed by the German government in 2011 [66]. However, there are also definitions and approaches that only state the intention of change, but do not give further specifics. An example comes from Park et al. (2012: 5) who describe transformation as a “discrete process that fundamentally (but not necessarily irreversibly) results in change in the biophysical, social, or economic components of a system from one form, function or location (state) to another, thereby enhancing the capacity for desired values to be achieved given perceived or real changes in the present or future environment” [6]. The definitions we encountered for transition in the ecosystem services literature mostly relate to forest transition, i.e., “the transition from net forest loss to net forest gain” (Melo et al., 2013: 464) [67]. On the contrary, outside of the reviewed ecosystem services literature, the term seems to be rather used in the sense of a transition towards sustainability, defined as long-term, multi-dimensional and fundamental transformation processes through which established socio-technical systems shift to more sustainable modes of production and consumption [68].

The definitions for transformation and transition differ both within the ecosystem services literature and the literature outside the field. However, our analysis confirms the statement by

Hölscher and colleagues that the concepts of transition and transformation are not clearly separated from each other [4]. In summary, our results clearly indicated that a more explicit use of (differences in) concepts of transformation, transition and regime shift is crucial to fostering a more profound understanding of ecosystem services and social-ecological changes and supporting the development of further research.

Furthermore, our study has shown that the concept of regime shift was most often defined within the ecosystem services literature in relation to the concepts of transition and transformation. Regime shift is a concept that strongly focuses on avoidable negative changes in ecosystems. Consequently, the possibility of positive change of a system with a more sustainable outcome is generally neglected. Moreover, change is represented in a rather static and simplified way by the concept of regime shifts because the system is assumed to simply switch to another stable yet less desired state if resilience is reduced to a certain threshold [8].

In contrast, the concept of transformation seeks to create more sustainable systems and gives more room for dynamics and complexity inherent in social-ecological systems. A better differentiation of the use of the concepts of transformation, transition and regime shift in ecosystem services research (as proposed) could thus enhance ecosystem service research by unifying the academic discourse and improving the communication of related results. In addition, concentrating on transformation rather than on regime shifts (Table 1) would assist in fostering research and practice capable of closing the feedback loop in the ecosystem services cascade, ultimately encouraging more sustainable environmental governance that would result in the adaptive management of ecosystems in order to maintain and enhance ecosystem services provision (Figure 6).

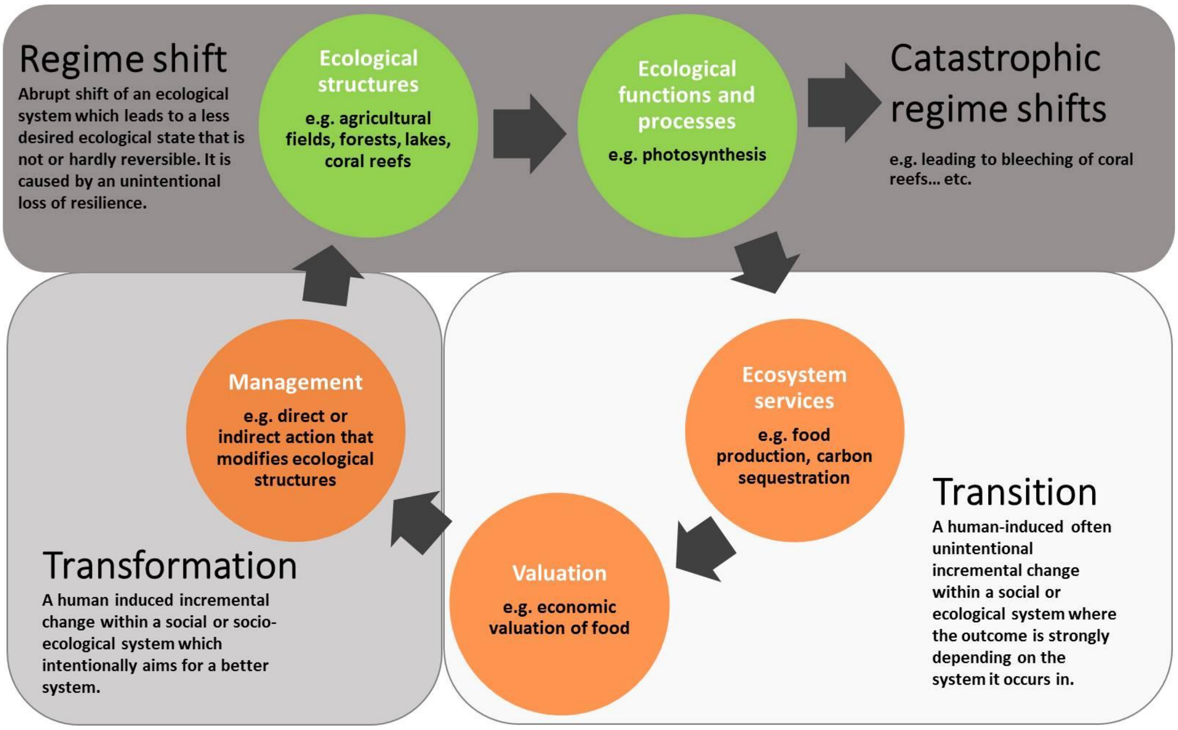

Figure 6. Ecosystem services cascade combined with the concepts of transformation, transition and regime shift (adapted from Haines-Young and Potschin, 2010; Brink et al., 2016). Biophysical stages of the cascade are indicated in green and social stages in orange.

Initially, the ecosystem services cascade was represented as starting with the stage of ecological structures (cf. Figure 6). However, as ecosystem services are the benefits that people derive from nature [7], there is an increasing consensus that people's perceptions should be understood as the starting point of the cascade, and the benefit (ecosystem service) as well as the valuation stage should be provided with more attention [64,69]. This can, for instance, be facilitated by investigating how benefits and values change after the structure has been managed. Another approach would be to influence people's perceptions, e.g., by education and raising awareness surrounding ecological functions and resulting ecosystem services, allowing for an inclusive and informed discussion on environmental governance in particular contexts and of specific ecosystems.

We showed that the structure stage within the cascade is equivalent to the biophysical side of ecosystem services, which can be influenced by regime shifts (Figure 6). Ecological functions and processes are on the biophysical side as well, but are influenced by human activities, which can be unintentional, such as forest transition (in the meaning of a shift from forest decrease to forest increase), or intentional, such as the draining of wetlands. If ecological functions and processes are impacted by catastrophic regime shifts, e.g., ocean acidification leading to bleaching of coral reefs, this would define an endpoint in the ecosystem services cycle as the fundamental ecological characteristics of the ecosystem, i.e., a coral reef community, is lost. Benefits derived from ecosystems and their valuation are both on the social side of ecosystem services and can be influenced by transitions, e.g., when the benefits or valuation of an ecosystem service by society change. In this case, transformation is equivalent to an intentional change in management with the goal of changing the system, e.g., the ecological structures (Figure 6).

As illustrated in Figure 6, our results indicate that transformation could be seen as a key concept for a reflected, designed, future- and solution-oriented implementation of the ecosystem services cascade. Therefore, it is vital to direct future research more towards analysing how to achieve future-oriented transformation rather than tracking what has happened in the past, which is dominating the current literature.

Accordingly, to implement the ecosystem services cascade in a future-oriented fashion, we conclude that additional research would need to have a better vision of how management and appropriation of ecosystem services should be designed in the future (target knowledge) and how to induce change to arrive at that point (transformational knowledge) [70]. Furthermore, to assure the value of ecosystem services in the long-term and not only increase it in the short-term, future-oriented policies and management are necessary. To achieve this, it is crucial to recognize the importance and inclusion of stakeholder knowledge more so than at present. Such knowledge co-production requires researchers and stakeholders to also identify deep leverage points, i.e., points in the system which are difficult to influence but might lead to transformation if intervention succeeds [71]. To accomplish this, changing the intent (i.e., the values, goals, world views) of actors who shape the social-ecological system could enable a transformation towards a more holistic and future-oriented use of the ecosystem services concept.

5. Conclusions

We have investigated the application of the concepts transformation, transition and regime shift within the scientific discourse on ecosystem services. Therefore, we analysed the literature on ecosystem services using a systematic literature review approach. Our analysis shows that research on the concepts of transformation, transition and regime shift within the ecosystem services literature is still unconsolidated. Definitions of the terms are unclear and partly overlapping, especially for transformations and transitions. Most papers do not give definitions at all which can lead to further confusion and separation of the three different discourses.

The largest share of papers giving definitions is dealing with regime shifts in the sense of a sudden change towards a more unsustainable state that should be avoided. This ignores the possibility of positive change leading to a more sustainable outcome in the system. Moreover, most of the research is directed towards the past instead of the future and is conducted without taking stakeholders’ perceptions of ecosystem service values into account.

We conclude that future research on ecosystem services and the concepts of transformation, transition and regime shift would benefit from using our definitions that clearly distinguish these concepts from each other. Moreover, a stronger orientation towards the future could be achieved by using the concept of transformations as it is directed towards positive change and involves stakeholders. This includes building visions for the future and creating strategies to reach the desired state.

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Supplementary material

A. Search strings in Scopus and Web of Science

Search string in the Scopus database (802 results):

TITLE-ABS-KEY ("ecosystem servic*" OR "natural capital" OR "environmental servic*") AND TITLE-ABS-KEY (transformatio* OR "regime shift" OR transitio* OR "system* innovation*" OR "radical change" OR niche OR "incremental change" OR "fundamental change" OR "societal change") AND (LIMIT-TO (DOCTYPE , "ar") OR LIMIT-TO (DOCTYPE , "re") OR LIMIT-TO (DOCTYPE , "ip")) AND (LIMIT-TO (LANGUAGE , "English")

Search string in the Web of Science Core Collection (787 results):

TS=("ecosystem servic*" OR "natural capital" OR "environmental servic*") AND TS=(transformatio* OR "regime shift" OR transitio* OR "system* innovation*" OR "radical change" OR niche OR "incremental change" OR "fundamental change" OR "societal change") AND LANGUAGE: (English) AND DOCUMENT TYPES: (Article)

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C. List of review categories

Category Number	**Category Name**	**Explanation**
1	Authors	
2	Title	

3	Journal	
4	Year	
5	Abstract	
6	Type of paper	Case study, conceptual paper, review
7	Country of first author	Country of main affiliation (only one)
8	Country of study	Country where the study was conducted (several entries possible)
9	Term for concept of change: transition	Number of times mentioned
9	Term for concept of change: transformation	Number of times mentioned
9	Term for concept of change: regime shift	Number of times mentioned
9	Term for concept of change: other term	Number of times mentioned
10	Term related to ES: Ecosystem services	Number of times mentioned
10	Term related to ES: Environmental services	Number of times mentioned
10	Term related to ES: Natural capital	Number of times mentioned
11	Term related to ES: other term	Number of times mentioned
12	Resilience	Number of times mentioned
13	Sustainability	Number of times mentioned
14	Mainstreaming	Number of times mentioned
15	Speed of change: abrupt	Number of times mentioned
16	Speed of change: abrupt	Number of times mentioned
17	Participation	Number of times mentioned
18	Equity	Number of times mentioned
19	Use of term "transformation"	Mentioning the term, building analysis upon concept
20	Use of term "ecosystem services"	Mentioning the term, building analysis upon concept
21	Incentive for using the term transformation	Change in the environment, change in the social sphere, appeal for societal change, justification of research, result of research, basis for analysis (multiple answers possible)
22	Knowledge type (according to Brandt et al., 2013)	System Knowledge, target knowledge, transformative knowledge (multiple answers possible)

23	Is the term transformation used as in everyday language?	Is it used without explanation or definition, assuming that the reader is familiar with the term's meaning? (yes/no)
24	Transformation definition	How do the authors of the paper define transformation, transition or regime shift? Definition copied from text.
25	Transformation citation	Which authors are cited for the definition of transformation, transition or regime shift?
26	Transformation example sentences	Example sentence copied from the text which shows how the authors use the term.
27	Is the term ecosystem services used as in everyday language?	Is it used without explanation or definition, assuming that the reader is familiar with the term's meaning? (yes/no)
28	Ecosystem services definition	How do the authors of the paper define ecosystem services (and/ or environmental services/ natural capital)? Definition copied from text.
29	Ecosystem services citation	Which authors are cited for the definition of ecosystem services (and/ or environmental services/ natural capital)?
30	Ecosystem services example sentences	Example sentence copied from the text which shows how the authors use the term.
31	Time span of the research	Time in months or years (copied from text).
32	Long term study or not	Yes/ no. Term has to be mentioned in the text.
33	Studied time frame: past or future?	Did the fundamental change take place in the past or is it projected for the future?
34	Stages of ecosystem services cascade	Which stages of the ecosystem services cascade are mentioned? Biophysical structure/process, ecosystem function, ecosystem service, benefit, values, policy action (multiple answers possible).
35	Ecosystem services categories (MEA 2005) studied in the paper	Provisioning, regulating, supporting, cultural (multiple answers possible).
36	Names of ecosystem services	Names of ecosystem services that are studied in the paper. Copied from text.
37	Adaptation/ mitigation	Is the paper mentioning adaptation and/or mitigation? (multiple answers possible).
38	Sectors analysed in the paper	Housing/built environment; Urban planning & land use planning; Water and sanitation; Energy; Transportation/traffic and telecommunication; Environment and natural resource management (including waste management); Social and public services: Health, education, security etc.; Rural planning & agriculture
39	Type of stakeholder involved in research	Which stakeholders are mentioned? Copied from text.

40	Proposed solution	Solution proposed by the authors of the paper. Copied from text.

3.2 Temporal dynamics of ecosystem services

Rau, A.-L., von Wehrden, H., Abson, D.J., 2018. Temporal Dynamics of Ecosystem Services. Ecol. Econ. 151. https://doi.org/10.1016/j.ecolecon.2018.05.009

Abstract

The ecosystem services concept evolved over the last 30 years from a general heuristic model highlighting importance of nature for human well-being to a framework for studying how the appropriation of specific ecological structures or processes influences that well-being. As the ecosystem service concept increasingly becomes an operational tool there is a need to account for the complexity of the relations between production and appropriation of ecosystem services. To date there has been a considerable focus on the spatial patterns of ecosystem services provision and appropriation. We propose a new way of categorizing them according to their temporal dynamics. We differentiate between linear and non-linear dynamics in both the provision and appropriation of ecosystem services. Based on our classification we suggest how temporal dynamics can be better integrated into ecosystem services research in four steps. These include setting the appropriate temporal boundaries of the system, identifying key types of dynamics of the ecosystem, assessing the spatial scale on which the dynamics play out in the system and developing measures for assessing these dynamics. Considering temporal dynamics of ecosystem services by following these steps has the potential to enable better planning of ecosystem services management and therefore, to enhance human well-being.

1. Introduction

The idea of human welfare benefits derived from ecosystems became prominent in the 1970's (see Westman, 1977). Since these early discussions, classifications of ecosystems in terms of their instrumental value to humans have gained momentum (Turner, 2016a). The ecosystem services concept itself—here defined as goods or services co-produced via human environmental-interactions (Kumar and Kumar, 2008)—was developed in the 1980s. Initially the concept was employed as a general heuristic model to highlight humanity's dependence on ecosystems and biodiversity—as typified by Paul and Anne Ehrlich's 'rivet poppers' metaphor

(Ehrlich and Ehrlich, 1981). Subsequently, ecosystem service research focused on understanding the type and nature of interactions between ecosystems and human well-being (Millenium Ecosystem Assessment, 2005; Daily et al., 1997). Increasingly the ecosystem service concept is now used as a framework for studying how humans appropriate ecological structures and functions in order to increase human well-being (e.g. Abson et al., 2014; Gómez-Baggethun et al., 2010; Seppelt et al., 2011) and as an explicit management tool (e.g. Bateman et al., 2013; Vihervaara et al., 2010).

In the 30 years since the term ecosystem services was first coined there have been considerable efforts to clarify the ecosystem services concept and how ecosystems contribute to human well-being (e.g. Haines-Young and Potschin, 2010). This has included a strong focus on creating typologies useful for categorizing and operationalizing ecosystem services. These typologies are largely based on the nature of the services particular ecological structures or functions can provide for humans (e.g. provisioning, regulating, cultural and supporting/habitat services (Millennium Ecosystem Assessment, 2005; TEEB, 2010). Based on these classifications refined typologies for ecosystem services have been proposed. Fisher et al. (2009) distinguish between intermediate services, final services and benefits and Banzhaf and Boyd (2012) present a definition and ecosystem services index compatible with GDP accounting that only includes “final products” as ecosystem services (Banzhaf and Boyd, 2012; Boyd and Banzhaf, 2007).

The use of such ecosystem services classifications has enabled the study of the ‘bundling’ of ecosystem servicing (e.g. Raudsepp-Hearne et al., 2010) and ecosystem services trade-offs (e.g. Rodríguez et al., 2006). These approaches recognise that multiple services are often jointly-produced by multiple ecosystem structures and functions and that this needs to be considered in the valuation and management of ecosystem services (e.g. Nelson et al., 2009). Similarly, consideration of the spatial distribution, mapping and analysis of ecosystem services has become a key feature of ecosystem service research (e.g. Kareiva et al., 2011; Plieninger et al., 2013; Syrbe and Walz, 2012).

Such ‘service type’ typologies are clearly useful for managing the trade-offs and synergies that exist between the provision and appropriation of multiple ecosystem services over multiple spatial scales. These typologies tend to unconsciously reinforce static, ‘snap shot’ assessments of ecosystem services, with little or no con of how ecosystem services might change across time (Abson and Termansen, 2011). However, the benefits appropriated from ecosystem services are not static, or fixed, rather they depend on dynamic ecosystem structures and functions (Andersson et al., 2015; de Groot et al., 2010; Fisher et al., 2009). To effectively manage ecosystem service provision, we need to know how ecosystem services vary both across space, and time. To date, only 3% of empirical papers on ecosystem services are dealing with temporal dynamics (Rau et al., 2018, in prep.).

Renard et al. (2015) demonstrated the importance of accounting for ecosystem services temporal dynamics in a study on historical dynamics of ecosystem services by showing changes in the spatial patterns and composition of ecosystem service bundles. This is especially important as different ecosystem services within one ecosystem service bundle can have different types of dynamics, e.g. ecosystem services within a forest during forest recovery. In this example, carbon storage recovered in a linear dynamic about 170 years after tree harvest whereas provision of wild edible berries recovered in a non-linear way and took 212 years to reach baseline level (Sutherland et al., 2016). Compared to the relatively sophisticated understanding and assessment of the spatial occurrence and appropriation of ecosystem services, the temporal variability and dynamics of ecosystem services are a crucially understudied aspect of the ecosystem services framework (Bennett et al., 2015).

Given the dynamic nature of energy and material flows in ecosystems, and the changing and context dependent appropriation of those flows by humans, static assessments of single ecosystem services are problematic as they are of limited usefulness for decision makers who have to develop long-term management plans that ensure continued flows of such services (Bennett, 2016). It is therefore vital that the temporal variability of ecosystem service provision is considered in operationalization of the ecosystem service concept (TEEB, 2010). Temporal dynamics are important in terms of both short-term variability and the long-term prescience of ecosystem service provision. For example, short-term temporal fluctuations in the provision of food may have serious consequences for human well-being that cannot be seen from analysis of the average level of provision. Meanwhile, over longer time periods food provision based on the liquidation (or drawing down) of natural capital—defined here as stocks of natural assets from which ecosystem goods and services follow—as is the case in soil mining in some intensive agricultural systems (Tilman et al., 2001), may currently provide higher flows of services, but may not be able to maintain these flows (and the associated human well-being) in the long-term. Failure to consider the temporal scale in the management of ecosystem services can also lead to adverse impacts generated by time sensitive trade-offs. This happens, for example, if short-term gains from provisioning services from agricultural ecosystems are preferred over supporting services such as water and soil quality, because the long-term effects are not taken into account (Rodríguez et al., 2006).

To date, there are few papers dealing with temporal conceptualizations of ecosystem services and these typically focus on ecosystem services in specific contexts. Fisher et al. (2009) suggested a spatio-temporal classification into services where the benefit is obtained in the same time and the same place that it is provided, such as soil formation, and services whose benefits are realized at another time and space, such as water regulation for lowland populations provided by a forest on top of a mountain (Fisher et al., 2009). Such an approach is interesting, but tells us little of the temporal variance in ecosystem service provision of appropriation. Martín-Lopez et al. (2009) argue that temporal heterogeneity needs to be taken into account in economic valuation techniques in order to provide accurate information regarding ecosystem service provision. Accounting for temporal variability is important not only for the supply of ecosystem services, but also for their valuation by stakeholders which can vary, even over short time spans (Hein et al., 2016). Related to the demand and supply side issues of temporal dynamics in ecosystem services, Tomscha et al. (2016) distinguished between ecosystem service capacity and demand in terms of ecosystem services dynamics. However, temporal dynamics in ecosystem services consist of more than simply variance over time. Bullock and colleagues (2011) provided an overview on the rate of recovery of ecosystem services or biodiversity in restored ecosystems and grouped the temporal dynamics into the categories asymptotic, linear, unimodal and stochastic. 'Natural influences and trends' impact the ability of ecosystems to provide services either in a periodic, episodic or permanent way (Bastian et al., 2012). Cyclical dynamics are often indirectly included in socio-ecological based heuristics such as panarchy and resilience (Holling, 2001; Walker et al., 2006), while non-linear dynamics are reported e.g. for lakes and woodlands (Scheffer et al., 2001). Despite the acknowledgement of the importance of temporal dynamics in relation to ecosystem services there is a general lack of frameworks that could help integrate temporal dynamics in ecosystem services research.

In this paper, we provide a tentative framework for conceptualizing temporal dynamics of ecosystem service provision and appropriation. We use literature from two important, well studied ecosystem services (carbon sequestration and food production) to exemplify these dynamics. We focus on food production and carbon sequestration as these two ecosystem services are well researched across multiple contexts, are fundamentally important services with regard to two of the global challenges humanity is facing—food security and climate change (Bellarby et al., 2014)—and both of these ecosystem services have strong temporal components that are vitally important in terms of understanding their role as sources of human well-being. Additionally, we present steps for better integrating temporal dynamics into ecosystem services research and summarize decision-making tools and frameworks for more adaptive management that can account for such temporal dynamics.

Based on the insights gained from an extensive literature search we propose a multi-dimensional classification of ecosystem services based on the type of service (according to the Millennium Ecosystem Assessment categories: provisioning, supporting, cultural and regulating), the dominant temporal dynamics related to either the supply of or demand for the particular service and the drivers that cause the dynamics. We believe that such a classification is potentially useful both for considering the long-term provision of ecosystem services and for detailed analysis of trade-offs among ecosystem services and the distribution of the benefits of appropriating ecosystem services across space and time.

2. Conceptualisation of temporal dynamics in ecosystem service provision

2.1 Linear and non-linear dynamics

As with many dynamic systems, ecosystem services provision and appropriation can take a number of different forms. In general, in dynamic systems we can identify linear and non-linear temporal variability. Linear dynamics are continuous, but not necessarily monotonic, increases or decreases of ecosystem services provision or demand (Figure 1 a). An example for a linear dynamic in ecosystem service provision is the long-term decline in net primary productivity in rangelands resulting from degradation (Paudel and Andersen, 2010; Pickup, 1996). Long-term linear trends can also be found in marine systems as overfishing leads to the depletion of food systems over decades (Karr et al., 2015; Mumby, 2006). Linear dynamics can be influenced by natural (e.g. environmental) or anthropogenic (e.g. management) drivers that cause them to oscillate around a (fixed or varying) mean in a relatively predictable periodic manner (Figure 1 b). We call these dynamics that generally follow a distinct, repeated pattern, periodic dynamics, and regard them as linear, because we understand them as repeating patterns of linear dynamics.

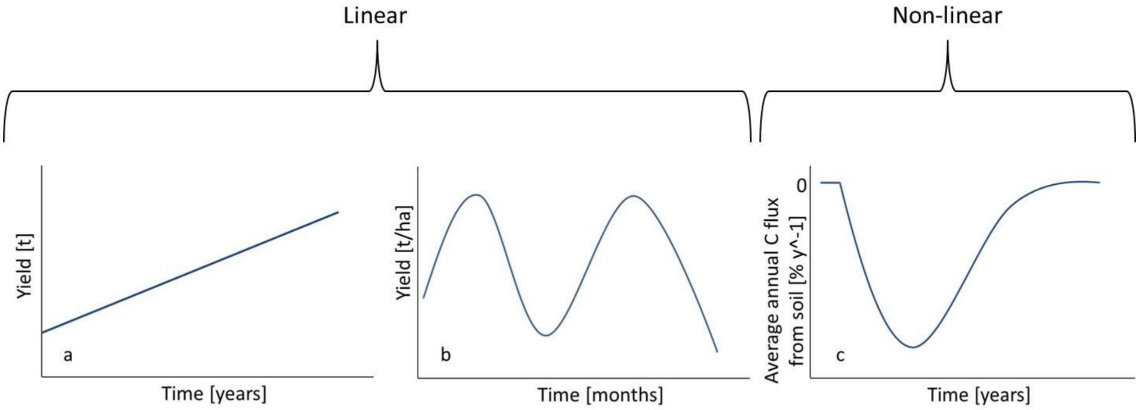

Figure 1. Dynamics of food production and carbon sequestration identified from the literature. a) Linear dynamic, e.g. global increase of yields over the last decades as described by the Millennium Ecosystem Assessment (2005). b) Periodic dynamic, e.g. variability of crop production through seasonal precipitation dynamics (as mentioned by Brown et al. 2012 and Rockström 2000). c) Event caused by change in management, e.g. average annual C flux from soil to atmosphere after changing from conventional tillage to no-till (West 2004, modified).

Periodic dynamics are often an integral part of ecosystems and their management. For example, they can be driven by natural oscillations such as the change of the seasons (Brown et al., 2012). Agricultural ecosystem services are typically well adapted to these periodic change of seasons, for example via the use of temporal crop rotations (Entz et al., 2001; Shrestha et al., 2015). The time scales across which such periodic dynamics, in provision or appropriation, oscillate may span from days to decades. We differentiate between periodic dynamics and event driven dynamics (below) based on the regularity, predictability and consistency of changes in either ecosystem services provision or appropriation.

Non-linear dynamics, in the following text called event driven dynamics, refers to systems that are affected by irregular perturbations of the provision or the demand of an ecosystem service. The irregularity may refer to either the amplitude or periodicity of perturbations. Events can be natural, such as floods, or can be the result of a change in management such as changing agricultural practices (Padmavathy and Poyyamoli, 2012). Event driven dynamics are not necessarily driven by system shocks or external perturbations. Linear changes to some system property may lead to sudden ecosystem service provision regime shifts—where a system flips to a new system state with different key functions and processes. For example, humans can linearly decrease resilience in an ecosystem by sequentially removing functionally redundant species from a system leading to a higher probability of regime shifts (Folke et al., 2004). The problem is in this case, that there might be a time lag between the dynamic of the ecosystem and the associated change in the provision of services. Therefore, the impending reduction in ecosystem services is unnoticed for a longer time, which results in an ongoing decrease of resilience and in an even stronger response of ecosystem services, making the detection of the causal connection of changes in the ecosystem and associated ecosystem services difficult to track (Folke et al., 2004). Event driven dynamics are perhaps not as obviously a 'system dynamic' as linear trends or periodic variations, because of their relatively unpredictable nature and the fact that any system may suffer some unforeseen perturbation. This begs the question what constitutes an ecosystem service with an event driven dynamic and an ecosystem service that might be influenced by some event? Here we argue for a pragmatic position based on the usefulness of the categorization from an operational perspective. Event driven ecosystem services dynamics relate to systems where events occur often enough for them to be considered important in the management of a particular ecosystem service.

2.2 Interactions of dynamics

It is important to note that these three broad dynamics do not necessarily occur in isolation from each other. For example, long-term linear trends in ecosystem service provision may be overlaid by short-term periodic variation, and interrupted by irregular events. Nor does the type of dynamic imply the time scale on which a temporal pattern occurs. This means that linear, periodic or event dynamics may occur at temporal scales ranging from days to several decades. All of three types of dynamics—linear, periodic and event—can occur across both the supply side, and demand side of ecosystems service provision and appropriation (Table 1). However, there is a wide variety within the given examples due to the fact that the existence of provision of ecosystem services often does not equal the appropriation of services by people in the system. Often, changes in ecosystem services are not recognized until people try to appropriate the service. Moreover, different temporal dynamics within the same ecosystem can influence each other by overlaying and disturbing each other. The following section discusses such supply and demand side dynamics for food provisioning and carbon sequestration.

Table 1. Examples for the categorization of temporal dynamics of ecosystem services.

	Linear		**Non-linear**
	Linear dynamics	**Periodic dynamics**	**Events**
Supply	Linear decline of the supporting service global biodiversity, shown by declining population trends and habitat extent as well as greater extinction risks (Butchart et al., 2010).	Crop failure in semi-arid regions of Eastern and Southern Africa caused by annual droughts every 10 years (Rockström, 2000).	Changing rate of carbon sequestered in the soil after a change in management on a field, e.g. from no tillage to tillage (Foereid and Hoegh-Jensen, 2004; Johnston et al., 2009; Smith, 2004).
Demand	Human appropriation of net primary production by conversion of natural vegetation to managed lands increased from 13% to 25% in the 20th century (Krausmann et al., 2013).	In the western Pamirs of Tajikistan, where fuelwood is an important source of energy, the demand for it is highest in winter, when people are heating their homes all day due to very low temperatures (Mislimshoeva et al., 2014).	The demand for products from the South American cinchona trees strongly increased when Jesuits discovered in the 17th century that they contain quinine, a treatment for malaria (Breedlove and Arguin, 2015)

2.3 Supply side and demand side dynamics

There are two important sources of temporal dynamics related to ecosystems services; biophysical dynamics related to the existence of ecological structures, processes and functions that can be appropriated by humans (as ecosystem services), and socio-economic dynamics related to how and when humans appropriate those structures, processes and functions (Abson et al., 2014). Following Burkhard et al. (2012) and Kroll et al. (2012), we will call these "supply side dynamics" and "demand side dynamics". For example, seasonal changes in daylight hours, or temperature, influence biomass production (supply side dynamics), and changing human populations or technological innovation influence the rate at which that biomass is appropriated from ecosystems (demand-side dynamics). Supply and demand side dynamics are not necessarily easy to separate. This is the case, for example, where the benefit is strongly co-produced via human interventions in ecosystems—as is the case in agricultural production as a provisioning ecosystem service. In agro-ecosystems changes in supply side dynamics are both driven by, and in turn drive, changes in the demand for and appropriation of those services.

Ecosystem service dynamics can have several drivers that play different scales. On large scales (the global scale), there are anthropogenic drivers such as climate change and natural drivers such as seasons, currents, El Nino etc. On smaller scales, there are anthropogenic and natural drivers as well. Small-scale anthropogenic drivers are management techniques such as cutting, burning and tillage whereas natural drivers are e.g. population dynamics.

3. Trends in the food and carbon sequestration literature

Our categorization of ecosystem services is therefore premised on the existent of three types of temporal dynamics (linear, periodic and event), which in turn may be driven by either the supply or demand side of ecosystem service provision and appropriation. Illustrative exemplars for each of these six categories of ecosystem services are outlined below. We would note that the categorizations are based on the dominant temporal dynamics in the example, but this does not mean that the other system dynamics were not also present. The primary purpose of the exemplars is to highlight the importance of capturing the described temporal dynamics in the description and management of the ecosystem services.

3.1 Linear supply-side dynamics

A linear increase in global cereal yields of 89% occurred between 1961 and 1986, followed by a slower increase of 31% in the time from 1987 to 2007. A linear increase in productivity of wheat on a global scale, ranging from 25% to 163% from 2000 to 2080, has been estimated (Ewert et al., 2005).

The supply of food is not only depending on adequate management, but also on the climate (Isik and Devadoss, 2006). Climate change has major impacts on the phenology of agricultural crop regions worldwide. The mean annual growing season for the tropical regions of Africa, South America, Asia and the eastern part of the US are predicted to become longer due to climate change. By contrast, shorter growing seasons are predicted for northern North America, northern Africa, northern India and South Asia (Brown et al., 2012). Considering these dynamics is important as a shortened growing season can have severe implications for the regions of northern Africa, northern India and South Asia as these regions show an increased vulnerability for reduced crop productivity, livelihood and food security (IPCC, 2014).

3.2 Linear demand-side dynamics

The demand for food production is increasing linearly. For example, worldwide undernourishment increased by 9% between 1990 and 2008 although global per capita food production increased at the same time (Barrett, 2010). The increasing demand for food production is also caused by changing diets, especially in countries like India and China. As the conversion efficiency of plant into animal matter is about 10%, increasing demand for meat makes it necessary to grow more feed. This increases the area that is used for agriculture, but also the intensification of management practices, for example, by using more mineral fertilizers, pesticides and irrigation (Godfray et al., 2010; Power, 2010). This increases yields in the short-term, but may lead to profound changes in ecosystems and decrease their long-term ability to provide food (Rodríguez et al., 2006). This is all the more severe as biofuels and rising living standards are predicted to enhance demand for food until 2030 (Funk and Brown, 2009). Therefore, recognizing these demand-side dynamics next to the supply-side dynamics is important to sustain food provision for the future in the light of globally increasing demand.

The need for carbon sequestration in agriculture and forestry as a way to mitigate climate change is in theory increasing, but this is not matched by the actual demand for these ecosystem services. There is a large gap between the need to sequester carbon and an actual demand for carbon sequestration that translates into alterations and management of ecosystem services to meet these demands which means that actually, carbon sequestration is useful for mitigating climate change, but only few incentives for management for carbon sequestration exist so far (Noormets et al., 2014). Moreover, while the amount of carbon sequestered in such systems may not have changed, human activity (the emissions of greenhouse gasses) has made such ecological functions increasingly valuable for humans. A previously ecological function has therefore been appropriated as an increasingly beneficial service for humans, without any change in the biophysical supply of this service. Seemingly paradoxically, the gap between actual and theoretically desirable supply could be closed by either stimulating demand (to supply the services from the suppliers' perspective) via the payment of ecosystem services schemes (Rodríguez-Entrena et al., 2012), or by lowering the demand (from the consumers perspective) by reducing the greenhouse gas emissions that turn these particular ecological functions into services.

As the demand for carbon sequestration is increasing, the need to take temporal dynamics into account is growing. We cannot assume that this ecosystem service will continue to be supplied at the current rate, or that the demand for it will remain constant. The degradation of ecosystems for short-term increases of the services they provide might lead to decreased ability to provide services in the future and in turn, influence the future demand for ecosystem services. Therefore, it is important to understand how these long-term linear trends will affect the ability of future generations to maintain their well-being, and to consider which sort of ecosystem services will be appropriated from ecosystems in the future.

3.3 Periodic supply-side dynamics

Carbon sequestration in tree plantations has clear periodic dynamics. During the first phase (when the saplings are initially planted), the system may be a net source of emissions due to carbon loss from vegetation and soil resulting from the disturbance related to the tree planting. This initial phase is followed by an accumulation period and a maturation period when carbon is stored in soils and trees at a high rate. Finally, the biomass within the plantation is appropriated by humans for timber, fire wood, building material etc., potentially resulting in a release of the previously stored carbon (Albrecht and Kandji, 2003).

On croplands, carbon sequestration is highly variable depending on the stage of growth. Apart from the first maximum in carbon sequestration related to high gross primary productivity during the growing phase of the crop, a second maximum after the harvest has been observed. This has been attributed to the fact that after the harvest, either inter-crops are grown on the field or weeds are spreading (Falge, 2002). However, the potential of crops for carbon sequestration in regions with pronounced seasonality is rather small in most cases, as the growing phase of most crops is restricted to a short time period. For example, agricultural fields in

Finland were shown to be carbon sinks for 40 days under barley production in contrast to 84 days under grass during the growing season. This resulted in a lower annual net ecosystem CO_2 exchange for grass caused by the longer period of CO_2 uptake (Lohila et al., 2004). Taking these dynamics into account is important as carbon sequestration can be used to mitigate climate change in a sustainable way. However, this is only the case if dynamics of the ecosystem structures providing this service will be taken into account.

3.4 Periodic demand-side dynamics

Since the first century BC, Bluefin tuna (*Thunnus thynnus*) was traditionally caught by the use of tuna traps in spring and summer as the fish are entering the Mediterranean sea for breeding (Garcia del Hoyo and Jimenez-Toribio, 2010). This traditional fishing method is perceived as more sustainable than industrial fishing (Florido-Corral, 2013). Usually, the first fishing period is from April to May when tunas are entering the Mediterranean Sea. The second fishing period takes place between June and August, when tunas have finished breeding and are returning to the Atlantic Ocean. However, tuna fattening farms expanded since 1995 and therefore, young fish were caught in large amounts to stock the farms (Garcia del Hoyo and Jimenez-Toribio, 2010). As a result, wild tuna populations declined. Therefore, catches from tuna traps diminished by 80% between 1999 and 2003 and traditional fishers struggle to catch an amount of fish that would be sufficient to secure their livelihood. Although there is a quota for Total Allowable Catch per year, tuna catches are severely under-reported, so that this measure is rather ineffective to protect the stock from declining (Esteban et al., 2016).

This example shows how long-term changes to an ecosystem service translate into a dramatic shift regarding how people are able to rely on this service. While the seasonal supply of tuna is declining, the seasonal demand of traditional fishers remains (Garcia del Hoyo and Jimenez-Toribio, 2010). If tuna populations further decline, this will have severe implications for their future well-being as they might not only lose their income, but also their cultural heritage (Florido-Corral, 2013). Especially regarding the intensification of food production, much of the debate is focusing on the sustainable use of ecosystem services (Loos et al., 2014; Tscharntke et al., 2012). However, fluctuations of food stocks and the associated consequences are part of intense discussions within the literature of ecological economics and associated fields (Anderson et al., 2008).

Paying attention to periodic dynamics is necessary to redesign the way in which ecosystem services are appropriated, particularly with regard to seasonal declines in food production and decadal natural climate variations that potentially impact both local and global food security (Chappell and LaValle, 2011). In the absence of detailed understanding of how to prevent undesirable management practices of ecosystem services with periodic dynamics and ensure the long-term provision of ecosystem services, there is a danger that the management of agro-ecosystems will not be suitable for changes in either demand or supply of food systems.

3.5 Events, supply-side dynamics

Events such as natural and managed forest fires have a strong impact on the carbon sequestration rate and the soil organic carbon stock of a forest. After a disturbance event, the level of carbon in the soil decreases immediately (Smith, 2004). The effects of a fire can last a long time after the event. The time it takes until a new equilibrium of soil organic carbon is approached after a disturbance is estimated at between 20 and 100 years (Foereid and Hoegh-Jensen, 2004; Johnston et al., 2009; Smith, 2004). Disturbances such as fires lead to changes in soil moisture and temperature regimes. Moreover, they cause succession of different species that vary in their quantities of carbon returned to the soil. Additionally, erosion increases after a fire event which destroys most of the older trees. Therefore, the potential of the soil to sequester carbon decreases (Lal, 2005).

Biotic drivers, such as pests and diseases, can cause events in food production. A prominent example occurred in Ireland between 1845 and 1850, when *Phytophthora infestans*, a fungal pathogen, eradicated almost the whole potato yield in five consecutive years (Fraser, 2003). Since society was highly dependent on potato yields, it was vulnerable to these crop failures which killed or displaced 25% of the Irish population. This vulnerability towards crop failure was in large parts due to socio-economic drivers. For instance, many people did not have non-agricultural income due to the shrinking linen-industry and many landlords did not grow grain on their fields as the grain prices had dropped. Therefore, many people were strongly depending on potato yields (Fraser, 2003). Static assessment of Irish potato yields in the year 1844 would have shown a well-functioning ecosystem service which would be a misguiding picture. Therefore, assessments of ecosystem service provision, e.g. ecosystem services modeling, should account for stochastic supply side risks. This would link the field of ecosystem services with other domains such as risk analysis and insurance. Creating deeper ties between these lines of thinking would surely be beneficial to enhance management options provided by the ecosystem services framework.

3.6 Events, demand-side dynamics

Increases in demand of an ecosystem service can also be caused by changes in policies. This was the case when in 2003 the EU Biofuels directive started to encourage member states to increase use of renewable fuels in transport up to 5.75% of the energy content of fuels until 2010 (European Commission 2003). This commitment was prolonged until 2020, with the goal of increasing the share of renewable fuels to 10% of the energy content (European Commission 2009). This policy has led to unexpected changes in the demand for feedstocks and to unforeseen land-use change (Anderton and Palmer, 2015). The increased share of biofuels in transport led to an increased demand for biofuels and therefore also for the feedstocks to produce them. This in turn has had an unexpected impact on ecosystem service provision (Dale et al., 2011). Land-use change caused by increasing area of monocultures for biofuels can have significant negative effects on biodiversity and ecosystem services such as pollination and pest control (Gardiner et al., 2010). Moreover, the prices of certain crops, especially rapeseed, are projected to increase. Higher food prices may in turn have severe implications on human well-being (Kim et al., 2013).

The risk for events on the demand side of ecosystem services is especially great, if risks on the supply side are added. Under the influence of climate change, extreme events such as droughts become more likely (IPCC, 2014). In 2008, for example, the Central Valley in California was severely impacted by drought and the resulting crop failure as well as a housing crisis. The effects of this "double exposure" created feedback links which made this crisis worse than the outcomes of its single parts (Leichenko et al., 2010). Many people working in the agricultural sector did not only lose their jobs, but also their houses. Additionally, the food prices increased and the financial crisis made farmers unable to borrow money for irrigation and seeds for drought-tolerant crops (Leichenko et al., 2010). This shows how demand side and supply side dynamics can interact and create new dynamics. Therefore, the vulnerability of an ecosystem towards several interacting factors and the long-term risk for events such as droughts need to be taken into account for the sustainable appropriation of ecosystem services.

4. Integrating temporal dynamics into the ecosystem services framework

In general, temporal dynamics still receive little attention in the ecosystem services literature, although there have been developments towards better integration of ecosystem service dynamics, e.g. by acknowledging that in a bundle of ecosystem services, different services can have different dynamics and that these dynamics also play an important role for stakeholders (see Hein et al., 2016; Sutherland et al., 2016). Currently across the ecosystem services literature from typologies (Chan et al., 2012; Johnston and Russell, 2011), valuation methods (Abson and Termansen, 2011) and assessments (TEEB, 2010), the issues of temporal variation in ecosystem services provision and appropriation is under researched. Therefore, we present four recommendations followed by four steps on how to integrate temporal dynamics into ecosystem service research.

Recommendation 1: Recognize that there are different types of temporal dynamics across all ecosystem services.

We identified three, potentially important, types of temporal ecosystem services dynamics (linear trends, periodic dynamics, irregular events) with each type of dynamic having both supply side and demand side drivers. Linear dynamics are continuous increases or decreases of ecosystem service supply or demand. Periodic dynamics are a special type of linear dynamics that show oscillations of the supply or demand of an ecosystem service around a mean value. Events are perturbations of the provision of, or demand for, an ecosystem service which occur occasionally and are, in contrast to periodic patterns, not steadily repeated.

While we have used food and carbon as illustrative examples, such dynamics can be expected from many different ecosystem services. Examples of temporal dynamics occurring in other ecosystem services include biodiversity (as a supporting ecosystem service) that is linearly declining on a global scale (Butchart et al., 2010), periodically varying demand for fuel wood in Tajikistan (Mislimshoeva et al., 2014) and event driven demand for specific species resulting from new uses of those species (for example, the increased demand for cinchona tree products after the discovery of their effectiveness as a treatment against malaria was detected (Breedlove and Arguin, 2015)). Focusing on creating a more established line of thinking between assessment of such dynamics and effective inclusion in mapping or valuation studies would be highly beneficial, and we propose that this highlights a clear future research agenda for the overall ecosystem service framework.

Recommendation 2: Recognize the difference between the supply and demand sides of ecosystem services.

As we have shown, different temporal dynamics exist in ecosystem service supply and demand. Therefore, future research has to consider system dynamics in the conceptualization, biophysical assessment and valuation of ecosystem services. Existing trends or possible events in ecosystem services provision have to be considered. The examples of the Irish potato blight (Fraser, 2003) and the crisis of the Californian Central Valley caused by double exposure to extreme drought and the financial crisis (Leichenko et al., 2010) show that even seemingly stable systems can rapidly collapse. Moreover, in both these cases the linear trends in demand (increasing yields over time) actually decreased the ability of these system to supply these ecosystem services in response to specific system perturbations (disease outbreaks and drought).

Recommendation 3: Recognize temporal grain.

It is necessary to move away from static assessments of ecosystem services (Birkhofer et al., 2015). This can be done by combining short-term studies with long-term studies. Short-term studies provide insights into immediate or potential changes in ecosystem services provision and their impacts on human well-being whereas long-term studies are useful to track linear temporal dynamics and inter-annual variations in ecosystem service supply caused by environmental conditions (Birkhofer et al., 2015) or temporal changes in ecosystem service demand.

At the moment, short-term studies on ecosystem services are prevalent. This may in part be due to a lack of long-term data on ecosystem service provision and appropriation that would allow meaningful analyses over long time periods. This issue is aggravated by the preponderance of funding schemes limited to a few years (Birkhofer et al., 2015). There is a need to establish long-term monitoring of ecosystem services, e.g. to reveal temporal trade-offs between different services (Rodríguez et al., 2006). The evaluation of ecosystem services through bundles of indicators is a very promising approach (Burkhard et al., 2012).

Recommendation 4: Recognize that the drivers of ecosystem service dynamics occur at multiple spatial scales

To distinguish between ecosystem services dynamics, it is helpful to differentiate between drivers. As we have shown, drivers can occur at multiple scales and be of natural or anthropogenic origin. Identifying the drivers of ecosystem services is especially important for their management. Typical anthropogenic drivers on a global scale are increasing CO2 values in the air, as shown by the Keeling curve of CO2 values measured at the Mauna Loa volcano and climate change causing increased average temperature on earth and higher climate variability (IPCC, 2014). An increasing CO2 level in the atmosphere can have strong effects on ecosystem services provided by coral reefs (Okazaki et al., 2017). Higher climate variability can lead to drought and flood events that also have a strong impact on ecosystems and the services they provide (IPCC, 2014). As small-scale drivers, anthropogenic drivers and natural drivers can be distinguished. An example for anthropogenic drivers is the change from conventional tillage to no-till agriculture leading to an increase in carbon sequestered by the agricultural field (West et al., 2004) whereas carbon sequestration due to ecological succession dynamics in different stages of forest growth (e.g. Sutherland et al., 2016) is an example for natural drivers. Recognition of temporal dynamics has the potential to increase sustainable management of ecosystem services and to maximize intergenerational equity. To facilitate better accounting of temporal dynamics in future research on ecosystem services, we propose the following four steps for future ecosystem services research.

Step one: How can appropriate temporal boundaries of the system be identified?

This requires consideration over what time period appropriation of ecosystem services should be assessed. Moreover, appropriate temporal scales must consider both supply and demand side dynamics. Supply side dynamics largely relate to the ecological structures, processes and functions that can be appropriated by humans whereas demand-side dynamics are related to how and when humans appropriate those structures, processes and functions.

Step two: Which key types of dynamics (linear, periodic, event) occur within the particular system?

In addition to identifying the dominant dynamics (both demand and supply side), potential thresholds, interactions and feedbacks between such dynamics should be considered. This temporal mapping of ecosystem service provision and appropriation should be considered as a compliment to call for increased spatial mapping in the ecosystem services literature over the last ten years.

Step three: On which spatial scale do the dynamics play out in the system?

As the dynamics depend on the spatial scale, it needs to be clarified, if a dynamic is looked at on a local, regional or global scale and how the spatial scale influences the type of temporal dynamics present in a particular system of interest.

Step four: Which measures are appropriate for assessing these temporal dynamics and their impact on human well-being?

For example, to account for the possibility of crop failures in the assessment of the value of different food provision services, the depletion of natural capital and sustainability over the long-term should be taken into account. The existing large bodies of literature on risk analysis and systems dynamics may be highly beneficial here in developing new methods for temporally explicit ecosystem services assessment and valuation.

Considering temporal dynamics of ecosystem services by following these steps might help in the long-term management of ecosystem services by giving the opportunity to better account for the event driven perturbations, periodic changes and long-term linear dynamics in both the provision of and demand for ecosystem services. Mapping such temporal patterns would enable better planning of ecosystem services management and aid in the development of new management strategies that suit the given dynamics. This would result in more sustainable management of ecosystem services and enhanced human well-being.

5. Decision support systems for adaptive management of ecosystem services

If temporal dynamics of ecosystem services are to be accounted for in policy contexts, more adaptive management approaches and practical decision tools are required. Such tools and approaches should be underpinned by scientific knowledge from scenario analysis, ecosystem services valuation and mapping and involving stakeholders affected by a decision process (Turner, 2016a). Therefore, in the following, we will present decision support systems that might be applied in the context of managing temporal dynamics in ecosystem service provision and appropriation.

The Driving Force-Pressure-State-Impact-Response (DPSIR) framework for the analysis of social-ecological systems was developed by the OECD (Organization for Economic Cooperation and Development) based on the Pressure-State-Response (PSR) framework introduced by Rapport and Friend (1979). This framework is used as a tool for structuring and communicating information about the interaction between society and the environment, e.g. by the European Environmental Agency (EEA, 2005). Driving forces are changes in the social or economic systems which trigger pressures on the state of ecosystems (Binimelis et al., 2009). Incorporating ecosystem services dynamics into such a framework would provide a more nuanced understanding of the state of the ecosystem supply while a focus on appropriate temporal scales, or grains, for both natural and anthropogenic drivers of ecosystem service dynamics would help determine suitable temporal boundaries for the DPSIR framework in relation to ecosystem service management. This in turn may lead to policies or altered management of ecosystems (Albert et al., 2015; Binimelis et al., 2009; Schenk et al., 2007; Stanners et al., 2007). Similarly, a focus on the temporal dynamics of ecosystem services would determine a suitable scale for considering the impacts from those changed policy responses.

Moreover, recognition of temporal dynamics in ecosystem services demand and supply is potentially useful regarding cost benefit analysis (CBA) when dealing with long-term management of ecological resources. Understanding patterns of temporal change in ecosystems services would inform attempts to discount future costs and benefits of different ecosystem service bundles. Discounting is a decision tool that compares future costs and benefits for different points in time (Turner, 2016b). High discount rates over long time frames reduce the net present value of costs and benefits in the distant future. Therefore, selecting the appropriate time frame that is considered in the management of ecosystem services is important (Turner, 2016b). A standard approach to discounting may mean, for example, that reducing short-term periodic or event driven decreases in ecosystem services is valued more highly than long-term linear declines. However, given that many ecosystem services (such as nutrient cycling, or biodiversity based resilience) do not have meaningful substitutes, and that often the demand of ecosystems services also changes over time, we would suggest that CBA may need to set different discount rates for ecosystem services with different temporal dynamics.

Finally, the balance sheet approach includes economic analysis, environmental analysis, equity and equality concerns and multiple stakeholder perspectives (Turner, 2016a). Therefore, it is especially suitable for highly contested environmental decisions. It can combine Cost-Benefit-Analysis (CBA) with distributional analysis to determine who wins or loses in a tradeoff situation. A temporal focus on ecosystem service supply and demand fits well with both the distributional focus of the balance sheet approach and its focus on both economic (e.g. market – based data and willingness-to-pay) and ecological information (Turner, 2016a). Including temporal dynamics in the multi-criteria trade-off analysis (the third balance sheet), could be helpful when comparing, for example, event based instability in ecosystem service appropriation compared to long-term linear changes. Here temporal trade-offs could be considered, in addition to the trade-offs between the provision of different ecosystem services at a single point in time.

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

Rau, A.-L., Burkhardt, V., Dorninger, C., Hjort, C., Ibe, K., Keßler, L., Kristensen, J.A., McRobert, A., Sidemo-Holm, W., Zimmermann, H., Abson, D.J., von Wehrden, H., Ekroos, J., 2019. Temporal patterns in ecosystem services research: A review and three recommendations. Ambio 1–17. https://doi.org/10.1007/s13280-019-01292-w

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.

1. 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 (Abson and Termansen, 2011; Birkhofer et al., 2015; Kremen, 2005), 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 (de Groot et al., 2010; Fisher et al., 2009). 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) 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 (Hicks et al. 2013, Reed 2008). 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 conceptualized 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?

2. Methods

2.1 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 (Figure 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 (Figure 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 (Figure 1). The obtained full texts were assessed using 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 Figure S1).

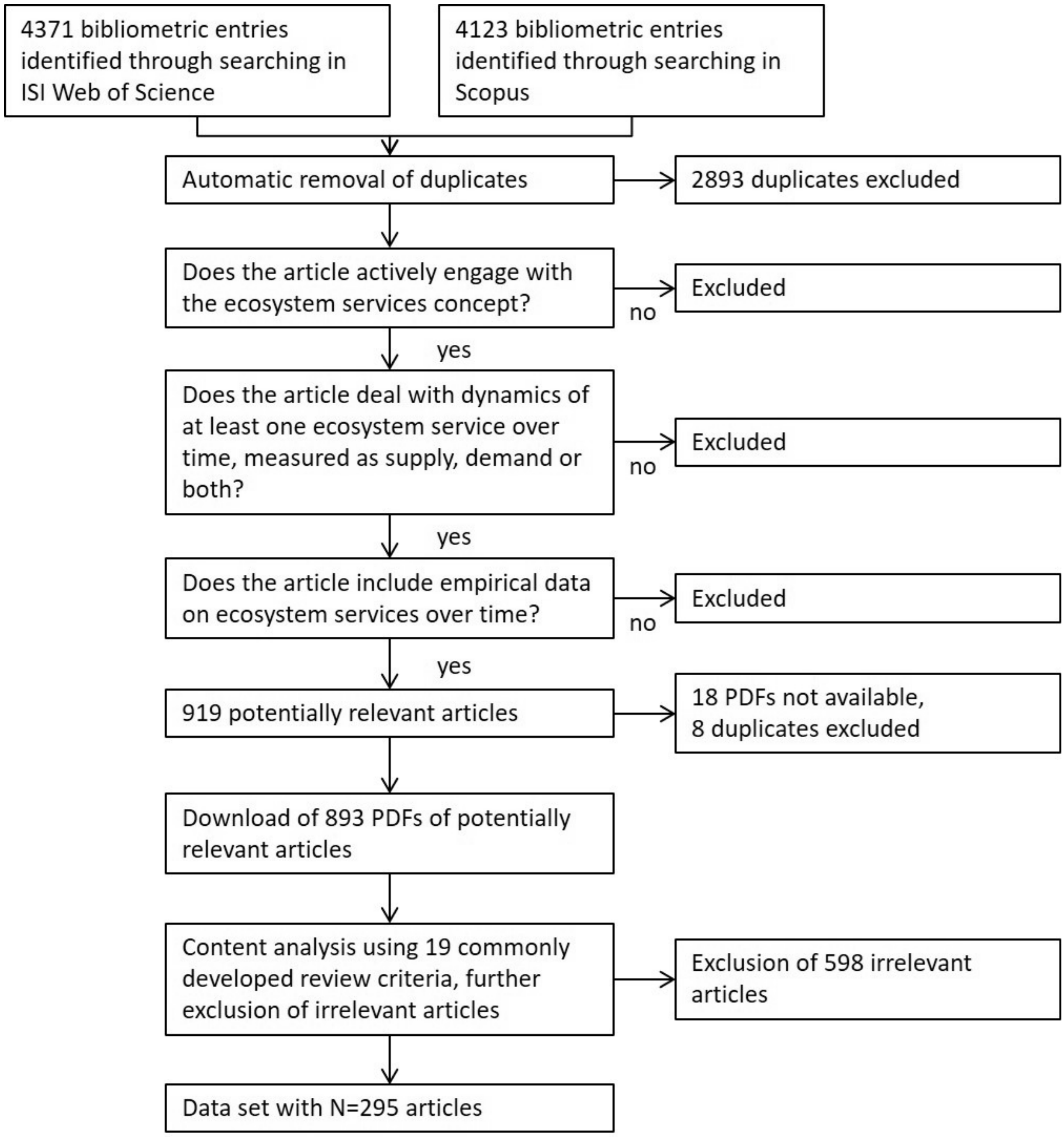

Figure 1. Review procedure

2.2 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.

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).

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, 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).

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 include 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 (Figure 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 Potschin, 2010, Figure 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 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.

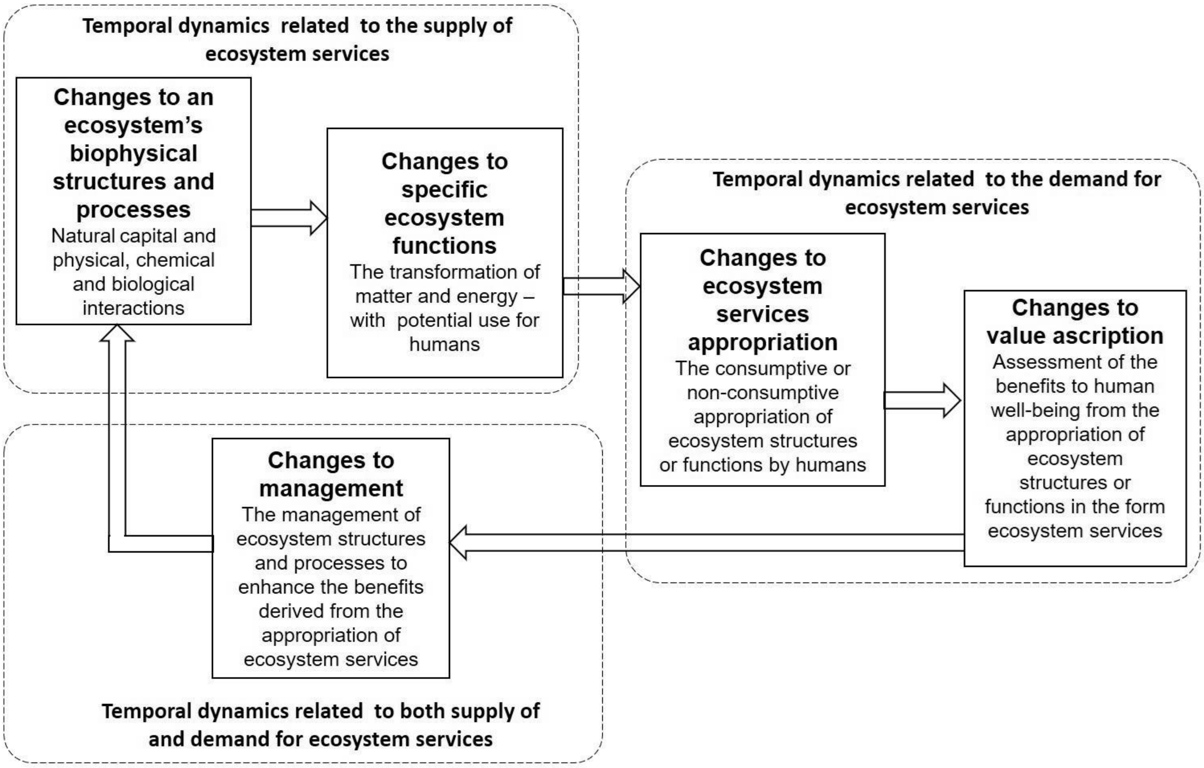

Figure 2. Supply and demand in the ecosystem services cascade (adapted from Haines-Young and Potschin, 2010).

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 includes 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. 2018). 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 organizations. 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 visualize 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 maximizing within-group similarity and minimizing among-group similarity (Legendre & 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 & 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.

3. Results

3.1 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 14931 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) (Figure 3).

Figure 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.

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 (Figure 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 (Figure 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 Figure S1).

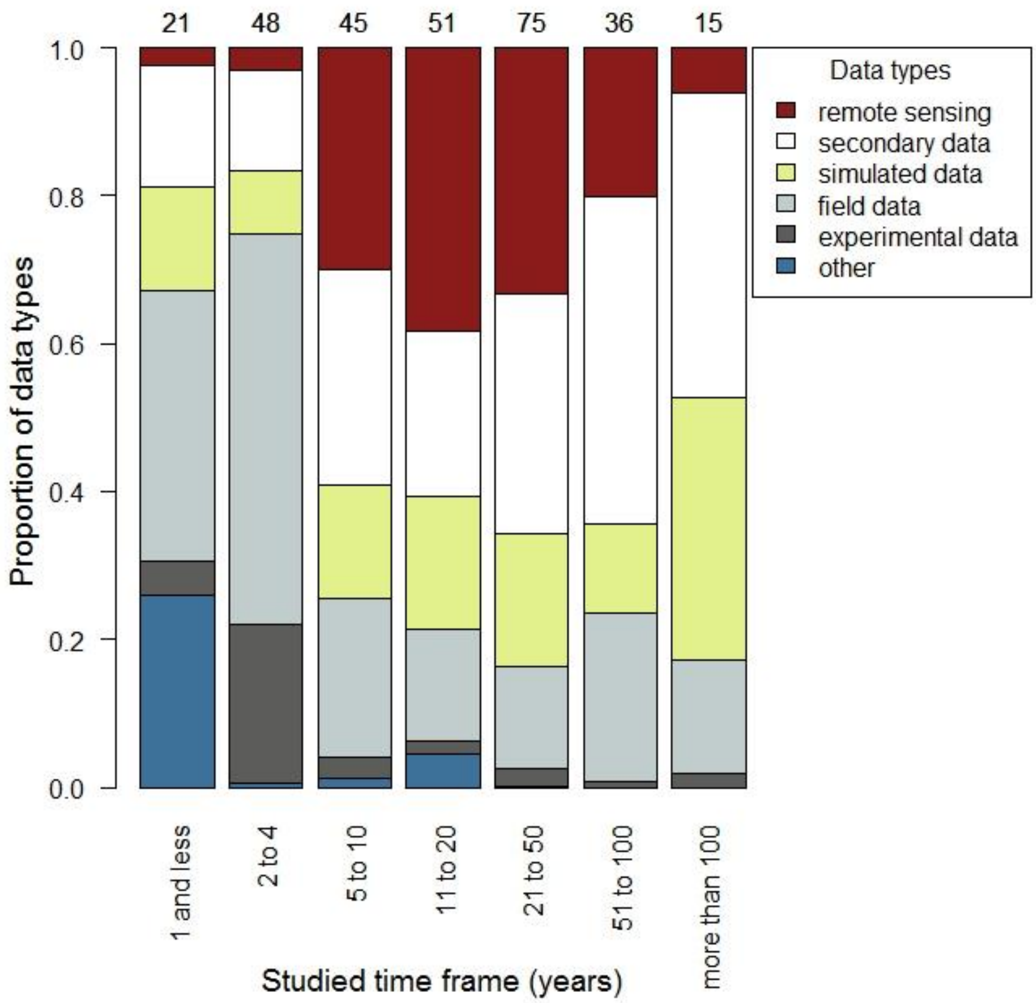

Figure 4. Research methods (data types) used in research on temporal aspects in ecosystem services in relation to time frames of the studies, i.e. the span of years that was analysed in a study. Proportions are given for frequencies in which different data types were used (note that one study might be 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.

3.2 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 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.

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 one 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%)

3.3 Temporal patterns of ecosystem services

3.3.1 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.

3.3.2 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 (Figure 5 and Appendix S6).

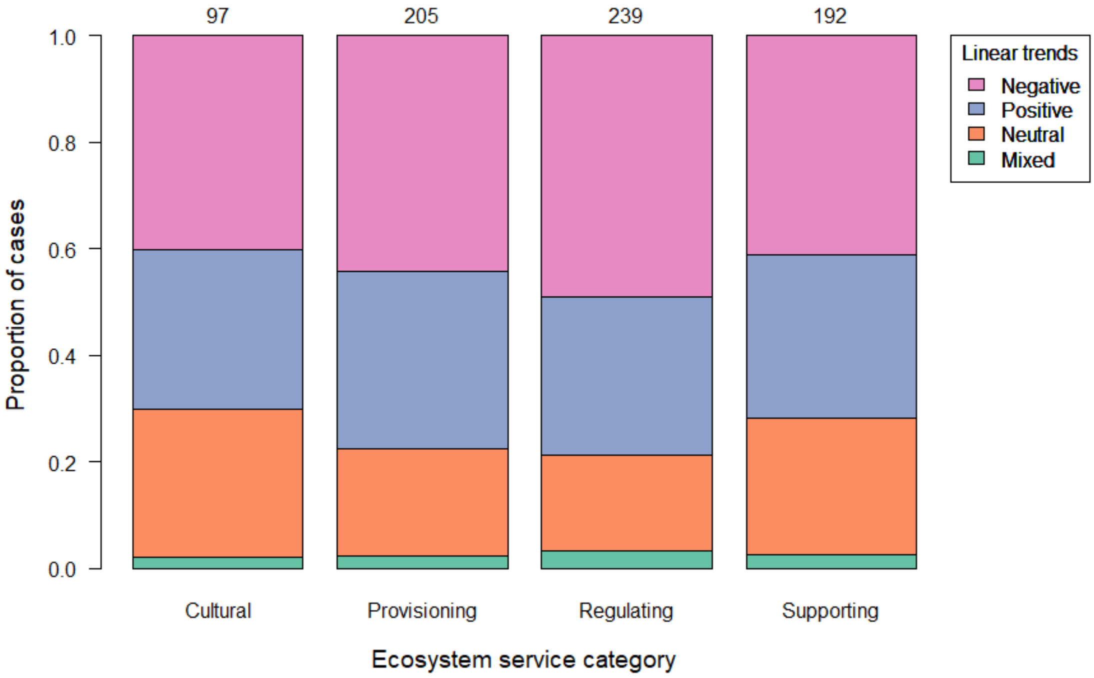

Figure 5. Linear trends in ecosystem services divided into MEA categories. “Mixed” means that more than one type of linear trend is given per case.

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 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.

3.3 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) (Figure 6, upper panel). In cases focusing on the supply of ecosystem services over time, human dependency on ecosystem services was rarely mentioned (Figure 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).

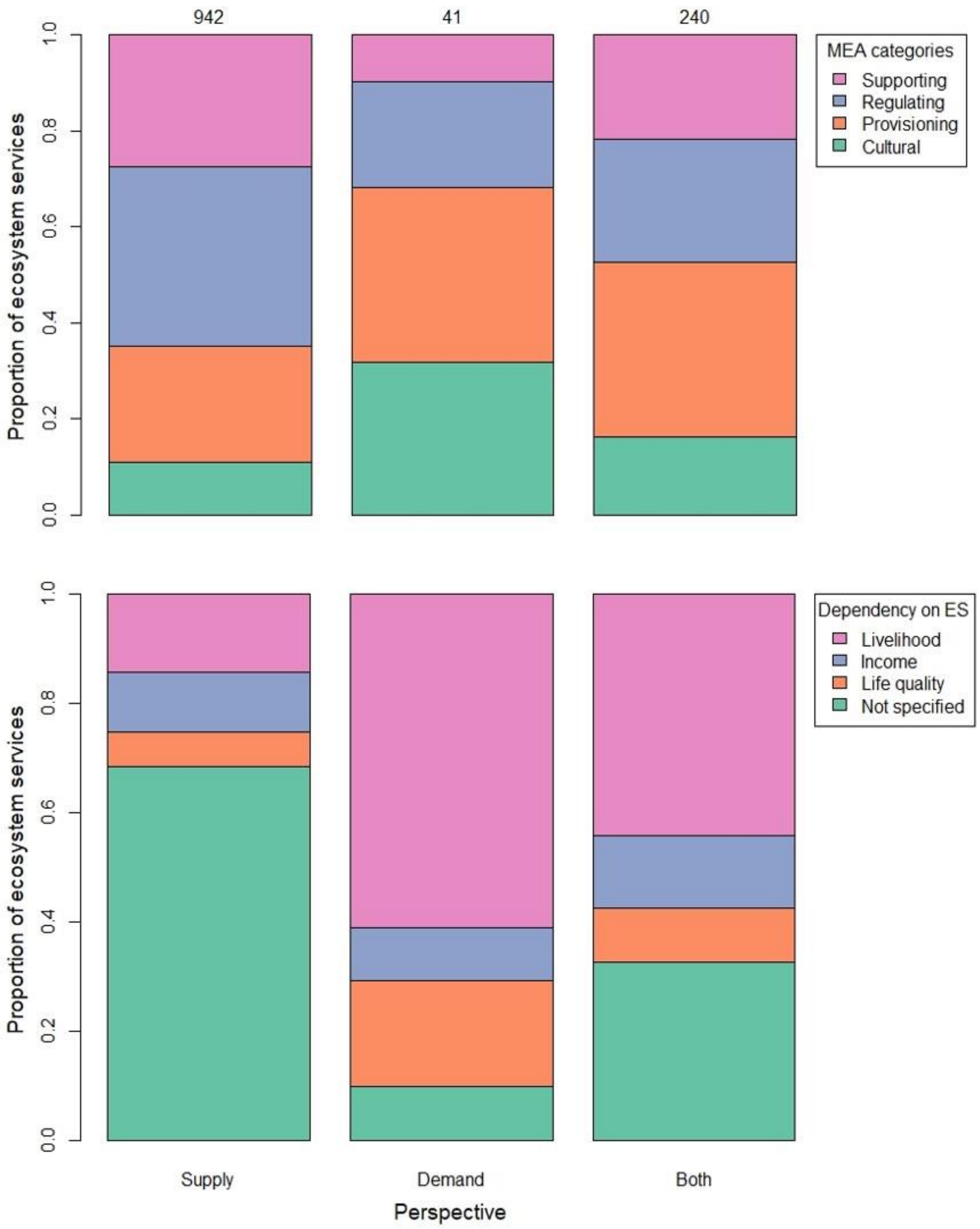

Figure 6. The distribution of ecosystem services included in studies on temporal patterns in ecosystem services in relation to supply and demand, separated according to MEA categories (Figure 6, upper panel), and human dependency on ecosystem services in relation to supply and demand (Figure 6, lower panel).

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.

4. 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 characterized 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 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 biophysically sustainable supply.

4.1Temporal 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 four years, in response to sown flower plantings on farms with insect-pollinated crops (Blaauw & 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 & 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).

4.2 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.

4.3 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 non-linear 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.

4.4 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., Maes et al., 2012; Raudsepp-Hearne et al., 2010; Rodríguez et al., 2006). 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.

5. 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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Appendices

Appendix S1

Search string in Web of Science

(TS=("ecosystem servic*" AND tempo*) OR TS=("ecosystem servic*" AND time*) OR TS=("ecosystem servic*" AND dynamic*) OR TS=("ecosystem servic*" AND season*) OR TS=("ecosystem servic*" AND period*) OR TS=("ecosystem servic*" AND episod*) OR TS=("ecosystem servic*" AND linear)) *AND* LANGUAGE: (English) *AND* DOCUMENT TYPES: (Article)

Search string in Scopus

TITLE-ABS-KEY("ecosystem servic*" AND tempo*) OR TITLE-ABS-KEY("ecosystem servic*" AND time*) OR TITLE-ABS-KEY("ecosystem servic*" AND dynamic*) OR TITLE-ABS-KEY("ecosystem servic*" AND season*) OR TITLE-ABS-KEY("ecosystem servic*" AND period*) OR TITLE-ABS-KEY("ecosystem servic*" AND episod*) OR TITLE-ABS-KEY("ecosystem servic*" AND linear) AND (LIMIT-TO(DOCTYPE,"ar")) AND (LIMIT-TO(LANGUAGE,"English"))

Appendix S2

Review manual

General rules:

- In a dropdown menu with 1/0, write 1 if the category applies and 0 if it does not apply.
- Please do not just leave the cell empty.
- No data: NA, not 0
- Value 0: e.g. term mentioned 0 times: 0
- Separate terms by semicolon, not by comma.

Table Appendix S2. Rules for filling out specific categories.

Category number	**Heading**	**Name of category**	**Explanation**
6	Included (old)	Included (old)	Already filled out
7	Included (new)	Included (new)	Is this paper after looking at the PDF still relevant? Choose between yes and no.
8	Reason for inclusion	comment	Here reviewer 1 commented, if a paper without empirical data was interesting for the discussion or, in case there was a “maybe” in column J, gave a justification.
9	Location	Fill in coordinates	Either take coordinates from the paper, if they are given, or look up coordinates in Google Maps and fill in as decimal degrees: e.g. 53.254525, 10.406294. If it is a whole country, write the name of the country. If it is a continent or global, write the name of the continent or “global”. If there are several locations, separate by semicolon.
10	Data	remote sensing; field samples/observations; experimental data; secondary data; simulated data	Choose from the given options. If more than one option applies, separate by semicolon. Secondary data: e.g. from administrations, data from other people that is not published yet.
11	Ecosystem services types	Give ecosystem services *for which temporal dynamics are given*. Fill in terms for ecosystem services according to Wilkinson 2013 page 4	Please write the terms exactly as in this table and separate them by semicolon. Multiple hits are possible.
12	Ecosystem services end	supply	Write a 1, if the paper deals with the supply side of ecosystem services (biophysical side).
13	Ecosystem services end	demand	Write a 1, if the paper deals with the demand side of ecosystem services (human/social side).
14	Dependency	To which extent people are depending on ES	Options are “lifelihood; income; life quality;not specified”. This category only applies for people who are immediately affected by ES. Multiple hits are possible.
15	Ecosystem services cascade	Possible answers are: “structure; function/process; benefit; valuation; management”	Write a 1, if the stage of the ecosystem service cascade is investigated in the paper. Stages: - Structure: e.g. whole ecosystem or just one part of it, e.g. single tree - Function/ process: ecosystem function, e.g. photosynthesis - Benefit: humans getting a benefit from the structure or function - Value: a valuation is given for the benefit. E.g. economic or social.

			- Management: Management practices that directly or indirectly modify ecological structures. According to: E. Brink et al. / Global Environmental Change 36 (2016) 111–123, p. 113 (in Dropbox “Full-text review” folder)
16	Temporal dynamics linear	linear	Does the paper describe a linear supply or demand for an ecosystem service which was measured? Write a 1, if this is the case.
17	Temporal dynamics linear	Linear trend	Choose between “positive; negative; neutral; not specified”. Positive: upward trend Negative: downward trend Neutral: staying the same
18	Temporal dynamics linear	Linear corresponding ES	For which of the studied ecosystem services is the linear pattern described? Write names according to Wilkinson 2013 and separate by semicolon.
19	Temporal dynamics periodic	periodic	Does the paper describe a periodic supply or demand for an ecosystem service which was measured? Write a 1, if this is the case.
20	Temporal dynamics periodic	Periodic corresponding ES	For which of the studied ecosystem services is the periodic pattern described? Write names according to Wilkinson 2013 and separate by semicolon.
21	Temporal dynamics periodic	Periodic subcategory for observed dynamics	Choose between “daily;monthly;seasonal;annual;decade;century;other”. If you choose “other”, please specify. Separate by semicolon. Multiple hits possible.
22	Temporal dynamics event	event	Does the paper describe an event for supply or demand of an ecosystem service which was measured? Write a 1, if this is the case.
23	Temporal dynamics event	event corresponding ES	For which of the studied ecosystem services is the event described? Write names according to Wilkinson 2013 and separate by semicolon.
24	Temporal dynamics categorical	categorical	Does the paper describe a categorical pattern (= a change between only two measurements) for supply or demand of an ecosystem service which was measured? Write a 1, if this is the case.
25	Temporal dynamics categorical	categorical corresponding ES	For which of the studied ecosystem services is the categorical pattern described? Write names according to Wilkinson 2013 and separate by semicolon.
26	Temporal scale	Choices are “=<1y”, “>1<=10y”, “>10<=100y”, “>100 y”	“=<1y”: temporal dynamic has been observed for up to 1 year “>1<=10y”: temporal dynamic has been observed for between more than 1 and up to 10 years “>10<=100y”: temporal dynamic has been observed for between more than 10 and up to 100 years

			“>100 y”: temporal dynamic has been observed for more than 100 years Put a 1 for the time scale that is investigated in the paper. If different ES are observed on different time scales. Multiple hits are possible. Separate by semicolon.
27	Stakeholder involvement	Were stakeholders involved? Choices: “information”; “consultation”; “collaboration”; “empowerment”	Classification (Brandt et al. 2013): - No involvement: no stakeholders were involved - Information: e.g. presenting your research to stakeholders - Consultation: getting information from stakeholders, e.g. by doing interviews or questionnaires - Collaboration: exchanging knowledge - Empowerment: giving stakeholders the knowledge and power to act independently Multiple hits possible. Separate by semicolon.

Appendix S3

Review categories

Category number		Name of category	Explanation
1	Author		
2	Title		
3	Journal		
4	Year		
5	Abstract		
6	Included (old)	Included (old)	Was the paper classified as potentially relevant by reading the abstract? (yes/no/maybe)
7	Included (new)	Included (new)	Is this paper after looking at the PDF still relevant? (yes/no)
8	Reason for inclusion	Comment	Comment by the reviewer, e.g. if a review or conceptual paper was interesting for discussion.
9		Location	Coordinates copied from Google Maps where a specific location was given. Otherwise names of larger regions such as “Europe”.
10	Data	Type of data	remote sensing; field samples/observations; experimental data; secondary data; simulated data (multiple answers possible)
11		Ecosystem services types	Terms for ecosystem services according to Wilkinson 2013 page 4.
12		Ecosystem services end: supply	If the paper deals with the supply side of ecosystem services (biophysical side) (1/0).

13		Ecosystem services end: demand	If the paper deals with the demand side of ecosystem services (human/social side) (1/0).
14		Dependency: To which extent people are depending on ES	Options are “lifelihood; income; life quality;not specified”. This category only applies for people who are immediately affected by ES. Multiple answers are possible.
15		Ecosystem services cascade	Stages: - Structure: e.g. whole ecosystem or just one part of it, e.g. single tree - Function/ process: ecosystem function, e.g. photosynthesis - Benefit: humans getting a benefit from the structure or function - Value: a valuation is given for the benefit. E.g. economic or social. - Management: Management practices that directly or indirectly modify ecological structures. According to: E. Brink et al. / Global Environmental Change 36 (2016) 111–123, p. 113
16		Temporal dynamics linear	Does the paper describe a linear supply or demand for an ecosystem service which was measured? (1/0)
17	Temporal dynamics linear	Linear trend	Possible answers are: “positive; negative; neutral; not specified”.
18	Temporal dynamics linear	Linear corresponding ES	For which of the studied ecosystem services is the linear pattern described? Names according to Wilkinson 2013. Multiple answers are possible.
19		Temporal dynamics periodic	Does the paper describe a periodic supply or demand for an ecosystem service which was measured? (1/0)
20	Temporal dynamics periodic	Periodic corresponding ES	For which of the studied ecosystem services is the periodic pattern described? Names according to Wilkinson 2013. Multiple answers are possible.
21	Temporal dynamics periodic	Periodic subcategory for observed dynamics	Possible answers are: “daily;monthly;seasonal;annual;decade;century;other”. Multiple answers possible.
22		Temporal dynamics event	Does the paper describe an event for supply or demand of an ecosystem service which was measured? (1/0)
23	Temporal dynamics event	Event corresponding ES	For which of the studied ecosystem services is the event described? Names according to Wilkinson 2013. Multiple answers are possible.
24	Temporal dynamics categorical	Temporal dynamics categorical	Does the paper describe a categorical pattern (= a change between only two measurements) for supply or demand of an ecosystem service which was measured? (1/0)
25	Temporal dynamics categorical	Categorical corresponding ES	For which of the studied ecosystem services is the categorical pattern described? Names according to Wilkinson 2013. Multiple answers are possible.

26	Temporal scale	Temporal scale Choices are “=<1y”, “>1<=10y”, “>10<=100y”, “>100 y”	Temporal dynamic has been observed for (possible answers): - Up to one year - 1 to 4 years - 5 to 10 years - 11 to 20 years - 21 to 50 years - 51 to 100 years - More than 100 years Multiple answers possible.
27		Stakeholder involvement	Classification (Brandt et al. 2013): - No involvement: no stakeholders were involved - Information: e.g. presenting your research to stakeholders - Consultation: getting information from stakeholders, e.g. by doing interviews or questionnaires - Collaboration: exchanging knowledge - Empowerment: giving stakeholders the knowledge and power to act independently Multiple answers possible.

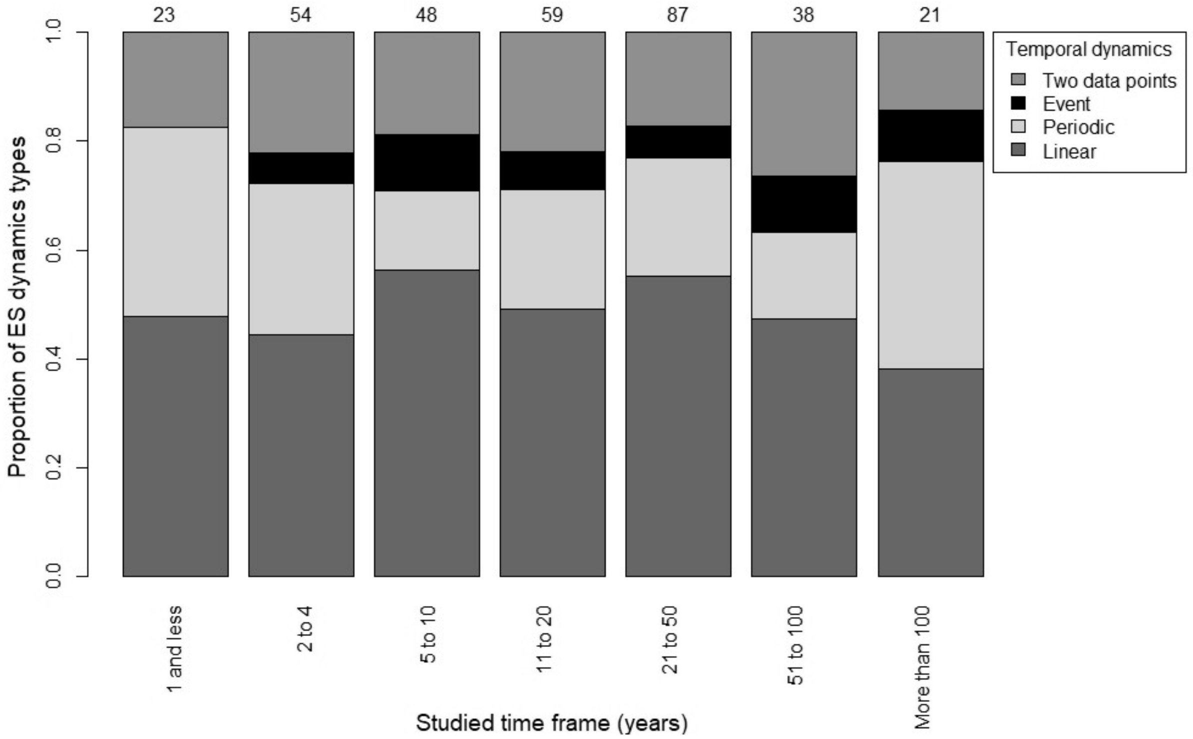

Figure S1. Distribution of temporal dynamics over the different time frames. No clear pattern is visible.

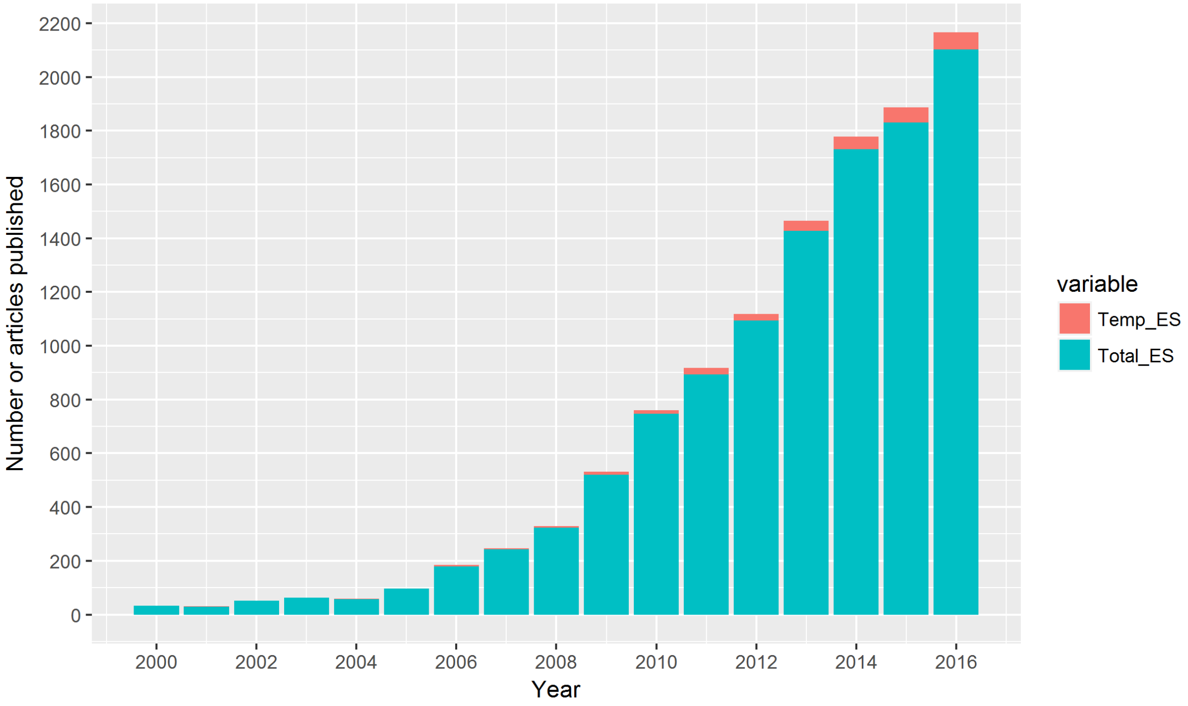

Figure S2. Development of research on temporal dynamics of ecosystem services (red) in relation to research on ecosystem services in total (blue).

Appendix S4

Reviewed literature

Group 1

Frazier, M. R., Lamberson, J. O., & Nelson, W. G. (2014). Intertidal habitat utilization patterns of birds in a Northeast Pacific estuary. Wetlands ecology and management, 22(4), 451-466.

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Group 2

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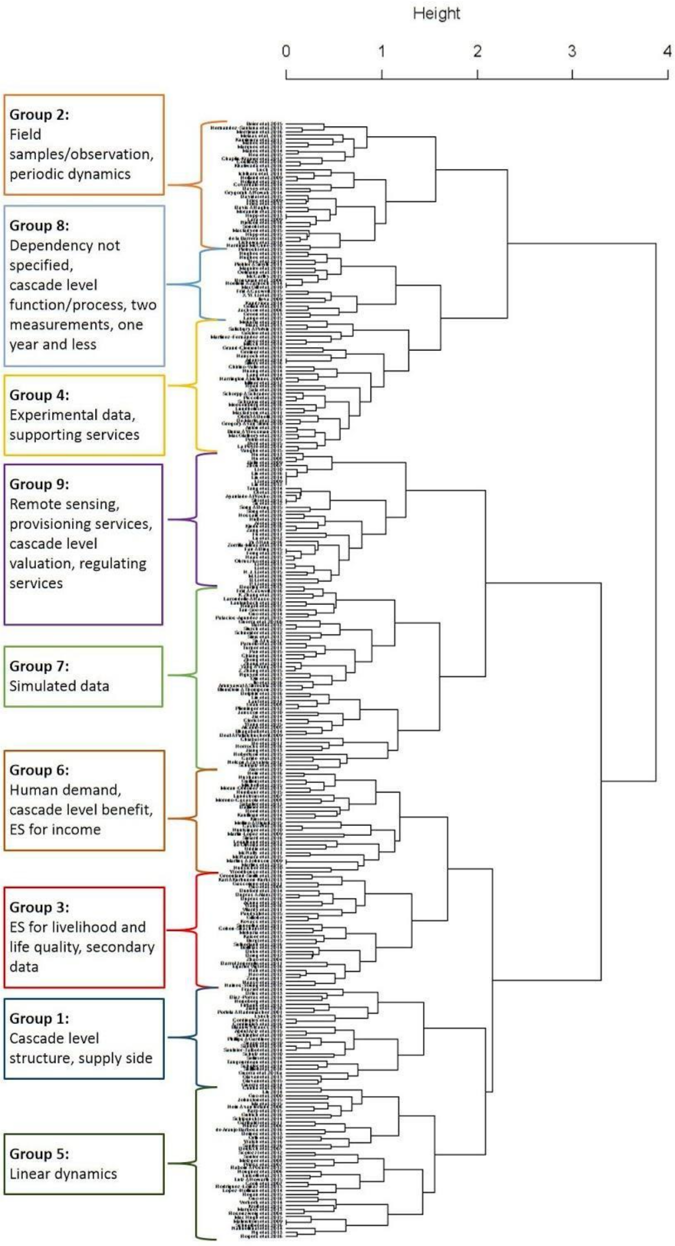

Figure S3. Dendrogram resulting from the cluster analysis. All 295 papers from our literature search were sorted into clusters that can be significantly described by the indicators on the left. A list of all papers in each group can be found in supplementary material B.

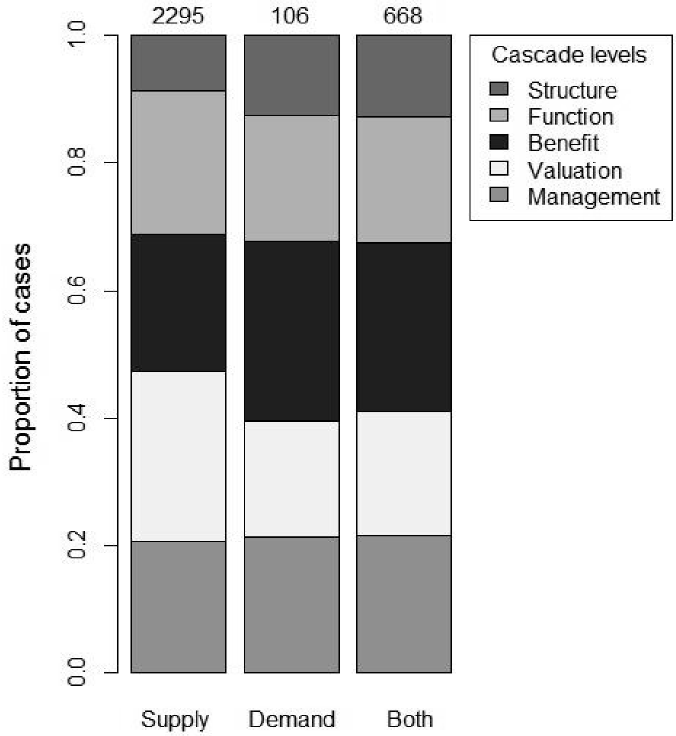

Figure S4. Levels of the ecosystem services cascade divided into supply and demand side.

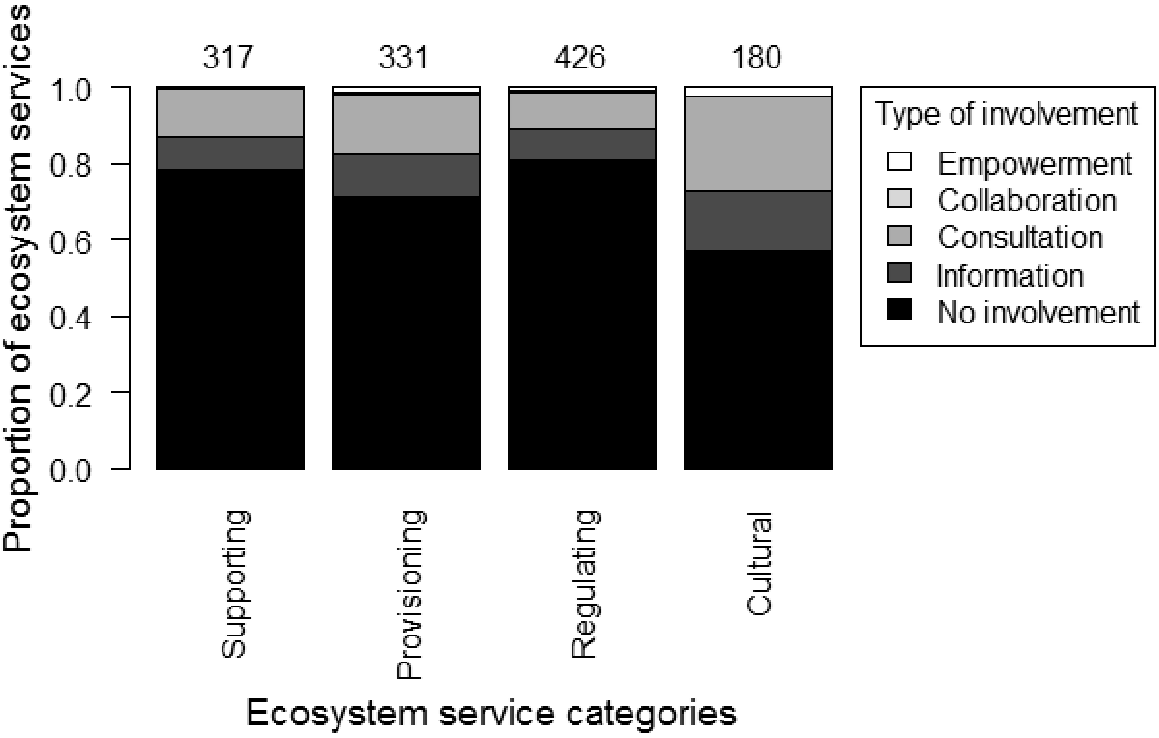

Figure S5. Type of stakeholder involvement (according to Brandt et al., 2013) per ecosystem service category (according to Millennium Ecosystem Assessment, 2005) studies focused on. Absolute number of ecosystem services per category are given on top of the bars.

Appendix S5. Dominating ecosystem service types studied concerning linear changes over time.

	Positive	Negative	Neutral	Mixed
Provisioning services				
food – agriculture	22	20	9	2
water – fresh water	5	22	11	2
fiber	11	16	5	1
food – commercial fishing	13	12	6	
fuel	9	9	6	
Regulating services				
erosion regulation/soil retention	15	16	12	1
climate regulation – local	13	20	5	1
water purification/waste treatment	11	23	4	1
water regulation	14	14	6	
air quality regulation		18		1
Supporting services				
biodiversity	11	33	17	1
nutrient cycling – carbon	15	10	6	1
soil formation	7	17	4	1
primary production	10	6	5	
nutrient cycling – nitrogen	6	5	6	1
Cultural services				
recreation and eco-tourism	15	27	9	1
cultural landscape/heritage values	2	3	8	1
educational and knowledge	5	4	5	
aesthetic	5	4	2	
spiritual and religious values		1	1	

Appendix S6. Description of periodic and non-linear temporal changes in ecosystem services over time

Periodic temporal changes in ecosystem services

Most periodic dynamics described regulating services (61 cases), followed by supporting (41 cases) and provisioning (34 cases) services. Cultural services only comprised 6 cases of periodic dynamics. Apart from a few exceptions, the most frequently studied ecosystem services were the same compared to those showing monotonic, linear trends over time. Individual cases describing periodic dynamics in provisioning services were dominated by food production (21 cases) and water provisioning (8 cases). Erosion regulation (13 cases) and water regulation (11 cases) dominated amongst regulating services, whereas nutrient cycling (23 cases) and biodiversity (10 cases) dominated amongst supporting services. Periodic dynamics of cultural services were only described concerning recreation and eco-tourism (4 cases) and aesthetic services (2 cases).

Non-linear temporal changes in ecosystem services

In total 23 studies presented 35 cases of ecosystem services with non-linear dynamics over time, i.e. changes characterized by events. The majority of the services studied were regulating (15 cases) and provisioning (12 cases). Water regulation and erosion regulation dominated amongst regulating services (four cases each), whereas food dominated amongst provisioning services (five cases). Seven cases concerned supporting services, four of which concerned biodiversity. Only one case described a non-linear change in cultural ecosystem services (spiritual and religious values).

Temporal changes of ecosystem services measured with two points in time

In a total of 321 cases, ecosystem services were measured at two points in time. Regulating services were most commonly considered (111 cases), followed by provisioning (80 cases), supporting (77 cases) and cultural services (53 cases). Amongst regulating ecosystem services, climate regulation (21 cases) was most commonly measured, followed by erosion regulation (18 cases). The two most commonly considered provisioning services were food (31 cases) and water provisioning (19 cases). Nutrient cycling (33 cases) stood out as the most commonly considered supporting service, whereas biodiversity (25 cases) was the second commonly considered supporting service. Finally, the two most frequently measured cultural services were recreation and eco-tourism (21 cases) and cultural landscape and heritage values (8 cases).

Chapter 4: Synthesis

4 Synthesis

4.1 Conceptual integration of the chapters

The common integrated overview of the chapters 3.1, 3.2 and 3.3 yields new insights into temporal aspects of ecosystem services. Figure 2 summarises the conceptual integration of the research articles. In general, each ecosystem service has a **supply** and a **demand side** (Figure 2). Therefore, each chapter of this thesis focuses on both sides. The first chapter introduced new definitions for the terms **transformation**, **transition** and **regime shift** based on their usage in the literature on ecosystem services while the second chapter presents a tentative framework for temporal dynamics of ecosystem services. The third chapter uses this framework and tests it against the literature on ecosystem services. Moreover, it also focuses on the supply and demand-side dynamics by analysing in how far **stakeholders** are involved in studies on temporal dynamics of ecosystem services.

The supply-side is recognized more often, especially in the case of **provisioning**, **regulating**, and **supporting services**. The concept of **regime shifts** is strongly related to the supply-side of ecosystem services and to ecosystems as it originally stems from ecology. On the other side, studies focusing on the demand for ecosystem services also focus on social systems, **stakeholders**, and **cultural ecosystem services**. In many cases, demand-side dynamics are less recognized than supply-side dynamics.

The smallest part of the literature on temporal aspects of ecosystem services focuses on both the **supply and demand sides**. Both sides are connected by the **management stage** of the ecosystem services cascade. Moreover, transformation is the concept that is most strongly associated with both perspectives.

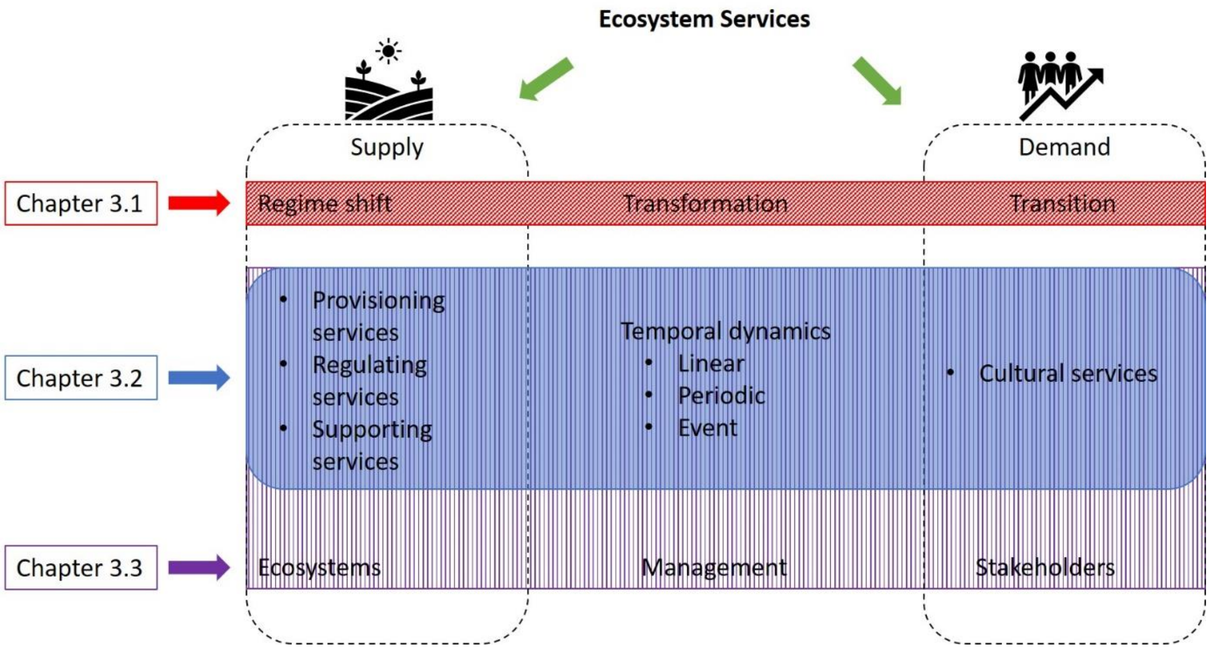

Figure 2. Relations of concepts and topics analysed in this dissertation.

4.2 Main findings

In the following, I present and discuss the main results of chapter 3 and derive recommendations from these results. The main results are clustered into the categories **temporal dynamics**, **research focus and orientation**, **concepts and definitions** and **ecosystem services focus of the research**. The main findings inside these categories are research gaps that inhibit research on temporal dynamics of ecosystem services from contributing to a more sustainable management of ecosystems and their services. Based on my main findings, I give four recommendations for future research on how to close these research gaps (Figure 3).

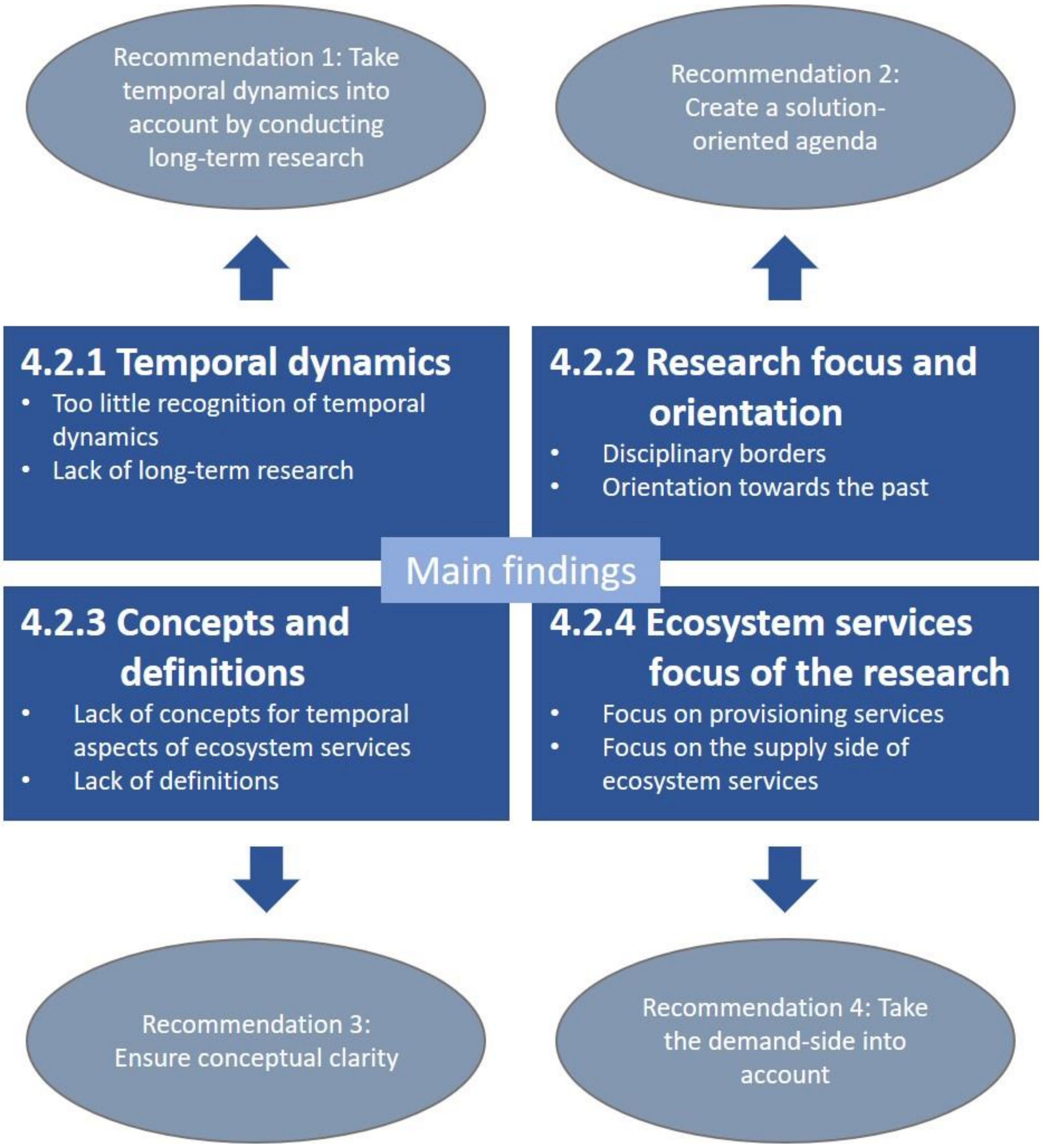

Figure 3. Overview on the relations between main findings and recommendations.

4.2.1 Temporal dynamics

Too little recognition of temporal dynamics

In general, temporal patterns have played a minor role in the literature on ecosystem services compared to spatial patterns. Only 2% of papers on ecosystem services considered changes in ecosystem services over time. In the papers that focus on temporal dynamics of ecosystem services, 26% of cases in which ecosystem services dynamics are described are based on only two measurements, mostly to compare the state of an ecosystem before and after an intervention (Rau et al. 2019, chapter 3.3). However, neglecting temporal dynamics decreases the ability of people to adapt to certain changes. For instance, the concept of climate change adaptation stresses the fact that, even if mitigation efforts are successful and greenhouse gas emissions can be strongly reduced, there will be climate change of some extent (Smith & Lenhart 1996, van Valkengoed & Steg 2019). Therefore, measures for adapting to the impacts of climate change such as higher mean temperature and an increasing number of extreme weather events need to be developed as early as possible (van Valkengoed & Steg 2019).

In fruit growing, where there is a long tradition of tracking temperature and weather events, an increase of hail events has already been detected some years ago. Hail can have strongly negative effects on fruit yields. In Germany, between 5% and 20% of acreage planted with pome fruit are damaged by hail per year, leading to financial loss of up to 20 million Euro (Vereinigte Hagel VVaG 2013, cited as in Hartwich & Gandorfer 2014). Apples that are damaged by hail have irreversible dents in their epidermis which strongly decreases their value. Depending on the severity of the damage, they are either sold as category II (fruits of middle quality) or discarded, but cannot be sold as highly priced dessert fruits of category I or E (fruits of good quality or highest quality, respectively) (Bundesanstalt für Landwirtschaft und Ernährung 2013; Bundeszentrum für Ernährung 2020). In this case, a hail event only lasting a few minutes can have a strong impact on farmers' income as all fruits in a region are damaged at the same time. Therefore, fruit farmers are adapting to climate change by increasingly building hail nets over their plantations (Hartwich & Gandorfer 2014).

Lack of long-term research

In chapter 3.3, I found that studies collecting field data in most cases only are conducted for a maximum of four years. Additionally, studies over long time spans of more than 50 years were either based on secondary data (43%) or simulated data (20%). This creates a gap between long-term simulating and short-term field studies. The lack of long-term field data sets is not only a problem in ecosystem services research. In biodiversity research, long-term monitoring is essential for observing changes of biodiversity over time. However, long-term data sets are relatively scarce (Magurran et al. 2010). Long-term field data cannot be replaced by simulations as the latter are too reliant on theoretical assumptions.

4.2.2 Research focus and orientation

Disciplinary borders

Moreover, my reviews showed that disciplinary borders are still prevalent even when it comes to a boundary object such as ecosystem services that is located at the overlap of economics, ecology and planning and therefore connects different disciplines with each other. This was especially highlighted by the cluster analysis I performed in chapter 3.1. This analysis showed that one of three groups of literature was clearly separated by focusing on the ecological system and change in the environment. The other two groups were more closely related with each other. One of them had a focus on the socio-ecological system and the other one was characterized by target knowledge and transformative knowledge as well as a social perspective.

This supports the observation that topics related to ecosystem services are still discussed in their own research community and therefore seen as two different points of view on the same topic. Especially ecology still distinguishes itself from other disciplines. For instance, this disciplinary divide was also observed in a review on urban ecosystem services (cf. Luederitz et al. 2015). In that case, 35% of case studies were written from a purely ecological research perspective whereas only 8% of case studies on urban ecosystem services were written from a governance perspective. The research perspective in many cases also determined which methods were used and which structures were analysed (Luederitz et al. 2015). This disciplinary divide is problematic as many real-life challenges can only be solved when researchers from different backgrounds and practitioners work together (Lang & Wiek 2017).

Orientation towards the past

In the literature on ecosystem services and concepts of change, I found 73% of articles dealing with changes that happened in the past. In chapter 3.1, I show that the concept of regime shifts is mostly used to exemplify change that happened in the past and lead to a negative outcome in terms of sustainability, such as the destruction of an ecosystem that lead to a decrease of the services it provided. By contrast, a concept that strives towards positive change with the goal of more sustainable systems is leverage points for sustainability transformation (Abson et al. 2017). To achieve long-term societal change towards a more sustainable system, small changes should be made that create fundamental changes in the whole system, following the idea of Donella Meadows' leverage points (cf. Meadows 1999). She distinguished between shallow leverage points that are easy to target, but also create little change regarding the whole system and deep leverage points where interventions are hard to implement but would yield a big transformational change (Meadows 1999). It was criticized that sustainability interventions that were made in the last decades rather fall into the category of weak leverage points as global development still follows an unsustainable trajectory. Therefore, it is proposed to make interventions in deep leverage points from the realms of institutions, people's connections to nature and knowledge production (Abson et al. 2017).

4.2.3 Concepts and definitions

Lack of concepts for temporal aspects of ecosystem services

An extensive literature search I conducted for chapter 3.2 pointed towards the fact that so far, there had not been any concepts or classifications for temporal variance of ecosystem services that are independent of specific contexts. This general lack of frameworks kept temporal dynamics from being integrated into ecosystem services research (Birkhofer et al. 2015). Therefore, this problem adds to the general problem of a lacking recognition of temporal dynamics of ecosystem services.

Lack of definitions

In my review on concepts of change in relation to ecosystem services (chapter 3.1), I recognized that only 13% of articles on concepts of change and 30% of articles on ecosystem services defined the respective terms. In the case of ecosystem services, this is less of a problem as this term is well-established in the research community. Most authors giving a definition for this term cite the Millennium Ecosystem Assessment (Millennium Ecosystem Assessment 2003, 2005 and 2006), Robert Costanza (Costanza et al. 1992; Costanza et al. 1997; Costanza et al. 2001; Costanza et al. 2007) and Gretchen Daily (Daily et al. 1997; Daily et al. 2000; Daily et al. 2009). However, in the case of transformation, transition and regime shift, these terms are used in many ways and there are no definitions that are universally applied. This is exemplified by 213 different first authors that papers on concepts of change and ecosystem services refer to when using these terms.

4.2.4 Ecosystem services focus of the research

Focus on provisioning services

In my review on temporal dynamics of ecosystem services, I found that most studies focused on provisioning services, which suggests that short-term provisioning services are exploited at the expense of regulating services. This might be the case because provisioning services such as yields of agricultural fields are utilized in the short term, which leads to a reduction of regulating services that are important for maintaining soil quality in the long term. These kinds of trade-offs were observed repeatedly in the literature (Rodríguez et al. 2006). A review on social benefits of wild bees presents an example in which felling trees would provide honey immediately, but would reduce other ecosystem services such as biodiversity, water purification and climate regulation in the future (Okoye and Agwu 2008; Matias et al. 2017).

Focus on the supply side of ecosystem services

In the literature on temporal dynamics of ecosystem services, the majority of articles (80%) focuses on the supply side of ecosystem services. This results in the fact that many papers that claim to analyse ecosystem services only describe ecological processes. These papers are written from the perspective of ecology and there is no interaction with stakeholders to quantify the extent in which they perceive the function of a landscape structure or process as an ecosystem service. In these cases, the authors ascribe the theoretical value to ecosystem functions. This is problematic, as an ecosystem function can only be classified as an ecosystem service if stakeholders perceive it as a benefit (Haines-Young and Potschin 2010). To gain insights into how ecosystem services are perceived and valued, the participation of local actors is crucial (Plieninger et al. 2013).

Another type of dynamics on the supply side of ecosystem services are population dynamics. However, as discussed above, these can only be treated as ecosystem services when there is a benefit which is appropriated by humans. Otherwise these “services” would in fact only be ecosystem functions. This is what clearly distinguishes temporal dynamics of ecosystem services from other ecological dynamics such as population dynamics. One example of population dynamics that can be seen as temporal dynamics of ecosystem services is pest regulation by predators. In organic fruit growing, pest regulation is an ecosystem service that is highly valued by farmers as it reduces the amount of pesticides needed and therefore the costs for plant protection (Tscharntke et al. 2005). However, as the population dynamics of predators such as ladybugs follow the population dynamics of aphids (Khan 2010), it takes some time until this regulating service shows its full potential. On a long-term scale, this could be interpreted as a periodic dynamic, as the numbers of predator and prey influence each other so that they circulate around a certain mean.

Also strongly related to the supply side of ecosystem services is the notion of regime shifts. It is embedded in the concept of resilience. Based on the definition by Holling et al. (1973), Folke et al. (2004) define resilience as "the magnitude of disturbance that a system can experience before it shifts into a different state". This concept claims that a gradual degradation of an ecosystem slowly leads to loss of resilience which in turn can lead to a sudden regime shift. Resilience might be reduced when humans are removing whole functional groups of species or whole trophic levels from an ecosystem (Folke et al. 2004). In my framework, the loss of resilience would be treated as a linear dynamic as it proceeds gradually, and the regime shift would be classified as an event as it is a non-linear dynamic.

4.3 Recommendations

To aid to the advancement of research on temporal aspects of ecosystem services, I developed the following four recommendations for researchers and practitioners based on my main findings. This should help future research to better account for temporal aspects of ecosystem services.

Recommendation 1: Take temporal dynamics into account by conducting long-term research

First, the most important step is to account for temporal dynamics at all. Learning from past developments is only possible through conducting longitudinal research (von Wehrden et al. 2017). Therefore, only by creating several data points in time, it is possible to describe the dynamics of ecosystem services supply or demand. Moreover, the gap between long-term simulating and short-term field studies needs to be filled. This could be done through long-term field studies which yield high-quality data that is less dependent on theoretical assumptions than simulations. Only by collecting data over a long time span, ecosystem service dynamics can be thoroughly documented and analysed to gain insights on possible future developments. Therefore, not only ecosystem services supply, but also demand should be analysed to make it possible to match dynamics of provision and appropriation and to adapt the management of ecosystems accordingly.

To get meaningful results, not only single ecosystem services, but bundles should be studied over time. This is important to prevent harnessing an ecosystem service at the expense of another ecosystem service. The costs of regulating and supporting services that are necessary for creating a product that the consumer values in the form of provisioning services are in most cases hidden from the consumer. To ensure long-term sustainable provision of ecosystem services, future research needs to focus more strongly on the temporal dynamics of interdependent ecosystem services. A greater focus on temporal interdependencies of regulating and supporting services as the "machinery" needed to produce human benefits is needed. As nowadays most funding programs only cover a maximum length of three to five years for research projects, research funding would strongly need to change to enable long-term research projects (Bergmann et al. 2014).

Recommendation 2: Create a solution-oriented agenda

Analysing the past to learn from mistakes that were made in managing a socio-ecological system is important to improve future actions. However, only focusing on events that happened in the past and lead to negative change neglects that systems can change towards a positive outcome for sustainability. The concept of transformation, however, encourages to set a goal for sustainability and to strive towards this more sustainable state in the future. Therefore, to work towards a more sustainable state in the future, this concept should be used more often. Focusing on transformation instead of regime shifts, that are currently focused on, could help closing the feedback loop between the management and structure stages in the ecosystem services cascade and lead to more adaptive management of ecosystems that would then lead to the maintenance and enhancement of ecosystem services provision.

Recommendation 3: Ensure conceptual clarity

In chapter 3.1, I showed that, for several reasons, it is important to clearly define the concepts that a study is based on. In this case, this is related to the topics of transformation, transition, and regime shift, but represents a general issue in sustainability science. As this scientific field deals with complex problems, it draws knowledge from several disciplines and researchers with different backgrounds such as economics, conservation biology, sociology, and philosophy

(Aronson 2011). To enable these researchers to work on complex problems together, it is important to use clearly defined terms or to define the concepts that are used in an article itself. Not doing so strongly inhibits the discourse on these topics and creates confusion and misinterpretation. In the future, this would inhibit transformation towards a more sustainable system.

Therefore, future research on temporal aspects of ecosystem services should clearly define each concept and distinguish similar concepts from each other. The definitions for the concepts transformation, transition and regime shift I presented in chapter 3.1 and the definitions for linear dynamics, periodic dynamics and events I presented in chapter 3.2 could be used for this purpose. This would foster a more profound understanding of ecosystem services dynamics and socio-ecological changes and therefore endorse future research on these topics.

Recommendation 4: Take the demand side into account by involving stakeholders' perceptions over time

As ecosystem services are defined as the benefits that people derive from nature (Daily et al. 1997), people's perceptions should be the starting point of the ecosystem services cascade which would give more importance to the benefit and valuation stages. However, our reviews on concepts of change and temporal dynamics of ecosystem services showed that only in one in five cases stakeholders were involved. In the future, stakeholders and their perceptions should be more often included into scientific research on ecosystem services. This would enable to compare how benefits and valuations of stakeholders change after an ecosystem has been managed.

Recent research does this already, especially by using the concept of nature's contributions to people. This framework strongly focuses on humans and the demand side. In comparison to the ecosystem services framework by the MEA on which it is based, it gives culture a central role in defining links between people and nature (Díaz et al. 2018). The way in which culture was restricted to the category of cultural ecosystem services that were hard to grasp and analyse was one of the major points of criticism of the ecosystem services framework (Schroeter et al. 2014). The concept of NCP was developed by the IPBES to be more inclusive towards stakeholders, e.g. by recognizing local and indigenous knowledge. However, temporal dynamics are only recognized for the ecological side which is also only represented in very few assessments of the IPBES (Mastrángelo et al. 2019). However, temporal dynamics on the stakeholder (demand) side are not integrated in this framework so far. To enable future research to analyse the full spectrum of nature's contributions to people, this framework would benefit from integrating temporal dynamics also for stakeholders' perceptions and demand.

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Chapter 5: Conclusion

5 Conclusion

The aim of this dissertation was to enable future-oriented research on temporal aspects of ecosystem services. Therefore, I analysed how temporal aspects are accounted for in the ecosystem services literature, I highlighted gaps and shortcomings in the recent scientific discourse and gave recommendations on how temporal aspects can be better taken into account by future research.

In the scientific discourse, temporal aspects are still underrepresented, although they are already recognized by practitioners such as fruit farmers. As most studies focus on only one point in time, it is not possible to learn from past developments to manage an ecosystem and its services in the future.

Moreover, disciplinary divides between concepts and methods are prevalent which leads to the fact that each topic is discussed from a different angle by different communities, although there might already be solutions to some of the problems in another research community or in practice. Additionally, a lack of concepts and definitions might add to the low recognition of temporal aspects of ecosystem services and might further inhibit exchange between different research communities.

The systematic review on concepts of change has furthermore shown that most of the literature focuses on change that has happened in the past. This is especially true for studies using the concept of regime shifts. While it is good to learn from the past, research on ecosystem services should not only describe the past, but also envision how ecosystem services could be used in a more sustainable way in the future.

To enable future research to aid to a more sustainable management of ecosystems and their services, I recommended to (I) take temporal dynamics into account by conducting long-term research, (II) create a solution-oriented agenda, (III) ensure conceptual clarity and (IV) take the demand side into account by involving stakeholders' perceptions over time.

The concept of nature's contributions to people which is based on the ecosystem services concept is already on a good path of strengthening the demand-side by taking local stakeholder's perceptions and cultural aspects into account. If the IPBES would find a way to integrate the temporal dimension into its NCP framework, as this is currently especially lacking on the demand side, this could develop into a holistic concept for a new integrative representation of ecosystems and their services. The results and recommendations from this dissertation could be helpful for taking this next crucial step.

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