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Review Paper

Analysis of relationships between ecosystem services: A generic classification and review of the literature

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ABSTRACT

The scientific literature contains many studies of trade-offs or synergies between ecosystem services (ES); however, it is challenging to qualify and compare these studies. To address this issue, we developed a structured generic methodological classification (typology) of studies that focuses on relationships between ES. The method focuses on characteristics of the spatial and temporal analyses performed and whether drivers of relationships between ES were considered. We used the typology to characterize 103 peer-reviewed articles from 1998 to 2017 identified from a search of the ISI Web of Science. Our results show that most of the studies (74%) focused on quantifying and analyzing ES relationships using a snapshot approach. Spatio-temporal analysis of ES relationships (6% of the studies) remains a major scientific challenge in research. While most studies analyzed drivers of relationships, they focused mainly on coarse indicators of land use and cover (change) and climate change (e.g. temperature and precipitation), and 70% of the studies analyzed relationships between 3 and 6 ES. This review highlights two key research issues: (i) going beyond analysis of coarse drivers by using indicators of land use and (ii) developing spatio-temporal analysis of ES relationships based on field methods to follow-up ES indicators over time or simulation models.

1. Introduction

Since the Millennium Ecosystem Assessment (MEA, 2005), the number of studies of ecosystem services (ES) has increased greatly (Vihervaara et al., 2010). Although focused mainly on analyzing and quantifying ES, studies have focused increasingly on analysis of ES “interactions” (Raudsepp-Hearne et al., 2010; Lee and Lautenbach, 2016). This is a major research issue for ES (Fu et al., 2015). ES assessment and relationships provide key information used to make decisions about natural resource management (Han et al., 2017) and land management or planning (Castro et al., 2014).

In some cases, ES can be independent, when “an increase in one service does not cause an increase or decrease of the other service” (Jopke et al., 2015). In other cases, trade-offs and synergies exist between ES (Qiu and Turner, 2013; Zheng et al., 2014). Trade-offs occur when the provision of one ES decreases due to an increase in the provision of another ES (Rodríguez et al., 2006; Bennett et al., 2009; Raudsepp-Hearne et al., 2010; Fu et al., 2015; Tomscha and Gergel, 2016). Synergies are more likely inferred when the combined effect of drivers acting on ES is greater than the sum of their separate effects (Carpenter et al., 2009; Felipe-Lucia et al., 2014).

Bennett et al. (2009) suggest that trade-offs or synergies between ES are due to two types of mechanisms: (i) direct interactions between ES or (ii) interactions via effects of common drivers influencing the ES (i.e. “indirect interactions” according to Birkhofer et al., 2015). Indirect interactions between ES occur when the ecological processes underlying ES (i.e. “supporting services”) interact, potentially at different temporal and spatial scales (Seppelt et al., 2011). The nature of the relationships (trade-off, synergy, neutral) can depend strongly on the temporal scale at which the interaction is analyzed (Holland et al., 2011; Renard et al., 2015; Li et al., 2017) or the spatial scale of the study (Anderson et al., 2009; Holt et al., 2015). ES can have spatial trade-offs and synergies over time when they rely on common landscape attributes in a heterogeneous area (Tomscha and Gergel, 2016). The potential non-linearity of temporal and spatial variations in ES relationships makes them difficult to analyze (Jaarsveld et al., 2005; Koch et al., 2009; Lester et al., 2013).

According to several authors (Bennett et al., 2009; Gos and Lavorel, 2012; Landuyt et al., 2016; Dade et al., 2018), understanding trade-offs and synergies between ES is incomplete when the drivers and mechanisms underlying the interactions are not examined carefully. According to Bennett et al. (2009), understanding the drivers and

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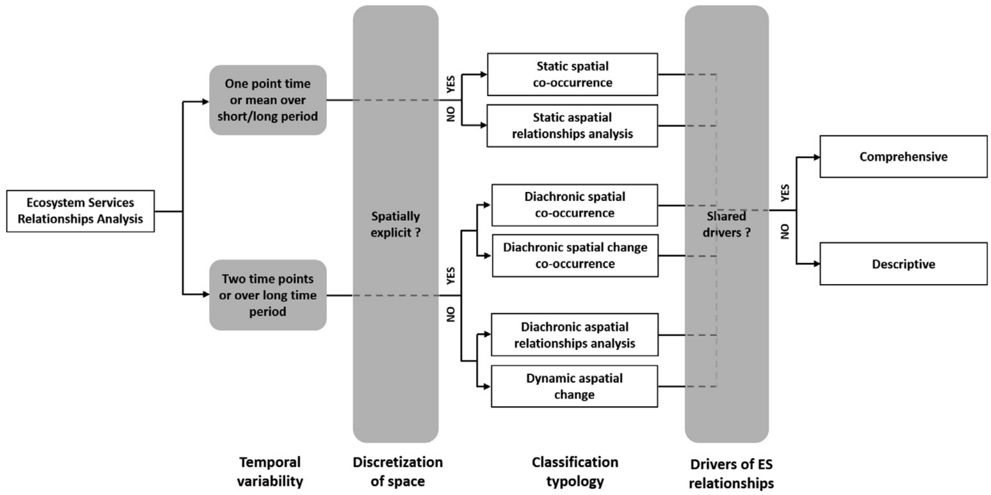

Fig. 1. The procedure used to identify six typology classes of quantitative studies of relationships between ecosystem services (ES). "Temporal variability" indicates studies that explicitly considered temporal dynamics. "Discretization of space" indicates studies that considered the spatial dimension of ES relationships. "Drivers of ES relationships" indicates whether studies considered the drivers that underlie the relationships or not (comprehensive vs. descriptive, respectively).

mechanisms that underlie the ES relationships "can help identify ecological leverage points where small management investments can yield substantial benefits". Identifying the common drivers and mechanisms of relationships between ES is necessary to better understand whether trade-offs or synergies between ES are likely to occur in an area, and can help to define effective management strategies that promote preferred ES (Bennett et al., 2009; Dade et al., 2018). For example, Lu et al. (2014) showed the influence of climate, especially precipitation, on ES interactions in the Loess Plateau of China. Liu et al. (2017) showed the influence of socio-economic factors on ES interactions in the Taihu Basin in eastern China. However, Kremen and Ostfeld (2005) and Nelson et al. (2009) noted that ecological and economic drivers underlying ES are poorly understood.

The scientific literature contains different terms to describe biophysical trade-offs or synergies between ES, e.g. "interaction", "association", "relationship". They are often used in a confusing manner (Vallet et al., 2018) and remain a source of misunderstanding (Cord et al., 2017). For example, for Spake et al. (2017), an ES "association" includes the drivers of or common ecological processes between ES. This definition, however, resembles the concept of ES "interaction" of Mouchet et al. (2014), who state that "association" should be used instead of "trade-off", "compromise" or "synergy" when the assessment of ES relationships is a "snapshot". Several authors highlight the need to standardize the terms used in studies to be able to capitalize on knowledge (e.g. Mouchet et al., 2014; Cord et al., 2017; Vallet et al., 2018). In this study, we use the generic term "relationships" to describe the biophysical trade-offs or synergies between ES.

Reviews of trade-offs and synergies between ES have already been published. For example, Seppelt et al. (2011) identified several aspects of ES studies, such as the biophysical realism of ecosystem data and models, and consideration of local trade-offs. Mouchet et al. (2014) developed comprehensive methodological guidelines for assessing trade-offs between ES and showed that a variety of statistical approaches (e.g. correlation analysis, principal component analysis, k-means clustering) have been used to investigate ES relationships. Lee and Lautenbach (2016) provided new information about characteristics of the trade-offs and synergies encountered most often in studies (e.g. trade-offs dominated relationships between regulating and provisioning ES). Cord et al. (2017) summarized the main research objectives of studies, such as (i) identifying and describing ES co-occurrence and (ii) identifying drivers and environmental or social pressures and their underlying mechanisms. More recently, Dade et al. (2018) focused on the drivers and mechanisms considered in studies and showed that only a few studies explicitly identified those that underlie ES relationships.

These reviews highlighted (i) the nature of relationships between the ES analyzed (trade-off, synergy, or neutral), (ii) statistical methods used to identify ES relationships, (iii) main objectives in studies of ES relationships, and (iv) the nature of drivers of ES relationships. It appears, however, that each review article addresses different characteristics without providing a generic classification that focuses on the key methodological characteristics of each study in the literature. Moreover, none of the reviews summarized the nature of the spatial (if present) and temporal analyses encountered most often in studies. In this context, the objective of the present study was (i) to develop a complete generic classification of analysis approaches of ES relationships and (ii) to use this classification to review the literature that focuses on ES relationships. We first present our new generic typology. Then, using this new typology, we characterize published studies that analyze relationships between ES. We present the method used to identify the scientific literature analyzed and then present the results of applying the method. Finally, we discuss results of our review and define a scientific agenda for the analysis of relationships between ES.

2. Synthetic typology classification

Analysis of previous reviews and the associated literature (e.g. Seppelt et al., 2011; Lu et al., 2014; Turner et al., 2014; Xue et al., 2015; Morelli et al., 2017) revealed the following core criteria for characterizing studies of ES relationships (Fig. 1):

(i) Temporal change in ES relationships: assessed on one date, on average over a period (i.e. without considering time), between two or more dates, or dynamically over a period.
(ii) Spatial distribution of ES relationships: assessed only for the whole case study area or at different locations within the area.
(iii) Ecological or socio-economic drivers of ES relationships: assessed without considering the drivers ("descriptive" studies) or by explicitly considering the drivers ("comprehensive" studies).

We defined six typology classes based on these criteria (Fig. 2):

- "Static spatial co-occurrence": studies that analyze the co-occurrence of ES (bundles) on one date (Fig. 2b) or on average over a period in different zones over the spatial extent of the study (see for example Fernandez-Campo et al., 2017)
- "Static aspatial relationship analysis": studies that analyze the co-occurrence of ES on one date or use mean indicators for a given period without spatial discretization of the study area (i.e. an average for the entire area) (Fig. 2a) (see for example Felipe-Lucia et al., 2014)
- "Dynamic aspatial change": studies that analyze dynamics of ES relationships via the temporal changes/variations in each individual

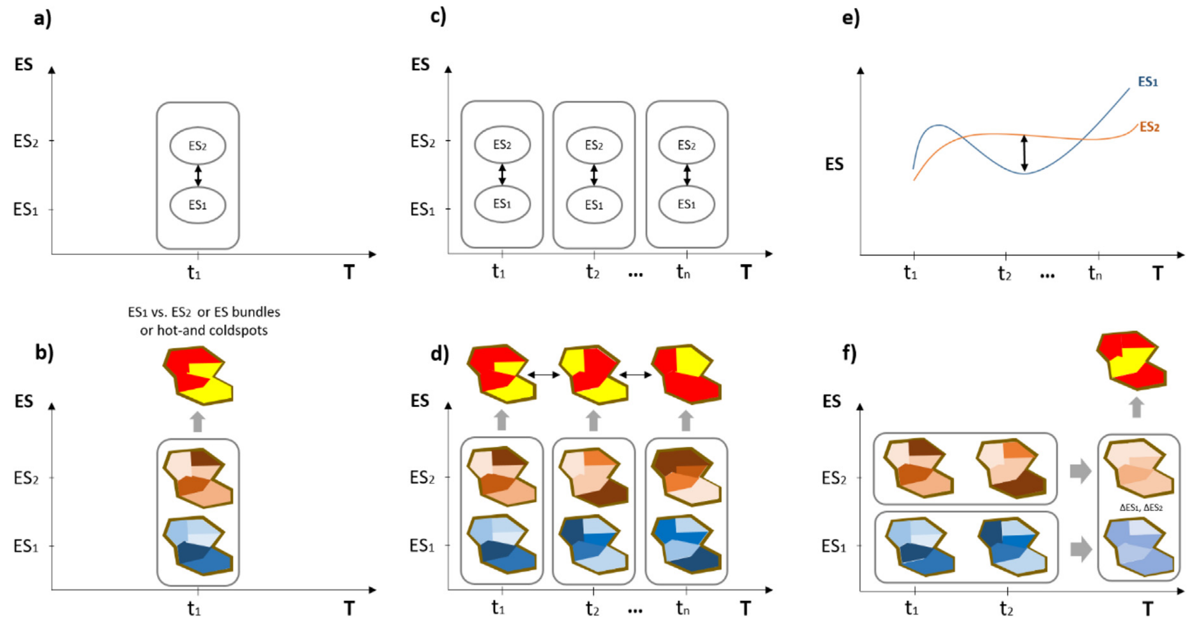

Fig. 2. Diagram of the typology of ecosystem service (ES) relationship analysis. a) Static aspatial relationship analysis; b) Static spatial co-occurrence; c) Diachronic aspatial relationship analysis; d) Diachronic spatial co-occurrence; e) Dynamic aspatial change; f) Diachronic spatial change co-occurrence. The charts are adapted from Bennett et al. (2009) and Li et al. (2017).

ES (e.g. normalized or standardized ES) for long-term periods or several time intervals without spatial discretization of the study area (Fig. 2e) (see for example Su et al., 2012)

- "Diachronic spatial co-occurrence": studies that analyze the co-occurrence of ES on two or three dates (Fig. 2d; t1-t2) (see for example Haase et al., 2012) or on average over several periods (Fig. 2d; t1-tn) (see for example Renard et al., 2015) in different zones over the spatial extent of the study
- "Diachronic aspatial relationship analysis": studies that analyze the co-occurrence of ES on two or three dates (Fig. 2c; t1-t2) (see for example Jia et al., 2014; Wu et al., 2017) or on average over several periods (Fig. 2c; t1-tn) (see for example Pang et al., 2017) without spatial discretization of the study area
- "Diachronic spatial change co-occurrence": studies that analyze ES relationships based on the change in each ES over time (two or more periods) over the spatial extent of the study (Fig. 2f) (see for example Cademus et al., 2014)

For each of the six classes, we separated the studies that explicitly analyzed drivers of ES relationships from those that did not.

Our typology is partly convergent to already existing typologies. The "static spatial co-occurrence" and "static aspatial relationship analysis" classes are similar to the "spatial correlation" (ES observed at time 1) approaches of Vallet et al. (2018); however, our typology clearly distinguishes whether the spatial location of relationships is considered ("static spatial co-occurrence") or not ("static aspatial relationship analysis"). The classes "static aspatial relationship analysis" and "diachronic spatial co-occurrence" are similar to the "b" and "d" methods of Li et al. (2017) (Fig. 3). To be more explicit, we also renamed the "space-for-time" approach of Tomscha and Gergel (2016) to "diachronic aspatial relationship analysis". The "diachronic spatial change co-occurrence" class is similar to the "change-over-time" approach of Tomscha and Gergel (2016); however, our typology considers the spatial location of relationships, which their study did not (see Li et al., 2017). Unlike the typologies available in the literature, our typology explicitly includes the drivers of ES relationships. The distinctions "comprehensive" and "descriptive" are similar to the "no mention" and "explicit" groups of Dade et al. (2018), whose study focused on this aspect of drivers. Our objective was to develop a typology that provides a generic and complete framework to characterize all studies of ES relationships. To demonstrate its robustness, we used it to characterize existing scientific studies published in peer-reviewed articles.

3. Method for reviewing articles

3.1. Literature exploration

To identify articles that address relationships between ES, we used the advanced search function of the ISI Web of Science Core Collection database (WoS, Science Quotation Index; Social Sciences Quotation Index, http://www.isiknowledge.com) in April 2018. We used the following query to search within titles, abstracts, and keywords of peer-reviewed articles published in English from 1998-2017: TS = (("ecosystem service*" OR ("ecosystem" AND "service*") OR "ecological service*" OR ("ecological" AND " service*")) AND ("trade-off*" OR "tradeoff*" OR "synerg*" OR "interaction*" OR "relationship*" OR "congruence*" OR "interrelation*" OR "inter-relation*" OR "compromise*" OR "association*")). We excluded review articles to avoid redundancy. This procedure identified 6956 articles.

3.2. Article selection

Due to the large number of articles selected, we used the bibliometric analysis and mapping software VOSviewer (van Eck and Waltman, 2010) and the bibliographical management software EndNote version 7.8 (http://endnote.com) to select the articles more finely and automatically. First, we imported the 6956 articles into VOSviewer and analyzed co-occurrence of the keywords provided by the authors (i.e. two keywords in the same article). Using this analysis of keyword co-occurrence, we identified and selected a set of relevant keywords (Appendix A). These keywords were then used in EndNote to sort the 6956 articles automatically. To ensure that our automatic selection was accurate, we used an sample subset of relevant articles to verify that they were in the final list of sorted articles. This procedure reduced the list to 1198 articles (Fig. 3).

We screened these 1198 articles manually, first using their titles and abstracts. Each abstract was scanned to ensure that its article addressed ES relationships (i.e. referred to analysis of trade-offs or synergies

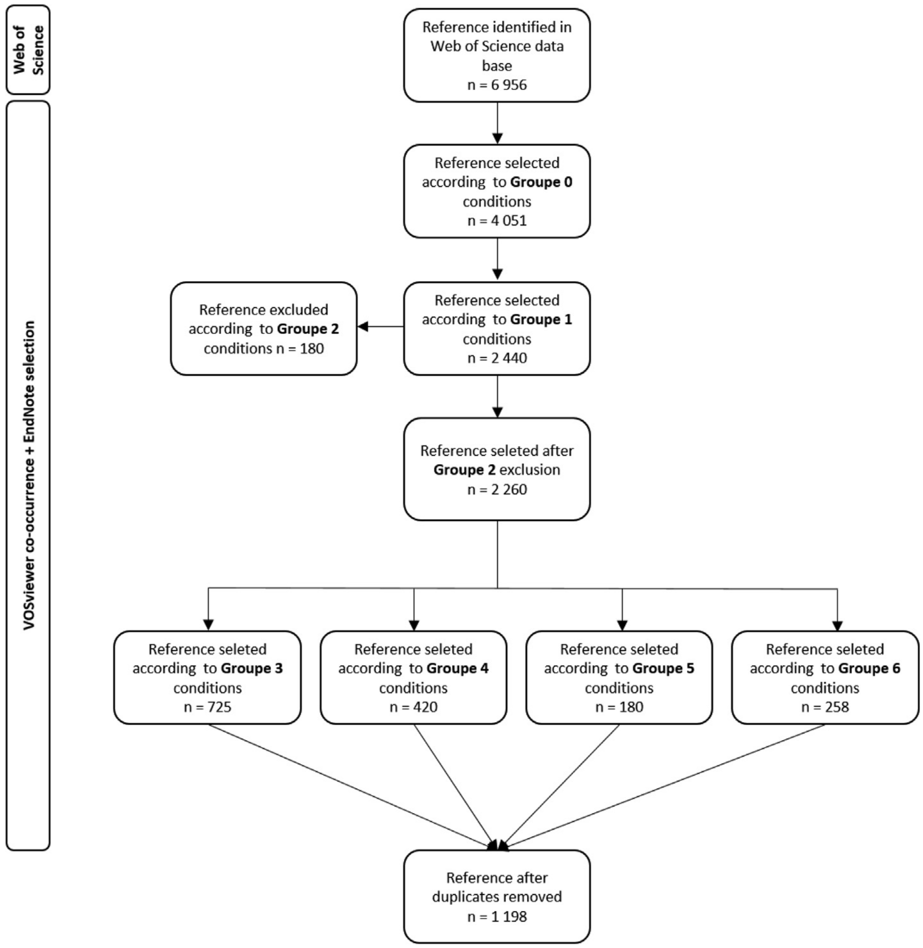

Fig. 3. Literature searches and article sorting process in EndNote 7.8. The methods for each group are shown in Appendix A.

between ES); if it did not meet this criterion, the article was excluded. If deemed relevant, the full text was scanned to select only articles containing quantitative information on ES relationships. Conceptual articles were excluded. Finally, we selected 103 articles (Appendix B) that described quantitative analyses of ES relationships. This set of 103 articles is larger than those in previous reviews (e.g. 92 articles reviewed by Howe et al. (2014); 67 case studies reviewed by Lee and Lautenbach (2016)).

3.3. Analysis of terms used in the literature

The analysis of keyword co-occurrence indicated a preference for the terms “trade-off” and “synergy” in the studies, regardless of the natures of the relationships between ES that were determined. In addition, we observed that “trade-off” was placed first in the title of many articles, even when the results showed only associations, trade-offs, or synergies between ES. This observation confirms the review of Tancoigne et al. (2014), who observed that no connection exists between the term “trade-off” and pairs of ES potentially in conflict. This could be because these terms are popular in the ES literature (see Abson et al., 2014), especially when relationships between ES are considered. The keyword co-occurrence analysis also revealed that “biodiversity” was strongly associated with “ecosystem services”, which confirms the importance of biodiversity in the supply of ES, as highlighted in previous studies (e.g. Costanza et al., 2007; Gamfeldt et al., 2008; Mace et al., 2012; Harrison et al., 2014; Ricketts et al., 2016).

4. Applying the typology to the selected articles

4.1. Nature of studies in the literature

When using the typology to classify the 103 articles, any articles that described two or more types of approaches were classified under the most complex method. The results indicate that studies that analyzed ES relationships only at one moment in time (“static spatial co-occurrence” and “static aspatial relationship analysis”) were most common (74%, n = 76) (Fig. 4). This trend in current research could be because the main approach in ES assessment is to use proxy variables (Nelson et al., 2009; Seppelt et al., 2011) based on snapshot data (Spake et al., 2017). Few studies used simulation models to perform assessments (Seppelt et al., 2011). Although a snapshot approach is an effective way to detect spatial “associations” between ES (Morelli et al., 2017), it is a potential source of error because it does not consider the temporal dynamics of relationships (Zheng et al., 2014). Analyzing relationships at one moment in time can result in erroneous assumptions about the drivers and mechanisms that underlie the relationships between ES (Bennett et al., 2009).

Most studies analyzed ES relationships in a study area without spatial discretization (i.e. “static aspatial relationship analysis”, “dynamic aspatial change”, and “diachronic aspatial relationship analysis”; 65%, n = 67) (Fig. 4). Our results confirm the observation of Hou et al. (2017) that “only a small number of studies have investigated the… spatial scale dependency of ecosystem service synergies and trade-offs thus far ”.

Few studies analyzed spatio-temporal dynamics of ES relationships (6%, n = 6): only 2% of studies (n = 2) were “diachronic spatial co-

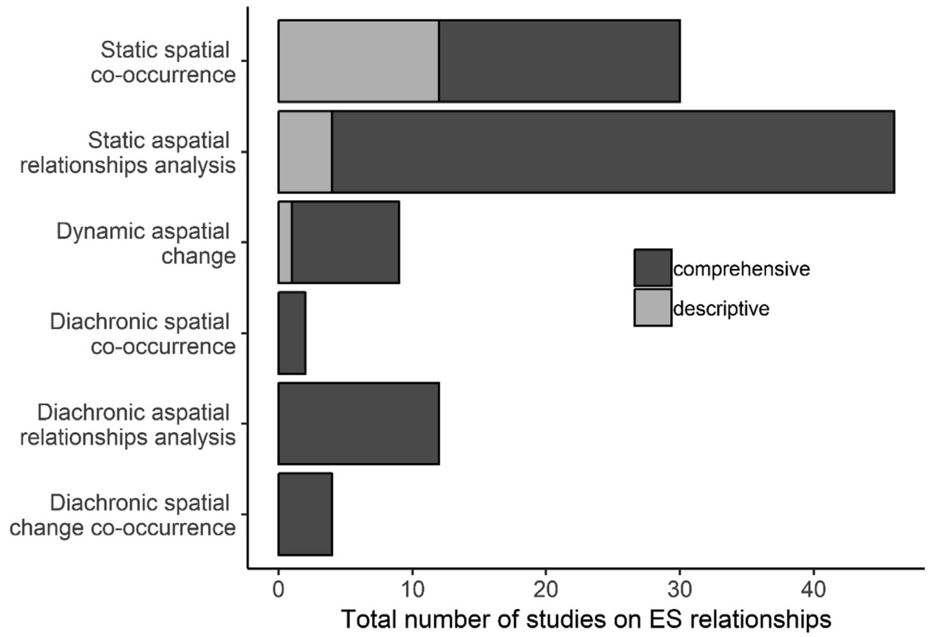

Fig. 4. Distribution of the 103 articles examined according to the typology developed.

occurrence", while 4% were "diachronic spatial change co-occurrence" (n = 4). Spatio-temporal analysis of ES relationships thus remains a major research challenge, as mentioned in previous studies (e.g. Bennett et al., 2009; Cord et al., 2017; Li et al., 2017). This could be due to a lack of follow-up in time and space of ES indicators sufficient to capture the spatio-temporal dimension of the relationships in a study area (Holland et al. (2011), Cord et al. (2017). For example, Martínez-Harms and Balvanera (2012) showed that in many studies of ES, "primary" data are lacking (e.g. soil data, field data, agricultural census data). Establishing sites to acquire long-term data on ES indicators would be one way to provide this missing information (Renard et al., 2015; Tomscha and Gergel, 2016). Another way to address the lack of following ES indicators in time and space is to use simulation models (e.g. InVEST, ARIES, STICS, SWAT), as have many studies that focused on assessing ES levels (rather than relationships). The limitations of these models (e.g. model uncertainty, application domain) must be considered and stated clearly. It is also necessary to consider the availability of input data, their associated uncertainties, and their spatial and temporal resolutions, as well as the fact that model's hypotheses more or less explicitly represent interactions between simulated processes. Nicholson et al. (2009) highlight that the fundamental lack of understanding of many processes that underlie the dynamics of ES hinders development of predictive models considerably.

4.2. Temporal change in the studies

We observed an increase in the number of studies over time, since 80% (n = 82) of the studies were published from 2014-2017 (Fig. 5). "Descriptive or comprehensive static spatial co-occurrence" studies were present from 2008-2017, while the number of "comprehensive static aspatial relationship analysis" studies increased greatly from 2014 to 2017.

4.3. Scale considered

Based on the 72% (n = 74/103) of articles that mentioned the scale of the study area, the scales studied most often were (i) regional (10^3-10^5 km^2) (41%, n = 30/74), (ii) watershed (10^2-10^3 km^2) (23%, n = 17/74), and (iii) local (< 10^2 km^2) (18%, n = 13/74) (Fig. 6). The global scale (> 10^6 km^2) was the least studied (7%, n = 5/74). Our results agree with those of the review of Lee and Lautenbach (2016), in which the regional scale (38%) was studied most often and the global scale (> 10^6 km^2) least often (6%).

The area of the study site determines the need and the relevance of using a spatial approach to determine ES relationships. For example, for areas smaller than 10 km^2 (local scale), the spatial approach seems less an issue (i.e. primarily "static aspatial relationship analysis"). The spatial dimension is however a challenge for areas ranging from 10^2 to 10^5 km^2 (watershed to regional scales) (i.e. many "static spatial co-occurrence" studies). Analyzing spatial variation in ES relationships at large spatial scales has limitations because the biophysical processes underlying the relationships between ES is more complex at a larger scale than at the local scale. As highlighted by Ploeg et al. (2018): "most properties in landscapes have some degree of correlation, but that depends on the scale at which observations have been made."

4.4. Type and frequency of ES

We standardized the different names that the 103 articles used for a given service to ES groups adapted from Malinga et al. (2015) (Table C.1 on Appendix C in the Supplementary material), recognizing that doing so may have influenced our results. The five ES analyzed most often were agricultural production (105% of the articles, since some described more than one (e.g. grain and timber production), n = 108/103), climate regulation (83%, n = 86), water quantity regulation (65%, n = 67), recreation and tourism (55%, n = 57), and nutrient regulation (43%, n = 44) (Fig. 7). Overall, 70% (n = 72) of the studies analyzed relationships between 3–6 ES (Fig. 8). This is higher than the range of 2–4 of Seppelt et al. (2011), who reviewed studies prior to 2011.

Fewer ES were studied when analysis of their relationships was more complex. Studies that were "descriptive or comprehensive static spatial co-occurrence" and "comprehensive static aspatial relationship analysis" examined nearly all of the ES mentioned above. In contrast, in studies that considered dynamics of relationships ("diachronic aspatial relationship analysis"), the main ES analyzed were agricultural production, climate regulation, water quantity regulation and, to a certain extent, erosion regulation. This could be because the data required to estimate these ES indicators are often available in national and/or regional databases, since they are the subject of long-term monitoring to

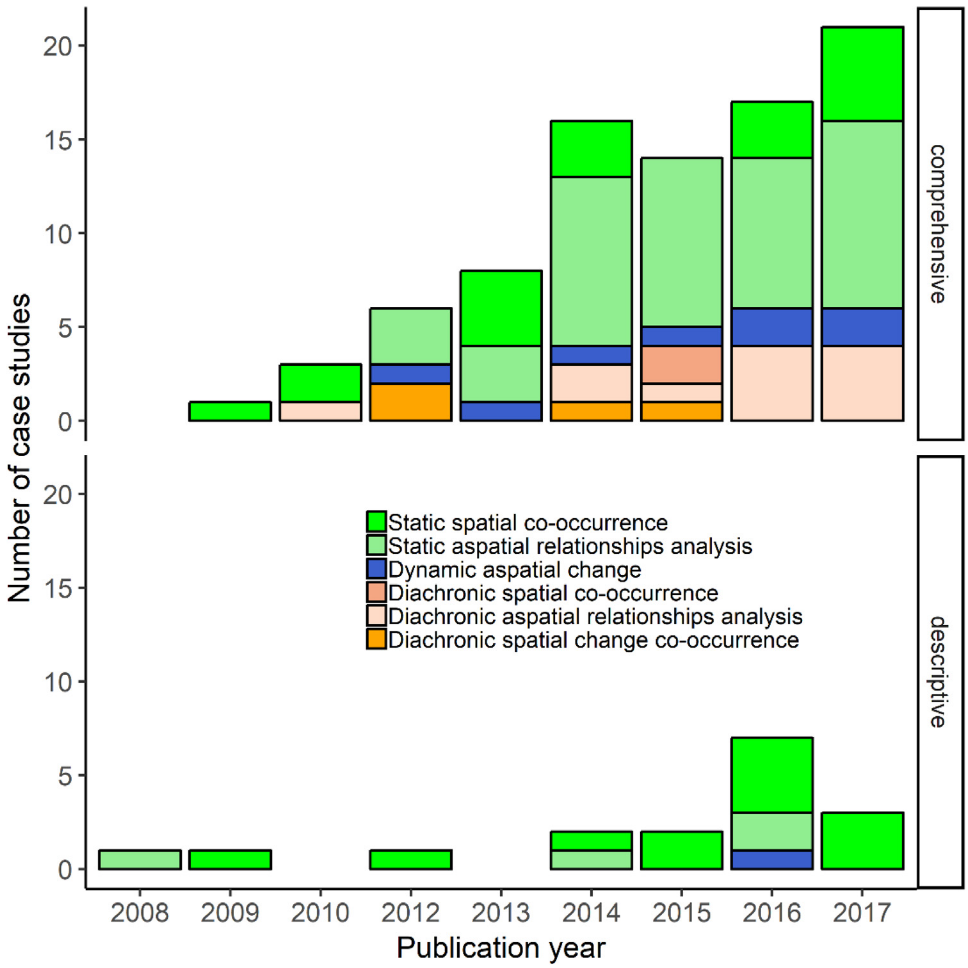

Fig. 5. Distribution of case studies (n = 103) over time according to the typology developed.

assess agricultural systems, water bodies, and climate change and at the core issues of the main agricultural and environmental public policies. This allows ES research to inform public policies at the interface with current societal challenges, like climate change, integrated water resources management, ecosystem preservation for food security. However, this could hide other important issues, poorly considered so far due to their less direct impact on major challenges like food security, such as crop pest regulation. To a certain extent, our results agree with

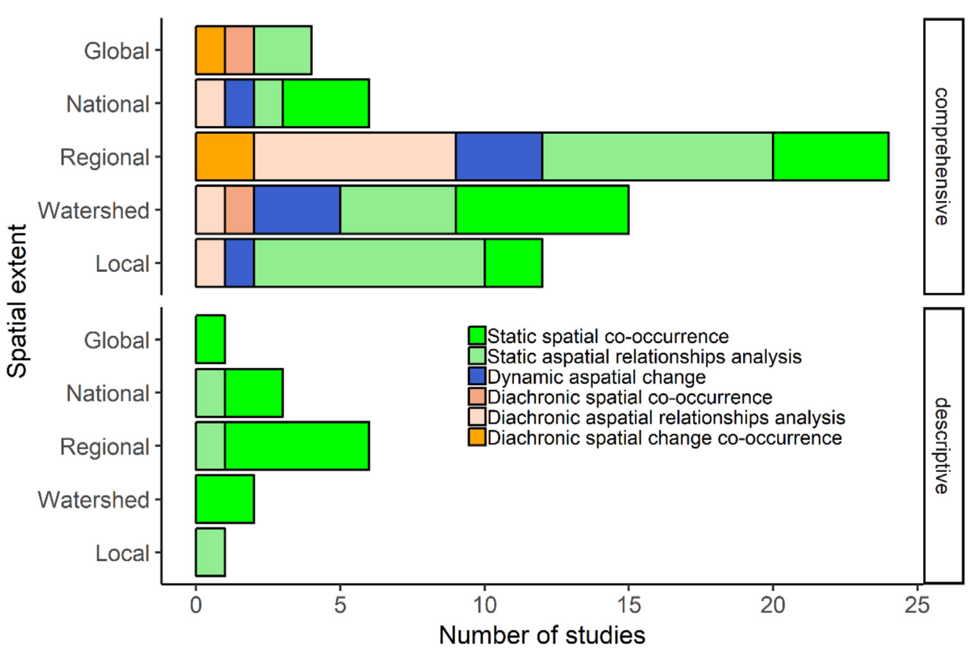

Fig. 6. Spatial scales considered in the articles reviewed. Scales: local (< 10^2 km^2), watershed (10^2-10^3 km^2), regional (10^3-10^5 km^2), national (10^5-10^6 km^2), and global (> 10^6 km^2). Approximately 28% of the studies (n = 29/103) did not indicate the resolution at which analysis was performed. Spatial scales adapted from Martínez-Harms and Balvanera (2012).

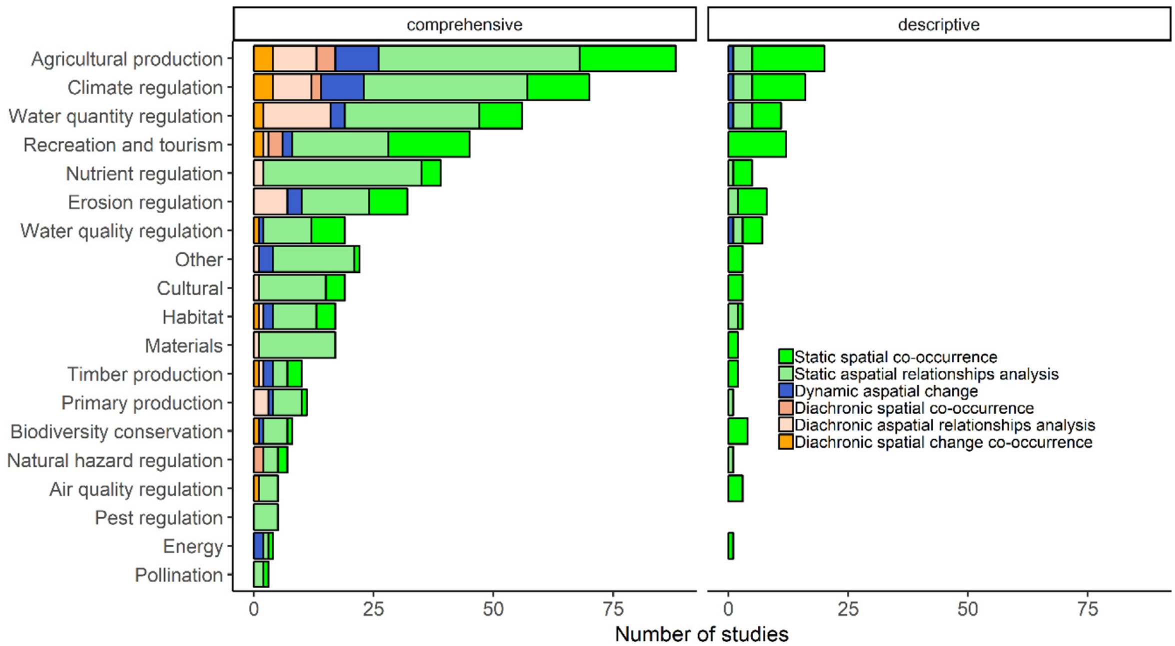

Fig. 7. The main ecosystem services (ES) considered in the studies examined.

those of the reviews of Egoh et al. (2012), Martínez-Harms and Balvanera (2012), Malinga et al. (2015), which identified carbon storage/sequestration, food production/provision, climate regulation, and water provision as the ES studied most often.

More detailed analysis showed that "comprehensive static aspatial relationship analysis" studies analyzed relationships of a relatively large number of ES (2–17), which was similar to the number of "descriptive or comprehensive static spatial co-occurrence" studies (2–12 ES). Most "comprehensive diachronic aspatial relationship analysis", "comprehensive dynamic aspatial change", and "comprehensive diachronic spatial change co-occurrence" studies analyzed relationships between 3–6 ES. Studies that considered temporal dynamics also considered fewer ES, possibly due to a lack of sufficient historical data to analyze a broad range of ES. Studies that considered the drivers of ES relationships ("comprehensive") analyzed relationships of a relatively large number of ES (2–17), while those that did not ("descriptive") analyzed relationships of 2–12 ES. Studies that analyzed spatio-temporal variations in ES relationships ("diachronic spatial co-occurrence" and "diachronic spatial change co-occurrence) were an exception, analyzing 5 or fewer ES.

4.5. Drivers of relationships

Most studies considered the drivers of ES relationships (83% of "comprehensive", n = 86) (Fig. 4). Studies analyzed most often the influence of land use and cover change (LUCC) by using coarse

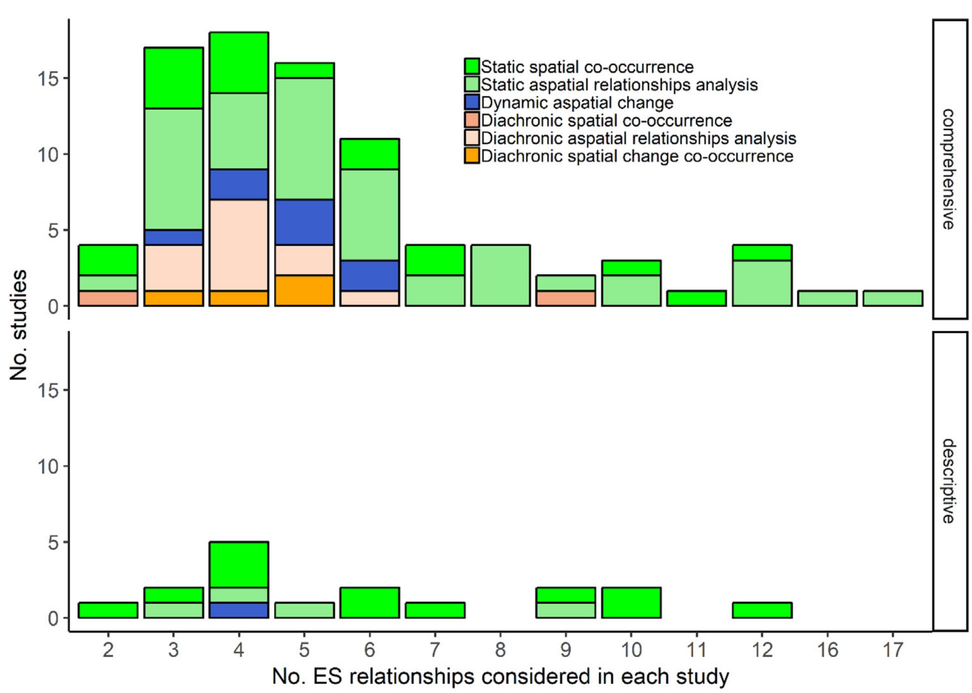

Fig. 8. Frequency of the number of ES studied simultaneously in the reviewed articles according to the typology.

descriptors such as the areas of urbanization, agriculture, deforestation, and grassland. More detailed studies considered climate as a driver by analyzing the influence of temperature or precipitation. A few studies addressed the influence of farming systems (e.g. organic vs. conventional) and less-intensive agricultural practices (e.g. input-use intensity).

Our results agree with those of the review of Dade et al. (2018), who showed that a large proportion of articles (86%) mentioned drivers of the trade-offs or synergies between ES, and that LUCC was the driver identified most often. This could be due to easily available data on the coarse composition of landscapes.

Analysis of drivers such as LUCC often refer to “implicit” consideration (vs. explicit quantitative assessment) of drivers of ES relationships (Dade et al., 2018). For example, Früh-Müller et al. (2016) stress that “landscape composition and landscape diversity are important determinants of ecosystem services”, and Grimaldi et al. (2014) show that “land-cover composition dynamics explained 45% ($P < 0.001$) of ES metric variance (…)”. However, land use and management (e.g. agricultural practices) “influence the system properties, processes and components that are the basis of service provision” (de Groot et al., 2010), and can improve or modify the ability to generate ES (Fu et al., 2015). We agree with Burkhard et al. (2012) on the need to analyze the influence of management practices on ecosystem structures and processes in order to provide actionable knowledge for developing ES on managed lands without modifying land cover deeply (e.g. agriculture to forest), which is often not possible or desired.

As mentioned, Bennett et al. (2009), Birkhofer et al. (2015) suggest that relationships between ES can be direct or indirect (i.e. via drivers). Our literature review did not identify the direct or indirect nature of ES relationships due to a lack of information in most articles. Given the nature of the drivers considered most often in studies, however, we argue that the studies reviewed focused largely on indirect relationships between ES. Do direct relationships between ES truly exist?

5. ES bundles vs. spatial interactions of ES

Studies of the spatial dimension of ES relationships (“static spatial co-occurrence”, “diachronic spatial co-occurrence”, and “diachronic spatial change co-occurrence”) often claim to analyze “spatial interactions” between ES. However, this type of analysis appears to refer only to spatial representation of aspatial correlations between ES i.e. spatial distributions of ES bundles. As reported by Vallet et al. (2018), “(…) they often present ES spatial correlations as interactions, even when they are not; they are simply evidence of non-random associations (Bennett et al., 2009; Cord et al., 2017)”. In other words, these studies do not address spatial “interactions” (action and retroaction) between ES but instead analyze the co-occurrence of ES by analyzing correlations over space (e.g. spatial covariance, overlaps, co-occurrence, correlation, congruence). This confirms the results of Mouchet et al. (2014), Lee and Lautenbach (2016), Dade et al. (2018) that indicate that analysis of relationships between ES generally corresponds to analyzing correlations between indicators of ES or overlap of ES.

This approach is suitable for identifying areas with specific ES-related issues (e.g. “hotspots” or “coldspots”) and has a visual format that facilitates communication between ecosystem managers (Maes et al., 2012). To avoid confusion in future studies and increase scientific consistency, we suggest that the analysis known as “spatial interactions” or simply “interactions” between ES (e.g. Qiu and Turner, 2013) should return to analyzing interactions in the biophysical landscape that occur across a variety of temporal and spatial scales (see Ploeg et al., 2018). The research challenges for this type of analysis should consider potential interactions between biological and physical processes, or processes that themselves result from elementary processes, that are expressed at different spatial and temporal scales.

6. Conclusion and research issues

Analysis of relationships between ES over space or time is a dynamic field of research. However, since concepts (e.g. interactions, trade-offs and synergies) used in the literature are often ambiguous and have several meanings, it is difficult to compare outcomes of studies addressing ES relationships and accordingly to capitalize on knowledge while developing it. To overcome this problem, we developed a generic 6-class typology that classifies results of quantitative analyses of ES relationships by distinguishing i) spatial vs. non-spatial analyses, ii) snapshots vs. temporal monitoring, and iii) consideration of relationships drivers or not. Using this typology, we classified 103 research articles published from 1998-2017 papers identified through a systematic search in the Web of Science database.

Given excessive misuse of the term “spatial interactions” in current studies, to avoid confusion in future studies and strengthen scientific cohesion, we recommend using “spatial interactions” or simply “interactions” between ES only to refer to identification and analysis of action and retroaction between ES over space within a landscape or region.

Application of our generic typology shows that i) the snapshot approach is the most common approach used in quantitative studies of ES relationships, (ii) considering the spatial dimension of the study area in studies of ES relationships is a challenge from watershed to regional and global scales and iii) analysis of spatiotemporal dynamics of ES relationships remains a major research challenge. Since 2011, most studies have analyzed relationships between 3–6 ES, while studies before 2011 considered 2–4 ES. Land use and cover changes was the principal type of driver identified, but usually using coarse indicators i.e. by considering general land cover classes.

To improve understanding of ES relationships and develop knowledge that stakeholders can act on, we identified two central research issues. First, we recommend that future studies focus more on finer and deeper identification of key drivers of ES relationships and evaluation of their respective weights. For example, analysis of the influence of management practices remains poorly addressed (Lal, 2013) while they influence key properties of ecosystems, such as manageable characteristics of soils, and in turn ES linked to the functioning of soil–plant systems. To reach this objective, we suggest that future work overcome limits of coarse land cover approach by analyzing effects of land use and soil and landscape characteristics on ES relationships. Land use, including spatiotemporal ecosystem configuration (e.g. rotation, grass strips…) and soil–plant management practices (tillage, fertilization, irrigation…), modifies ecosystem’s structure and functioning (Gaba et al., 2014; Hasan et al., 2020), and hence, influenced ES and their relations (Cord et al., 2017; Han et al., 2017). Manageable and non-manageable soil characteristics are key drivers of soil functioning and of the numerous associated ES linked to water, nutrients, pollutants and carbon cycles (Robinson et al., 2012; Dominati et al., 2014). Landscape configuration, not only composition (land cover), determines material and energy flows within an over ecosystems and so ES linked to regulation of baseline flows and extreme events and biological regulations (Verhagen et al., 2016). To deal with the complexity induced by this type of analysis, research studies must go beyond the use of main traditional analysis methods as correlation/association or principal components analysis. As mentioned by Mouchet et al. (2014), promising methods include structural equation modeling (Grace, 2006), a causal inference approach increasingly used in ecology, or multivariate regression tree, as an interesting method to analyze complex ecological data (De'ath, 2002). Second, to develop spatiotemporal (vs. snapshot) analysis of ES relationships it is necessary to ensure the availability of required data over space and time. Two main strategies should be developed to address this lack of data: (i) develop and/or use of process-based simulation models (Seppelt et al., 2011; Dade et al., 2018) and (ii) develop and/or use data collected from Long-Term Ecological Research sites (see for example Syswerda and Robertson (2014). These two strategies should be coupled to ensure an empirical validation of the simulated results and possible use of models to inform sampling strategies of empirical studies.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecoser.2020.101120.

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