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Analyzing trade-offs between ecosystem services in multi-functional landscapes

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Abstract

The urgent need to preserve multiple ecosystem services is one of the key challenges in natural resource management globally. A management decision can cause undesired consequences when a decision is made without a comprehensive understanding of provided ecosystems services. These consequences can lead to trade-off situations when a service increases at the cost of another service. An informed decision is therefore crucial to reduce unexpected trade-offs between ecosystem services and to preserve multiple ecosystem services at the same time. The international community initiated the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) to strengthen the link between the scientific evidence and policy making. To support the IPBES process, various review studies have been conducted in the ecosystem services research community. Yet, they often appear to be qualitative; therefore, a quantitative synthesis on relationships requires further investigation. At the same time, an effective way of quantifying less-studied ecosystem services (i.e., cultural ecosystem services) has to be found.

The first two studies presented in this thesis contribute to the synthesis of case studies on relationships between multiple ecosystem services. In the first study, a dominant relationship between pairwise combinations of ecosystem services was determined based on 67 case studies with 476 pairs of ecosystem services. Also, the effect of scale, land systems (a combined measure of land use and bioms), and the methods used to determine the relationship on the pattern of dominant relationships was tested. Across case studies, the trade-off relationships were dominant between provisioning and regulating services, whereas synergistic relationships were dominant between different regulating services, or between different cultural services. Increases in cultural services did not influence regulating services, which led to no-effect relationships between them. The dominant pattern of relationships was not influenced by either scale or land system archetype. It is partly due to biased case studies, which hampered the comparison. The method used to determine the relationships influenced the direction of relationships between ecosystem services, which calls for further attention when a researcher or practitioner chooses a method to analyze relationships between ecosystem services.

The relationships were further investigated based on the management choices in the second study. The second study focuses on the impacts of alternative agricultural practices on multiple ecosystem services in the Mediterranean basin using the meta-analysis method. As the ecosystem services provisioning in the Mediterranean basin is threatened by ongoing climate change and unsustainable use of rural land, the alternative agricultural management approaches may reduce unexpected trade-offs between agricultural production and regulating services. The frequently found alternative agricultural practices in case studies (conservation tillage, cover cropping, mulching, manual weed management, organic fertilizer use, irrigation system) were compared to the pairwise conventional practices based on 155 published case studies. The results showed that all regulating services were positively affected by the conservation schemes since they improve the soil quality. However, the impacts on food provisioning services were inconsistent.

In the last study, a new methodological framework was developed to quantify and map cultural ecosystem services using crowd-sourced photos uploaded in the Flickr archive.

Subsequently, the quantified cultural ecosystem services were compared with other services such as carbon sequestration and flora and fauna diversity in the Mulde watershed in Saxony, Germany. Based on semantic tags and the network analysis of tags, the thematic information of photos was classified into nine clusters, two of which were related to cultural ecosystem services. The hotspots identified based on the contents of photos were related to butterfly richness. Photos were rarely related to carbon sequestration.

Taken together, this PhD thesis investigated relationships between multiple ecosystem services on three different spatial scales: a global synthesis, Mediterranean agro-ecosystems and the river Mulde watershed. The results of this thesis emphasize that trade-off and synergy effects need to be evaluated to successfully assess multiple ecosystem services. I further identified a lack of results in cultural services and therefore provide a methodological guideline to perform a quantification of cultural ecosystem service.

Zusammenfassung

Es besteht ein unmittelbarer Handlungsbedarf um Ökosystemdienstleistungen (ÖSD) zu erhalten und dies ist eine der größten, aktuellen Herausforderung bei der Nutzung natürlicher Ressourcen und Ökosysteme. Entscheidungen über die Nutzung und Bewirtschaftung unserer Landschaft können unerwünschte Folgen haben, wenn die Entscheidung nicht auf einem umfassenden Verständnis der ÖSD basiert. Diese unerwünschten Folgen erfordern Kosten-Nutzen Abwägungen (trade-offs), vor allem dann wenn eine Ökosystemdienstleistung wächst zu Lasten einer anderen sinkenden Leistung. Eine allumfassende, auf gutem Wissen basierende Entscheidung ist demnach unabdingbar um unerwartete Kosten zu reduzieren und zahlreiche ÖSD gleichzeitig zu erhalten. Die internationale Gemeinschaft hat die Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) ins Leben gerufen um die Zusammenarbeit zwischen wissenschaftlichen Grundlagen und politischen Entscheidungen zu stärken. Um die Realisierung von IPBES zu unterstützen wurden zahlreiche Literaturstudien in des ÖSD Gemeinschaft durchgeführt. Diese Literaturstudien erscheinen jedoch oft als qualitative Zusammenfassung, aber eine quantitative Untersuchung über diesen Zusammenhang werden noch benötigt. Ein qualitativer Zusammenfassung über diese Beziehung und der Einfluss von Verwaltungsmaßnahmen auf die Beziehung benötigen noch weitere Untersuchen in Fallstudien um in politische Entscheidungsprozesse eingebunden werden zu können. Gleichzeitig müssen in Zukunft effiziente Methoden zur Quantifizierung weniger untersuchter ÖSD gefunden werden. Gleichzeitig muss eine effiziente Methode um weniger untersuchte ÖSD, wie z.B. kulturelle Dienstleistungen, zu erfassen, gefunden werden.

Die ersten beiden hier vorgestellten Studien tragen zur Synthese von Fallstudien über den Zusammenhang mehrerer ÖSD bei. Zuerst wurde ein starker Zusammenhang in 67 Fallstudien mit 475 gepaarten ÖSD herausgearbeitet. Auch der Effekt von Skala, Landsystemen (einem kombinierten Maß aus Landnutzung und Biomen) und der Methode, die zur Feststellung des Zusammenhanges zwischen zwei starken Verbindungen herangezogen wurde, wurden untersucht. Über alle Studien hinweg lag die Kosten-Nutzen Abwägung vor allem zwischen Versorgungsleistungen und regulierenden Leistungen, wohingegen synergistische Beziehungen vor allem bei verschiedenen regulierenden Leistungen zu finden waren oder zwischen kulturellen Leistungen. Eine Steigerung der kulturellen Leistungen beeinflusste die regulierenden Leistungen nicht, was zu einer ‘ohne-Effekt-Beziehung’ zwischen den beiden führte. Das vorliegende Muster der Beziehungen wurde nicht durch die Skala oder das Landsystem beeinflusst. Dies ist teilweise durch Fallstudien mit systematischen Fehlern, die die Vergleichbarkeit behindern, beeinflusst. Die Beziehung zwischen ÖSD wurde auch von der Methode, die für die Erfassung der Zusammenhänge genutzt wurde, beeinflusst. Dies erfordert eine erhöhte Aufmerksamkeit, wenn ein Wissenschaftler oder Praktiker eine Methode zur Analyse der Beziehung zwischen ÖSD heranzieht.

Die Zusammenhänge wurden in der zweiten Studie im Zusammenhang mit Nutzungsentscheidungen untersucht. In einer Meta-Analyse wird dabei der Einfluss alternativer landwirtschaftlicher Bewirtschaftungsmethoden auf mehrere ÖSD im Mittelmeerraum untersucht. Die Versorgungsleistungen im Mittelmeerraum werden von Klimawandel und nichtnachhaltiger Landnutzung der ländlichen Gebiete bedroht. Die alternativen landwirtschaftlichen Bewirtschaftungsmethoden könnten die unerwarteten Kompromisse

(trade-offs) zwischen landwirtschaftlicher Produktion und regulierenden Leistungen reduzieren. Die oft gefundenen alternativen Bewirtschaftungsformen in den Fallstudien (konservierende Bodenbearbeitung, Deckfrüchte anbauen, mulchen, manuelle Unkrautentfernung, organischer Dünger, Bewässerungsanlagen) wurden mit paarweisen konventionellen Praktiken verglichen, basierend auf 155 veröffentlichten Fallstudien. Die Ergebnisse zeigten, dass alle regulierenden Leistungen positiv von den Naturschutzmaßnahmen beeinflusst wurden, da es die Bodenqualität verbessern konnte. Jedoch waren die Einflüsse auf Ernährungsversorgungleistungen inkonsistent.

In der letzten Studie dieser Dissertation wurde ein neues methodisches Konzept entwickelt um kulturelle Dienstleistungen zu quantifizieren und kartographisch darzustellen, durch die Fotos, die von vielen Nutzern (crowd-sourcing) auf Flickr zur Verfügung gestellt wurden. Folglich wurden die so quantifizierten kulturellen Leistungen mit anderen ÖSD, wie Kohlenstoffsequestrierung und Diversität der Flora und Fauna im Mulde Wassereinzugsgebiet in Sachsen in Deutschland verglichen. Auf Grundlage von semantischen Etiketten (‘tags’) und der Netzwerkanalyse dieser ‘tags’, wurde die thematische Zugehörigkeit der Bilder in 9 Kategorien eingeteilt, von denen zwei im Zusammenhang mit kulturellen Dienstleistungen standen. Der ‘Hotspot’, der durch den Inhalt der Bilder identifiziert werden konnte, lag bei Schmetterlingsdiversität. Bilder konnten selten in einen Zusammenhang mit Kohlenstoffsequenzierung gebracht werden.

Zusammengefasst betrachtet die vorliegende Doktorarbeit den Zusammenhang zwischen mehreren ÖSD auf drei verschiedenen räumlichen Skalen: auf der globalen Ebene, in mediterranen Agroökosystemen und im Einzugsgebiet des Flusses Mulde. Die Ergebnisse dieser Arbeit zeigen, dass Kosten-Nutzen Abwägungen und Synergien evaluiert werden müssen um mehrere ÖSD erfolgreich feststellen zu können. Ich habe weiterhin festgestellt, dass Ergebnisse zu kulturellen Dienstleistungen weitestgehend fehlen und stelle deswegen eine methodische Leitlinie für eine Evaluierung von kulturellen Dienstleistungen vor.

Contents

1. Introduction

Humans are dependent on ecosystems and their resources. They use and modify land to derive goods and services of needs. They profit thereby from a large number of goods and services provided by ecosystems (so called "ecosystem services"). An ecosystem is "a dynamic complex of plant, animal, and microorganism communities and the non-living environment interacting as a functional unit" (MA, 2005, p.5). Human-beings and their activities are part of this ecosystem (MA, 2005), and human modifications of ecosystems affect the provisioning of ecosystem services directly and indirectly. Depending on the decisions they make regarding how to manage land, an ecosystem can provide different goods and services to society.

Trade-offs between ecosystem services occur as consequences of these decisions. Trade-offs occur when an increase in a service can lead to a reduction in another service. Synergistic and no-effect relationships between services also occur when either services increase or they are not affected by each other. Almost any decision will involve trade-offs among services. To avoid unexpected trade-offs and enhance synergies between services, a comprehensive understanding of relationships between services is crucial for informed decision-making to secure multiple ecosystem services.

This PhD thesis deals with the quantification of relationships between ecosystem services both based on meta-analyses of the published literature, and an empirical case study. Specifically, it investigates (i) relationships between ecosystem services regarding scales, land systems and methods, and (ii) the impacts of management choices on the relationships based on published case studies. In the empirical case study, it investigates the quantification of cultural ecosystem services, and the relationship between cultural ecosystem services and carbon sequestration and biodiversity.

This chapter reviews the conceptual background and the state-of-the-art knowledge regarding relationships between ecosystem services. The research gaps that this thesis aims to fill are then identified along with objectives and an outline of the thesis.

1.1 Background

1.1.1 The concept of ecosystem services

Ecosystems have provided a wide range of benefits for human society for many millennia. These benefits include essential goods such as food, clean water, materials for shelter, as well as various cultural benefits. These tangible and intangible benefits that people obtain from ecosystems are increasingly termed as 'ecosystem services' (ES) (Daily, 1997, Daily et al., 2000). The Millennium Ecosystem Assessment (MA) shaped the concept of ES and highlighted its linkages to human well-being such as security, basic material, and health (MA, 2005). The MA has categorized the different ES into four categories: provisioning services (e.g., food, timber, clean water), regulating services (e.g., climate regulation services, pollination, erosion control), cultural services (e.g., recreation, outdoor activities, religious values), and supporting services (e.g., nutrient cycling, habitat protection). The supporting services do not directly serve human well-being, but underpin processes and functions on which other services depend (de Groot et al., 2002, 2010, Haines-Young and Potschin, 2010). This is why the supporting services category was excluded and merged into the regulating services category from other ES classification schemes such as CICES (Common International Classification of Ecosystem Services) (Haines-Young and Potschin, 2013). Since publication of the MA (MA, 2005), the number of publications on ES research has drastically accelerated (Olander et al., 2017).

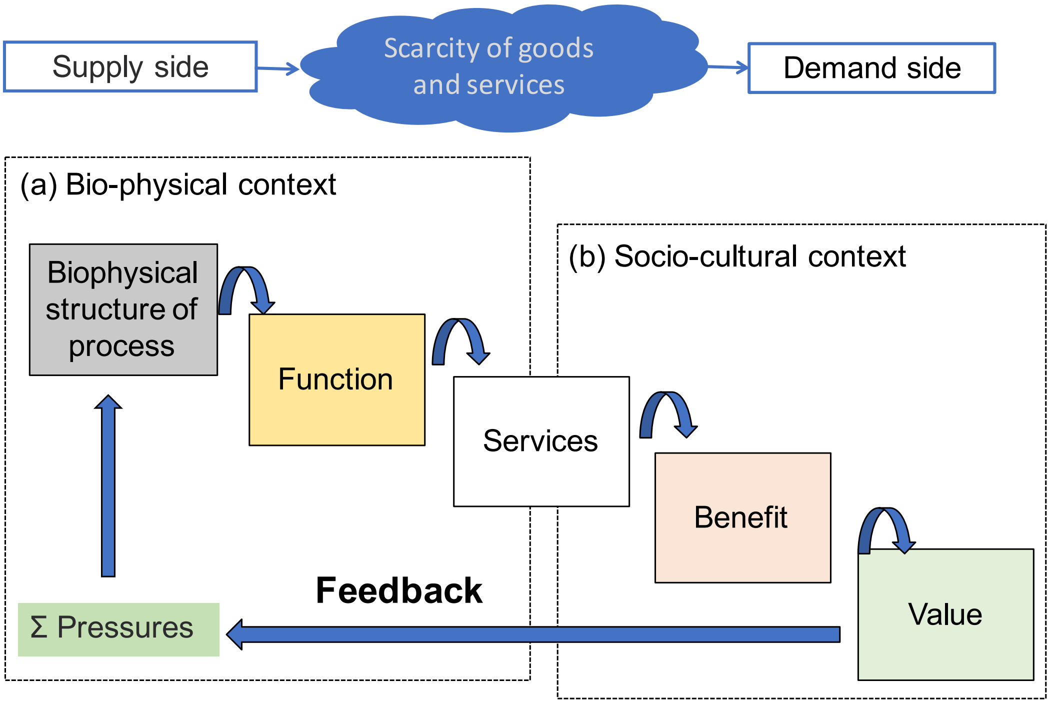

Figure 1.1: The ecosystem services cascade model adapted from Haines-Young and Potschin (2010) and de Groot et al. (2010).

Understanding the connections between the underlined functions and the benefits is the first step towards comprehending the effect of human decisions on ecosystems and derived services, and their trade-offs. To better address the connections between the underlined functions and the benefits that people finally obtain, Haines-Young and Potschin (2010) suggested a cascade model (Fig. 1.1). The cascade model visualizes 'the production chain' of ES: on the left side, it shows a biophysical context of an ecosystem which is related to the supply side of ES, whereas on the right side, a socio-cultural context is shown (Fig. 1.1). The biophysical context refers to the biophysical processes, their functions and capacities to provide services ("ES supply"). The socio-cultural context refers to how the provided services become a value ("ES demand"). For example, vegetation cover is a biophysical structure which slows water flow (function). This function provides a service, 'flood protection'. This flood protection service contributes to security and human health (benefit). This benefit is valued according to how much money people are willing to pay (WTP) to preserve this benefit (value) (de Groot et al., 2010, p.264). As one can argue that ES can be only valued when it is used by people (e.g., Wallace, 2007), the cascade model highlights the connection between the supply side (i.e., bio-physical context) and the demand side (i.e., socio-cultural context). Also, it shows a feedback function. According to the value, people make different decisions. Overuse of a certain service affects the biophysical condition, which will involve trade-offs among services. Nowadays, this framework is widely used as a tool for framing and organizing the ES research and also for helping to link between the ES concept and practices (Potschin-Young et al., 2017).

To manage the various ES wisely without further pressure on ecosystems, decisions have to be made carefully (Daily et al., 2009). Linkages between scientific knowledge and the decision-making process is a crucial step for informed decision-making (Cash et al., 2003, Daily et al., 2009). Daily et al. (2009) showed how to integrate ES into a decision-making process (Fig. 1.2). Various decision options create potential actions and scenarios (Fig. 1.2, (a)). A biophysical model realizes services from the ecosystem capacity (Fig. 1.2, (b)). The derived services are translated into values based on economic and cultural models (Fig. 1.2, (c)). The information of ES values is delivered to a decision-making process through institutions. As a result, the information on ES contributes to sound decision-making (Daily et al., 2000, 2009). As the ES concept received increasing attention from the scientific community, efforts on operationalization of the concept in practice have been geared as well (Schetke et al., 2016, Olander et al., 2017, Potschin-Young et al., 2017).

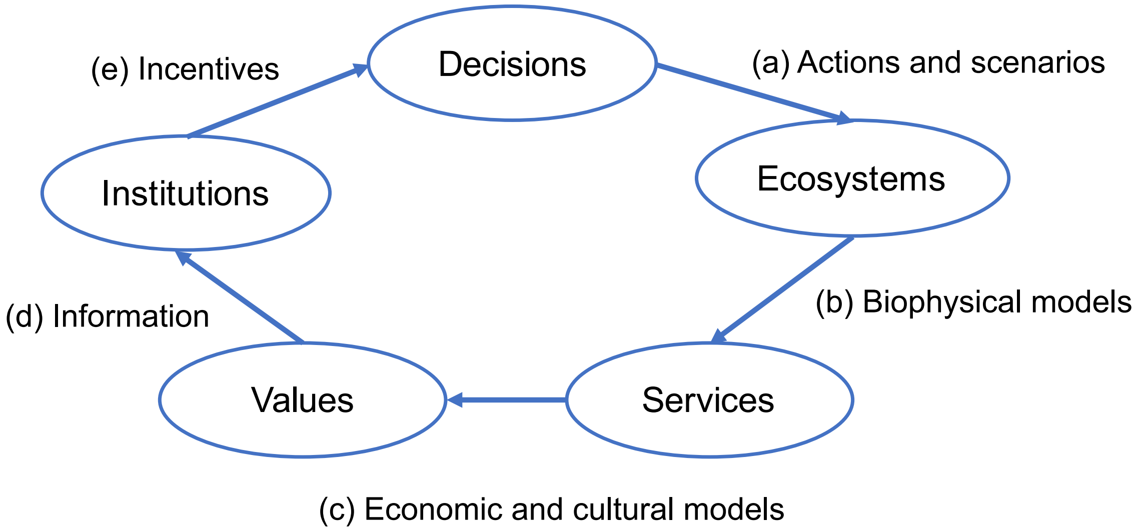

Figure 1.2: The framework of ES in decision-making adapted from Daily et al. (2009).

To stimulate this process and to deliver information to the decision-making process, global institutions have been established. High-level policy platforms such as "The Convention on Biological Diversity (CBD)"[1] and the "Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES)"[2] were established to strengthen the science-policy interface for biodiversity and ES, and ultimately to support sustainable ES managements (Hulme et al., 2011, Díaz et al., 2015). Since its establishment, thousands of scientists all over the globe have participated in the platform to provide knowledge and to synthesize existing research outcomes. Research initiatives such as OPerationalizing Ecosystem Research Applications (OPERAs)[3] and Operationalisation of Natural Capital and Ecosystem Services (OpenNESS) [4] were initiated for this purpose. However, despite an increase in awareness among the scientific community, practical applications of the ES concept have not yet been fully transferred from the scientific outcomes (Lautenbach et al., 2017b, Olander et al., 2017). There is a need for further development of efficient synthesis and delivery of the information (Smith et al., 2017).

1.1.2 Trade-offs between ecosystem services in decision-making

A 'Trade-off' is a situation when an increase in one objective leads to a reduction of another objective. Trade-offs occur when deciding between limited available resources. In economics, trade-offs are often termed as the 'opportunity cost' which is defined in the New Oxford American Dictionary as "the loss of potential gain from other alternatives when one alternative is chosen." (Stevenson and Lindberg, 2015). To minimize unexpected consequences, decision-makers should have a comprehensive understanding of gain and loss caused by their decisions on natural resource management.

Trade-offs can be found in natural resource management. As ecosystems generate multiple ES simultaneously (Foley et al., 2005, Bennett et al., 2009), a decision about which ES to produce can, directly and indirectly, affect various aspects of trade-offs. Different contexts for trade-offs in ES research are summarized in Fig. 1.3. From the supply side of ES, trade-offs occur among different services. Given the limited land area, a decision on ES for the same space (e.g., forest vs. settlement) generates trade-off among them by competing for space. Trade-offs are found not only in adjacent areas but potentially also in areas separated by large distances. Impacts of a decision in a certain location are found in other systems nearby or far away (e.g., telecoupling (Liu et al., 2013, Liu and Yang, 2013) or off-site effects (Pascual et al., 2017)). As an example, in a tele-coupled world, a food trade system affects both importing and exporting countries: The soybean farming in Brazil (exporter) influences, as a spillover effect, the farming system in China (importer) and some unknown countries (Liu et al., 2013), which potentially modify the land system and the service provision in those coupled areas. Therefore, decision-makers should be aware that their decision can cause an unexpected loss (trade-offs) or gain (synergies) in other locations. The third type of trade-off in ES research is the trade-off between management options (Fig. 1.3). Some ES studies focus on different management options. By providing decision-makers with possible options, possible trade-offs are tested. As a consequence of these decisions, trade-offs affect different groups of beneficiaries with different interests

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[1] https://www.cbd.int/convention

[2] http://www.ipbes.net

[3] http://operas-project.eu

[4] http://www.openness-project.eu

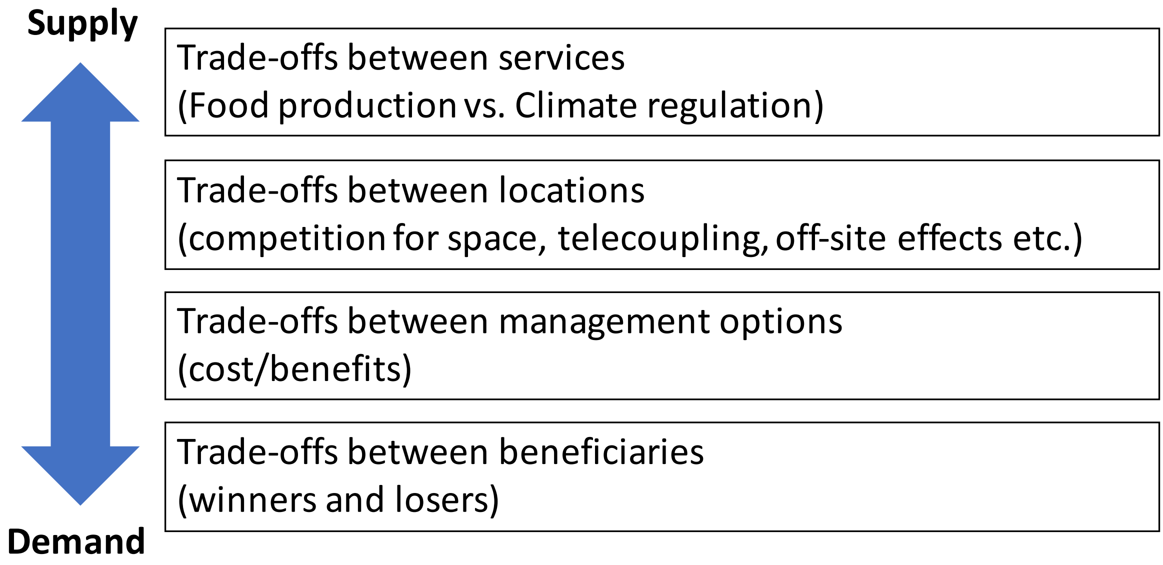

Figure 1.3: Trade-offs found in ES research (after discussions in a session themed "trade-off analyses" during the OPERAs symposium in Lisbon, Portugal in 2014). Various types of trade-offs from the supply to the demand side of ES are demonstrated.

(Howe et al., 2014). For example, a decision on changing land cover from arable land to forest may affect not only produced services (from food provisioning service to carbon sequestration), but also related sectors and people. Among various trade-off situations shown in Fig. 1.3, this thesis focuses on the trade-offs between services (the first category of the summary in Fig. 1.3).

1.2 State-of-the-art knowledge

1.2.1 Relationships between ecosystem services

There is an increasing awareness of a need for quantifying multiple ES simultaneously (Ring et al., 2010, Turkelboom et al., 2016). There are various methodological approaches introduced to analyze those relationships among ES. In this section, I briefly summarize currently applied methodological approaches in multiple ES research.

Multiple ES have been 'bundled' when they repeatedly occurred together within a landscape (Kareiva et al., 2007, Braat and de Groot, 2012). This approach highlights that the bundles represent the landscape characteristics and identify trade-offs and synergies. Also, it shows patterns of ES provisions based on the information on the land use and land cover types within a given region (e.g., Raudsepp-Hearne et al., 2010, Martín-López et al., 2013). Raudsepp-Hearne et al. (2010) investigated these bundles empirically and illustrated with ‘flower’ diagrams (also known as radar or spider plots). Since their publication, the ES-bundle flower diagram has become a common means of identification for bundles of ES at the landscape or regional scales (e.g., O’Farrell et al., 2010, Nemec and Raudsepp-Hearne, 2012, Queiroz et al., 2015). The bundle analysis is frequently done based on a GIS analysis and complementary statistics such as cluster analyses and descriptive statistics (Mouchet et al., 2014). This approach is useful for mapping spatial patterns of multiple ES provision. However, as the focus of the bundle approach is a bunch of ES simultaneously, it is hard to define pairwise relationships from the bundle results.

Modeling methods are also generally used to quantify relationships between ES (Lavorel et al., 2017). Multiple ES are included in models, and trade-offs are analyzed by running the model for different sets of alternatives. There are many variants among models from process-based models (e.g., Lund-Potsdam-Jena General Ecosystem Simulator [LPJ-GUESS] (Smith et al., 2001) or the Soil Water Assessment Tool [SWAT] (Arnold et al., 1999)) to a simplified mapping model (e.g., InVEST - Integrated Valuation of Ecosystem Services and Tradeoffs (Sharp et al., 2016)). Suitable choices on model types need to be made depending on the research questions and the data types.

As the term ‘trade-off’ itself came from economics, the “production possibility frontier” is often used to analyze the trade-off relationship between pairwise ES (Fig. 1.4). The production possibility frontier in the ES research refers to possible combinations of the provision of multiple ES (White et al., 2012, Lautenbach et al., 2013, Cavender-Bares et al., 2015). In other words, the optimal (efficiency) frontier is defined as a state of the maximum production of multiple services that can be generated from the given land (Nelson et al., 2008, p.9472) (Fig. 1.4, A, B, and C points). By moving production A to C in Fig. 1.4 the production of ES1 increases, whereas the amount of ES2 decreases. In this case, trade-offs occur due to the potential conflict between ES1 and ES2 provisions. This approach is combined with modeling tools. For example, Lautenbach et al. (2013) combined the SWAT model and the optimization analysis to analyze a trade-off relationship between bioenergy and food crop production, and water quantity and quality regulation services.

However, it is challenging to quantify multiple ES from a single field campaign or model. That is why synthesizing multiple case studies is used as a possible means of deriving agreed relationships among multiple ES across case studies. For that reason, several review studies on relationships among multiple ES were conducted (e.g., Pilgrim et al., 2010, Kandziora et al., 2013, Deng et al., 2016). Yet, these reviews are mostly qualitative.

1.2.2 Quantification of ecosystem services

Before quantifying relationships between ES, a quantification of each individual ES is required. The quantification of ES in a biophysical context is an unavoidable step for economic and financial valuation for most of the services (Alkemade et al., 2014) (See Fig. 1.1). Inherently, the concept of ES consists of a range of individual ES. Therefore, various methodological approaches have been applied to quantify individual ES. Those services, for which goods and services can be translated into stocks (i.e., provisioning services), are quantified in a more straightforward way. For example, provisioning of food, water, and other raw materials is generally quantified by the total or average amount of yield

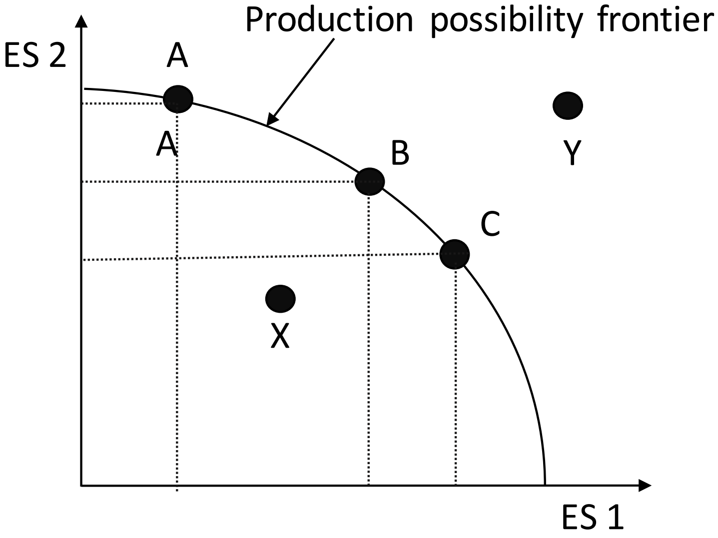

Figure 1.4: A diagram of the production possibility frontier curve (PPF) for ES1 and ES2 production. ‘A’, ‘B’ and ‘C’ points refer to the efficient allocation of resources to produce both ES1 and ES2. The point ‘X’ lying below the PPF curve refers to the inefficient production. The ‘Y’ is impossible to reach given the current condition.

and biomass for a crop, water, and other raw material species, respectively (Kandziora et al., 2013). Regulating services (including supporting services) are less tangible benefits compared to the provisioning services (Kandziora et al., 2013, Karp et al., 2015). They are defined as ‘services obtained from the regulation of ecosystem processes’ (MA, 2005). As regulating services are not easily translated into an economic value and not traded in markets, they are often not recognized by the public (Kumar et al., 2010, Kandziora et al., 2013). Field measurements (Dickie et al., 2011, Lavorel et al., 2011), as well as process-based models (Lautenbach et al., 2013, Karp et al., 2015), are generally used to quantify regulating services. In addition, look-up tables, proxy-based analyses or GIS analyses are used (Eigenbrod et al., 2010).

Cultural ecosystem services (CES) are intangible and the most anthropocentric services, which hinders direct quantification (Burkhard et al., 2009, Daniel et al., 2012, Milcu et al., 2013, Gliozzo et al., 2016). CES include not only physical and intellectual experience with ecosystems but also a spiritual and symbolic definition of ecosystems (Collaboration for Environmental Evidence, 2013). Stated-preference measures such as interviews (e.g., Plieninger et al., 2013) and surveys (e.g., Gee and Burkhard, 2010, van Berkel and Verburg, 2014) have been used to quantify those CES. However, as stated preference measures are limited in temporal and spatial contexts (Wood et al., 2013), it is hard to apply them on a large scale and in remote areas. Among CES, recreation and tourism are the most studied cultural services (Milcu et al., 2013) as there are more quantitative indicators available such as the number of visitors (e.g., Hein et al., 2006, Eigenbrod et al., 2009) or proxy-based potential recreational areas (e.g., Chan et al., 2006, Eigenbrod et al., 2010, Maes et al., 2012), for instance.

Photos have been used as an indicator of landscape type preferences in multiple ways. Examples include the analyses of photos i) as a basis for questionnaires where respondents were asked to rank photos which represent different features of landscape configuration (Tveit, 2009, Barroso et al., 2012, van Berkel and Verburg, 2014), and ii) as indicators for people's perceptions of landscapes by analyzing their photos, e.g., from photo contests (Kohsaka and Flitner, 2004), or from local volunteer photographers (Garrod, 2008).

Crowd-sourced social media data have received increasing attention as an alternative data source for people's revealed preferences. With over 1,870 million active global users as of January 2017 (Chaffey, 2017), social media data has been actively used for business (Mangold and Faulds, 2009, Kaplan and Haenlein, 2010), for education (Friesen and Lowe, 2011, Tess, 2013) for politics (Loader and Mercea, 2011, Bennett, 2012), and also shows a possibility for conservation (Minin et al., 2015) and climate sciences (Ford et al., 2016). In the ES research community, geotagged photos (e.g., *Flickr*[5] and *Panoramio*[6]) or texts (e.g., *Twitter*[7]) provide an important opportunity given the limited time and resources to collect real-time data in these regards (Ford et al., 2016).

1.3 Research gaps

While the overarching ES concept has been consolidated in the last decade, we still face difficulties to make use of it in practical applications. Although there have been various case studies on relationships between ES, it is difficult to determine an agreed direction of relationship based on a single case study. For informed decision-making, synthesized scientific evidence is needed. At the same time, an effective means of quantifying less-studied ES has to be found. For the time being, I would argue that there are the following major gaps in ES research:

- Although there have been efforts to synthesize existing knowledge about relationships between ES, they have remained qualitative. A quantitative overview of relationships between multiple ES is missing.
- The term 'trade-off' implies a decision-making issue. Although it is widely accepted that a management option affects many ES simultaneously, we have not established a well-specified parameter table for the use of ES in a practical implication. Depending on how the land is managed, trade-offs or synergies between ecosystem services occur. However, impacts of a management option on a multitude of ES are not extensively accounted based on a large volume of literature. Furthermore, quantitative comparisons of the impacts of different management choices on different ecosystem services (i.e., how big the impact of a certain management choice would be) are seldom investigated.

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[5] http://www.flickr.com

[6] http://panoramio.com, however, no longer available after November 4, 2016

[7] https://twitter.com

- As stated above, a quantification of an individual ES is a prerequisite step for analyzing relationships among multiple ES. However, it is difficult to quantify ES at large scales where ground observations are not affordable. It is often improbable to quantify ES at a large-scale due to the difficulty in data acquisition. This is especially true for cultural ES for which remote sensing or other alternative data sources are underdeveloped. A feasible quantitative framework to analyze cultural ES would be beneficial for further quantifying cultural ES as well as relationships with other ES.

1.4 Objectives of the thesis

The goal of this thesis is to improve the understanding of relationships between ES. Specifically, I aim to i) synthesize existing knowledge on relationships between ES and derive common relationship patterns, ii) investigate impacts of management choices on the relationships between ES using a meta-analysis method, and finally iii) develop a novel indicator to quantitatively analyze cultural ES that can be used for quantifying relationships with other services. In this section, three main objectives of the thesis are summarized. Additionally, hypotheses related to each objective are formulated.

Objective 1: A synthesis of current knowledge of relationships between ES. To support informed decision-making on ES management, the information on relationships between multiple ES is essential. However, decision-makers would not have time and resources to collect existing case studies and to summarize their results. Therefore, provision of a synthesis would be beneficial to support them. Such a synthesis can guide other researchers for the further research on relationships between ES by identifying knowledge gaps through a synthesis. For this reason, currently available case studies on relationships between ES are synthesized based on the following three hypotheses.

- Hypothesis I is that a general dominant relationship between ES can be derived from existing case studies.
- Hypothesis II is that the scale or the land system archetype influences the relationship identified from hypothesis I. In other words, I want to test if the relationship between ES differs at different scales or in different land systems.
- Hypothesis III is that the relationship between ES is influenced by the methods that were used to determine the relationship in the case study.

Objective 2: Investigate the impact of management choices on multiple ES in agricultural regions. A relationship between ES can be differently affected by management options, especially in multifunctional landscapes. The impacts of different management choices should be examined to find a reasonable management option by minimizing trade-off effects. For this objective, multifunctional agricultural land in the Mediterranean basin is investigated to find alternative solutions to preserve various ES provided in this region based on published literature. A hypothesis of this study is that alternative agricultural managements (e.g., reduced tillage, cover crop, mulching, use of organic fertilizer, manual weed management, irrigation) have an overall positive effect on ES. Different sets of indicators for ES will be analyzed.

Objective 3: Develop a new indicator to quantify and map cultural ecosystem services (CES) and their trade-offs with other ES. An effective means of quantifying less-studied ES should be investigated. Using crowd-sourced photos available in a social network service, I develop a method to quantify and map CES, such as outdoor recreation, landscape aesthetics and existence values, by analyzing the contents of the photos. A hypothesis of this study is that analyzing the contents of photos improves the classification of CES and therefore improves the quantification of CES in a given study area. In addition, how this information can be used in a trade-off analysis with other services will be further investigated.

1.5 Outline of the thesis

This thesis covers a range of ES relationships based on meta and case study analyses from global to local scales (Fig. 1.5). An overview diagram of this thesis is shown in Fig. 1.5.

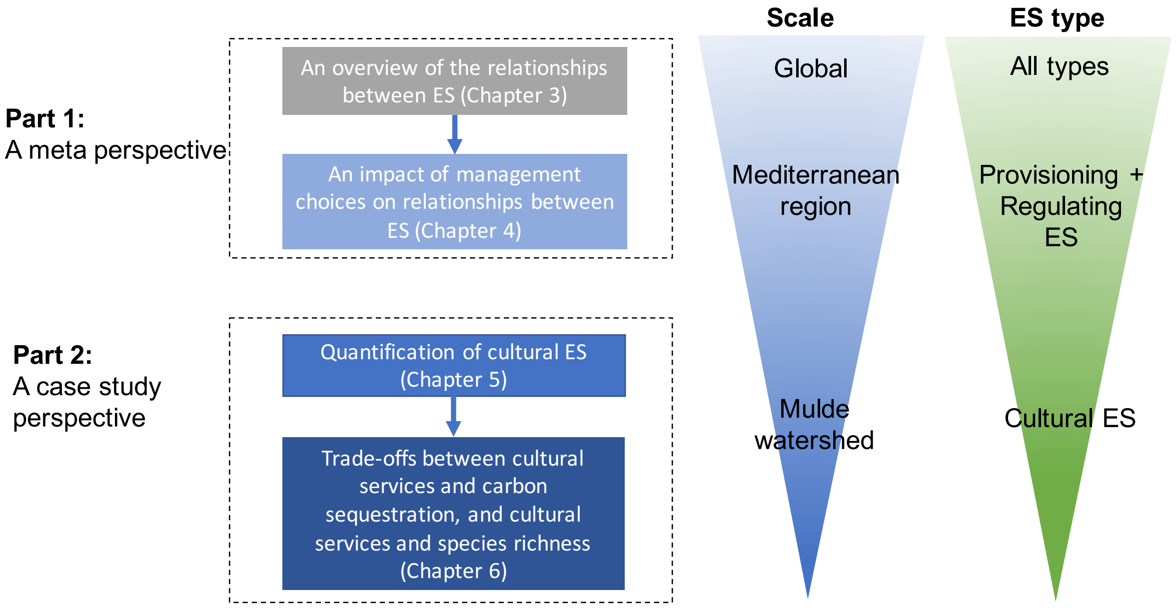

Figure 1.5: The overview of the thesis

The methods and data used are described in chapter 2. The aim of chapter 2 is to provide a general background of each method applied across the chapters in this thesis. It includes the process of systematic reviews and meta-analysis, and an application of social media data to analyze cultural ES.

The results section of this thesis starts with the outcome of a global synthesis including all types of ES found in case studies (chapter 3). A quantitative review of relationships between ES across case studies is given and the results of the above mentioned three hypotheses are summarized.

In chapter 4, the result from the meta-analysis on the impact of alternative conservation farming practices on ES is described. The focus area of this study is the Mediterranean basin, where the provision of ES is threatened by climate change and unsustainable use of rural areas.

The second part of the thesis moves from a meta-analysis to a case study perspective. In chapter 5, a case study on CES (i.e., outdoor recreation, landscape aesthetics and existence values) in the Mulde watershed is given. A novel indicator to quantify CES is explored in this chapter. Crowd-sourced photos are used as an indicator of people's revealed preference on landscape aesthetics and recreational activities. In this study, not only the temporal and spatial information of the photos but also the contents of the photos are analyzed to extract thematic information on CES from geotagged photos. Based on the thematic analysis, the photos in a study area are distinguished between CES- and non CES-related photos.

In chapter 6, relationships between the CES, which are identified in chapter 5, and carbon sequestration, and CES and floral/fauna species richness are further analyzed. The identified CES areas from chapter 5 are compared with the locations of carbon sequestration and species richness hotspots.

In chapter 7, the major results of each chapter (chapter 3, 4, 5 and 6) will be discussed along with contributions from this thesis to the ES research community. Also, conclusions are drawn.

2. Methods and data

2.1 Overview of meta-analyses used in this thesis

Information is fed to reduce uncertainties and to choose a possible best option to cope with changing conditions (Schmidt et al., 2010). Impacts from such information increase when the information that was produced from individual studies builds a common language and is delivered to decision-makers. As a result, the informed decisions help to improve ES provision and human well-being (Posner et al., 2016). Review studies provide the strongest and most reliable information compared to a single case study or individual opinions (Mupepele et al., 2016). Fig. 2.1 shows a hierarchical ranking of Level-of-Evidence across scientific studies, on which review studies are located at the top. As this PhD thesis aims to provide the reliable evidence on a general pattern of relationships between ES across case studies, and therefore to contribute to the informed decision-making, review studies were conducted. Two steps were taken in this thesis. The first approach used in chapter 3 was a majority vote-counting approach across the globe and all types of ES, whereas the second approach used in chapter 4 was a statistical meta-analysis. In this chapter, the methods used in each chapter are given.

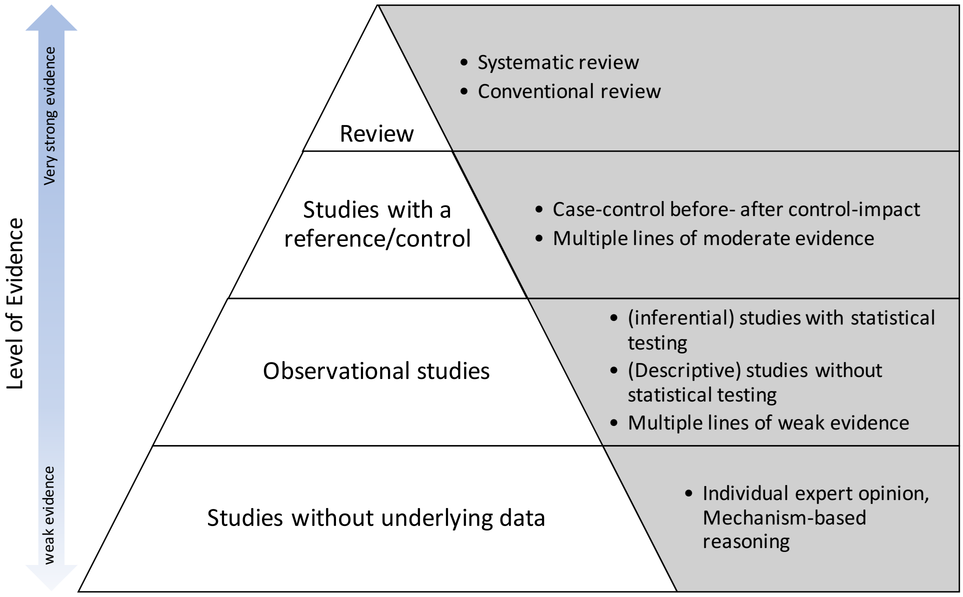

Figure 2.1: The hierarchical framework of Level-of-Evidence of scientific studies adapted from Mupepele et al. (2016).

2.2 Systematic review

Review articles are categorized into two main types, namely narrative and systematic reviews. Narrative reviews summarize different studies and provide state-of-the art knowledge of a given topic, qualitatively based on reviewers' expertise and experience. This type of review is more relevant to a broader topic. However, in this way, it generates reviewer bias (Collins and Fauser, 2005). Also, narrative reviews do not usually state a hypothesis and do not involve systematic mapping of literature (Bilotta et al., 2014). On the other hand, systematic reviews aim to provide a transparent and reproducible summary of a given topic (Higgins et al., 2002). By involving a systematic literature search, it attempts to reduce reviewer bias as well. Unlike narrative reviews that generally provide qualitative assessments (Roberts et al., 2006), a systematic review provides a rigorous methodological standard to derive evidence-based information that can support informed decision-making (Sackett and Rosenberg, 1995, Collaboration for Environmental Evidence, 2013, Bilotta et al., 2014). This method was first applied in health care interventions (Pullin and Stewart, 2006), and since then has been widely adapted in various fields of research such as ecology (Vetter et al., 2013), environmental management (Pullin and Stewart, 2006) and social sciences (Petticrew and Roberts, 2006). Regardless of topic-specific characteristics, the process (Fig. 2.2) appears to be similar, and it is explained below following descriptions from Petticrew (2001) and Bilotta et al. (2014).

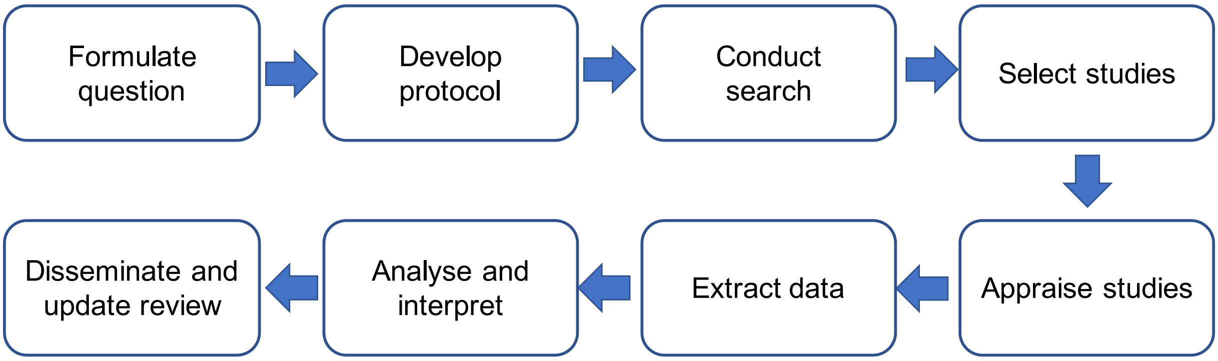

Figure 2.2: Key stages of the systematic review process adapted from (Bilotta et al., 2014).

Formulating a question: Before starting a literature search, a concrete research question should be developed. In this stage, research hypotheses are formulated with regards to interventions and comparisons. Three hypotheses were formulated for chapter 3 and one hypothesis was formulated for chapter 4. The three hypotheses in chapter 3 were i) a dominant relationship between ES exists for each ES pair, ii) this relationship is influenced by the scale with which the relationship had been studied as well as by the land system, and iii) this relationship is affected by the method applied to characterize the relationship among them. The hypothesis for chapter 4 was that conservation farming practices have a positive effect on multiple ES, which potentially leads to synergistic relationships between ES.

Develop protocol: After developing hypotheses, a protocol for the comparisons and for the basis of the database is established. This step can help an efficient organization to plan a literature search. By doing it, this stage helps to reduce authors' bias.

Conduct search: This stage includes defining search keywords to navigate publications. Keywords for chapter 3 were *"ecosystem service*"* or *"environmental service*"* or *"ecological service*"*, and *"trade-off*"* or *"tradeoff*"* or *"synerg*"* of the topic field. Keywords for chapter 4 included *("agro*" OR "agri*" Or "farm*") AND (mediterranean*) AND (management*)* in the topic field.

Select studies & Appraise studies: Through title, abstract and full paper screenings, relevant publications are selected. In this step, criteria to exclude not-related publications should be developed. For both studies in chapter 3 and 4, a list of excluding criteria was developed at this stage. Both studies only included case studies, therefore review studies and opinion papers were excluded. As chapter 3 focused on relationships between ES, case studies including results on relationships were included for the further analysis, whereas for chapter 4, farming management options should be included as they were the key issue. Geographical locations of the case studies were not important for chapter 3, whereas case studies located in the Mediterranean region were only included in chapter 4. This step is conducted based on "the guidelines of systematic review and evidence synthesis in environmental management" (Collaboration for Environmental Evidence, 2013). This guideline helps the process of systematic review in a reproducible way.

Extracted data: Depending on the aim of the systematic review, data analyses can be a structured summary or followed by a statistical meta-analysis. A structured summary can be a quantitative description of the collected publications and discussions. Generally, mean, standard deviation and the sample size are collected from the case studies.

Analyze and interpret: Based on the thorough analysis, a policy neutral summary of the evidence is provided. The interpretation is not only related to policy advice, but also to research gaps for future research needs. The results and interpretations are given in chapter 3 and 4 along with detailed explanations for each step of reviews.

Disseminate and update review: The analysis and the conclusion derived from the analysis is written and peer reviewed.

2.2.1 Data collection

A literature search was conducted following the PRISMA (Preferred Reporting Items for Systematic reviews and Meta-Analyses) process, which supports conceptual and practical advances of systematic reviews (Moher et al., 2009) (Fig. 2.3). Literature searches for both chapter 3 and 4 were conducted in the ISI Web of Knowledge core database based on peer-reviewed publications using the keywords identified above.

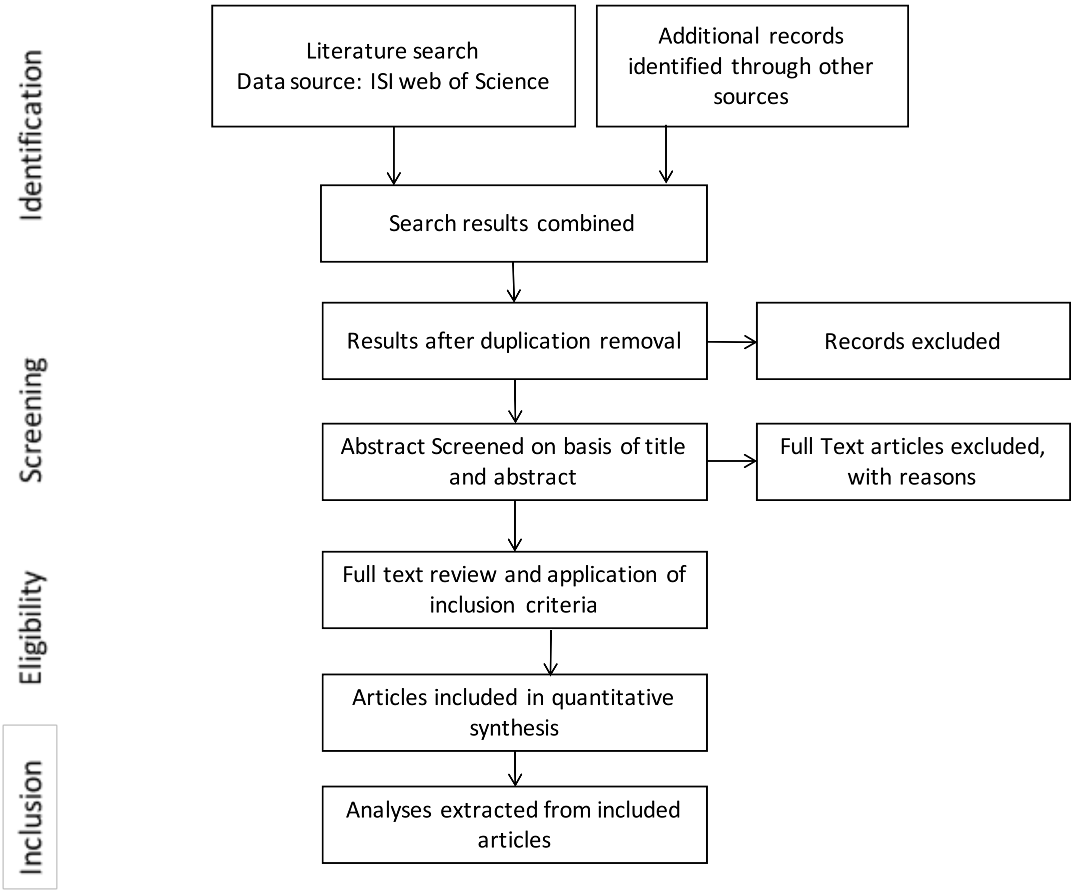

Figure 2.3: The PRIMA (Preferred Reporting Items for Systematic reviews and Meta-Analyses) process for the data collection (Moher et al., 2009). It includes four steps: *Identification, Screening, Eligibility, Inclusion.* Initial data collection with identified keywords is done in the Identification step. Titles, Abstracts of collected papers are screened in the Screening step. Through the screening of the chosen papers from the previous step, papers are chosen for full paper screening and screened whether they are eligible for further analysis in the Eligibility step. Finally, chosen papers are prepared for further analysis in the Inclusion step.

2.2.2 Analysis

2.2.2.1 Majority vote-counting used in chapter 3

A vote-counting method adds up the number of positive and negative results (Light and Smith, 1971). Vote-counting methods are simple and easy, and usually applied when reviewed studies did not provide enough information to estimate the mean difference between treatment and control groups (Hedges and Olkin, 1980). However, the vote-counting method has a limitation regarding its statistical power. Because it does not weight case studies with their variance or the number of samples (Stewart, 2010). Yet, it can still provide a general direction of relationships (i.e., positive, negative, or no-effect) for the specific variables with consideration of a level of significance or support toward the relationships (Lewis and Pattanayak, 2012).

In this thesis, chapter 3 was conducted from a vote counting perspective to derive a general relationship pattern across various ES and various land systems. The results of case studies were categorized into three categories: ‘trade-off’ when the relationship of studied ES was negative, or the direction of change was opposite (one increases when another one decreases), ‘synergy’ when both services changed in the same direction, and ‘no-effect’ when services were independent. For an uncertainty check of the results of relationships based on case studies, I calculated a ‘level of agreement’. The level of agreement of a pair of ES_i and ES_j is calculated as

$$Level\ of\ agreement_{i,j} = max(obs_{i,j,k}) / \sum_k (obs_{i,j,k}) \times 100, \tag{2.1}$$

where $obs_{i,j,k}$ is the number of observations for the pair of ESi and ESj in the relationship category k. When there is not a dominant relationship (i.e., two categories shared ‘50%’ each, or three categories shared ‘33.3%’ each), or the level of agreement was too low (below 50%), the category was assigned as ‘not-decided’.

2.2.2.2 Meta-analysis used in chapter 4

A meta-analysis is defined as a statistical technique to summarize results from multiple individual case studies quantitatively (Hedges et al., 1999, Higgins et al., 2002, Vetter et al., 2013). It is part of a systematic review which contributes to “Analyze and interpret” shown in Fig. 2.2. The meta-analysis is used in chapter 4 in this thesis. This technique in ecological studies became popular as many ecological and conservation research questions cannot be tested from a single case study regarding various ecological systems (Osenberg et al., 1999). As interest in experimental ecology increased, the importance of summarizing multiple results has increased as well (Hedges et al., 1999). A key advantage of meta-analysis methods is to calculate the magnitude of effects across studies, so called “effect-size”, based on a larger population (Koricheva et al., 2013). It increases the statistical power of a treatment effect as it quantifies inconsistent results across case studies (Koricheva et al., 2013, Vetter et al., 2013). This method is appropriate to answer a specific question, whereas the above-mentioned vote counting approach or narrative review is applicable for a broader question (Collins and Fauser, 2005). However, the meta-analysis method should be carefully applied as it has limitations. As the result of such meta-analyses relies on case studies, the quality of case studies is important. Furthermore, the heterogeneous study design may generate bias in the results and it is often not clear where the bias came from (Eysenck, 1994). Thus, the quality of included case studies should be carefully controlled from the data collection process.

Response ratio An effect size is a commonly used quantitative measure in meta-analyses to quantify the magnitude of the effect of treatment (Hedges et al., 1999, Osenberg et al., 1999, Borenstein et al., 2009). Several metrics are used as an effect size unit. Examples include the mean difference and the correlation coefficient between two variables

(Kelley, 2012). The correlation coefficient between two variables are used when two variables are independent (one variable is not a predictor of another variable) (Kelley, 2012). One example of mean-based metrics is the response ratio. The response ratio is the proportionate change of the treatment compared to the control management (Eq. 2.2). It is used when the output is measured on a physical scale (e.g., length, mass, quantity), which is the reason why it is commonly used in an ecological meta-analysis (Borenstein et al., 2009, Lajeunesse, 2011). The natural log transformed equation is frequently used (Eq.2.3) (e.g., Lajeunesse, 2011, Aguilera et al., 2013a, Torralba et al., 2016). This response ratio is also weighted by the variance or the sample size when the standard deviation is not given (Aguilera et al., 2013a). In chapter 4, the case studies were weighted using the sample sizes: studies with larger sample sizes were weighted more in aggregation (Adams et al., 1997) (Eg. 2.4)

$$Response\ Ratio = X_{Treatment}/X_{Control}, \tag{2.2}$$

$$ln(Response\ Ratio) = ln(\overline{X_{Treatment}}) - ln(\overline{X_{Contral}}), \tag{2.3}$$

$$W_{ij} = \frac{N_{ij}^{CS} N_{ij}^{C}}{N_{ij}^{CS} + N_{ij}^{C}} \tag{2.4}$$

, where N_{ij}^{CS} and N_{ij}^{C} are the sample size of the conservation option and the conventional option of the management i in study j, respectively (Hedges and Olkin, 1985, Adams et al., 1997).

2.3 Quantification of cultural ecosystem services (CES) based on crowd-sourced photos (chapter 5)

In chapter 5, cultural ecosystem services were quantified and mapped based on crowd-sourced photos. The thematic information of photos was extracted from tags. Tags are semantic information of photos that describe the contents of a photo. Since photos have been widely shared on the Web (e.g., *Flickr*[1] and *Panoramio*[2]), tags have been also widely used to help users organize their online resources, and share them with other users (Cattuto et al., 2007, Anderson et al., 2008, Tisselli, 2010, Kohara and Yanai, 2013). I used a tags network analysis to define the themes of photos to distinguish between CES related photos and non-CES related photos. All photos were downloaded from the Flickr photo archives, and the tags were collected from a cloud computing platform, *Clarifai*®. In this section, I explain the process of this analysis.

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[1] http://www.flickr.com

[2] http://panoramio.com, however, no longer available after November 4, 2016

2.3.1 Data collection

2.3.1.1 Flickr photos

From the Flickr photo archive, I downloaded all geotagged photos since 2005 within the Mulde basin in the federal state of Saxony in Germany (6,256 km^2) (Fig. 5.1) from the Flickr®photo archive. I excluded urban areas (10.2% of the study area) from the data collection as our focus was on CES in non-urban areas. The data collection was done on 2 January 2017 to cover all the photos taken and uploaded until 31 December 2016. The photos were identified and acquired through the Flickr Application Programming Interface (API)[3]. Finally, 12,635 photos with meta information such as user id, pictured date, and coordinates were collected in approximately for two days. Note that the Flickr archive is unsteady in a sense that photos and meta-information can be altered anytime. Therefore, photos added or modified later than the date of data collection were not accounted for.

2.3.1.2 Automatic tagging

I used an image annotation engine developed by *Clarifai* among a variety of image annotation techniques (e.g., Jin et al., 2005, Yang et al., 2006, Wang et al., 2008). The image annotation engine of Clarifai recognizes visual patterns of images and videos based on machine learning, and assigns tags automatically for any given input images or videos using deep convolutional neural networks (DCNNs) (Clarifai, 2016). The deep convolutional neural networks approach is one of the state-of-the-art algorithms in image recognition (Guo et al., 2016, Lecun et al., 1998, Krizhevsky et al., 2012, Yang and Hospedales, 2015). The Clarifai engine uses several large deep convolutional neural networks to robustly recognize visual features from pixels of images for annotating images (Zeiler and Fergus, 2014). Clarifai won the ImageNet Large Scale Visual Recognition Challenge competition in 2013, which underlines its performance (Russakovsky et al., 2015, Guo et al., 2016). For a detailed list of examples and the theory of deep learning methods for visual recognition, see a review study from Guo et al. (2016).

I used a pre-trained model (general-v1.3) provided by Clarifai®to assign 20 tags per photo with the associated probability of each tag. I accessed Clarifai API version 1 through a GNU R package `clarifai` (Sood, 2016) by which I analyzed the photos. Note that Flickr also provides automatic tag suggestions but I did not use it because the image recognition algorithm behind it is unclear[4] and uncertainty of tagging is unprovided.

2.3.2 Analysis

2.3.2.1 Network analysis

Subjects commonly used in ES evaluation can be viewed from a network perspective. As components of networks, they can be analyzed using standard network analysis methods

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[3] https://www.flickr.com/services/api

[4] https://help.yahoo.com/kb/flickr/sln7455.html

and reveal information which was hidden in traditional ES evaluation. Networks have been applied in various fields of research such as physics (Newman, 2003), social sciences (Otte and Rousseau, 2002, Borgatti et al., 2009), geographical networks (Jo et al., 2014), and neurosciences (Greicius et al., 2002) to derive and extract information from networking patterns. The patterns are not randomly created, but it rather shows an underlying structure and relationships (Luke, 2015). An example of networks is demonstrated in Fig. 2.4. A network consists of nodes and edges. Nodes represent each actor in the network, whereas edges represent connections. Nodes can be assigned from the arbitrary information of target objects: tags of a photo were nodes in the network in chapter 5 in this thesis. In networks, nodes can be grouped, or clustered based on similarities or dissimilarities between them. Often connections are assumed to share similar meanings (Luke, 2015). In various research areas, network analysis has been used to analyze patterns between texts and keywords (Lee et al., 2011, Isenberg et al., 2017, Santonen and Conn, 2016) to classify similar topics and trends.

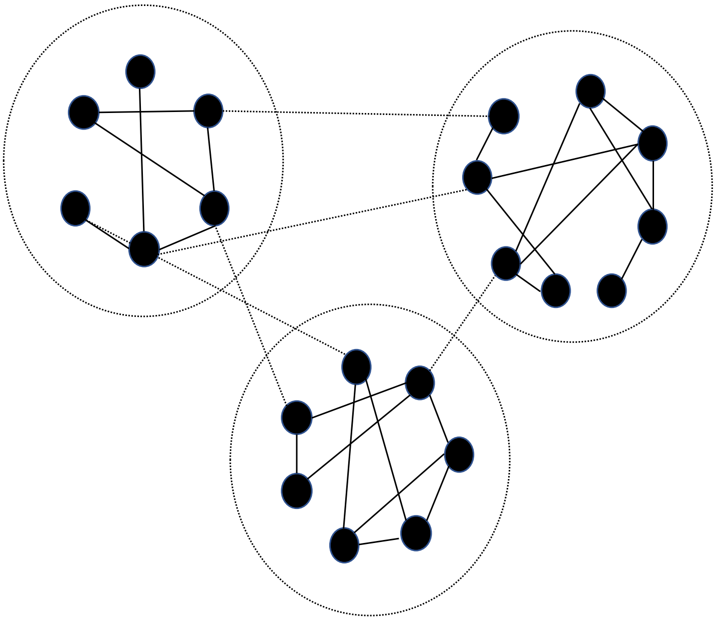

Figure 2.4: An example of networks adapted from Newman and Girvan (2004, p.1)

2.3.2.2 Cluster detection

When tags repeatedly occur in the same photo, it is assumed that the tags share similar features (Mousselly-Sergieh et al., 2013). The co-occurrence is calculated as the number of photos in which the two tags occur together (Begelman, 2006, Anderson et al., 2008, Sigurbjörnsson and van Zwol, 2008, Hu et al., 2012, Mousselly-Sergieh et al., 2013). Based on the co-occurrence, tags were clustered by applying semantic similarity among tags. The cluster detection algorithm used in chapter 5 was ‘Walktrap’. The algorithm performs a series of random walks over a network and generates a dissimilarity matrix based on the likelihood of reaching one node from another in a given random walk; random walks will tend to stay inside closely related tags instead of jumping to other tags. The optimal cluster size was determined using Newman's modularity (Q) (Newman, 2004, Newman and Girvan, 2004). For each *k*, the median modularity was calculated from the 100 resampled datasets without replacement (Eq. 2.5). The analysis was done in `R` version 3.3.1 (R Core Team, 2016) using the package `igraph` (Csardi and Nepusz, 2006). The visualization of the tag-network was done in Gephi (Bastian et al., 2009, Jacomy et al., 2014).

Modularity The fitness of the detected clusters was evaluated using the modularity (Q) (Newman, 2004, Newman and Girvan, 2004). This metric has been widely used in many community detection algorithms (Fortunato et al., 2004, Danon et al., 2005, Pons and Latapy, 2006, Newman, 2006). Closely following Newman and Girvan (2004), Q was calculated as follows,

$$Q = \sum_i (e_{ii} - a_i^2). \tag{2.5}$$

Let us assume k is the number of clusters and $\mathbf{e}$ is a k x k symmetric matrix. e_{ii}, an element of the matrix $\mathbf{e}$, is the fraction of edges in the network that links between two clusters i and j. For a given division of a network into k clusters, the modularity measures the number of within-cluster edges, relative to the expected value of random cluster edges with the same quantity in a cluster. If the number of within-cluster edges is smaller than the random model, the modularity is close to zero. By increasing the number of clusters (k), or moving down along the dendrogram, one or two peaks of modularity are often found (Newman and Girvan, 2004). When the modularity is at its maximum peak, it is considered that the corresponding k is the optimal number of the clusters. For the robustness of the result, a Monte Carlo approach was used. For 100 iterations, I sampled 80% of the database without replacement and formed clusters using the Walktrap algorithm to get the confidence interval of the modularity. The optimal cluster size was chosen based on the median value of the Monte Carlo modularity. The cluster names were given based on the subjective interpretation of the tags of each cluster by the researchers.

2.3.2.3 Assigning dominant cluster to photos

A cluster with the largest proportion among different clusters was assigned as the dominant cluster of the photo, and the proportion of the dominant cluster is the supporting ratio (Eq. 2.6). The dominant cluster was determined by a weighted majority voting. The supporting ratio of the dominant cluster for the photos was calculated as:

$$\mathit{Supporting\ ratio}(\%) = \mathit{max}_k(\mathit{tags}_k) / \sum_k (\mathit{tags}_k) \times \mathit{100}, \tag{2.6}$$

where $tags_k$ is the number of tags for each cluster (the index of the cluster is k). The higher the supporting ratio for a photo is, the more tags belonging to the same cluster in the photo.

To consider the credibility of the tags as well as to avoid ties, I assigned weights to tags based on the probability information supplied by the Clarifai engine for each tag. The cluster information was aggregated at a 2.5 km grid pixel to produce a spatial raster of the cluster information (Fig.5.7).

2.3.2.4 Photo-user-days

The photo-user-days were calculated as the total annual days that a photographer took at least one photo within a cell in the study area. The cell size in this analysis was 1 km by 1 km. By using the photo-user-days instead of the total number of photos one avoids a bias caused by photographers taking an exceptionally high number of photos in a single day. This step provides an overview map of current usage of most visited areas in the study area (Fig. 5.9). I compared the photo-user-days calculated based on the whole data set and the one calculated based on the CES-related photos.

2.3.2.5 Analysis of spatial distribution of photo-user-days

I tested for the influence of protected areas on photo-user-days using a quasi-poisson generalized linear model. I used aggregated information on the location of special protection areas, special areas of conservation, nature reserves, protected landscapes and nature conservation parks provided by the Saxonian State Agency for Environment, Agriculture and Geology (LfULG) (LfULG, 2017). The area covered by the protected areas was intersected with the 1 by 1 km raster cells. Photo-user-days of the different clusters were used as the response, and the area covered by protected areas was used as the predictor. Spatial autocorrelation of the residuals was tested by Moran's I, but it was not significant. I used the `R` packages `raster` (Hijmans, 2016), `sp` (Pebesma and Bivand, 2005), and `spdep` (Bivand et al., 2017) in this analysis.

3. A Quantitative Review of Relationships between Ecosystem Services

Abstract

Ecosystems provide multiple ecosystem services (ES) to society. Ignoring the multifunctionality of land systems in natural resource management generates potential trade-offs with respect to the provisioning of ES. Understanding relationships between ES can therefore help to minimize undesired trade-offs and enhance synergies. The research on relationships between ES has recently gained increasing attention in the scientific community. However, a synthesis on existing knowledge and knowledge gaps is missing so far. We analyzed 67 case studies that studied 476 pairwise ES combinations. The relationships between these pairs of ES were classified into three categories: "trade-off", "synergy" or "no-effect". We tested three hypotheses: 1) a dominant relationship between ES exists for each ES pair; 2) this relationship is influenced by the scale at which the relationship had been studied as well as by the land system the analysis took place; and 3), this relationship is further affected by the method applied to characterize the relationship. For the first hypothesis, we demonstrated a comprehensive matrix of pairs of ES. Most pairs of ES (74%) had a clear association with one category: the majority of case studies reported similar relationships for pairs of ES. A synergistic relationship was dominant between different regulating services and between different cultural services, whereas the relationship between regulating and provisioning services was trade-off dominated. Increases in cultural services did not influence provisioning services ("no-effect"). For the second hypothesis, our analysis showed that the overall pattern of ES relationships did not change significantly with scale and land system archetypes except for some ES pairs. The regional scale was the most commonly considered, and case studies were biased among different land system archetypes, which might affect our ability to find the effect of scale or land system archetypes on the pattern of relationships. The analysis for the third hypothesis showed that the choice of methods used to determine the relationship had an effect on the direction of the relationship: studies that employed correlation coefficients showed an increased probability to identify no-effect relationships, whereas descriptive methods had a higher probability of identifying trade-offs. Our results provide helpful information of which services to include in ES assessments for the scientific community as well as for practitioners. Furthermore, they allow a first check if critical trade-offs and synergies have been considered in an analysis.

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3.1 Introduction

Decision making on resource managements received worldwide attention in the past decades given the urgent need to preserve ecosystems and find a sustainable balance between long-term and short-term benefit and costs of human activities (Berkes and Folke, 1998, MA, 2005, Carpenter et al., 2009, Liu et al., 2015). However, a management decision can cause undesirable consequences if it lacks understanding of the complex nature of ecosystems which lead to the multi-functionality of land systems (Holling, 1996, Bennett et al., 2009). A land system does not provide only one function but combinations of a variety of overlapping functions (Bolliger et al., 2011, p.203), each of which provides different ecosystem goods and services to society. Land systems thus have a potential to provide multiple ecosystem services (ES) (Burkhard et al., 2009, Tallis and Polasky, 2009, Mastrangelo et al., 2014, Schindler et al., 2014). Due to functional trade-offs and synergies among the different components of this multi-functionality within the land, a decision potentially influences which services people can get or lose at the same time (Wiggering et al., 2006, Paracchini et al., 2011). Therefore, a comprehensive understanding of the multi-functional land system and of the different ES derived from it is crucial in natural resource management to avoid undesired and often unaware trade-offs and to enhance synergies among ES (Rodríguez et al., 2006, Hillebrand and Matthiessen, 2009, Bolliger et al., 2011, Mastrangelo et al., 2014). A key challenge that decision makers face now is to consider multiple ES and their potential consequences rather than focusing only on a few services in isolation (Cork et al., 2007, Tallis and Polasky, 2009).

The concept of multi-functionality has been originally developed at the landscape scale (Bolliger et al., 2011, Mastrangelo et al., 2014). However, it can be transferred to larger scales at which parts of the multi-functionality present at the landscape scale might be hidden due to aggregation effects. Likewise, the concept can be applied at smaller scales but one has to keep in mind that some functions might diminish at small scales such as functions that lead to water regulation, seed dispersal, pollination and pest control that connect different parts of the landscape. Therefore, interactions across multiple scales are important to be considered in decision-making (Willemen et al., 2012, Dick et al., 2014).

The global research community endeavors to elaborate the concept of ES both in theory and practice to preserve multiple ES (MA, 2005, Carpenter et al., 2009). The Millennium Ecosystem Assessment (MA, 2005) has raised the awareness of the importance of identifying multiple ES and their interactions (Raudsepp-Hearne et al., 2010, Willemen et al., 2012). The number of publication has risen rapidly in last decades on this issue (Bennett et al., 2009). Bennett et al. (2009) stressed the importance of understanding direct and indirect relationships among multiple ES. Recent studies focusing on multiple ES have taken several perspectives using various methodological approaches. The concept of “bundles” of ES has been commonly applied in the assessment of provisioning multiple ES in a landscape (e.g. Raudsepp-Hearne et al., 2010, Martín-López et al., 2013). This approach tries to identify groups of ES that co-occur repeatedly in landscapes showing patterns of the provision of ES derived from the different land use and land cover types (Raudsepp-Hearne et al., 2010, Turner et al., 2014). It is frequently based on a GIS analysis at the landscape or the regional scale (O’Farrell et al., 2010, Nemec and Raudsepp-Hearne, 2012). Often complementary statistical or descriptive analyses have been used to identify the bundles.

Another research line tends to focus on ecosystem processes and functions that underpin ES (Dickie et al., 2011, Lavorel et al., 2011). The relationships among multiple ES are either identified by statistical analysis of field data or by the analysis of the output process models such as the Lund-Potsdam-Jena General Ecosystem Simulator (LPJ-GUESS) (Smith et al., 2001) or the Soil Water Assessment Tool (SWAT) (Arnold et al., 1999). Lautenbach et al. (2013) for example analyzed the relationships between bioenergy crop and food production, water regulation and water quality regulation using SWAT together with an optimization approach.

Relationships of ES pairs can be categorized into ‘trade-off’, ‘synergy’, and ‘no-effect’. The term ‘trade-off’ in ES research has been used when one service responds negatively to a change of another service (MA, 2005). An attempt to maximize the provision of a single service will lead to sub-optimal results if the increase of one service happens directly or indirectly at the cost of another service (Holling, 1996, Rodríguez et al., 2006, Haase et al., 2012). When both services change positively in the same direction, the relationship between two ES is defined as synergistic (Haase et al., 2012) - this is also called a ‘win-win’ relationship (Howe et al., 2014). When there is no interaction or no influence between two ES, this is defined as a ‘no-effect’ relationship.

The relationship between a pair of ES can differ across different scales and across different socio-ecological systems (Kremen, 2005, Hein et al., 2006, Bennett et al., 2009). An example for this is the “externality” of a decision on a certain service as pointed out by Rodríguez et al. (2006): a decision that seems to influence ES positively for a specific region might cause substantial trade-offs in areas nearby or faraway (e.g.‘off-site effects’ (Seppelt et al., 2011) and ‘telecoupling’ (Liu et al., 2013, Liu and Yang, 2013)). If the effects of this decision are viewed at a larger scale including all those negatively influenced areas, the relationship between ES might be characterized by a trade-off. Cimon-Morin et al. (2013) showed in their review study that the relationship between biodiversity and ES changes with scale and region. The relationship between carbon storage and habitat was, for example, described mainly as synergistic at the global scale, but at a finer scale regions of high biodiversity and high carbon storage might be disjunct leading to a trade-off relationship. Furthermore, the relationship can change in different land systems. Land systems are defined by the terrestrial components of environmental systems such as vegetation and soil type, as well as human-environment interactions such as land use intensity, socio-economic factors (Oliver et al., 2004, Dearing et al., 2010, Václavík et al., 2013, Verburg et al., 2013). A decision on increasing a service can affect the other services differently in different land systems. For example, West et al. (2010) showed differences in a trade-off relationship between carbon sequestration and food provisioning among regions with different land systems.

Given the increasing interests on relationships between ES in literature, two recent review studies (Mouchet et al., 2014, Howe et al., 2014) addressed aspects of relationships between ES. Mouchet et al. (2014) provided a methodological guideline for assessing trade-offs between ES, whereas Howe et al. (2014) analyzed relationships between ES with a focus of beneficiaries and users. However, neither of the two studies analyzed pairwise relationships between ES, which is a first step to investigate relationships among multiple ES (Chan et al., 2006, Raudsepp-Hearne et al., 2010, Jopke et al., 2014). Kandziora et al. (2013)

provided a matrix of pairwise relationships between ES on a conceptual level, but the relationships between ES have not been studied so far based on case study results.

In this study, we aim at quantifying pairwise relationships based on a quantitative review of relationships between ES based on the published literature. As the aforementioned literature showed, the relationship between ES has been studied at various scales, in different land systems using various methodological approaches, which complicates the synthesis. We, therefore, addressed three key hypotheses to investigate the relationships between ES: first, a dominant relationship between ES exists for each ES pair; second, this relationship is influenced by the scale at which the relationship had been studied as well as by the land system the case study took place; and third, this relationship is further affected by the method applied to characterize the relationship.

3.2 Material and methods

3.2.1 Literature search

We carried out a literature search in the ISI Web of Knowledge database based on combinations of keywords including “ecosystem service*” or “environmental service*” or “ecological service*” in the first part, and “trade-off*” or “tradeoff*” or “synerg*” in the second part of the topic field. We limited the time period from 1998 to 2013, but decided to include four relevant studies published in 2014 in addition. Our query resulted in 585 scientific papers.

We only included case studies written in English. Studies that did not analyze the relationships between ES were clearly out of scope and therefore not further considered. If a case study analyzed more than one ES pair, we considered all pairwise combinations. In total our analysis is based on 67 case studies - with 476 ES pairs (Appendix A).

3.2.2 Database and classification

The ES categories were defined according to the Common International Classification of Ecosystem Services (CICES) classification V4.3 (Haines-Young and Potschin, 2013). CICES is a widely applied ES classification system, which has been practically applied as a basis for the national ecosystem assessment, for example, in Belgium (Turkelboom et al., 2013), in Germany (Naturkapital Deutschland TEEB DE, 2014) and in Finland (Mononen et al., 2016). Examples of other ES classification systems include Millennium Ecosystem Assessment (MA) (MA, 2005), National Ecosystem Services Classification System (NESCS) and Final Ecosystem Goods and Services Classification System (FEGS-CS) by the United States Environmental Protection Agency (Landers and Nahlik, 2013). One of CICES’ advantages is that it contains a nested hierarchical structure (Haines-Young and Potschin, 2013). The highest level of CICES, the ‘Section’, distinguishes between provisioning, regulating and maintenance, and cultural services. The next hierarchical levels are ‘Division’, ‘Group’, and ‘Class’ (Fig 3.1). The analysis of this study was mainly based

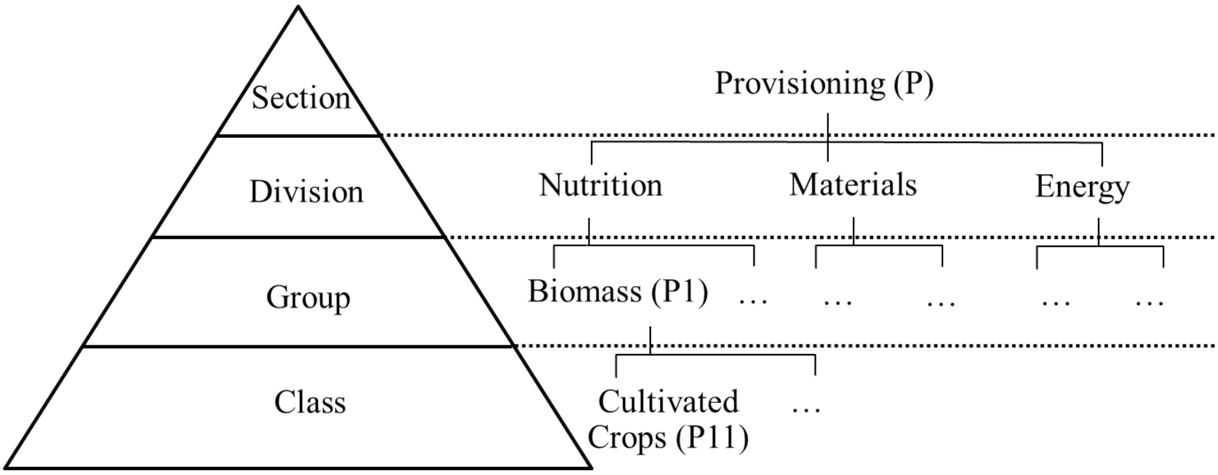

Figure 3.1: The CICES nested hierarchy structure (left) and example of provisioning section and ES code in brackets (adapted from Haines-Young and Potschin (2013))

on the ‘Group’ level of CICES (Fig 3.1, see Table 3.3 for the detailed list of CICES). From now on ‘ES’ refers to the ‘Group’ level of ES in CICES unless mentioned.

In this study, we focused on the pairwise relationships between ES as described in case studies. The relationship between each pair of ES was classified into three categories: “trade-off”, “synergy” and “no-effect”. “Trade-off” was assigned when one service increased with reduction of another service, whereas when both services interacted positively, “synergy” was assigned. When there was no interaction between two services, “no-effect” was assigned. If the direction of the relationship between the pair of ES was not clearly described, it was classified as “other”.

For case studies using correlation coefficients a threshold had to be defined to distinguish “no-effect” relationships from relevant relationships. There is no clear vote from the literature about such a threshold in the ES literature. Applied statistics textbooks agree that a Pearson’s correlation coefficient under 0.35 is characterizing either a negligible (Hinkel et al., 2003) or a weak relationship (Weber and Lamb, 1970, Mason and Lind, 1983, Taylor, 1990). In ES literature, however, a Pearson’s correlation coefficient of 0.2 is often considered as a meaningful correlation (e.g. Chan et al., 2006, Jopke et al., 2014). In this study, we assigned the “no-effect” label to relationships with a correlation coefficient between -0.25 and 0.25.

It was even more difficult for case studies using multivariate statistics to set a threshold to distinguish a “no-effect” relationship from a synergistic or trade-off relationship. The square of the factor loadings is the proportion of variance in each of the items (the observed traits) explained by the factor (the unobserved trait). For example, the factor loading of 0.32 is equivalent to 10% explained variance (Tabachnick and Fidell, 1989). In this study, we used a threshold: if the loading was reported and it was greater than 0.32, the relationship was identified according to the direction (+ for “synergy” or - for “trade-off”) over the different factors or PCs. When the loading was too small, “no-effect” was assigned. When the loading was not reported at all and only the bi-plot was reported from the study, the direction of variables (+ for “synergy” or - for “trade-off”) was considered for the relationship.

The dominant relationship for each pair of ES was determined based on the relative importance of each relationship category. The ratio of studies in the dominant relationship category (Eq. 3.1) was calculated across all case studies – the category with the highest ratio was assigned as the dominant relationship for each pair of ES. We used the term “level of agreement” to describe the certainty of relationships from the case studies.

The level of agreement of a pair of ES_i and ES_j is calculated as

$$Level\ of\ agreement_{i,j} = max(obs_{i,j,k}) / \sum_{k}(obs_{i,j,k}) \times 100, \tag{3.1}$$

where $obs_{i,j,k}$ is the number of observations for the pair of ESi and ESj in the relationship category k. The higher the level of agreement for a pair of ES, the higher the percentage of studies that showed the same direction of relationship. For ties (i.e. two categories shared ‘50%’ each, or three categories shared ‘33.3%’ each), or if the level of agreement did not exceed 50%, we assigned the pair to the “not decided” category.

The spatial scale of the case study was determined following the criteria provided by Martínez-Harms and Balvanera (2012) (Table 3.1) according to the size of the study area. The land system in which a case study took place was assigned according to the map of land system archetype (LSA) of Václavík et al. (2013) that matched the location of the study site. The LSA is a classification schemes of land systems based on socio-economic, ecological and land use intensity factors (Václavík et al., 2013). Václavík et al. (2013) defined at the global scale, therefore, ES case studies at regional or larger scales sometimes overlapped with more than one LSA. In this case the dominant LSA was assigned if it covered more than 50% of the study area. Otherwise, all LSAs were considered within the study area - in our analysis at maximum three LSAs were assigned to one pair of ES. Marine case studies that could not be mapped to the LSAs which are by definition only terrestrial (Václavík et al., 2013) were assigned to an extra category called ‘ocean’ (Fig. 3.8).

We differentiated between the method used to quantify ES (preparation of the results) and the method used to identify the relationship between the ES (analysis of the results). We only considered the latter in the analysis. If, for example, a study used GIS modeling to quantify ES and described the relationship between ES - based on the GIS analysis - qualitatively, we categorized the method for this pair as “descriptive”. The method used to identify the relationship was categorized into five groups: “descriptive”, “correlation”, “regression analysis”, “multivariate statistics”, and “other” (Table 3.1).

3.2.3 Statistical analysis

To test our hypotheses that the scale, the LSA as well as the method used affect the dominant relationship of ES, we applied two statistical analyses. In the first step we

Table 3.1: Criteria used for classification of scale and the land system archetype (LSA)

Criteria	Categories	Rationale	Reference
Spatial scale	Patch	10-10^2 km^2	Martínez-Harms and Balvanera (2012)
	Local	10^2-10^3 km^2	
	Regional	10^3-10^5 km^2	
	National	10^5-10^6 km^2	
	Global [1]	$> 10^6$ km^2	
Land system archetype	LSA 1	Forest systems in the tropics	Václavík et al. (2013)
	LSA 2	Degraded forest/crop land systems in the tropics	
	LSA 3	Boreal systems of the western world	
	LSA 4	Boreal systems of the eastern world	
	LSA 5	High-density urban agglomerations	
	LSA 6	Irrigated cropping systems with rice yield gap	
	LSA 7	Extensive cropping systems	
	LSA 8	Pastoral systems	
	LSA 9	Irrigated cropping systems	
	LSA 10	Intensive cropping systems	
	LSA 11	Marginal lands in the developed world	
	LSA 12	Barren lands in the developing world	
Method	Descriptive	Qualitative description without any explicit quantitative measures	
	Correlation	Measures of the degree of statistical dependency between two variables such as Pearson's correlation coefficient or Spearman's rank correlation coefficient	
	Regression analysis	Regression analysis such as (generalized) linear models	
	Multivariate statistics	Analysis of pattern in multidimensional data without assuming a dependent variable such as PCA, cluster and factor analysis	
	Other	The relationship between ES was already built in the quantifying ES process	

focused on the overall pattern of relationships between pairs of ES. In the second step we tested each pair of ES separately for effects of scale, the LSA and the method used. Subsets of the data were prepared for each category of scale, LSA and method (Table 3.1). The minimum number of case studies to participate in the comparison was set to 10 for each subset. We combined the national, the continental and the global scale into one category, "large scale", due to the limited number of case studies in these categories. Among 12 LSAs, only three LSAs (i.e. "boreal systems of the western world" (LSA3), "extensive cropping systems" (LSA7), and "intensive cropping systems" (LSA10)) satisfied this threshold to participate in the comparison. The method used could not be performed for the overall pattern analysis due to the limited number of case studies in the categories.

In the first step we tested the null hypothesis that the overall structure of the relationships between ES pairs was independent of scale and LSA. To compare the outcomes of different subsets of scales and LSAs, a bootstrap approach was used. The bootstrap is a statistical approach that relies on random sampling with replacement (Efron and Tibshirani, 1994b). By repeatedly sampling with replacement, the underlying true distribution can be estimated without relying on parametric assumptions. Hierarchical structures in the data, such as the ES case study relationship in our analysis, need to be respected in the sampling strategy by sampling only subsets of the data. The bootstrap sampling is used to estimate the variance of estimated values (i.e. standard errors). In our case, the estimated variance was used to construct hypothesis tests (Efron and Tibshirani, 1994b) as parametric assumptions were not sufficed.

The subset membership - i.e. the assignment of one of the three relationships to the ES pair in the case study - was permuted at the case study level during the bootstrap because case studies often analyzed multiple pairs of ES leading non-independence between ES pairs from the same case study. This sampling strategy respects the hierarchical structure of our data set. For each bootstrap sample a measure of similarity between the original data and the permuted subset was calculated. As the measure of similarity, the Euclidean distance between the two subsets of ES relationships normalized by the total number of ES pairs in the subset was used. This allowed us to test the null hypothesis that both subsets belong to the same underlying distribution.

Afterwards, we tested each pair of ES separately for effects of scale, the LSA and the method based on the contingency table. For each pair of ES we created three contingency tables: (i) relationship vs. scale, (ii) relationship vs. LSA, (iii) relationship vs. method used to quantify the relationship. We fitted a generalized linear model with a Poisson distribution with the number of elements in the cells of the contingency tables as the response and the type of relationships and scales, LSAs or the methods as predictors to all three contingency tables for each ES pair if the number of elements in the table was sufficiently high. We tested each table for the significance of the differences of deviances by comparing the saturated model which contained the interaction between both factors to the model with just the main effects (Faraway, 2005). If the deviance of the model was not significantly reduced by including the interaction, we rejected the null hypothesis that the relationship between the two ES was moderated by scale, by LSA or by the method used. We tested all ES pairs for an effect of the method used to quantify the relationship. For the effect of scale, we only tested the 14 pairs of ES that were studied across all scales. For the effect of LSA none of pairs was studied in all 12 LSAs. Therefore, we tested for the pairs which were studied in multiple LSAs: this led to the analysis of 19 ES pairs. The analysis of the effect of the method used to identify the type of relationship was done at the level of the case studies and not at the ES pair level since case studies typically applied the same method. We excluded the "other" category for the analysis. All analyses were performed using `R` version 3.2.0 (R Core Team, 2015).

3.3 Results and Discussions

3.3.1 Empirical pattern of the relationships between ecosystem services

Among the 48 types of ES defined at the class level in CICES, 33 - including one abiotic service (i.e. renewable abiotic energy source) - were found in our data set (Fig 3.1, Table 3.3). The most studied ES class was "global climate regulation service (R101)" (n = 114) followed by "cultivated crops (P11)" (n = 103), "physical use of landscape (C12)" such as hiking (n = 93), and "maintaining nursery population and habitats (R62)" (n = 85). We found 207 different combinations of ES at the CICES class level (Fig 3.1). More than half of those combinations at the class level (n = 105) were, however, recorded only one time. Since this did not provide enough support to analyze patterns, we decided to drop the analysis at the class level and tested all three hypotheses at the CICES group level (Fig 3.1). At the group level in CICES 94 types of combinations of ES pairs were analyzed (Fig 3.2). A pair of two ES that belonged to the same CICES group but to different CICES classes was analyzed as well. To investigate the first hypothesis that a dominant relationship between ES exists for each ES pair, we compiled a matrix of relationships between ES. Fig. 3.2 shows the empirical pattern of pairwise relationships between ES groups – non-empty cells at the main diagonal refer to pairs of ES classes that belong to the same CICES group. To the best of our knowledge, this is the first study in which such a comprehensive matrix of relationships between ES has been compiled based on case study results.

The number of observations available to identify the dominant relationship ranged between 1 and 29. Twenty-one types of pairs of ES at the group level were observed only one time and more than half of the pairs (n = 61) were supported by less than 5 observations. Only 12% of the pairs were supported by more than 10 observations. The most studied pair of ES at the group level was the pair "atmospheric composition and climate regulating" (R10) and "biomass provisioning" (P1) services with 29 observations.

The level of agreement ranged from 25% to 100% (Fig 3.3). For 74% of the pairs, the level of agreement to determine the dominant relationship was higher than 50% – the other pairs were assigned to the "not decided" category (n=24).

The relationship between regulating services was dominated by a synergistic relationship. On the other hand, provisioning services and regulating services tended to trade-offs (Fig 3.2). Cultural services showed a trend for synergistic effects mainly with other cultural and regulating services, and a no-effect relationship with provisioning services. Note that this pattern of relationships shown here does not necessarily imply causality.

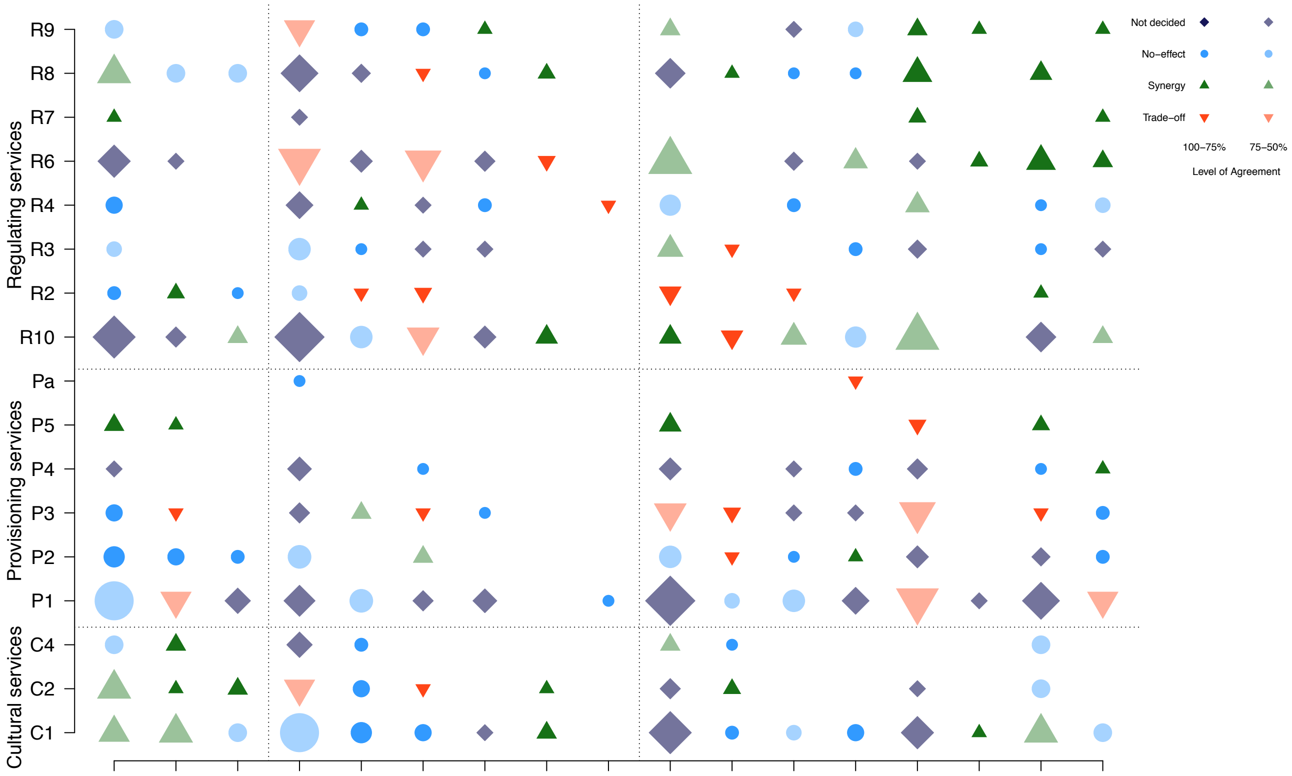

Figure 3.2: Result from analysis of 67 case studies with 476 pairs of ecosystem services, showing the empirical pattern of relationships between them. X and Y axis represent the ES classification code used in the analysis (See Table 3.3). The size of the symbol indicates the square root scaled number of studies. The color intensity represents the level of agreement. C: Cultural services, P: Provisioning services, R: Regulating services. C1: Physical and experiential interactions, C2: Intellectual and representative interactions, C4: Other cultural outputs, P1: Nutrition biomass, P2: Nutrition water (i.e. drinking purpose), P3: Materials biomass (e.g.for production and agricultural uses), P4: Material water (i.e. non-drinking purpose), P5: Biomass-based energy sources, Pa: Renewable abiotic energy source, R10: Atmospheric composition and climate regulation, R2: Mediation by ecosystems, R3: Mass flows, R4: Liquid flows, R6: Life cycle maintenance, habitat and gene pool protection, R7: Pest and disease control, R8: Soil formation and composition, R9: Water conditions.

3.3.1.1 Trade-off dominated relationships

The level of agreement for the trade-off relationships ranged between 54% and 100% (Fig. 3.3). The most agreed trade-off relationship among those pairs with more than 5 observations was “biomass for production such as timber and fodder” (P3) and “atmospheric composition and climate regulation” (R10) with a level of agreement of 75% (n=8). On the one hand forests are important in terms of carbon fixation and storage, but on the other hand they are in many land systems used for timber production. In this case, a decision on how long forests are kept as carbon sinks or when trees are cut to be used for timber production generates trade-offs. Different forest management schemes influence the type of services from which people obtain benefits, which generates such trade-off among them (Backéus et al., 2005, Seidl et al., 2007, Olschewski et al., 2010).

A clear agreement on a trade-off relationship was also found for the relationship between the pair of “life cycle maintenance, habitat and gene pool protection” (R6) and “food provisioning” services (P1) with a level of agreement 72% (n=18). Previous studies pointed out a negative relationship between agricultural intensity and natural habitat (Mattison and Norris, 2005, Reidsma et al., 2006, Phalan et al., 2011). In order to compensate the loss of habitat in agricultural areas, more sustainable farming managements were often suggested (Altieri, 1999, Landis et al., 2000, Altieri, 2004, Lichtfouse et al., 2009) such as organic farming, which promises to increase ES nursery and habitat protection. However, there are doubts whether this allows producing sufficient food to feed the world population (Bengtsson et al., 2005, Zhang et al., 2007, de Ponti et al., 2012). Organic farming was found to increase species richness by providing better habitats and nursing ES (Bengtsson et al., 2005), but at the same time, meta-analyses showed that crop yield could be lowered by up to 20-34% compared to conventional farming (de Ponti et al., 2012, Seufert et al., 2012).

Even though the general pattern between R6 and P1 shows a clear trade-off relationship at the group level of CICES, it should be also noted that a contrary relationship was found in one sub category of R6. The CICES class “pollination and seed dispersal” (R61) showed a synergistic relationship with P1 (e.g. Boreux et al., 2013). Overall 35% of the global production comes from crops that depend on animal pollinators (Klein et al., 2007), which might lead to a synergistic relationship between food provisioning and habitat protection (Aizen et al., 2008, Lautenbach et al., 2012, Garibaldi et al., 2013). It was not seen at the aggregated group level of CICES due to the limited number of case studies on R61.

3.3.1.2 Synergy dominated relationships

The level of agreement for synergistic relationships varied between 55% and 100% (Fig. 3.3). The strong synergistic relationships were found in the group of regulating services. Especially “habitat and gene pool protection services” (R6) showed a clear synergistic relationship with most other regulating services. Regulating services have been described as generally associated with ecosystem processes and functions (Kremen, 2005, Bennett et al., 2009, de Groot et al., 2010) and mostly positively related to biodiversity (Balvanera et al., 2006, Mace et al., 2012, Harrison et al., 2014). de Groot et al. (2002) defined "habitat and gene pool protection services" (R6) as a basis for other functions, which is in line with its observed synergistic relationship with other regulating services. The synergistic relationship between "habitat and gene pool protection services" (R6) and "soil formation regulating services" (R8) with a high level of agreement (88%) has been reported by studies that emphasized the interactions between soil functions and the role of soils in living habitats (e.g. Young and Ritz, 2000, Crawford et al., 2005, de Groot et al., 2010, Larvelle, 2012).

Another relatively strong synergistic relationship was found among the group of cultural services. Among pairs of cultural services, four out of five showed a dominant synergistic relationship. This is in line with findings from Daniel et al. (2012) on interrelationships between cultural service categories such as aesthetic services that contribute to the provisioning of recreation services, which leads to the synergistic relationship between them.

3.3.1.3 No-effect dominated relationships

The level of agreement for no-effect relationships varied between 52% and 100% (Fig. 3.3). The dominant no-effect relationship was found between provisioning and cultural services. Among pairs of provisioning and cultural services, "water provisioning service" (P2) and "physical and experimental interactions" (C1) was the most agreed no-effect relationship with a level of agreement of 100% (n = 7).

The dominant no-effect relationship between provisioning and cultural services could be explained by common drivers (Bennett et al., 2009) and different land use designs when the services occur in different locations (Raudsepp-Hearne et al., 2010). Bennett et al. (2009) proposed "common drivers" to understand relationships between ES. For example, introducing agricultural tourism by allowing people to watch the production process increases cultural services, but does not affect the amount of the agricultural production (Bennett et al., 2009, p.4). In this case, cultural and provisioning services do not share a common driver, therefore the relationship between them is no-effect. Another explanation for the no-effect relationship between provisioning and cultural services would be that cultural services such as tourism and cultural heritage are often captured in protected areas (e.g. national parks) where no production activity would be allowed (e.g. Martín-López et al., 2007, Raudsepp-Hearne et al., 2010). However, there was a disagreement on this relationship. Rodríguez et al. (2006) described the relationship between provisioning and cultural services as a 'trade-off' relationship – forest management for timber production could for example discourage recreational visits to this forest. It might depend on the types of ES whether they share a common driver or location to derive synergies or trade-offs.

Here we note that the types of cultural services that were covered in the analysis were rather limited; 69% of those case studies that analyzed cultural services focused on "physical and experimental interactions" (C1), whereas "spiritual services" (C3) were not considered at all in the studies analyzed.

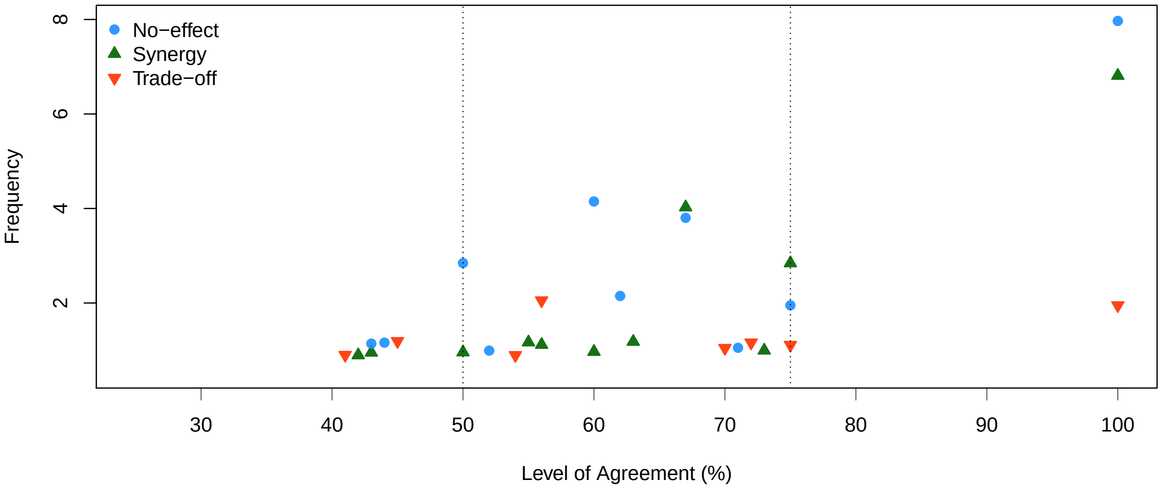

Figure 3.3: The distribution of the level of agreement (jittered for clarity) with the dominant relationship excluding pairs with a single observation and pairs with the equal level of agreement between two or three categories. The shape of symbols indicates the dominant relationship. We presented here the original value of the level of agreement before assigning the 'not-decided' category for those with the level of agreement under 50%.

Table 3.2: The number of pairs of ecosystem services in each category of relationships under the 50% and 70% threshold of the level of agreement conditions to set the "not-decided" category.

	Trade-off	Synergy	No-effect	Not decided
50% threshold	14	27	29	24
70% threshold	10	19	18	47

3.3.1.4 Sensitivity of the pattern towards changes in the threshold of the level of agreement

To determine the dominant relationship, we used 50% as a threshold for the level of agreement (Eq. 3.1) following the majority rule. However, one might think that '50%' is not enough to support a decision for the dominant relationship. We investigated whether the result of the dominant relationship would be different with a different threshold. Table 3.2 showed how many pairs would be affected by the different threshold level for the "not decided" category. If the threshold was raised up to 70%, about 24% of pairs of ES were influenced by the decision and changed to the "not decided" category (see Table 3.2 and Fig 3.3). However, the overall direction of the dominant relationships between groups of ES (i.e. the "section" level of ES (Fig 3.1)) did not change thereby. See Fig. 3.10 where we present the relationship matrix of pairs of ES with the threshold 70% for the level of agreement.

3.3.1.5 Sensitivity of the pattern towards the analysis at the CICES group level

Results might be potentially influenced by using the CICES group level for the analysis. However, we assume that only a single "not-decided" pair has to be considered as an artifact from the aggregation of ES at the CICES group level (Fig 3.1): the pair of "physical and experiential interactions" (C1) and "soil formation and composition" (R8). While most case studies for this pair were conducted at the same scale and in the same LSA using the same methodology, the direction of the relationship was different across the case studies. Six observations were synergistic, whereas five observations were identified as no-effect. All no-effect relationships were observed in "physical activities such as hiking and leisure fishing" (C12), whereas four among six synergy relationships were observed in "experiential use such as bird watching" (C11) at the class level in CICES (Fig 3.1). Another example was presented in Section 3.3.1.1, where "life cycle maintenance, habitat and gene pool protection" (R6) and "food provisioning" services (P1) showed a trade-off relationship, whilst "pollination and seed dispersal" (R61) at the class level of R6 showed a synergistic relationship.

Except these a few cases it was not possible to use the class level of CICES for the analysis due to the limited number of observations at this level. Our analysis at the group level in CICES provides an overall pattern of relationships over 94 pairs of ES. Furthermore, to our knowledge, the analysis of relationships between ES at the group level was rarely done before. Previous review studies provided results at a section level in CICES (e.g. provisioning, regulating, cultural services) (Rodríguez et al., 2006), or based only on examples (Bennett et al., 2009).

3.3.2 Scale and land system archetypes of ecosystem service relationships

In testing the second hypothesis that the relationships between pairs of ES are moderated by scale or LSA, the bootstrap approach did not reveal any significant difference between subgroups of the case studies based on scale or LSA. Neither spatial scale nor LSA membership had a significant influence on the overall pattern of the relationships between the services – p-values for each test are given in Table 3.5 and 3.6.

The spatial scale of the studies was spread unevenly. The regional scale was most frequently studied (38%), followed by the plot scale (22%) and the continental scale (10%). The global scale was the least studied (6%) (Fig. 3.7). Forty-one pairs of ES (44%) were studied only at a single type of scale, which hindered the comparison of the relationship pattern among scales.

Among the 14 pairs of ES that were included in the contingency analysis, significant differences across scale were only identified for two pairs of ES: the pair of "soil formation and composition regulation" (R8) and "biomass provisioning" (P1) ($p = 0.0067$) and the pair of "soil formation and composition regulation" (R8) and "atmospheric composition and climate regulation" (R10) ($p = 0.0321$). Both pairs included "soil formation and composition regulation" (R8). The result for both pairs showed a synergistic relationship at the small scale, whereas at the larger scale, the relationship was no-effect and not-decided for the pair of R8 and P1, and the pair of R8 and R10, respectively. "Soil formation and composition regulation" (R8) are generally considered not only as a direct driver for enhancing "biomass provisioning" (P1) in agricultural lands (Hobbs et al., 2008), but also as an indirect driver for enhancing carbon and nutrient cycling which can influence "atmospheric composition and climate regulation" (R10) by affecting biotic processes (van Breemen, 1993, Barrios, 2007). This synergistic role of "soil formation and composition regulation" (R8) was often studied in experiments at a finer scale (Six et al., 2000, Hobbs et al., 2008). At a larger scale, this relationship did not clearly appear – e.g. Jopke et al. (2014) showed a no-effect relationship at the continental scale.

Only one pair was considered at every scale: the pair of "atmospheric composition and climate regulation" (R10) and "biomass provisioning" (P1). The results at each scale showed different relationships, but the interaction between the type of relationship and scale was not statistically significant from the test of independence of components in the contingency table ($p = 0.4213$). At the plot and at the local scale the dominant synergy was dominant (50%; n=3), while trade-off (54%; n=6) was dominant at the regional scale and no-effect (46%; n=5) at the national, continental and global scales.

Case studies were also unevenly distributed across LSAs (Fig. 3.8): only three types of LSAs (i.e. "boreal systems of the western world" (LSA3), "extensive cropping systems" (LSA7), and "intensive cropping systems" (LSA10)) among 12 were studied in more than 10 case studies. A geographical bias of the distribution of ES case studies was already stressed by Seppelt et al. (2011). The land system "boreal systems of the eastern world" (LSA4), "high-density urban agglomerations" (LSA5), and "irrigated cropping systems with rice yield gap" (LSA6) were not at all considered in the case studies. Thirty-two pairs of ES (34%) were studied at a single LSA. LSA10 was most frequently observed when only a single type of LSA was considered. At maximum, seven LSAs were considered for a pair of ES, the pair of "atmospheric composition and climate regulation" (R10) and "life cycle maintenance, habitat and gene pool protection" (R6).

While the overall pattern of relationships between ES at the group level was indifferent to LSA, a few ES pairs showed interesting differences across LSAs from the contingency analysis. The relationship for the pair of "life cycle maintenance, habitat and gene pool protection" (R6) and "atmospheric composition and climate regulating" (R10) showed significant difference across the LSAs ($p = 0.0269$): synergy in "forest systems in the tropics" (LSA1), "extensive cropping systems" (LSA7), and "intensive cropping systems" (LSA10), no-effect in "irrigated cropping system" (LSA9) and "marginal lands in the developed world" (LSA11), and not decided in "boreal systems of the western world" (LSA3). Stored carbon in vegetation and soil was generally measured to quantify climate regulating services (R10) in every LSA. However, for "habitat protection services" (R6) different approaches were used in different LSAs. A possible explanation is that in "forest systems in the tropics" (LSA1) and "extensive cropping system" (LSA7) species richness as well as carbon sequestration are positively influenced by the presence of forest instead of arable land areas, while in "irrigated cropping system" (LSA9) and "marginal land" (LSA11) such a clear common driver is missing. Other pairs which differed significantly across LSAs were the pair of "existence and bequest" (C4) and "biomass provisioning"

(P1) (p = 0.0152) and the pair of “biomass provisioning” (P1) and “Water provisioning (i.e. non-drinking purpose)” (P4) (p = 0.0331).

3.3.3 Methods used to determine the relationship

The results from the difference of deviance test for the third hypothesis that the direction of the relationships is affected by the choice of method was significant (p = 0.0294). Correlation coefficient methods showed a higher probability to identify a no-effect relationship, whereas descriptive methods showed a higher probability to identify a trade-off relationship and less no-effect relationships. Among 476 pairs, 56 pairs of ES (11.7%) were analyzed based on descriptive methods (Fig 3.9). We tested whether the pattern of the relationship changed without pairs from case studies based on descriptive methods. The overall pattern of the result did not change (Fig 3.11); however, eight pairs of ES changed the dominant relationship: three pairs were changed from “not-decided” to either “synergy” or “no-effect”, two pairs changed to “no-effect” from either “trade-off” or “synergy”. Two trade-off pairs were dropped and one pair changed from “synergy” to “no-effect”.

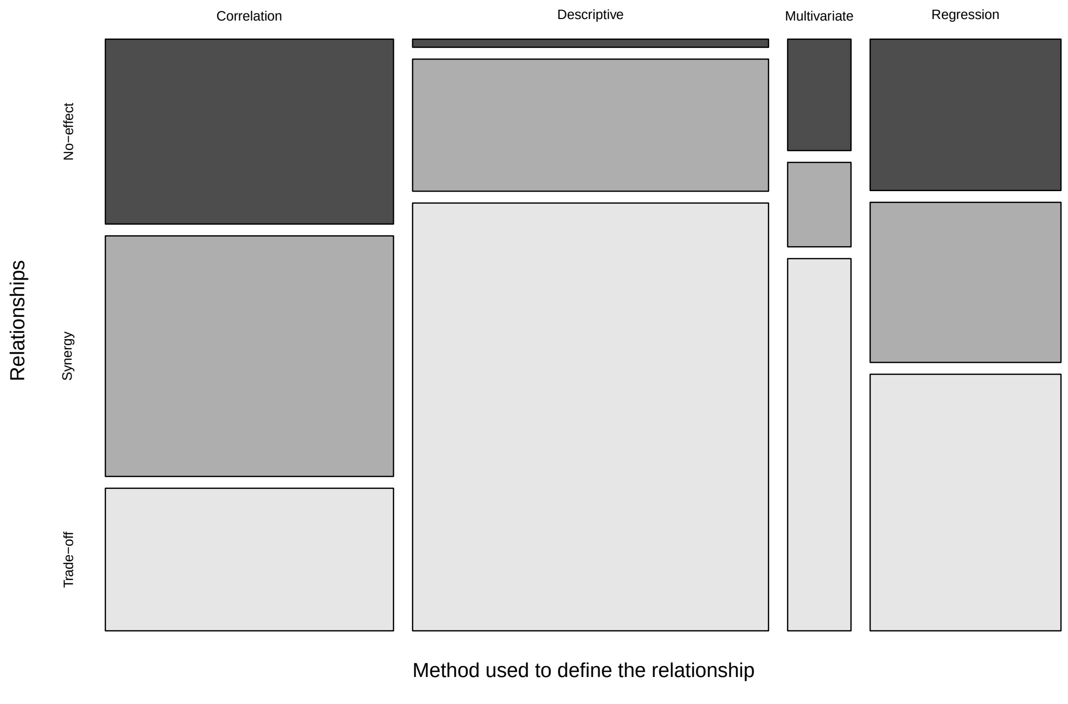

Figure 3.4: Mosaic plot for method used and the relationships between two ecosystem services. Mosaic plots represent the counts in a contingency table by tiles. The size is proportional to the cell count (Friendly, 1994).

Multivariate statistics showed less no-effect relationships (Fig 3.4 and Fig 3.5). It was problematic for case studies using multivariate statistics to set a threshold to distinguish

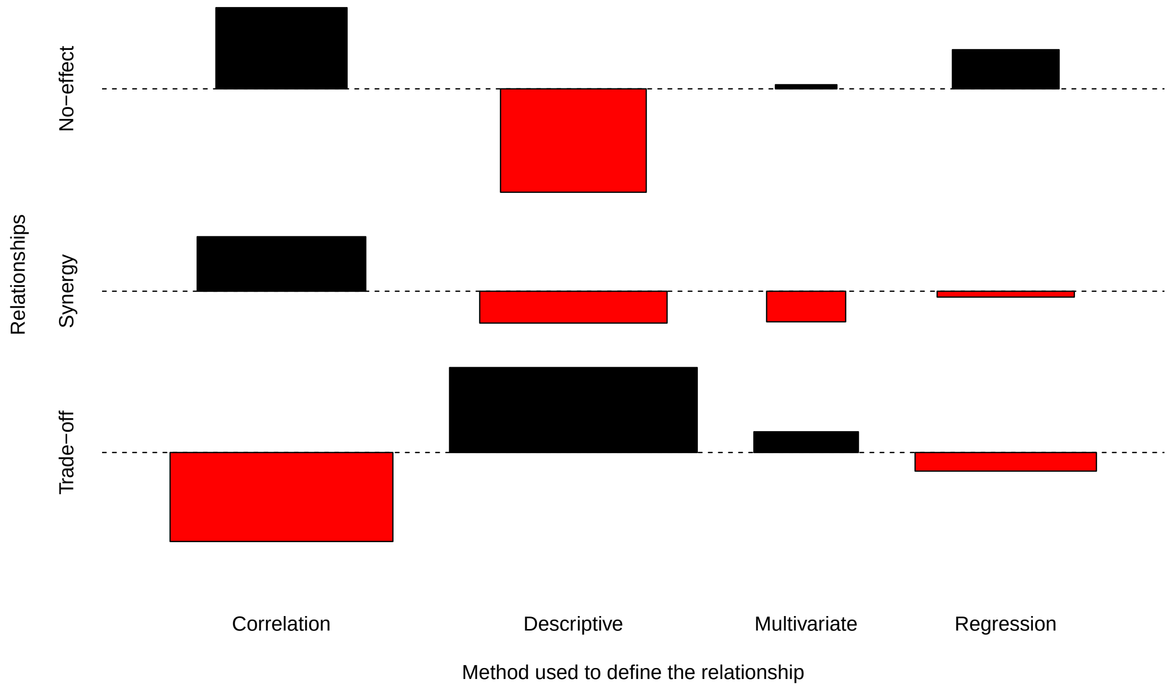

Figure 3.5: Association plot for method used in the relationships between two ecosystem services. In the Cohen-Friendly association plot, each cell is represented by a rectangle that has (signed) height proportional to d_{ij} and width proportional to the square root of the expected counts e_{ij}, so that the area of the box is proportional to the difference in observed and expected frequencies. The rectangles in each row are positioned relative to a baseline indicating independence ($d_{ij}= 0$). In other words, cells with more observed than expected frequencies are above the line with the black color, whereas cells that contain less observed than expected frequencies fell below the line with the red color (Cohen, 1980).

“no-effect”. While it is possible to identify thresholds for the strength of the relationship based on the loadings in PCA or factor analysis as well as for the uncertainty of assigning an ES to a cluster, this was rarely done in practice. Multivariate statistics were frequently applied in trade-off of ES researches to identify bundles of ES by using PCA or factor analysis in order to find ES that tend to occur together (e.g. Lavorel et al., 2011, Maes et al., 2012). However, without an agreed threshold within ES research communities, using multivariate statistics to define relationships between ES might lead to ignorance of no-effect relationship. Since the assignment of ES to different bundles does typically neither include the strength of the association nor the attached uncertainty, no-effect relationships might be undetectable by the approach. Correlation approaches make it easier to define no-effect relationships based on the absolute strength of the correlation. If the correlation is stronger than a threshold, significance of the correlation should be tested – potentially corrected for nuisances such as spatial auto-correlation (Dormann et al., 2007).

Regression type I models were also frequently used to describe the relationship between ES. From a theoretical point of view, the use of a regression type I model seems questionable to describe relationships between ES since the approach distinguishes two ES into dependent and independent variables - errors are only considered for the dependent variable not for the independent variables. Only regression type II models (Legendre and Legendre, 2003) - which have not been used in the case studies-, in which errors for both predictors and response are considered seem appropriate to model ES relationships as long as no directional effect of one ES on the other can be assumed.

Methods were evenly distributed across the types of pairs of ES and across the scales. In other words, the decision on which types of method to use to define the relationship was neither influenced by the type of ES nor by the scale of the study.

It has been already reported (Vatn and Bromley, 1994, Jacobs, 1997, Martín-López et al., 2013) that the choice of the method to value ES can bias results. We emphasize here that not only valuation methods but also method used to define relationships should be chosen with a care. Researchers should be aware that their decision on methods used might limit the result in a certain direction.

3.3.4 Further limitations

Although our review was comprehensive and thoroughly conducted, we imposed constraints on our review that might have biased our result. We only considered peer-reviewed scientific articles written in English found in Web of Knowledge for our analysis. This has excluded some pairs of ES that are considered for a certain region in gray literature. However, using non peer-reviewed literature has the drawback that quality standards are lower (Pullin and Stewart, 2006, Nieto-Romero et al., 2014, Harrison et al., 2014).

3.4 Conclusions

We conducted a quantitative review of relationships between ES based on the published literature to investigate three key hypotheses: 1) a dominant relationship between ES exists for each ES pair; 2) this relationship is influenced by the scale at which the relationship had been studied as well as by the land system; and 3), this relationship is further affected by the method applied to characterize the relationship. Our analysis showed 1) there is a certain pattern of relationships between ES; 2) the relationship between ES was not significantly influenced by scale or the land system except for a few pairs; and 3) the decision which method to use might influence the result. Descriptive methods showed a higher probability to identify more trade-off relationships, whereas multivariate statistics was less likely to identify 'no-effect' relationships.

Comprehensive information is required for well-informed policy decisions that do not ignore side-effects in multi-functional land systems. However, this information is often expensive and difficult to obtain. The missing information can directly and indirectly influence the policy decision as well as its impact on multi-functional land systems, and therefore human well-being (OECD, 2003). The fundamental challenge in practice is to minimize the inefficient and inappropriate impacts on provisioning of multiple ES by enhancing understanding of multi-relationships between ES. Making this information more explicit and accessible is more likely to drive at more balanced conditions (Carpenter et al., 2009).

In this study, we tried to fill the knowledge gap on relationships between ES by a synthesis of relationships between ES studied in published case studies. We identified typical relationships between a number of pairs of ES. To the best of our knowledge, this is the first study in which such a comprehensive matrix of relationships between ES has been complied. Our results provide an overview of relationships of ES studied so far together with the information on the level of agreement between study results. This equips practitioners with a practical summary to examine the underlying impacts of their decision in advance. Furthermore, our results highlights pairs of ES for which more input is needed from the scientific community. The results might help further during the design of research projects and give important hints for decision makers and reviewers to check research plans and to ask critical questions with respect to research outcomes. Researchers can identify i) ES pairs not being studied and knowledge gaps for their further research, and ii) how the services that a researcher plans to investigate interact with other services from this study. If important relationships between ES could not be studied, our analysis might provide hints on the direction of the neglected effect.

While we were able to show that for a few pairs of ES the dominant relationship changed as a function of scale or of land system, we were not able to show this for the majority of cases. The limited number of case studies and the uneven distribution across ES groups, scales and land system archetypes is a potential explanation for it. Therefore, we encourage the development of a research agenda that allows filling those gaps to come to a more complete picture on relationships between different ES. Being able to predict the direction of a relationship between ES as a function of scale and land system would be an important step for decision support and ecosystem management but it would be by no means the end of the research agenda. We need higher quality studies that follow i) good modeling practice or analyze their data properly, ii) reporting uncertainties along with point estimates, iii) more evenly spread across the scales and land systems, and iv) which reports not only the direction but also the strength of the relationship in a comparable way. Bundle analysis based on an overlay of relatively simple GIS tools presumably would not fulfill high quality standards and should be therefore treated with care. Based on the results of such data, a next step would be the performance of a meta-analysis to untangle more details on ES relationships.

Supplementary materials

Table 3.3: CICES classification (Haines-Young and Potschin, 2013)

Section	Division	Group	Code	Class	Code
Provisioning	Nutrition	Biomass	P1	Cultivated crops	P11
				Reared animals and their outputs	P12
				Wild plants, algae and their outputs	P13
				Wild animals and their outputs	P14
				Plants and algae from in-situ aquaculture	P15
				Animals from in-situ aquaculture	P16
		Water	P2	Surface water for drinking	P21
				Ground water for drinking	P22
	Materials	Biomass	P3	Fibres and other materials from plants algae and animals for direct use or processing	P31
				Materials from plants, algae and animals from agricultural use	P32
				Genetic materials from all biota	P33
		Water	P4	Surface water for non-drinking purposes	P41
				Ground water fro non-drinking purposes	P42
	Energy	Biomass-based energy sources	P5	Plant-based resources	P51
				Animal-based resources	P52
		Mechanical energy	P6	Animal-based energy	P61
Abiotic Provisioning	Energy	Renewable abiotic energy source	Pa	e.g. wind, waves, hydropower	Pa
Regulation and Maintenance	Mediation of waste, toxics and other nuisances	Mediation by biota	R1	Bio-remediation by micro-organisms, algae, plants and animals	R11
				Filtration/ sequestration/ storage/ accumulation by micro-organisms, algae, plants and animals	R12
		Mediation by ecosystem	R2	Filtration/sequestration/ storage/ accumulation by ecosystems	R21
				Dilution by atmosphere, freshwater and marine ecosystems	R22
				Mediation of smell/ noise / visual impacts	R23
	Mediation of flows	Mass flows	R3	Mass stabilisation and control of erosion rates	R31
				Buffering and attenuation of mass flows	R32
		Liquid flows	R4	Hydrological cycle and water flow maintenance	R41
				Flood protection	R42
		Gaseous/air flows	R5	storm protection	R51
				Ventilation and transpiration	R52
	Maintenance of physical, chemical, biological conditions	Life cycle maintenance, habitat and gene pool protection	R6	pollination and seed dispersal	R61
				Maintaining nursery population and habitats	R62
		Pest and disease control	R7	Pest control	R71
				Disease control	R72
		Soil formation and composition	R8	Weathering processes	R81
				Decomposition and fixing processes	R82
		Water conditions	R9	Chemical condition of freshwaters	R91
				Chemical condition of salt waters	R92
		Atmosphere composition and climate regulation	R10	Global climate regulation by reduction of greenhouse gas concentrations	R101
				micro and regional climate regulation	R102
Cultural	Physical and intellectual interactions with biota, ecosystems, and land-/seascapes	Physical and experiential interactions	C1	Experiential use of plants, animals and land-/seascapes in different environmental settings	C11
				Physical use of land-/seascapes in different environmental settings	C12
		Intellectual and representative interactions	C2	Scientific	C21
				Educational	C22
				Heritage, cultural	C23
				Entertainment	C24
				Aesthetic	C25
	Spiritual, symbolic and other interactions with biota, ecosystems, and land-/seascapes [environmental settings]	Spiritual and/or emblematic	C3	Symbolic	C31
				Sacred and/or religious	C32
		Other cultural outputs	C4	Existence	C41
				Bequest	C42

Table 3.4: The number of pairs in each relationship category for each pair of ecosystem services ES1 and ES2. Dominant result was decided based on the category with the maximum number for each pair of ecosystem services. If the level of agreement did not exceed 0.5, the dominant relationship was assigned to “Not decided”.

ES1	**ES2**	**Trade-off**	**Synergy**	**No-effect**	**Other**	**Sum**	**Dominant result**	**Level of agreement**
C1	C1	0	5	4	0	9	Synergy	0.56
C2	C1	0	8	3	0	11	Synergy	0.73
C4	C1	0	2	3	0	5	No-effect	0.6
P1	C1	10	3	14	0	27	No-effect	0.52
P2	C1	0	0	7	0	7	No-effect	1
P3	C1	1	0	3	0	4	No-effect	0.75
P4	C1	0	1	1	0	2	Not decided	0.5
P5	C1	0	3	0	0	3	Synergy	1
R10	C1	5	9	7	0	21	Not decided	0.43
R2	C1	0	0	2	0	2	No-effect	1
R3	C1	0	1	2	0	3	No-effect	0.67
R4	C1	0	0	4	0	4	No-effect	1
R6	C1	2	5	4	1	12	Not decided	0.42
R7	C1	0	1	0	0	1	Synergy	1
R8	C1	0	6	5	0	11	Synergy	0.55
R9	C1	0	2	3	0	5	No-effect	0.6
C2	C2	0	1	0	0	1	Synergy	1
C4	C2	0	3	0	0	3	Synergy	1
P1	C2	5	0	4	0	9	Trade-off	0.56
P2	C2	1	0	3	0	4	No-effect	0.75
P3	C2	1	0	0	0	1	Trade-off	1
P5	C2	0	1	0	0	1	Synergy	1
R10	C2	0	2	2	0	4	Not decided	0.5
R2	C2	0	2	0	0	2	Synergy	1
R6	C2	1	1	0	0	2	Not decided	0.5
R8	C2	0	2	3	0	5	No-effect	0.6
P1	C4	2	2	3	0	7	Not decided	0.43
P2	C4	0	0	2	0	2	No-effect	1
R10	C4	0	2	1	0	3	Synergy	0.67
R2	C4	0	0	1	0	1	No-effect	1
R8	C4	0	2	3	0	5	No-effect	0.6
P1	P1	5	2	4	0	11	Not decided	0.45
P2	P1	3	0	6	0	9	No-effect	0.67
P3	P1	1	1	1	1	4	Not decided	0.25
P4	P1	2	1	3	0	6	Not decided	0.5
Pa	P1	0	0	1	0	1	No-effect	1
R10	P1	12	6	10	1	29	Not decided	0.41
R2	P1	1	0	2	0	3	No-effect	0.67
R3	P1	3	0	5	0	8	No-effect	0.62
R4	P1	3	1	4	0	8	Not decided	0.5
R6	P1	13	4	1	0	18	Trade-off	0.72
R7	P1	1	1	0	0	2	Not decided	0.5
R8	P1	4	5	7	0	16	Not decided	0.44
R9	P1	5	2	1	1	9	Trade-off	0.56
P3	P2	1	2	0	0	3	Synergy	0.67
R10	P2	3	0	5	0	8	No-effect	0.62
R2	P2	1	0	0	0	1	Trade-off	1
R3	P2	0	0	1	0	1	No-effect	1
R4	P2	0	1	0	0	1	Synergy	1
R6	P2	2	2	1	0	5	Not decided	0.4
R8	P2	1	1	1	0	3	Not decided	0.33
R9	P2	0	0	2	0	2	No-effect	1
P3	P3	1	0	0	0	1	Trade-off	1
P4	P3	0	0	1	0	1	No-effect	1
R10	P3	7	1	2	0	10	Trade-off	0.7
R2	P3	2	0	0	0	2	Trade-off	1
R3	P3	1	0	1	0	2	Not decided	0.5
R4	P3	0	1	1	0	2	Not decided	0.5
R6	P3	7	1	2	3	13	Trade-off	0.54
R8	P3	1	0	0	0	1	Trade-off	1
R9	P3	0	0	2	0	2	No-effect	1
R10	P4	2	1	2	0	5	Not decided	0.4
R3	P4	0	1	1	0	2	Not decided	0.5
R4	P4	0	0	2	0	2	No-effect	1
R6	P4	1	0	2	1	4	Not decided	0.5
R8	P4	0	0	1	0	1	No-effect	1
R9	P4	0	1	0	0	1	Synergy	1
R10	P5	1	3	0	0	4	Synergy	0.75
R6	P5	2	0	0	0	2	Trade-off	1
R8	P5	0	2	0	0	2	Synergy	1
R4	Pa	1	0	0	0	1	Trade-off	1

Table 3.4: (Continue) The number of pairs in each relationship category for each pair of ecosystem services ES1 and ES2. Dominant result was decided based on the category with the maximum number for each pair of ecosystem services. If the level of agreement did not exceed 0.5, the dominant relationship was assigned to "Not decided".

ES1	ES2	Trade-off	Synergy	No-effect	Other	Sum	Dominant result	Level of agreement
R10	R10	0	3	1	0	4	Synergy	0.75
R2	R10	3	0	1	0	4	Trade-off	0.75
R3	R10	0	4	2	0	6	Synergy	0.67
R4	R10	1	1	5	0	7	No-effect	0.71
R6	R10	3	12	3	1	19	Synergy	0.63
R8	R10	2	5	3	0	10	Not decided	0.5
R9	R10	0	2	1	0	3	Synergy	0.67
R3	R2	1	0	0	0	1	Trade-off	1
R8	R2	0	1	0	0	1	Synergy	1
R4	R3	0	0	2	0	2	No-effect	1
R6	R3	1	1	0	1	3	Not decided	0.33
R8	R3	0	0	1	0	1	No-effect	1
R9	R3	0	1	1	0	2	Not decided	0.5
R6	R4	0	3	2	0	5	Synergy	0.6
R8	R4	0	0	1	0	1	No-effect	1
R9	R4	0	1	2	0	3	No-effect	0.67
R6	R6	0	1	1	0	2	Not decided	0.5
R7	R6	0	2	0	0	2	Synergy	1
R8	R6	1	6	0	1	8	Synergy	0.75
R9	R6	0	3	0	0	3	Synergy	1
R9	R7	0	1	0	0	1	Synergy	1
R8	R8	0	4	0	0	4	Synergy	1
R9	R9	0	1	0	0	1	Synergy	1

Table 3.5: P-values for H0 that different subsets of spatial scales belong to the same underlying distribution based on 10,000 bootstrap samples. In the bracket, the number of case studies and the number of ES pairs are given.

Scale	**Large (14/104)**	**Regional (24/264)**	**Local (11/38)**	**Plot (14/59)**
Large	-	0.38	0.44	0.36
Regional		-	0.18	0.12
Local			-	0.25
Plot				-

Table 3.6: P-values for H0 that different subsets of land system archetypes belong to the same underlying distribution based on 10,000 bootstrap samples. In the bracket, the number of case studies and the number of ES pairs are given.

LSA	**LSA10 (20/297)**	**LSA7 (22/157)**	**LSA3 (11/98)**
LSA10	-	0.42	0.44
LSA7		-	0.13
LSA3			-

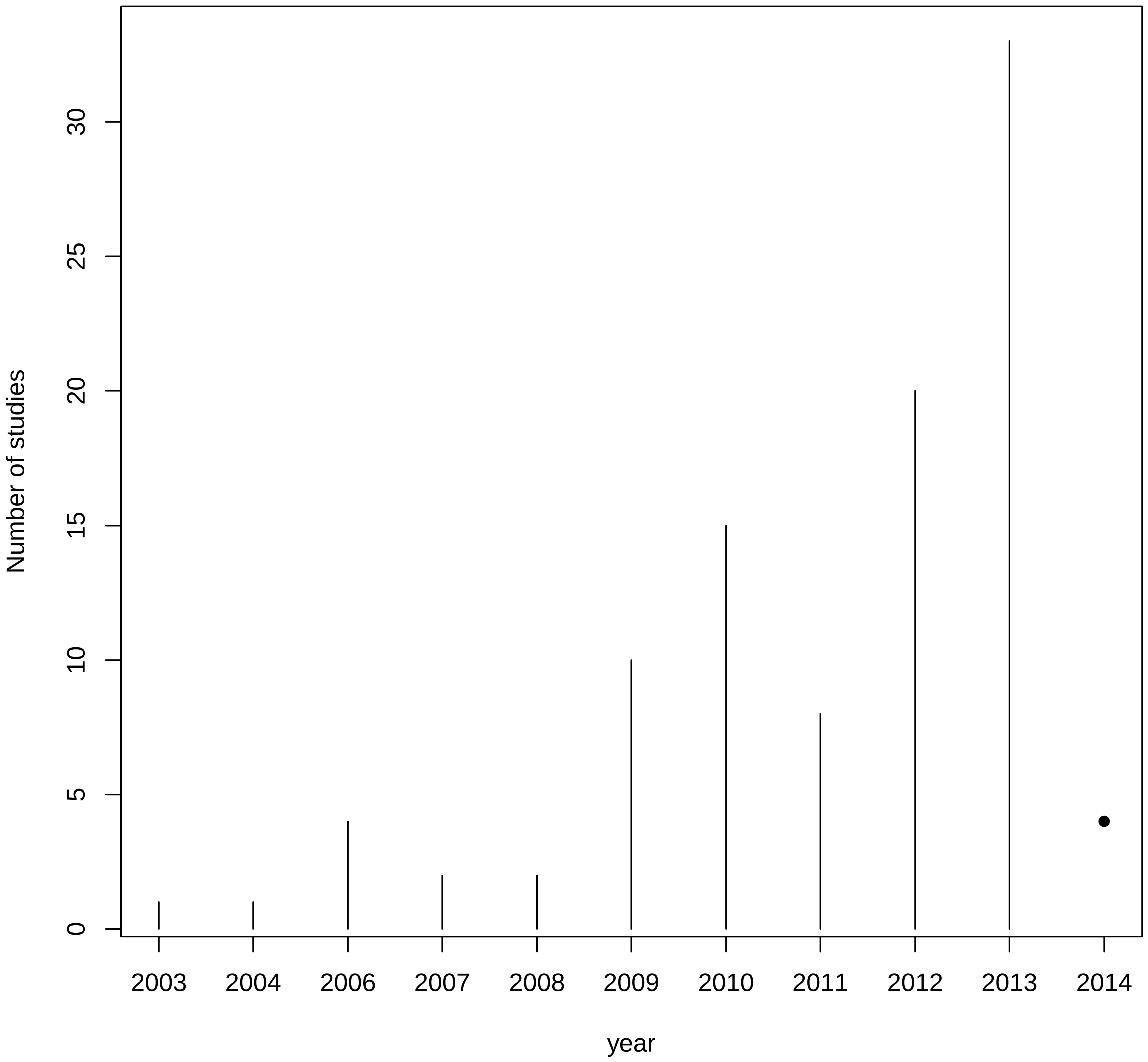

Figure 3.6: Number of scientific articles based on case studies that discussed trade-offs of ES from 2003 to 2013. The literature search stopped 2013 - still we considered some influential studies from 2014 if we come across them.

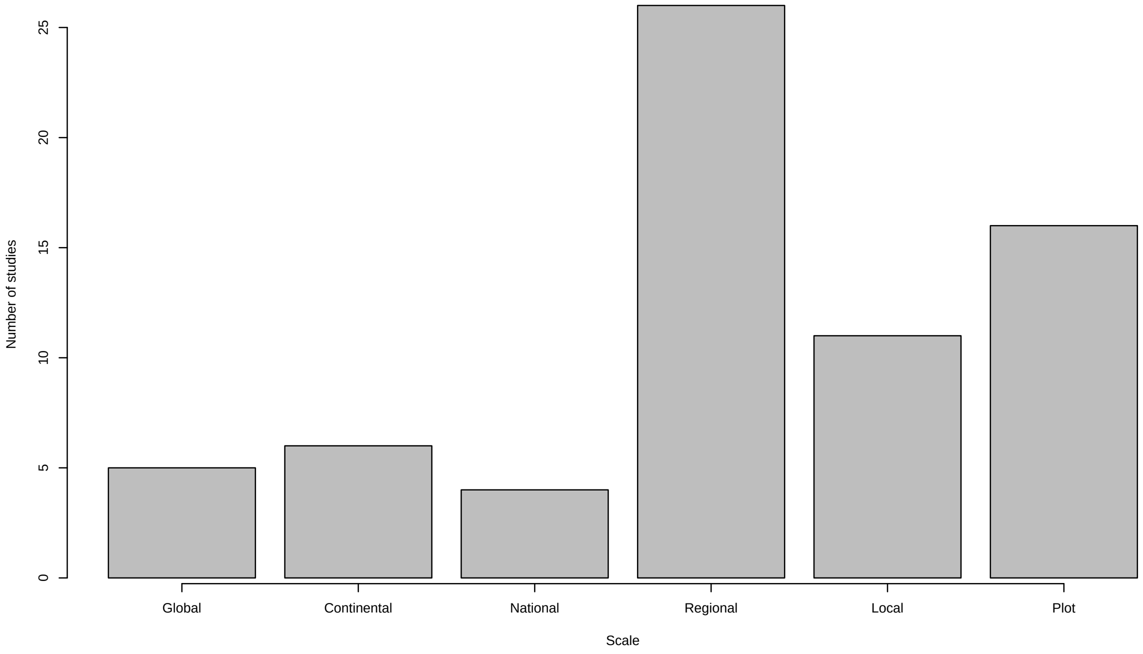

Figure 3.7: The number of case studies at the different scales.

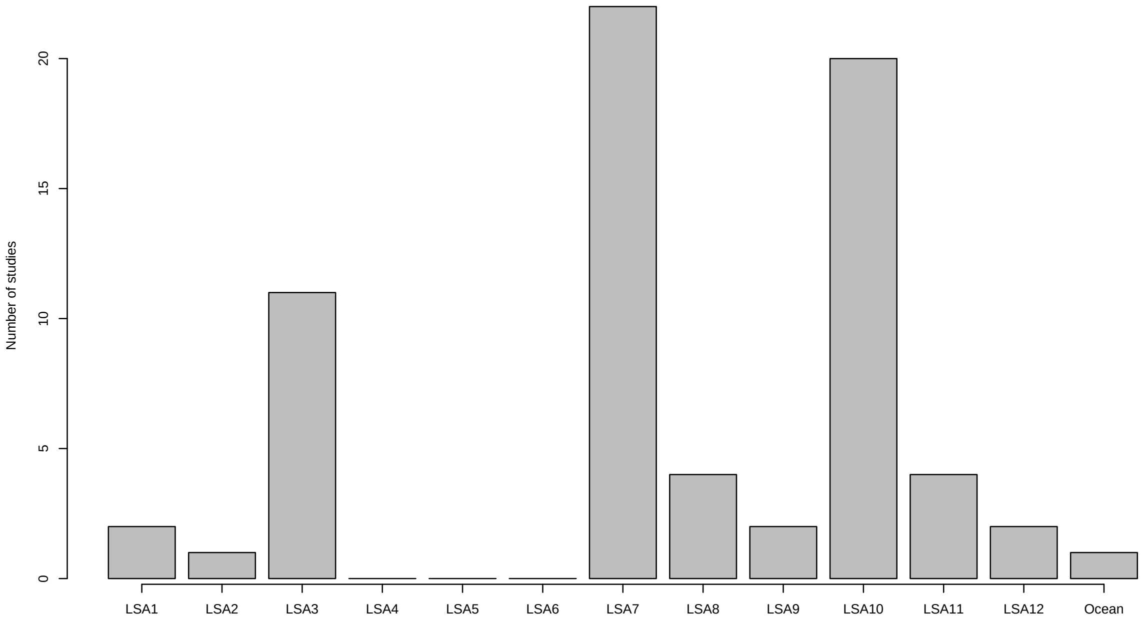

Figure 3.8: The number of case studies in the different Land System Archetypes (LSA). LSA1: Forest systems in the tropics, LSA2: Degraded forest/crop land systems in the tropics, LSA3: Boreal systems of the western world, LSA4: Boreal systems of the eastern world, LSA5: High-density urban agglomerations, LSA6: Irrigated cropping systems with rice yield gap, LSA7: Extensive cropping systems, LSA8: Pastoral systems, LSA9: Irrigated cropping systems, LSA10: Intensive cropping systems, LSA11: Marginal lands in the developed world, LSA12: Barren lands in the developing world.

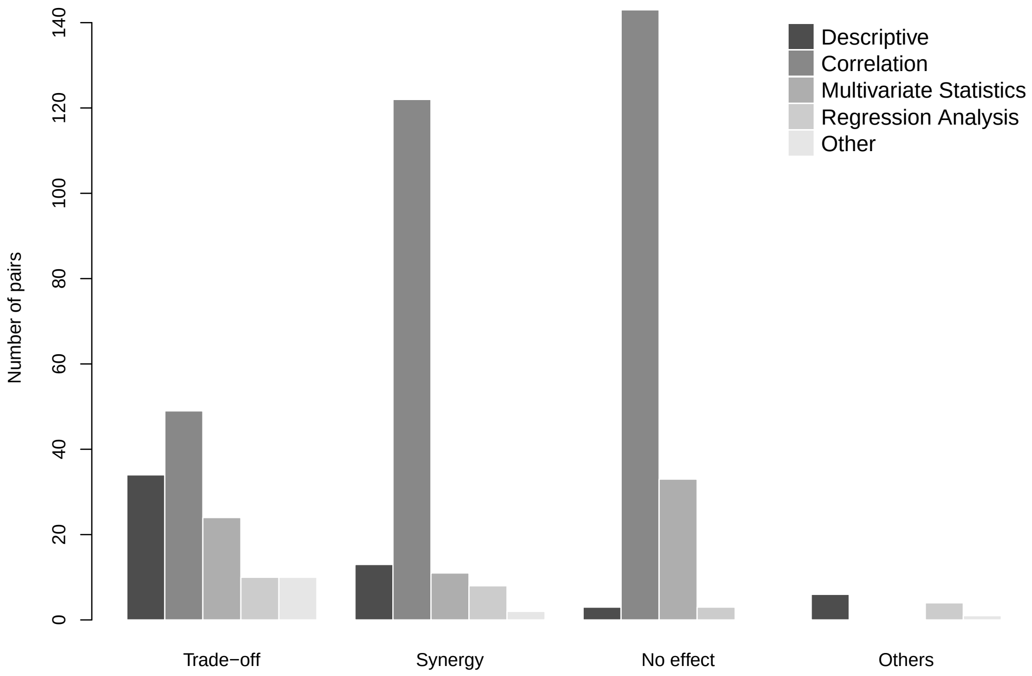

Figure 3.9: The frequency of methods used in different results of the relationship between two ES.

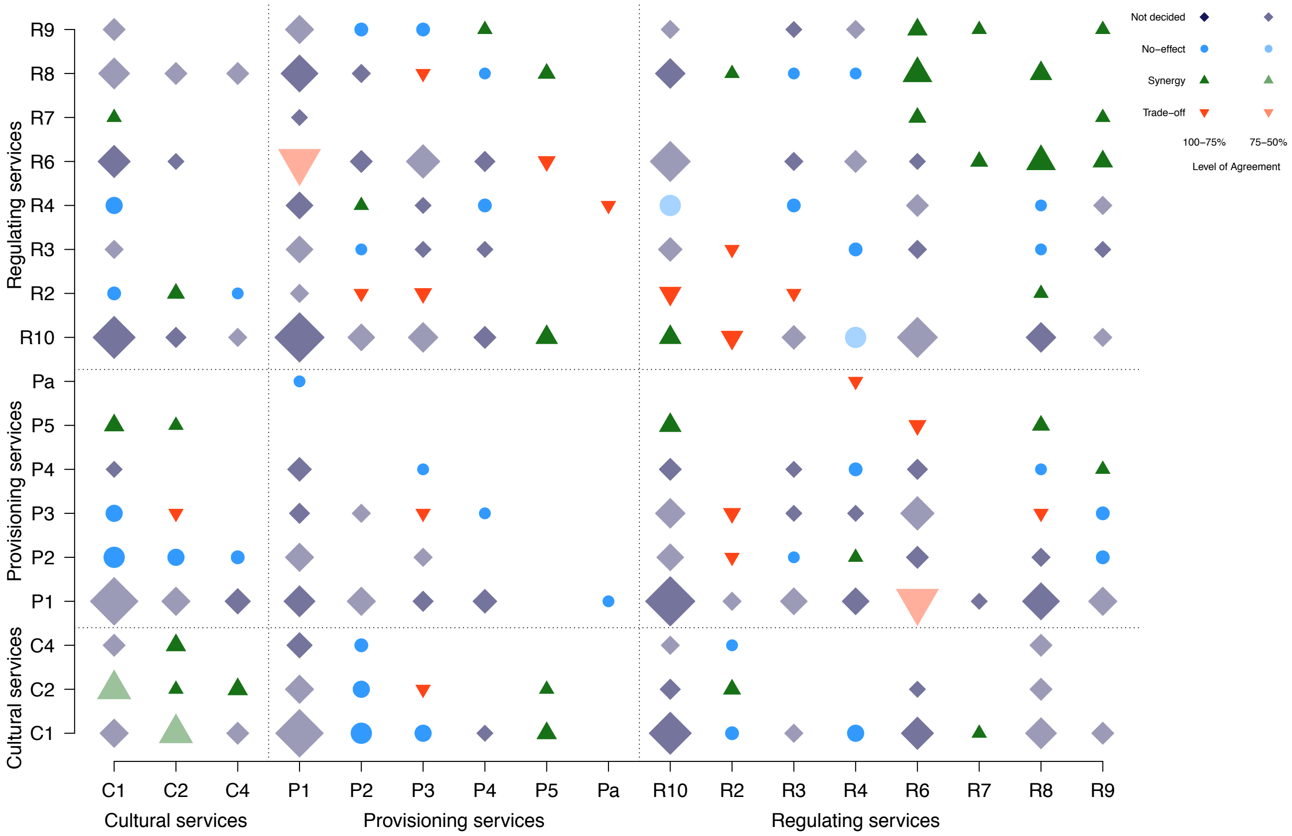

Figure 3.10: Result from analysis of 67 case studies with 476 pairs of ecosystem services with threshold 70% to determine the “Not decided” relationship, showing the empirical pattern of relationships between them. X and Y axis represent the ecosystem service classification code used in the analysis. The size of the symbol indicates the square root scaled number of studies. The color intensity represents the level of agreement. C: Cultural services, P: Provisioning services, R: Regulating services. C1: Physical and experiential interactions, C2: Intellectual and representative interactions, C4: Other cultural outputs, P1: Nutrition biomass, P2: Nutrition water (i.e. drinking purpose), P3: Materials biomass (e.g.for production and agricultural uses), P4: Material water (i.e. non-drinking purpose), P5: Biomass-based energy sources, Pa: Renewable abiotic energy source, R10: Atmospheric composition and climate regulation, R2: Mediation by ecosystems, R3: Mass flows, R4: Liquid flows, R6: Life cycle maintenance, habitat and gene pool protection, R7: Pest and disease control, R8: Soil formation and composition, R9: Water conditions.

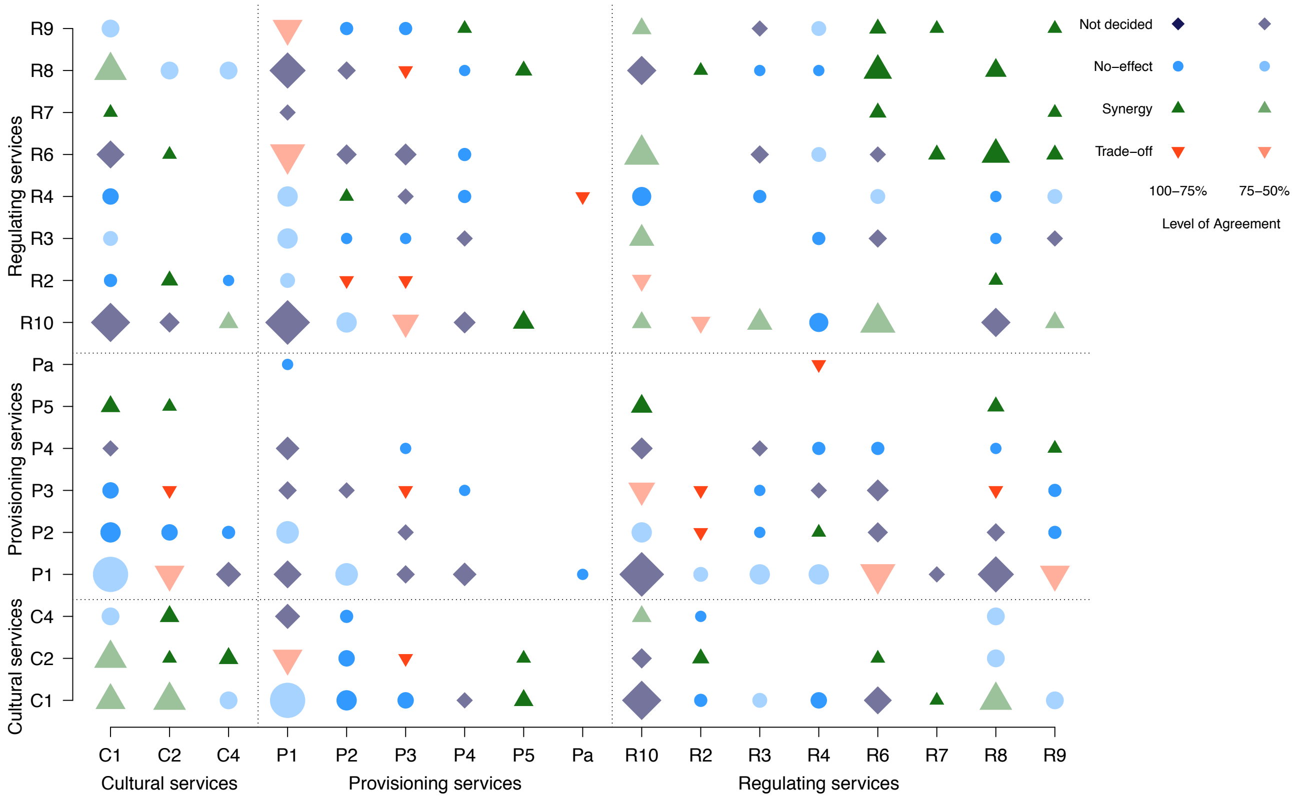

Figure 3.11: Result from analysis of 42 case studies with 420 pairs of ecosystem services excluding pairs identified by descriptive methods with threshold 50% to determine the "Not decided" relationship, showing the empirical pattern of relationships between them. X and Y axis represent the ecosystem service classification code used in the analysis. The size of the symbol indicates the square root scaled number of studies. The color intensity represents the level of agreement. C: Cultural services, P: Provisioning services, R: Regulating services. C1: Physical and experiential interactions, C2: Intellectual and representative interactions, C4: Other cultural outputs, P1: Nutrition biomass, P2: Nutrition water (i.e. drinking purpose), P3: Materials biomass (e.g.for production and agricultural uses), P4: Material water (i.e. non-drinking purpose), P5: Biomass-based energy sources, Pa: Renewable abiotic energy source, R10: Atmospheric composition and climate regulation, R2: Mediation by ecosystems, R3: Mass flows, R4: Liquid flows, R6: Life cycle maintenance, habitat and gene pool protection, R7: Pest and disease control, R8: Soil formation and composition, R9: Water conditions.

4. The impact of conservation farming practices on Mediterranean ecosystem services provisioning - a meta analysis

Abstract

In the Mediterranean region, the long-term provision of ago-ecosystem services (ES) is threatened by ongoing climate change and concurrent exploiting ways of farming practices. Alternative management practices such as conservation agriculture could be expected to ensure sustainability of ES from Mediterranean agro-ecosystems. Conservation agriculture, is characterized by minimal soil disturbance, permanent soil cover, and diversification of crop species. We analyzed the impacts of alternative agricultural management practices (conservation tillage, cover cropping, mulching, manual weed management, organic fertilizer use, no-irrigation system) on multiple ES based on 155 published case studies (1994-2015). The effect size of various management options on four provisioning and four regulating ES were quantified. Impacts of conservation management options on ES are not uniform. All regulating services were positively affected by the conservation management options except for under the no-irrigation system. In contrast, the provisioning services were inconsistently influenced by the conservation management options in different ways. For crop yield, environmentally sustainable soil management was beneficial, but organic fertilization (effect size = -0.17), manual weed management (effect size = -0.35) and no-irrigation system (effect size = -0.5) led to lower crop yields. The impact on crop biomass was mainly negative but not significant. Water availability was especially important to enhance both provisioning and regulating services. Overall, alternative agriculture management practices led to more positive than negative effects on ES in the study region. Stimulating the application of conservation management practices is therefore an important policy option for decision makers given the vulnerability of ES in the Mediterranean basin.

* This study has been submitted to *Regional Environmental Change*

4.1 Introduction

Ecosystems in the Mediterranean basin provides numerous ecosystem services (ES) to society, most landscapes also host high levels of biodiversity (Pretty, 2008, Martín-López et al., 2016, Malek and Verburg, 2017). Yet, ecosystems in the basin are threatened by both climate change and socio-economic factors (Giorgi, 2006, Hill et al., 2008, Bajocco et al., 2012). As the Mediterranean climate is characterized by a high-precipitation period during mild winter and a high-temperature period during summer (Perez, 1990, Sanz-Cobena et al., 2017), seasonal dryness with increased water stress is an issue. Many Mediterranean ecosystems are threatened by potentially severe water shortage (Wimmer et al., 2015, Holman et al., 2017) and potentially causing drought-related decline in the future (Guiot and Cramer, 2016). Unsustainable uses of rural land accelerate land degradation in the Mediterranean basin (Bajocco et al., 2012).

Key challenges faced with respect to the management of land ecosystems in the Mediterranean basin are 1) to maintain food production for the local population as well as for exports and, at the same time, 2) to avoid undesired trade-offs between agricultural production and other ES produced (Smith et al., 2013, Balbi et al., 2015). Such challenges can be partly resolved by sound and sustainable ways of farming (Kroeger and Casey, 2007), but estimates of the potential for doing so vary widely. Depending on the management of the agricultural land, services that we obtain differ due to trade-off relationships between ES as management options affect services differently (Andersen et al., 2013, Palm et al., 2014). A review of qualitative relationships between pairwise ES indicated often a negative effect of intensive farming on regulating services, such as air and water quality regulating services (Pilgrim et al., 2010). To meet food security objectives as well as environmental objectives in agro-ecosystems, sustainable solutions will need to enhance ES and minimize trade-offs effects (Pretty, 2008, Foley et al., 2011).

Conservation agriculture has been increasingly recognized for its capacity to minimize trade-offs between ES and maximize synergies in ES supply (Hobbs et al., 2008, Pretty, 2008, Palm et al., 2014). Conservation agriculture is characterized mainly by minimal soil disturbance, permanent soil cover, and diversification of crop species (FAO, 2008). It aims to improve biodiversity and biological processes in soils, and encourages applications of organic fertilizers in order not to interfere with biological processes (FAO, 2015a). Conservation agricultural practices provide an alternative for preserving multiple ES provided in agricultural land (Poisot et al., 2004, Howden et al., 2007). Several conservative practices were investigated by review studies in the Mediterranean Basin (e.g., Kassam et al., 2012, Aguilera et al., 2013a,b). However, these review studies focused either on a single ES (i.e., carbon sequestration, Aguilera et al. (2013a)) and a limited number of management options (i.e., fertilization and irrigation, Aguilera et al. (2013b)), which makes a comprehensive comparison of relationships between multiple services affected by farming practices difficult. Specifically, impacts of conservation management options on multiple ES in comparison with conventional management options have not been yet extensively investigated until now.

Here, we aimed to fill that knowledge gap by conducting a meta-analysis on the impact of conservative management practices on ES in the Mediterranean basin based on published literature. More specifically, we aimed to identify the positive and negative impacts of conservation farming practices on ES in the Mediterranean basin.

4.2 Material and methods

4.2.1 Literature selection

For a systematic and reproducible literature review, we followed the four-step procedure suggested in "the guidelines of systematic review and evidence synthesis in environmental management" (Collaboration for Environmental Evidence, 2013). Target literature was selected following the Preferred Reporting Items for Systematic reviews and Meta-Analyses (PRISMA) framework: *Identification, Screening, Eligibility, Inclusion* (Moher et al., 2009) (Fig. 4.5). Literature searches were conducted in the ISI Web of Knowledge core database targeting peer-reviewed articles published online until April 30th, 2015. Initially, we tested our query by including a specific management option such as 'irrigation' because the water shortage is conceived as a potential threat to the Mediterranean agricultural system. The search terms for the initial query was *("agro*" OR "agri*" Or "farm*") AND (mediterranean*) AND (ecosystem*) AND (management*) AND (irrigat*)* in the topic field. The preliminary query resulted in 45 papers. Then, we strove to capture the diversity of farming practices studied in case studies and we therefore did not include restrictive search terms à priori. We carried the additional literature search with combinations of keywords including *("agro*" OR "agri*" Or "farm*") AND (mediterranean*) AND (management*)* in the topic field. Similarly, we strove to include all papers that contained relevant information on ES, and a large number of indicators were used in the literature to quantify the supply of those services. We, therefore, refrained from using 'ecosystem services' as a search term. It helped to include relevant papers such as traditional agronomy research out of the domain of ecosystem services research. The additional query returned data records for 1,881 peer-reviewed articles.

The first (n = 45) and the second query (n = 1,881) resulted in total 1,926 papers (*Identification*). After removing duplicate articles (n = 17) and adding one relevant article manually, a total of 1,910 articles was used as the initial data base. From this initial database, we screened articles using title, abstract and full text (Fig. 4.5, (*Screening*, *Eligibility*). We selected empirical case studies which measured ES-related properties both for conservation (treatment) and conventional (control) management options. Pure simulation modeling studies and reviews were excluded thereby. While all these papers reported from the Mediterranean Basin, yet, we also included seven well-designed papers reporting from Mediterranean climate regions outside the basin (i.e., South and South West Australia, the Cape of South Africa, Central Chile, and California (di Castri and Mooney, 1973, Perez, 1990)). Finally, a total of 155 publications was included in the main analysis (Fig. 4.5, *Inclusion*).

4.2.2 Preparation of the Management and ES datasets

4.2.2.1 Management types and options

We considered six major management types (i) tillage, (ii) mulching, (iii) use of cover crops, (iv) fertilization, (v) weed management, and (vi) water management (Table 4.1), which had more than 10 case studies in our literature database. In the following, we describe shortly each management type and the corresponding pairwise conventional (control) and conservation (treatment) management options.

Tillage Conservative tillage aims to minimize soil disturbance. Tillage physically disturbs upper soil layers, thereby facilitating soil aeration, water infiltration as well as inhibiting weeds growth (Phillips et al., 1980). However, it is also known that tilling could rather destroy the soil structure and harm soil organisms, which can lead to soil quality degradation (Six et al., 2000, Montgomery, 2007). The effect of tillage in yield and biomass production has also been questioned (Alvarez and Steinbach, 2009). In the Mediterranean region, heavy tillage using machinery is prevailing similar to many other agricultural regions. However, conservation tilling (i.e., reduced tillage frequencies or tillage depths) or no-tilling has also been applied in the region to maintain physical, chemical, and biological soil quality (Sartori and Peruzzi, 1994, Vita et al., 2007). We used conservation tillage including no-tillage and reduced-tillage as treatment and the conventional tillage as control in our meta-analysis.

Mulch Mulching is another alternative soil management practice. It helps to pertain more vegetation cover on the topsoil, thereby protecting the surface soil. Such protection could help to maintain the soil structure, leading to nurture soil organisms (FAO, 2015b). It also protects the soil from erosion and keeps moisture contents (García-Orenes et al., 2009). Generally organic materials - such as plant residues, straw, and leaves - are used for mulching, but non-organic materials such as a plastic cover can also be applied as well (Kasirajan and Ngouajio, 2012). In our study, mulch was regarded as a conservation practice, thus considered as a treatment. No-mulch was used as the control in the meta-analysis.

Use of cover crops Cover crops are planted to cover the ground to prevent the soil loss and maintain soil quality, water retention, and soil nutrients (Reeves, 1994). To meet those objectives, cover crops should meet requirements, such as a rapid growth rate and disease tolerance (Reeves, 1994, 137-138). Legumes, herbal crops, and grain crops are often cultivated as cover crops (e.g., Ruiz-Colmenero et al., 2013, Campigli et al., 2014, Njeru et al., 2014). In our analysis, use of cover crops was considered as treatment and no use of cover crops as control.

Fertilization Use of organic fertilizer has been reported to have less impact on environmental conditions, which potentially secures more ES (Sandhu et al., 2010). Review studies on the effect of organic practices on environmental impacts revealed that organic fertilizer use improved soil quality by leading to higher soil organic matter content (Mondelaers et al., 2009, Tuomisto et al., 2012). For the effect of fertilizer management we compared organic fertilizer or non-fertilizer with inorganic fertilizer as control. We did not distinguish between different types of input organic materials in our analysis because of insufficient data.

Weed management Weeds are plants competing with crops for water and nutrient during the growing season (Hager, 2015). A significant yield loss can occur due to the light and nutrient competition between crops and weeds (Slaughter et al., 2008) - hence, weed control is a critical topic in agriculture. In conventional agriculture, farmers often control weeds using agro-chemicals. Since negative effects on ecosystems and biodiversity have been reported (Cox and Surgan, 2006), there have been efforts to reduce its usage. In our analysis, we compared the impact of the conservative weed management practices which do not require chemicals (treatment) against practices involving chemical applications (control).

Water management Irrigation provides a controlled amount of water to the crops to reduce water stress (Walker, 1989). In semi-arid regions such as the Mediterranean basin, irrigation increases productivity compared to the rain-fed agriculture (Iglesias et al., 2011). Yet, it can have side effects. For example, poor management can lead to salinization by overusing ground water (Baldock et al., 2000, Bouarfa et al., 2009). We contrasted in our meta-analysis rain-fed system as treatment with irrigated system as the control group. Various irrigation systems including surface, drip, and sprinkler methods were all regrouped as ‘Irrigation’, for simplicity.

4.2.2.2 Ecosystem services (ES) and indicators

Indicators used to study the phenomena in the case studies were assigned to ES classes using the Common International Classification of Ecosystem Services (CICES) classification V4.3 (Haines-Young and Potschin, 2013). CICES follows a nested hierarchical structure of ES, which includes the level of ‘section’, ‘division’, ‘group’, and ‘class’ (Haines-Young and Potschin, 2013). For our analysis we chose the group level to aggregate indicators (Table 4.5). The mapping of indicators to ES was based on several established frameworks (Dale and Polasky, 2007, Stott et al., 2009, Dominati et al., 2010, de Groot et al., 2010, Verhulst et al., 2010, Palm et al., 2014).

The mean, standard deviation, and sample size for indicators studied in each case study were extracted from texts, figures, and tables of the original literature. If a study presented the data only on the figures, we used WebPlotDigitizer (Rohatgi, 2017) to extract the data.

Table 4.1: Six major management types and corresponding conventional (control) and conservative (treatment) management options evaluated in the meta-analysis.

Management type	**Conventional option (control)**		**Conservative option (treatment)**	
	Name	Issues	Name	Desired effect
Tillage	Conventional tillage	Severe soil disturbance and increased GHG emissions	Reduced tillage; No tillage	Minimal soil disturbance, GHG emissions, improved soil cover and erosion control
Mulch	No mulch	Soil erosion, soil degradation, soil moisture loss	Mulch (residue, straw, grain, plastic)	
Cover cropping	No cover cropping		Cover cropping	
Fertilization	Chemical fertilizer application	Soil and water quality degradation	Organic fertilization; No fertilization	Soil and water quality improvement
Weed management	Chemical application	Biodiversity loss and food safety	Manual control; No weed control	Nurturing biodiversity and food safety
Water management	Irrigation	Avoiding water stress but increasing salinization and water pollution	Rain-fed (no irrigation)	Reducing soil and water pollution

Table 4.2: Indicators analyzed in this study and related ecosystem services (ES). ES were named following the Common International Classification of Ecosystem Services (CICES) at the group level (Haines-Young and Potschin, 2013).

Indicator	Description	Medium	Related ES	Reference
Yield	Agricultural output, yield of crops per unit area	Vegetation	Nutrient, Material biomass	Diskin (1999)
Biomass	A plant attribute, a mass of biological organism, it can be measured by a dry weight (harvest and dry) above and below ground	Vegetation		
Harvest Index (HI)	The ratio of the yield of grain to the biological yield	Vegetation		Donald and Hamblin (1976)
Soil organic carbon (SOC)	A measurable component of soil organic matter	Soil	Soil formation and composition, Atmospheric composition and climate regulation	Soil Quality (2017)
Total organic carbon (TOC)	Carbon stored in soil organic matter (SOM)	Soil		Soil Quality (2017)
Total nitrogen (TN)	The sum of nitrate-nitrogen (NO_3-N), nitrite-nitrogen (NO_2-N), ammonia-nitrogen (NH_3-N)	Soil	Soil formation and composition	Bremner (1965)
beta-Glucosidase (BetaGlu)	It catalyzes the hydrolysis of terminal non-reducing residues in beta-D-glucosides with release of Glucose. It is an indicator for the soil biological condition	Soil		Reference MD (2012), Loganathan and Narendiran. N. (2014)
Microbial biomass carbon (MBC)	Microbial biomass is the weight of microorganisms in soil (generally fungi and bacteria) and Microbial biomass carbon is the carbon contained in the living organisms	Soil		Baaru et al. (2007), Soil Quality (2017)
Dehydrogenase activity (DHA)	A measure of soil enzyme activities	Soil		Quilchano and Marañón (2002)
Bulk density	The degree of compaction. Generally calculated as mass of soil divided with volume of a whole	Soil		Soil Quality (2017)
Water content	The quantity of water within soil (the water evaporated from the soil)	Soil	Material water	Gardner et al. (2000)

Table 4.2: Indicators analyzed in this study and related ecosystem services (ES). ES were named following the Common International Classification of Ecosystem Services (CICES) at the group level (Haines-Young and Potschin, 2013). (continued)

Indicator	Description	Medium	Related ES	Reference
Runoff	The water flows over the land surface	Soil	Mass flow regulating services	Kosmas et al. (1997)
Sediment redundant	The amount of sediment reloaded by water erosion	Soil		Gobin et al. (2004)
Soil loss	The amount of soil eroded by water erosion	Soil		Gobin et al. (2004)
Shannon Index	A diversity index. The more various characters there are, the more diverse the system is.	Vegetation, fungi, bacteria	Life cycle maintenance, habitat and gene pool protection	Shannon (1948)
Species richness	A diversity index. The number of different species	Vegetation, fungi, bacteria		Colwell (2009)

4.2.3 A meta-analysis: impacts of management options on ES

We analyzed the impact of different management options on ES from publications through a meta-analysis. A meta-analysis is a statistical method to summarize the results from the findings across multiple case studies by calculating effect sizes (Higgins et al., 2002, Vetter et al., 2013). The effect size is a measure of the magnitude of effects of a treatment group (Lipsey and Wilson, 1993). We calculated the response ratio as an effect size unit for each indicator (Hedges et al., 1999, Borenstein et al., 2009) (Eq. 4.1). This metric has been widely used for meta-analyses in ecology and agricultural studies (e.g., Aguilera et al., 2013a, Curran et al., 2014, Torralba et al., 2016). The response ratio was calculated as a proportionate change in the indicator value of the treatment group ($\overline{X_{CS}}$) compared to the pairwise control group ($\overline{X_C}$). We used the natural logarithm of the response ratio (log(RR); lRR) for the analysis:

$$log\ Response\ Ratio = ln(\overline{X_{CS}}/\overline{X_C}) = ln(\overline{X_{CS}}) - ln(\overline{X_C}), \tag{4.1}$$

, where positive values indicate a higher value in the treatment group (conservation practices), whereas negative values indicate a lower in the treatment group (conservation practices).

To account for the differences between the different studies and that several measures are used in practice, we calculated the weighted mean of lRR from individual studies for deriving representative response ratio per indicator. In the meta-analysis, numbers from the studies are weighted by the inverse of the reported standard deviation/standard error of the indicators, thereby, a case study which is more certain about the estimated effect is weighed higher during aggregation (Borenstein et al., 2009). Weighting by the standard deviation is the standard approach in the meta-analysis as it explicitly accounts for the variance - however, the standard deviation was not reported in all case studies. We contacted the corresponding authors of the studies which did not provide uncertainty information (n = 33) but obtained answers only from five authors. Moreover, provided uncertainty information is often incompatible among the studies due to heterogeneous in structure (e.g., the standard deviation of the sampled raw data or the standard error of the aggregated mean).

To secure enough number of studies, we decided to weight observations using the sample sizes: studies with larger sample sizes were weighted more during aggregation (Adams et al., 1997). With this simpler approach, the weighted log response ratio (WlRR) between management option i is calculated as

$$WlRR_i = \frac{1}{N_i} \sum lRR_{ij} \times W_{ij} \tag{4.2}$$

, where N_i is the number of the studies for the management i, lRR_{ij} is the log response ratio of the management i in study j, and W_{ij} is the weight, which is defined as

$$W_{ij} = \frac{N_{ij}^{CS} N_{ij}^{C}}{N_{ij}^{CS} + N_{ij}^{C}} \tag{4.3}$$

, where N_{ij}^{CS} and N_{ij}^{C} are the sample size of the conservation option and the conventional option of the management i in study j, respectively (Hedges and Olkin, 1985, Adams et al., 1997). Note that if a study had not provided the sample size, we excluded the study from the analysis (n=1).

For the uncertainty analysis, we report the means and 95% confidence intervals (CIs) of the WlRR. The CIs were constructed by non-parametric bootstrapping (n_{boot} = 10000) (Adams et al., 1997) using the percentile method (Davison and Hinkley, 1997). The bootstrapping was, however, only conducted for management options with larger than seven case studies (n $\geq$ 8) as the bootstrap is unreliable when the same size is too small (Efron and Tibshirani, 1994a). For those with the sample size less than 8 (n < 8), we reported the mean weighted response ratio (WlRR) without estimated CIs. We considered the effect of treatment as significant if the 95% bootstrap CI did not overlap with zero. To aid interpretation, mean response ratios and lower and upper limits of CIs were graphically examined using violin plots (n $\geq$ 8) (Adler, 2005). When the sample size was less than 8 (n < 8), the strip chart was constructed to visualize data points. All calculations were done in `R` version 3.3.1 (R Core Team, 2016) using the packages `boot` (Canty and Ripley, 2017) and `vioplot` (Adler, 2005).

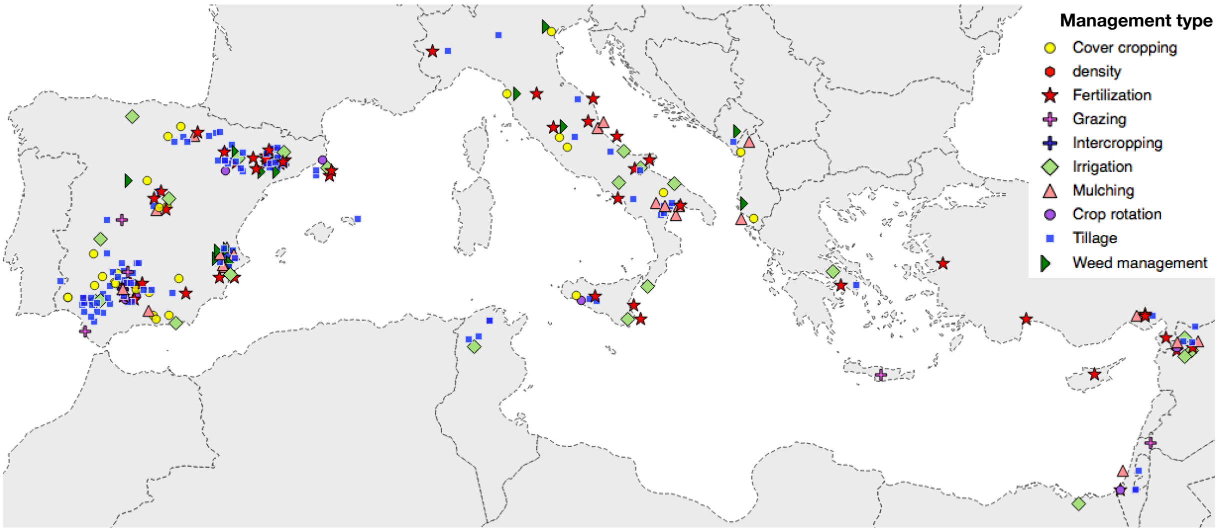

Figure 4.1: Map of the 188 studied sites in the 155 selected publications for the analysis. The different symbols refer to the studied management options in each study location. Note that the figure includes all management options found in the case studies. However, the major six management options were only considered in the further analysis.

4.3 Results

4.3.1 Studied management types

Final selection of the publications included 155 articles covering 188 measurement locations (Fig. 4.1): most of the case studies were located in the Mediterranean basin (96.2%); there were four study sites in the Mediterranean climate located in North America, two in South America, and one in Australia. In the Mediterranean basin, case studies were concentrated in European Mediterranean countries. The majority of the studies (92.9%) were implemented on agricultural land, 59.6% among which analyzed cereal crops, 22.6% orchard, and 12.3% horticulture. A small portion (4.5%) of the studies analyzed silvopastoral and *dehesa* systems, which is a typical extensive multifunctional agro-silvopastoral system in the Mediterranean region especially in Spain and Portugal (Joffre et al., 1988, Paleo, 2010).

Ten different management options were found in the selected 155 publications. The most frequently studied management was ‘Tillage’ (n = 87) followed by ‘Fertilization’ (n = 47), ‘Mulch’ (n = 23), ‘Water management’ (n = 22), ’Cover Crop (n = 21), and ‘Weed management’ (n=14). We took these six major management types ($n > 10$) in the following analysis. Less frequently encountered management options included ’Crop rotation’ (n = 10), ‘Grazing’ (n=5), ‘Planting density’ (n = 1), and ‘Inter-cropping’ (n=1).

The majority of case studies focused on a single management type (n = 95; 60.9%, Fig. 4.7) as shown at the main diagonal of the matrix, in many studies multiple management options were jointly investigated. Some pairs were distinctive: tillage and mulch (n = 15) and tillage and cover crop (n = 10). Soil management practices were often studied together. Tillage was most frequently studied with other management practices (n = 19). At most four management practices were analyzed in a same study (n = 1).

4.3.2 Indicators used in the literature

In the selected case studies, 167 indicators were used.The most frequently measured indicator was 'Yield' (n = 70) followed by 'Soil Organic Carbon (SOC)' (n = 40), 'Biomass' (n = 28), and 'Total Nitrogen (TN)' (n = 24). Among the all indicators only 7.8% indicators (n = 13) appeared in more than 10 case studies. About 60% of the indicators appeared only in a single case study (n = 100). The usage pattern of the indicators was related to management types (Fig. 4.2). For example, 'Bulk Density' was frequently measured in studies dealing with the cover crop management, whereas studies about weed or water management hardly considered bulk density simultaneously (Fig. 4.2). Likewise, for water management, 'pH' and 'Harvest Index (HI)' were frequently measured, and 'Soil loss' and 'Runoff' were often used in the studies that investigated the use of cover crops.

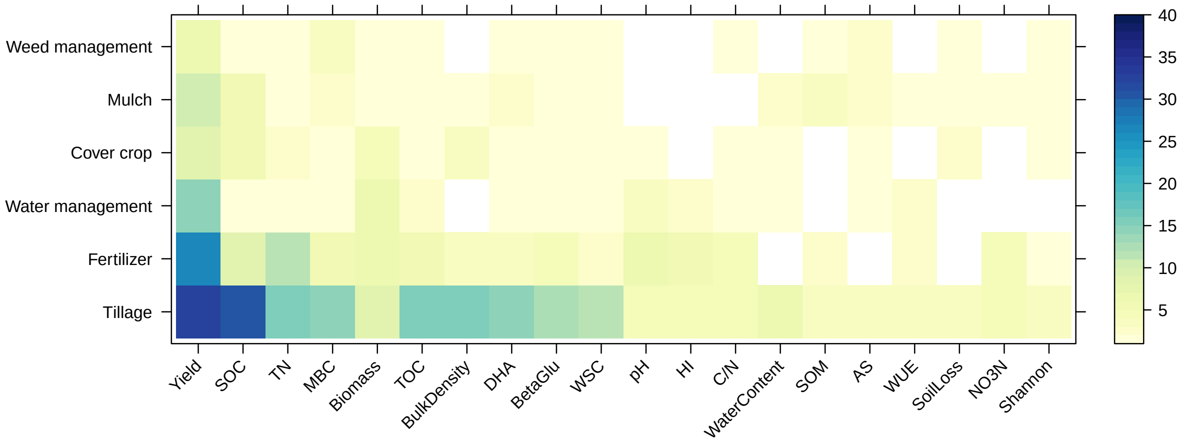

Figure 4.2: Top 20 indicators addressed across the case studies for each management practices. The colors represent the number of case studies; Y-axis refers to management types; x-axis refers to indicators: SOC: Soil Organic Carbon, TN: Total Nitrogen, MBC: Microbial Biomass Carbon, TOC:Total Organic Carbon, BulkDensity: Bulk density, DHA: Dehydrogenase Activity, BetaGlu: beta-Glucosidase, WSC: water soluble carbon, HI: Harvest Index, SOM: Soil Organic Matter, AS: Aggregate stability, WUE: Water Use Efficiency, Shannon: Shannon Index. The explanation of indicators is given in Table 4.2.

The indicators were assigned to nine different ES described in Table 4.5: four types of provisioning and five types of regulating services (Fig 4.3). Cultural services were not analyzed in the selected case studies. 'Pest and disease control' was only observed in studies that were excluded from further analysis due to seldom encountered management options. The majority of studies analyzed one type of ES (66.4%, n = 103), whereas 33.5% of studies analyzed multiple ES in a study (48 studies analyzed two ES, 4 studies analyzed three ES). The most frequently studied ES was ‘Soil formation and composition’ (n = 76) followed by ‘Nutrition biomass’ such as food (n = 68) (Fig 4.3).

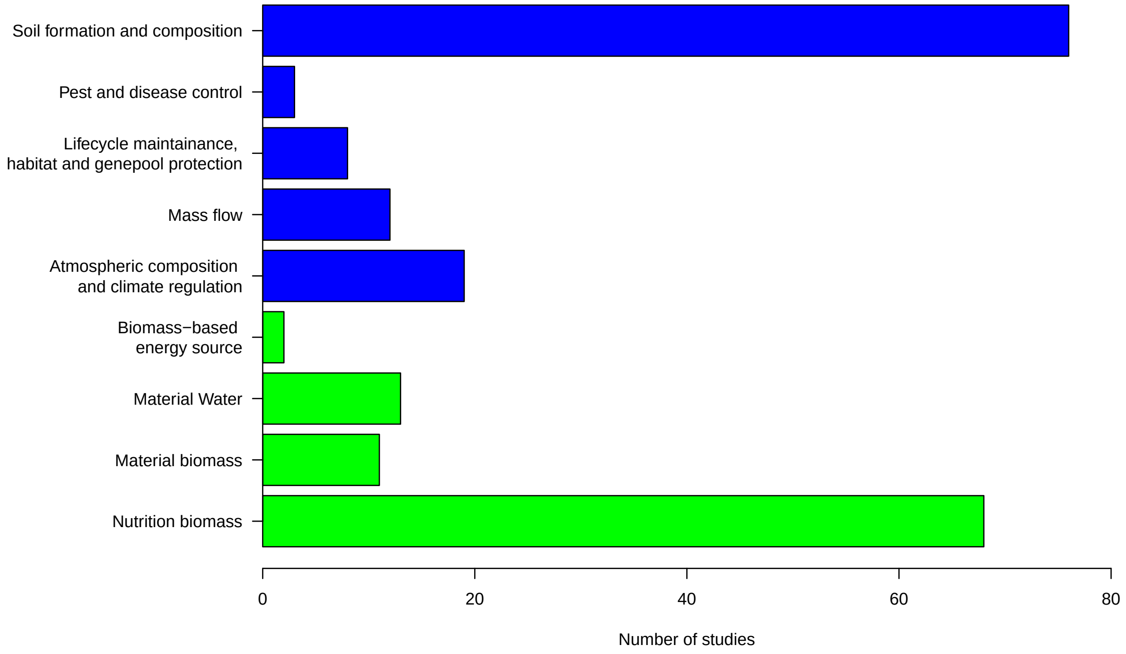

Figure 4.3: The frequency with which ecosystem services were included across the case studies. The color indicates the different ES groups: Provisioning ecosystem services are depicted green and regulating ecosystem services blue.

4.3.3 Impacts of conservative management options on ES

We quantified overall impacts of management options on ES based on the meta-analysis (Fig. 4.4). The results indicated that the conservation management practices overall increased yield and biomass. The yield was even slightly higher in reduced soil disturbance systems as a result of conservation tillage, mulch, and cover crops. However, the effect of tillage was not significant (Fig. 4.4, (a)).

Our result showed that water content in mulching condition was higher than in conventional farming system (Fig. 4.4, (b)), which might explain the increased yield when applying mulching. Exceptions of the positive effect on yield were the use of organic fertilizer and organic weed management (mow, manual controlling), as well as rain-fed. WlRR was -0.14 and -0.24 for the organic fertilizer and the manual weed management, respectively. Under the rain-fed system, yield was most negatively affected (WlRR = -0.501, significant).

Indicators related to ‘Soil formation and composition’ showed an overall positive effect size by the conservative practices (Fig. 4.4, (a)-(d)). ‘Soil Organic Carbon’ as an indicator for ‘Atmospheric composition and climate regulation’ or ‘Soil formation and composition’ was affected positively by reduced tillage (WlRR = 0.088, significant), use of organic fertilizers

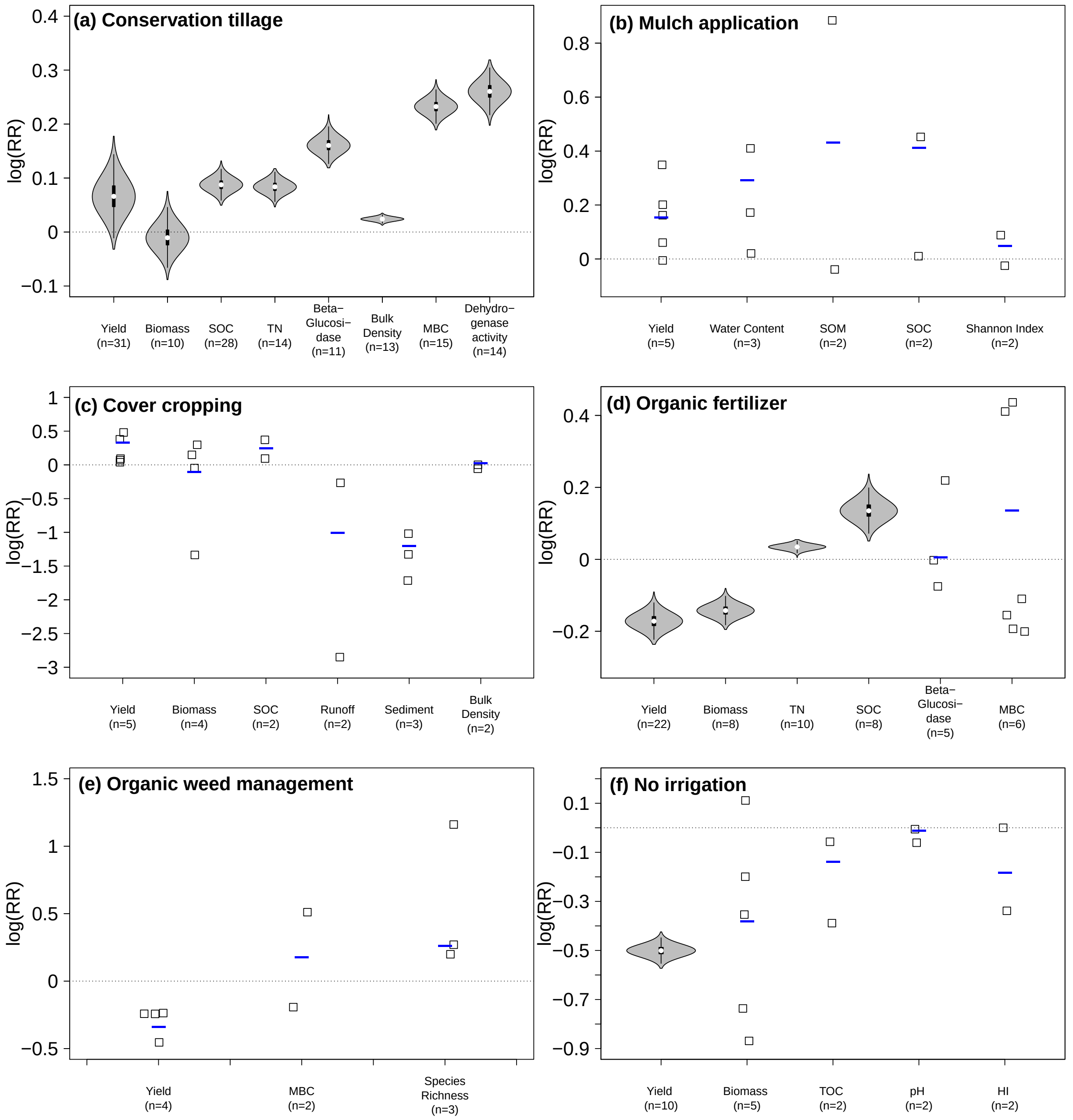

Figure 4.4: Violin plot (a, d, f) with overlayed boxplot of the mean effect size (log response ratio; log(RR)) of the conservation management options on different indicators for ecosystem services from Table 4.2. The variance was constructed by non-parametric bootstrapping ($n_{boot} = 10000$) when the sample size was lager than seven ($n \geq 8$). When the sample size is less than eight ($n < 8$), strip chart (b, c, e) of the effect size was plotted (jittered for clarity). Blue hyphens indicate the mean weighted response ratio for those with the sample size less than eight. A dashed line at zero distinguishes between situations where conservation management options are better than conventional management options ($\log(RR) > 0$) and situations where conventional management options are better than conservation management options ($\log(RR) < 0$). We considered the effect of treatment as significant if the violin plot did not overlap with zero. SOC: Soil organic carbon, SOM: Soil organic matter, TN: Total nitrogen, MBC: Microbial biomass carbon, HI: Harvest Index.

(WlRR = 0.15, significant) and cover crop (WlRR = 0.213) and mulch (WlRR = 0.403). ‘Species richness’ was only found in case studies that considered the weed management, and the WlRR positive, 0.246.

The aggregated results showed a positive effect on regulating services by all types of conservation practices (Table 4.4). The provisioning services showed mixed results and the relationships between provisioning and regulating services were mixed thereby. For example, the results showed positive changes in both ‘Nutrient biomass’ and ‘Material Water’. Note that this result does not necessarily include a causal relationship between them. The use of organic fertilizer or non use of fertilizer had a positive effect on regulating services, whereas a negative effect on provisioning services. Non irrigated system had a negative impact on all types of services. Among other regulating services, ‘Mass flow’ such as erosion control was affected by cover crops. Our result revealed that the cover crop application reduced the sediment loss as well as run off (Fig. 4.4).

4.4 Discussions

4.4.1 The impacts of management options on ES

Four provisioning, five regulating and no cultural ES were studied in the case studies in our data set. Given the touristic attraction of the highly valued Mediterranean landscape, cultural services might be a potential asset for farmers to diversify their income (Nickerson et al., 2001, Sharpley and Vass, 2006, Brandth and Haugen, 2011). It is likely that this could be done without much harm to the environment as the relationships between cultural services and other ES were found out to be ‘no-effect’ or ‘synergistic’ in a recent review study (Lee and Lautenbach, 2016). An example of cultural ES in agricultural areas is ‘agritourism’ by allowing people to watch or to physically experience farming activities (Bennett et al., 2009). Also ‘traditional ecological knowledge’ is a representative example of cultural ES in the region, which is related with the management practices of farmers and the transmission of their experiential knowledge (Iniesta-Arandia et al., 2015). In the following sections, provisioning and regulating services are discussed in detail.

4.4.1.1 Provisioning services

Food production is the primary function of agricultural land (Palm et al., 2014, Balbi et al., 2015). Changing climate as well as unsustainable farming practices threaten food supply in the Mediterranean basin (Iglesias et al., 2011). Our results showed a potential for alternative management options to increase crop yield. The conservation management options that were applied to reduce soil disturbance such as tillage, mulch and cover crop increased yield (Table 4.4) even slightly (Fig. 4.4). This positive effect on yield corresponds to previous reports in the Mediterranean climate (see a review study from Kassam et al. (2012)). For example, Crabtree (2010) showed about 30-50 percent of crop productivity increases due to the no-till management over 10 years in south western Australia under the Mediterranean climate, which also secured farmers’ income condition. However, previous

Table 4.3: Summary results of the weighted response ratio (WlRR) and the bootstrap confidential intervals

Variables	Weighted response ratio (WlRR)	Standard Error	5 % CI	95 % CI	Sample size
A. Conservation tillage					
Yield	0.066	0.0281	0.011	0.122	32
Biomass	-0.01	0.021	-0.0498	0.0328	10
TN	0.084	0.01	0.065	0.1038	14
SOC	0.088	0.013	0.0751	0.1262	28
Beta - Glucosidase	0.161	0.0126	0.1374	0.187	11
Bulk Density	0.024	0.003	0.0181	0.0296	13
MBC	0.233	0.0117	0.2102	0.2555	15
Dehydrogenase activity	0.261	0.0164	0.229	0.294	14
B. Mulch					
Yield	0.1462				5
Water Content	0.284				3
SOM	0.423	-	-	-	2
SOC	0.4034	-	-	-	2
Shannon Index	0.0398	-	-	-	2
Beta-Glucosidase	0.212	-	-	-	1
MBC	0.101	-	-	-	1
C. Cover cropping					
Yield	0.299	-	-	-	5
Biomass	-0.141	-	-	-	4
SOC	0.213	-	-	-	2
Runoff	-1.041	-	-	-	2
Sediment	-1.239	-	-	-	3
Bulk Density	-0.0076	-	-	-	2
Shannon Index	0.021	-	-	-	1
Soil Loss	-1.068	-	-	-	1
D. Organic fertilization					
Yield	-0.1724	0.019	-0.208	-0.135	22
Biomass	-0.1421	0.0147	-0.1565	-0.0941	8
TN	0.0437	0.0053	0.033	0.0539	10
SOC	0.15	0.024	0.105	0.1976	8
Beta-Glucosidase	-0.0012	-	-	-	5
MBC	0.129	-	-	-	6

Table 4.3: Summary results of the weighted response ratio (WlRR) and the bootstrap confidential intervals (cont.)

Variables	Weighted response ratio (WlRR)	Standard error	5 % CI	95 % CI	Sample size
E. Weed management					
Yield	-0.3571	-	-	-	4
MBC	0.159	-	-	-	2
Species Richness	0.246	-	-	-	3
Shannon Index	0.529	-	-	-	1
TOC	0.09	-	-	-	1
TN	0.0883	-	-	-	1
F. Rain-fed (no irrigation)					
Yield	-0.501	0.019	-0.539	-0.463	10
Biomass	-0.391	-	-	-	5
TOC	-0.1475	-	-	-	2
pH	-0.021	-	-	-	2
Harvest Index	-0.193	-	-	-	2

studies in other climate regions outside Mediterranean regions showed that in cooler and wetter places the impact was opposite (Ogle et al., 2012): a positive impact was found in Sub-Sahara Africa (Giller et al., 2009), yet negative or negligible results were reported from Argentina (Alvarez and Steinbach, 2009), Scandinavia (Rasmussen, 1999) and North America (DeFelice et al., 2006). Management options directly and indirectly affect soil and water conditions in agricultural areas (Zalidis et al., 2002).

Conservation farming practices affect those water and soil nutrient positively which in turn increases yield (Giller et al., 2009, Gordon et al., 2010, Palm et al., 2014). The effects on improved soil quality and water storage were also found in our result (Fig. 4.4), which may explain the slightly increased yield in mulching system. Furthermore, the positive effect of conservation farming on yield was particularly observed during the dry season as it led to relative yield stabilization (López-Bellido et al., 1996). However, it should be also noted that rain-fed management in the Mediterranean region was not able to supply enough water to keep both provisioning (i.e., yield) and regulating services.

The organic weed management and the use of organic or no fertilizer improved 'Soil formation and composition' services, but showed a negative effect on yield. This trade-off relationship caused by organic managements among other conservation agricultural managements has been widely recognized globally (de Ponti et al., 2012, Seufert and Ramankutty, 2017), indicating that the yield difference between organic and conventional farming is about 20%.

4.4.1.2 Regulating services

Most of the regulating services analyzed in our study were positively affected by conservation management options which highlights the role of conservation management options to improve soil composition. The 'Soil formation and composition' service was the most

Table 4.4: The conservation managements were compared to the paired conventional managements. For a detailed description, see Table 4.1: up arrow: positive effect, down arrow: negative effect, -: not significant

	Provisioning services				Regulating services			
	Nutrition biomass	Material biomass	Material water	Energy sources	Atmospheric composition and climate regulation	Mass flow	Lifecycle maintenance, habitat and gene pool protection	Soil formation and composition
Conservation tillage	-	-			↑			↑
Mulch	↑		↑			↑	↑	↑
Cover crop	↑	↓			↑	↑		↑
Organic weed management	↓				↑		↑	↑
Use of organic fertilizer	↓	↓		↓	↑			↑
Rain-fed (no irrigation)	↓	↓	↓					↓

studied ES and positively affected by most of the considered conservation options (Table. 4.4).

A list of indicators for the 'Soil formation and composition' service was found in the case studies with respects to physical, chemical and biological conditions. Even though it is often not clear which soil properties are most appropriate to reflect the impact of conservative management on ES provision (Palm et al., 2014), our review showed positive effects of conservation management across all indicators and across physical, chemical and biological soil conditions. Some soil indicators related with soil carbon could be further linked to 'Atmospheric composition and climate regulation'.

The 'Atmospheric composition and climate regulation' service was positively affected by conservation management. This result is in line with previous review studies. The review by Aguilera et al. (2013a) shows that conservation tillage has a positive effect on carbon sequestration, especially when combined with organic fertilizer application and mulching. Also, N2O emissions were reduced by 23% by applying organic fertilizers compared to conventional fertilizers (Aguilera et al., 2013b). Among conservative management options, mulching was the most effective method with the largest effect size to increase 'Soil organic carbon (SOC)' in our results. This is in line with the results from Blanco-Canqui and Lal (2007), Palm et al. (2014) showing the importance of organic residue for carbon sequestration.

Improvement of soil cover had a positive effect on the 'Life cycle maintenance, habitat and gene pool protection' in our data set. Conventional practices in agricultural land systems are generally recognized as leading to a loss of biodiversity by disturbing soil (McLaughlin and Mineau, 1995) and habitats. Soil disturbance destroys not only the soil structure but also associated soil biodiversity (Montgomery, 2007, Kassam et al., 2012). Alternative management options can provide an opportunity to improve biodiversity related indicators. Furthermore, the enhanced soil biodiversity can have a synergistic relationship with other ES. Bender et al. (2016) highlight the importance of soil organism for the ES provision through their essential role in important ecosystem functions.

The largest effect size across all regulating services was found for the ES 'Sediment retention' (WlRR = -1.239) and 'Runoff reduction' (WlRR = -1.041) for cover crop management. The conservative soil cover management decreased runoff and soil loss, which contributes to an improved 'Mass flow regulation' (Table 4.4). Cover crops are primarily applied to prevent top soil from the wind and water erosion (Langdale et al., 1991, Fageria et al., 2005). As soil erosion removes top soil fertility and therefore, productivity capacity (Pimentel et al., 1995), the reduced soil erosion provides an important opportunity.

In our analysis, rain-fed water management affected all ES negatively. This result indicates the importance of water stress in this region. Water shortage is one of the biggest challenges in the Mediterranean basin (Iglesias et al., 2007). Improving water availability can be a key issue to secure multiple ES. Irrigation requirement is likely to increase by between 4 and 18 % by 2°C global warming in the Mediterranean basin (Fader et al., 2016). However, it should also be noted that the poor management of irrigated agriculture can potentially cause other impacts on the water availability and the environment in the Mediterranean region (Pereira, 2004). Also, depending on where the irrigation system has been installed, it can increase soil erosion in cultivated soils on slopes, which is more often found in the

Mediterranean Basin such as Greece (Baldock et al., 2000). An improved efficient irrigation system would be beneficial for water resource management in the future (Pereira, 2004, Fader et al., 2016).

4.4.2 Limitations of the meta-analysis

Although we followed a standardized process to systematically collect publications and data points, some considerations should be taken account. We only considered peer-reviewed published literature, which automatically excluded gray literature that may contain relevant information on management options and ES in the Mediterranean basin, especially in the Maghreb countries. We only included case studies based on in-situ experimental results, which implicates that off-site effects of the farming practices were not taken account for. Off-site effects such as drinking water quality, agricultural pollution, salinization, and eutrophication in soils and water are crucial for surrounding areas (Pascual et al., 2017). It should be addressed in the future research.

There was some bias observed within studied management options. Tillage was the most studied management option, whereas weed management had the least data points. To address more generous and comprehensive recommendations, balanced data support will be beneficial. Also, each case study should provide relevant uncertainty information that can be fed to weight case studies properly.

We selected target indicators in the preliminary analysis. We selected indicators based on their frequency - so comparisons were allowed, and their relevance based on suggestions from previous studies (Table 4.5). Yet, the uncertainties of selecting indicators were not assessed. As developing suitable indicators is ongoing work in the ES community (e.g., Maes et al., 2016, Diaz-Balteiro et al., 2017, Grunewald et al., 2017, Lavorel et al., 2017), we expect a clearer connection between tested indicators and the ES quantification.

4.5 Conclusions

Conservation agricultural management options showed comparative strengths and weaknesses – they often improved soil quality and some options could potentially decrease the yield. Water availability should be importantly considered in agricultural management to enhance both provisioning and regulating services. Overall, the sustainable agricultural management options were beneficial for ES in the region. Especially, the conservation management options tended to alleviate trade-offs and fostered synergies in ES. The incorporation of such mechanism in designing policy could substantially influence policy decisions to secure multiple ES. Also, it should be considered in policy making that farmers may experience a yield reduction from organic fertilizer use or organic weed management, which can be expected to immediately affect their income. Hence, income support for some periods may be beneficial for the long-term application of conservation farming practices. The time lag between an application of conservation practices and the impact on either provisioning services or regulating services can differ; provisioning services such as crop production may have an immediate reduction, whereas regulating services need a longer time to be affected. Therefore, a long-term investigation will be required for future research.

In Mediterranean agriculture, it is non-trivial to prospect long-term impacts of conservation management practices on ES. For achieving long-term policy targets in the region, we recommend decision makers to consider trade-offs and synergies between the services in designing agricultural policies, which could make conservation schemes more attractive. We hope that the presented results help stakeholders to make sound and sustainable agricultural policies in the region within near future.

Supplementary materials

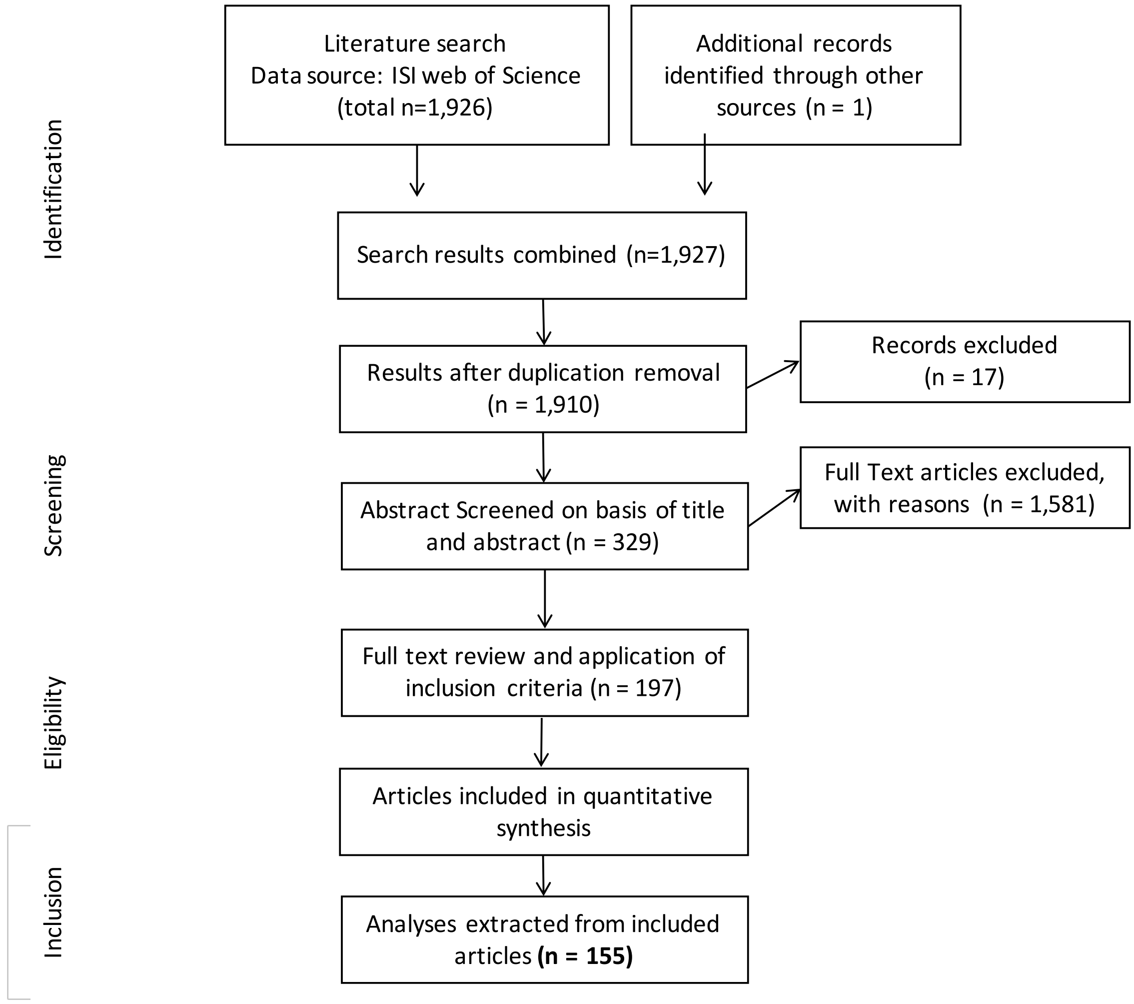

Figure 4.5: Target publication selection using the Preferred Reporting Items for Systematic reviews and Meta-Analyses (PRISMA) framework (Moher et al., 2009). Identification: identifying research questions and keywords to search relevant studies, Screening: title, and abstract screening, Eligibility: after full paper screening, specifying study characteristics, Inclusion: decision making whether to include the studies or not.

Table 4.5: The types of ecosystem services (ES) and closely related indicators. ES were named following the CICES classification at the group level (Haines-Young and Potschin, 2013). Indicators were classified following definitions in previous publications indicated in each category.

Ecosystem Services	**Description**	**Agro-Ecological indicators**	**Reference**
Provisioning Services:			
Nutrition biomass	Cultivated crops, wild plants, plants and algae from in-situ aquaculture	Yield, biomass, quality depending on the crop types (e.g., food, fodder, and energy crops)	Dale and Polasky (2007), de Groot et al. (2010)
Material biomass	Fibers, timber, plant and algae and animal materials for fodder		
Biomass-based energy sources	Plant/animal-based resource		
Material water	Collected water	Water content	de Groot et al. (2010)
Regulating Services:			
Mass flows	Erosion/landslide protection, Buffering and attenuation of mass flows	Runoff, soil sediment	Dale and Polasky (2007), de Groot et al. (2010)
Lifecycle maintenance, habitat and gene pool protection	Pollination, maintaining nursery populations and habitats	Diversity index	Dale and Polasky (2007), de Groot et al. (2010)
Pest and disease control	Pest and disease control	Diversity index	de Groot et al. (2010)
Soil formation and composition	Weathering, Decomposition and fixing processes	**Physical**: Bulk density, Porosity, Aggregate Stability	Verhulst et al. (2010), Palm et al. (2014)
		Chemical: Total Nitrogen, P, pH	Verhulst et al. (2010), Palm et al. (2014)
		Biological: Soil Organic Matter, Soil microbial organism, Dehydrogenase activity, Beta-Glucosidase	Stott et al. (2009), Verhulst et al. (2010), Palm et al. (2014)
Atmospheric composition and climate regulation	Global, micro, regional climate regulation	CO_2 Flux, CH_4 Flux, Soil carbon, N_2O Emission	Dominati et al. (2010)

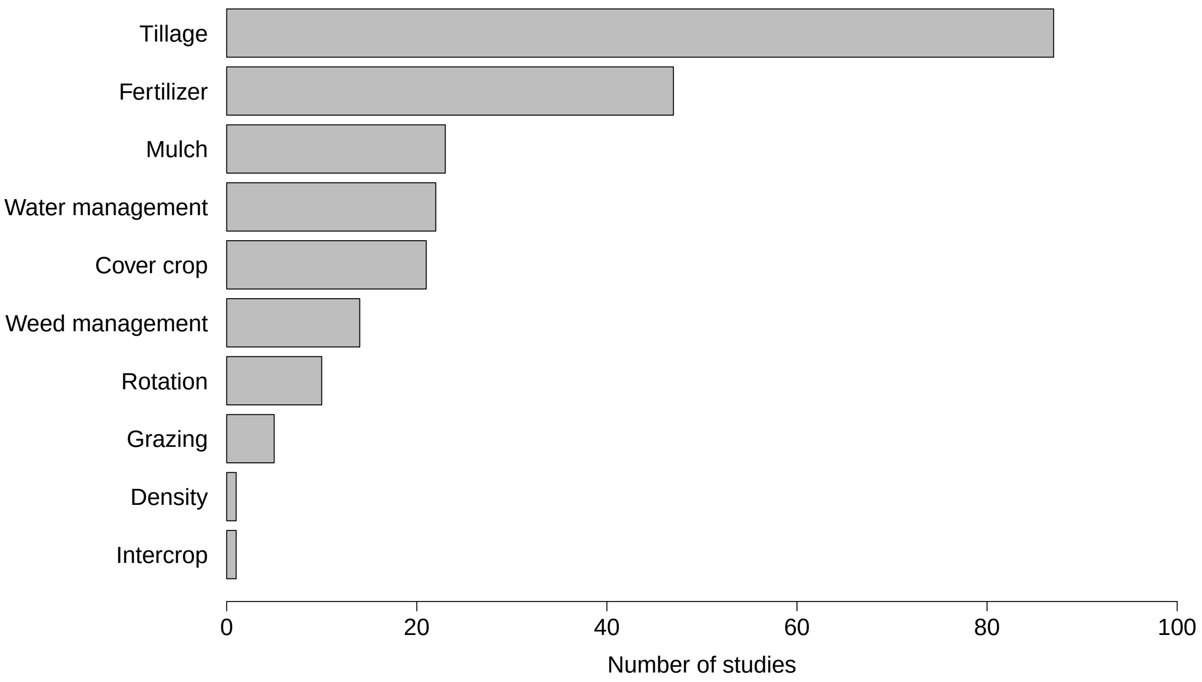

Figure 4.6: Number of case studies categorized by management practice. Multiple farming practices can be chosen in a study.

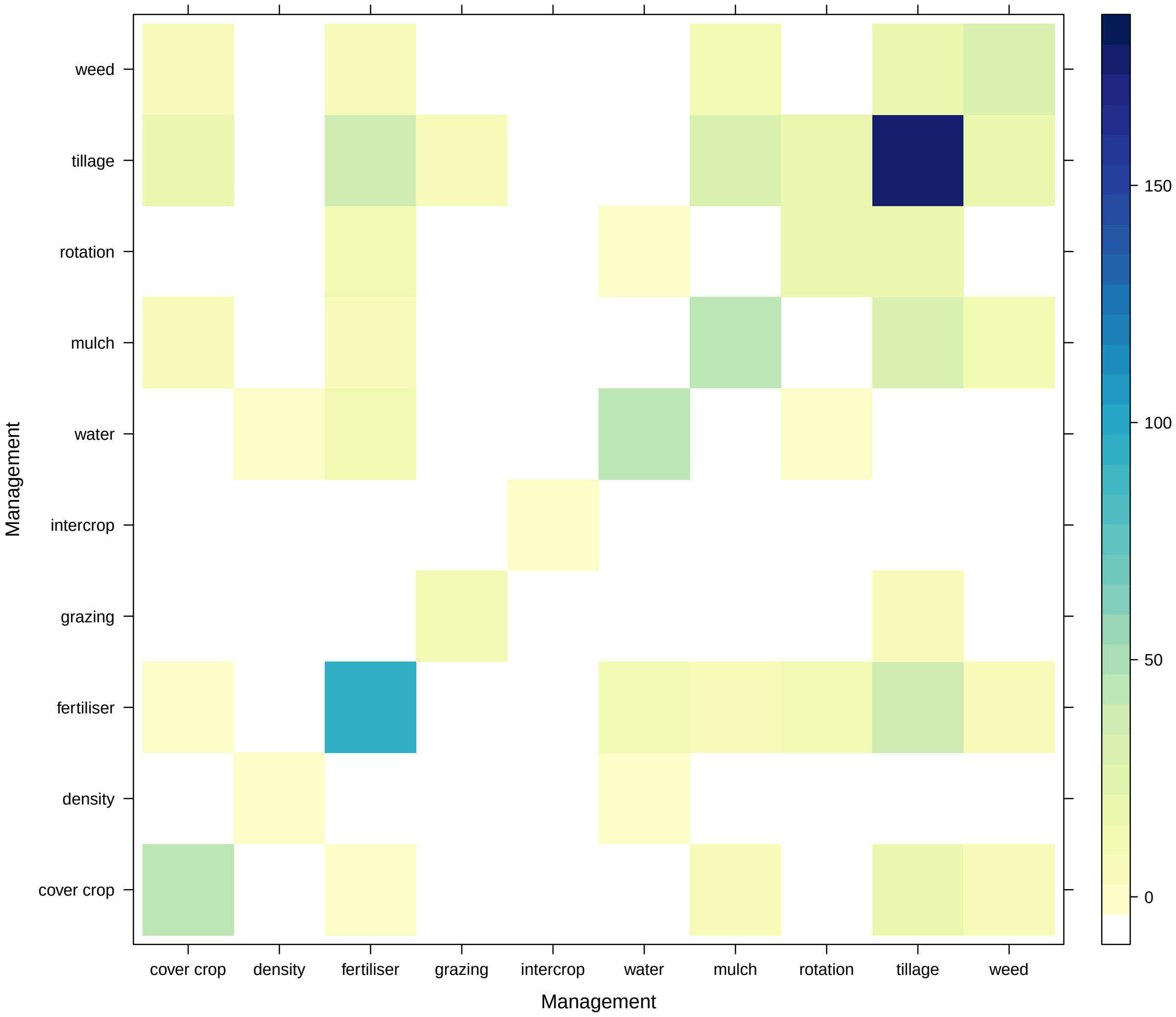

Figure 4.7: Pairwise farming practices investigated in same studies are indicated by the opaqueness of green color, which is proportional to the number of the pairs in the case studies. The names of practice types are abbreviated: weed (weed management), till (tillage), rota (crop rotation), water (water management), intercrop (intercropping), grazing (controlling grazing intensity), ferti (fertilization), density(control crop density), cover (cover cropping)

5. Big data analysis to map cultural ecosystem services from unlabeled crowd sourced images

Abstract

Crowd-sourced geotagged photos in social media offer an alternative indicator for preferences on ecosystem services produced by land systems. However, the potential of the analysis of the content of the images has not yet been fully explored. So far photo content is analyzed based on user-labeled tags or the manual labeling of photos. Both approaches are limited especially for large-scale studies regarding the enormous volume of photos because of its inconsistency and cost-ineffectiveness. Moreover, photo tags alone do not reveal information included in the spatial and thematic relevance of the photos. To address the issue, we developed a new approach to extract detailed thematic information from crowd-sourced photos using machine learning and network analysis. The approach was tested in the Mulde river basin in Saxony, Germany (2005-2016). All public Flickr photos (n = 12,635) belonging to the basin were tagged by deep convolutional neural networks through a cloud computing platform Clarifai ®. The machine-predicted tags were analyzed by a network analysis that leads to nine hierarchical clusters that were used to distinguish between photos that belonged to Cultural Ecosystem Services (CES) (65%) and not (35%). This approach allows a more reliable mapping of the use of CES compared to existing approaches and it can be transferred to different regions at low costs.

* This study is under review in *Ecological Indicators*

5.1 Introduction

Landscapes and ecosystems are modified globally, changing their potential to provide ecosystem goods and services (ES) demanded by society. A quantification of ES is essential for the assessment of trade-offs of land use decisions needed for informed decision making. Cultural ecosystem services (CES) are the most anthropocentric and subjective ES, which makes them particularly difficult to quantify (Daniel et al., 2012, Milcu et al., 2013, Gliozzo et al., 2016). A number of previous CES studies examined stated preferences based on survey data (e.g., Gee and Burkhard, 2010, van Berkel and Verburg, 2014) and interviews (e.g., Plieninger et al., 2013). Individual surveys and interviews are advantageous as they encourage participation of the local stakeholders in a CES valuation (von Heland and Folke, 2014, Delgado-Aguilar et al., 2017). Yet surveys are often expensive to conduct and have a limited scope on time and space (Norton et al., 2012, Wood et al., 2013). Furthermore, they can be easily biased as stated preferences often do not correspond with revealed preferences (Cord et al., 2015).

Recently an alternative indicator for preferences on landscape aesthetics and recreational activities has been introduced to overcome the limitations of the stated preferences measures. Social media databases of geotagged photos that have been uploaded to crowd sourcing photo archives, such as *Flickr*[1] and *Panoramio*[2], have been used to understand cultural usages of landscapes (Keeler et al., 2015, Gliozzo et al., 2016, Sonter et al., 2016, van Zanten et al., 2016). These photos are used as a proxy for the revealed preferences of the general public without the need of individual questionnaires (Wood et al., 2013). Despite the limitations of the approach such as a biased user population and behavior (Ruths and Pfeffer, 2014, Yoshimura and Hiura, 2017), previous studies using geotagged photos from the Flickr archive have shown that the visitation rate extracted from the Flickr photos and user information matched well with the one calculated from the empirical visitor data (Wood et al., 2013, Keeler et al., 2015, Sonter et al., 2016), which highlights the reliability of the indicator to assess the demand for outdoor recreation and landscape aesthetics. While different photo archives attract different user communities, van Zanten et al. (van Zanten et al., 2016) found a high degree of correspondence among three photo archives (i.e., Flickr, Instagram, Panoramio). Given that only 23% of existing CES studies used spatially explicit information (Hernández-Morcilloa et al., 2013), timely collected geotagged photos provide an important opportunity to quantify and map CES (Weyand et al., 2016).

Previous studies using geotagged photos in CES analyses can be grouped into three categories: the first group focuses on the spatial and temporal information of photos (Casalegno et al., 2013, Keeler et al., 2015, Gliozzo et al., 2016, Tieskens et al., 2017). The focus of these studies has been on the location and the users by whom the photos were taken and uploaded. The Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST) recreation model has applied the concept of photo-user-days (Sharp et al., 2016), which represents the total number of days in each mapping unit where at least one photo was taken by a user (Wood et al., 2013, p.6), and it has begun to be applied in various CES analyses (e.g., Keeler et al., 2015, Sonter et al., 2016). A second group of the studies aims

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[1] http://www.flickr.com

[2] http://panoramio.com

at relating landscape context and biophysical settings with the locations of geotagged photos (Pastur et al., 2016, Tenerelli et al., 2016, van Zanten et al., 2016). Pastur et al. (2016), for example, could relate the location of the photos representing the aesthetic value of the landscape of Southern Patagonia to biophysical characteristics such as the presence of water bodies and vegetation types. A third group analyzes the content of the photos. The focus of the analysis has been not only on the spatial and temporal information of the photos, but also on the thematic information such as 'why' and 'what' users have taken and uploaded (Minin et al., 2015). So far, different types of CES were manually classified (Richards and Friess, 2015, Thiagarajah et al., 2015, Pastur et al., 2016). Since the manual labeling of photos is a labor intensive task (Minin et al., 2015), it is only applicable for a relatively small number of photos. Richards and Friess (2015) stated that one person could process approximately 140 photos per hour. Such a manual labeling approach is not applicable for 'big data' such as the immense data available in crowd sourced photo archives.

To interpret a large volume of photos within a feasible time frame, we assigned tags on photos using a machine learning based method and analyzed the tags using a network analysis method. A tag is a label or an annotation that provides simple and direct information of objectives (Schmitz, 2006). Tagging allows users to manage and to share their online resources through keywords (Cattuto et al., 2007, Anderson et al., 2008, Tisselli, 2010). Analyses of user-provided or machine-predicted tags are widely used in image or multimedia annotations such as *Flickr*, *Instagram*, and *Youtube*[3] (Schmitz, 2006, Cattuto et al., 2007, Anderson et al., 2008). While Flickr provides users with tag suggestions, tagging is not mandatory and strictly guided in Flickr, thus often leading to photos with no user-provided tags (Sigurbjörnsson and van Zwol, 2008, Tisselli, 2010). Different languages used in tagging (e.g., English: *mountain*, German: *Berg*) is another source of data inconsistency. To overcome these problems with user-provided tags, we adopted an automatic tagging based on deep convolutional neural networks (DCNNs) provided by the cloud computing platform, *Clarifai*[4] (Goodfellow et al., 2016, Rusk, 2016). Tags co-occurring repeatedly in the database were grouped into clusters by hierarchical clustering. Hierarchical clustering is a widely used data analytic tool for community detection (Newman and Girvan, 2004, Lancichinetti and Fortunato, 2009, Fortunato, 2010) and builds a hierarchical structure (Newman and Girvan, 2004, Fortunato, 2010). We assume that individual tags indicate contents of photos (Boutell et al., 2004) and clusters of tags based on tags co-occurrence reflect themes of the photos (Arase et al., 2010) – e.g., CES and non-CES themes.

We tested the proposed approach in the Mulde basin in Saxony, Germany. The basin is characterized by a mosaic of forests, arable land and urban areas (Fig. 5.1), and recreational areas such as the Ore mountains in the southern part are important for the local economy. In this basin, quantification of cultural usages of the landscape is crucial to investigate trade-offs between CES and other ES such as carbon storage and vegetation diversity for afforestation programs (Lautenbach et al., 2017a). For the quantification, we analyzed all publicly available Flickr photos taken in the last decade using a cutting-edge machine learning algorithm. Specifically, the objectives of this study are i) to identify

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[3] http://www.youtube.com

[4] https://www.clarifai.com

users' activities based on the contents of photos estimated by the machine-learned tags–'what' are in the photos and 'why' they were taken; ii) to quantify 'how many' photos are related to CES themes; and iii) to identify CES hotspots in the study area–'where' users visited particularly for CES related themes.

5.2 Material and methods

5.2.1 Study area

The study was conducted in the Mulde basin in the federal state of Saxony in Germany, which covers an area of 6,256km^2. The Czech territory of the Mulde watershed (approximately 6%) was excluded in the analysis. The basin is a mosaic of agricultural and forest patches. The largest part of the basin in the German territory is used for agricultural purposes: 53% of the area is covered with cropland and 7% of the area is pasture. Forest covers 26% of the watershed. Urban areas (10.2%) were excluded from the analysis since we focused on outdoor recreations outside of urban areas.

The Ore mountains ("Erzgebirge" in German), which are located in the southern Saxony, are for example one of the most important tourist areas in Saxony (Landestourismusverband Sachsen e.V., 2015) where people spend 96.50 Euro per day and person on average (Hodeck and Hovemann, 2016). The number of tourists who stay over night has increased since 2004, and reached more than three million over night stays every year (Landestourismusverband Sachsen e.V., 2015). The main purpose of traveling to the Ore mountains was 'nature' (60%) followed by 'hiking' (58%) as named in a survey by the tourist office of the mountains (TV Erzegebirge, 2014). Sport tourism such as winter sports (42%) and mountain biking (42%) obtained a particular attention in this region as well.

This study is a part of the CONNECT project (`http://www.connect-biodiversa.eu`) that compares different ES in the Mulde basin and conducts a trade-off analysis between them. Trade-offs between carbon-sequestration and plant species richness in the same study area have been quantified (Lautenbach et al., 2017a) in the overarching project.

5.2.2 Cluster detection in tag-network

To identify groups of photos based on the assigned tags, we investigated co-occurrence of the tags. Networks analyses in semantic keywords have been applied in various research fields such as scientific journal article keywords (Yi and Choi, 2012, Isenberg et al., 2017, Santonen and Conn, 2016), or social networks such as Twitter (Lee et al., 2011) to group keywords with similar topics and to classify trending topics of knowledge. We assumed that photos with similar themes share similar semantic tags. Tag co-occurrence is therefore regarded as an indicator to determine the contents of the photos. To analyze this, first we converted a 2-mode matrix (a photo-by-tags matrix) to a 1-mode tag co-occurrence matrix. The 1-mode matrix is a tag-by-tag matrix, the cells in which indicated how many times the two tags occurred together (Schnegg and Bernard, 1996). The co-occurrence

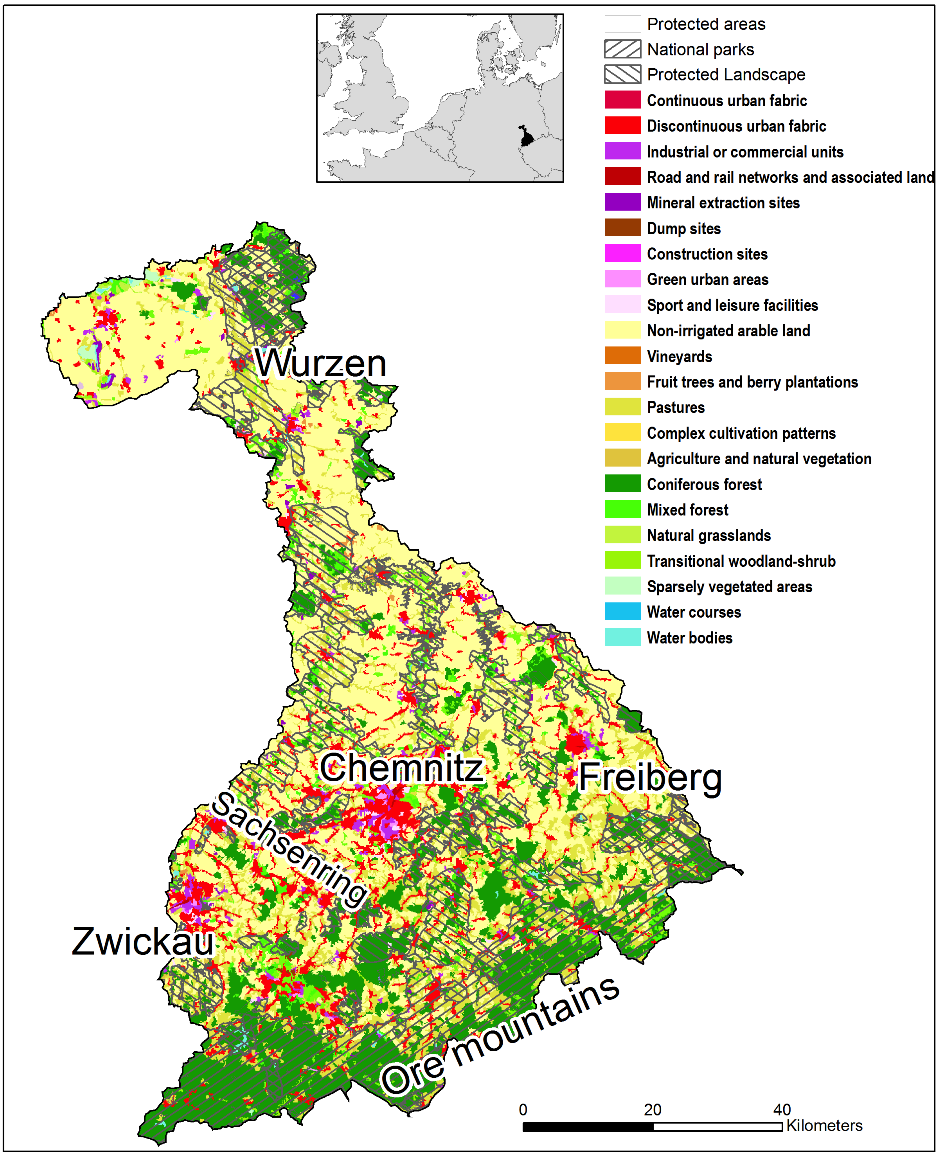

Figure 5.1: The Mulde watershed in Saxony in Germany. Colors indicate different land cover types. In addition, it shows the major urban areas in this region and the Ore mountains ("Erzgebirge" in German). The land cover data was taken from the 2006 CORINE Land Cover data (CLC2006; Umweltbundesamt, DLR-DFD 2009), and the data of special protection areas, special areas of conservation, nature reserves, protected landscapes and nature conservation parks provided by the Saxonian State Agency for Environment, Agriculture and Geology (LfULG) (LfULG, 2017).

between two tags was calculated as the number of photos in which the two tags were used together (Begelman, 2006, Anderson et al., 2008, Sigurbjörnsson and van Zwol, 2008, Hu et al., 2012, Moussely-Sergieh et al., 2013). Tags that appeared five times or more were included in the further analysis (n = 1,316). Therefore, our 1-mode matrix was a 1,316 by 1,316 matrix. Based on the co-occurrence matrix, the tags were transformed into an undirected tag-network. We calculated eigenvector and degree centralities to evaluate the importance of the nodes, i.e., tags (Table 5.2).

Walktrap algorithm Among the various algorithms applied to detect communities (i.e., clusters) within networks (e.g., Fortunato et al., 2004, Luke, 2015, Yang et al., 2016), we used the Walktrap algorithm that runs based on random walks (Pons and Latapy, 2006). The key idea of the algorithm is that short random walks tend to stay in the same community. Then, the distance between nodes and between subgroups is measured for the structural similarity. For supporting the use of the algorithm, we compared the proportion of clusters by the increasing number of clusters found by the Walktrap and by the Fast-greedy algorithm, another popular algorithm to detect communities in networks (Fig. 5.2). The proportion of clusters with the Fast-greedy algorithm did not change with the increasing number of clusters larger than four. A comparative study by Yang et al. (2016) also showed that the Fast-greedy algorithm underestimated the number of subgroups, whereas the Walktrap algorithm was more accurate regardless the network size (even when the number of nodes > 1000).

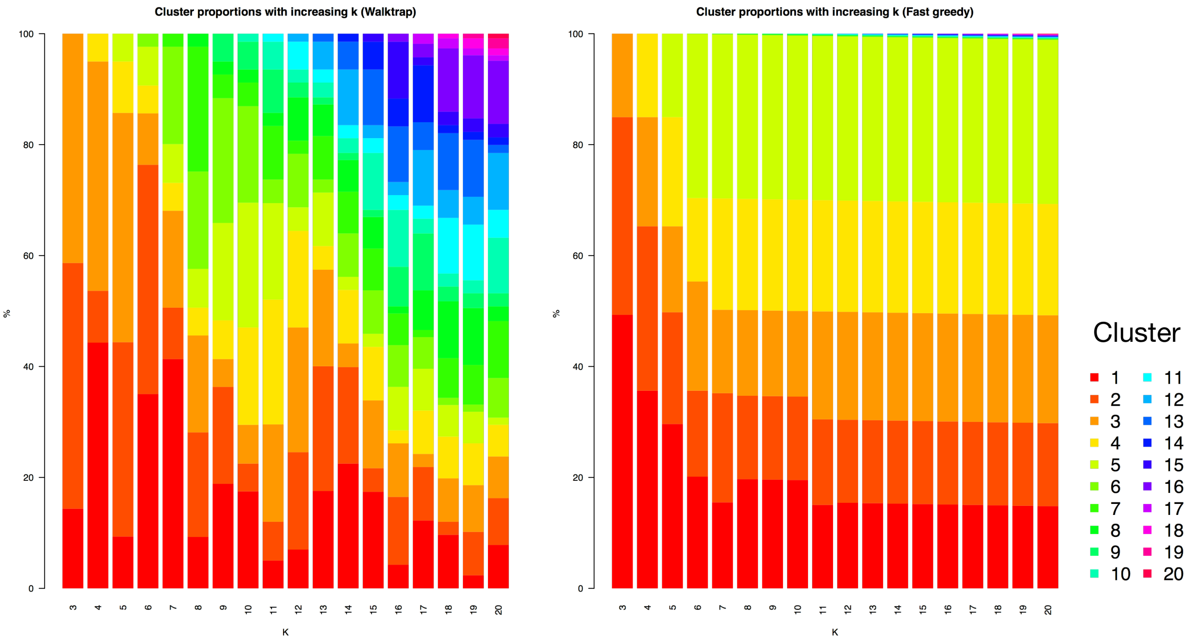

Figure 5.2: The cluster proportion changes with the increasing number of clusters (from 3 to 20) found by the Walktrap (left) and the Fast-greedy (right) algorithms.

5.2.2.1 Uncertainty assessment

We considered two aspects of uncertainties; tagging uncertainty and dominant cluster uncertainty. First, to evaluate performance of automatic tagging, we manually analyzed tags for 100 randomly sampled photos (examples in Fig. 5.8). The automatically assigned tags were grouped into three categories: 'relevant', 'possibly relevant' (i.e., the tag was not directly but indirectly related to the content of the photo), and 'irrelevant'. Assuming that 'relevant' and 'possibly relevant' are 'correct' and 'irrelevant' are 'incorrect', we calculated the Hamming loss (Tsoumakas et al., 2010) of the tagging, which is an accuracy measure for multi-label classification. It is defined as the average number of tags their prediction and observation do not correspond and values range between zero (all tags correct) and

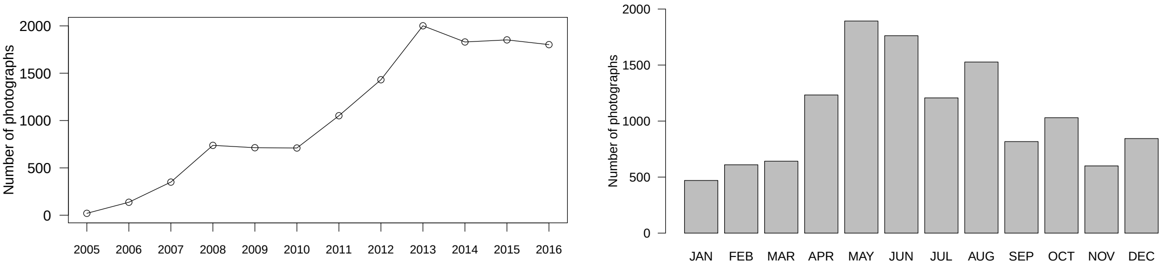

Figure 5.3: The number of photos taken in the Mulde basin and uploaded to the Flickr photo archive from 2005 to 2016 (left). The right side shows the distribution of photos over the months (2005–2016) (right).

one (all tags incorrect). Second, the uncertainty of the dominant cluster assignment was evaluated using the distributions of the supporting ratios of the major clusters (Fig. 5.10).

5.3 Results

During the study period (2005–2016), 12,635 photos were uploaded by 725 users within the study area. The average number of the uploaded photos per user was 17.43. The distribution was right-skewed: the maximum number of photos uploaded by an individual user was 1,620, whereas 259 users uploaded only a single photo during the whole period. During the study period, 27.5% of the users posted photos of the Mulde basin in multiple years, and two users posted photos during 10 years. The number of the uploaded photos increased over the study period with a sharp increase in 2010 (Fig 5.3 (left)). The largest number of photos was taken in May (n = 1,893, 15%) followed by June (n = 1,762, 13.9%) and August (n = 1,527, 12.1%). In contrast, smaller numbers of photos were taken in January and November (Fig 5.3 (right)). The number of user-provided tags was also right skewed: in our database, 2,555 photos (20.2%) had no user-provided tag, and 590 photos had only one user-provided tag. The average number of user-provided tags was 10.03, and the maximum number of user-provided tags assigned in our database was 74 (cf. the maximum number of tags allowed in Flickr is 75).

5.3.1 Photo contents analysis–tagging and tag co-occurrence network analysis

The Clarifai engine assigned 20 tags per photo (examples provided in Fig. 5.8). In total, 2,317 unique tags were assigned to the 12,635 photos. The most frequently assigned tag was ‘no person’ (assigned to 9,445 photos, 74.8%) followed by ‘outdoors’ (assigned to 8,550 photos, 67.7%), ‘nature’ (assigned to 6,362 photos, 50.3%), and ‘landscape’ (assigned to 6,181 photos, 48.9%) (Table 5.2). The 1,316 tags that appeared more than five times were included in the tag-network analysis. For the 100 randomly sampled photos, the Hamming

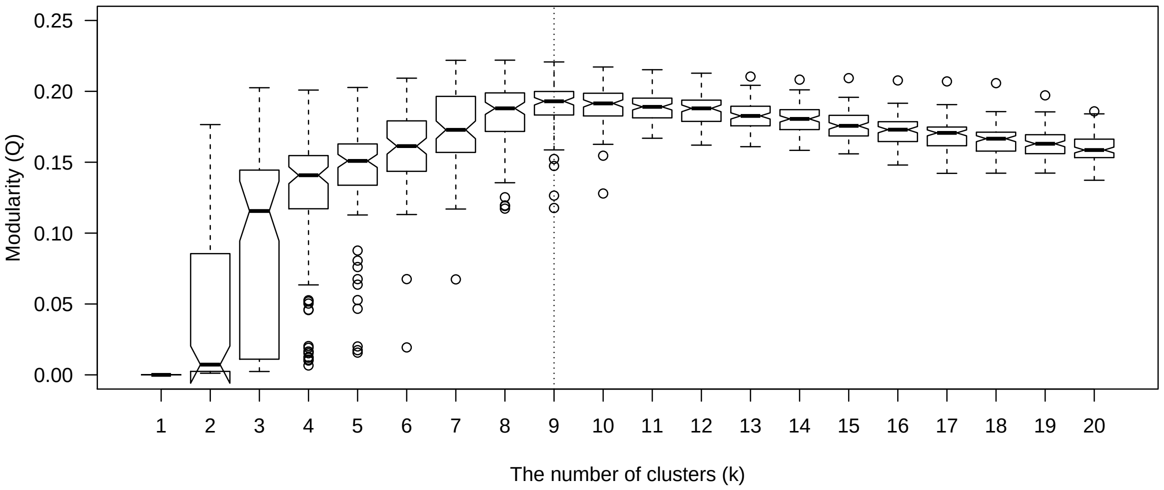

Figure 5.4: Modularity (Q) of the tag clusters is shown with the changing number of clusters (k). The optimal cluster size was based on the median modularity of 100 Monte Carlo simulations. In each simulation the clustering was based on a random sample of 80% of the photos: the number of clusters (k) is fixed as nine in the following analyses.

loss (Tsoumakas et al., 2010) of the assigned tags, i.e., the ratio of the mislabeled tags, was 0.20.

The co-occurrence of tags in photos was represented in a 1-mode co-occurrence matrix. The most frequent pair was ‘no person’ and ‘outdoors’ shown in 58.8% of the photos (n = 7,428), followed by the pairs of ‘nature’ and ‘outdoor’ (45.2%; n = 5,713), ‘nature’ and ‘no person’ (44.7%; n = 5,642), and ‘landscape’ and ‘no person’ (43.5%; n = 5,499) (Table 5.2). The co-occurrence matrix was transformed into a undirected tag-network. The mean and the median degree (i.e., the number of links) of the tag-network were 146.1 and 88. The mean and the median k-coreness (Lin et al., 2014) were 80.2 and 75.0.

In Fig. 5.6, we visualize the tag network wherein tags with higher eigenvector centrality located in the center. In the network, we clustered the tags using the Walktrap algorithm (Pons and Latapy, 2006), which finds densely connected tags by performing random walks. The optimal cluster size was determined by the maximum modularity (Q) rule (Newman, 2004). Modularity increased sharply with increasing number of clusters up to k=9 (Q = 0.193), then gradually decreased (Fig. 5.4): the k was fixed as 9 in the following analyses. The number of tags per cluster was unevenly distributed (Fig. 5.6 and Table 5.1): 296 tags in the largest cluster and 31 in the smallest cluster.

Clusters were denominated based on 10 tags with the highest eigenvector centrality in each cluster (Table 5.1). Among the nine clusters, two clusters were CES-related themes: “landscape aesthetics” and “existence values”. The “landscape aesthetics” cluster included tags representing scenery, whereas the “existence values” cluster included tags for specific species such as ‘butterflies’ or ‘flower’ (Pastur et al., 2016). The other clusters involved site-specific activities, but rather to non-CES activities such as “car racing” or “concerts”.

By increasing the number of clusters, the clusters become more specific as it breaks large clusters into several sub-clusters as illustrated in the dendrogram (Fig. 5.5).

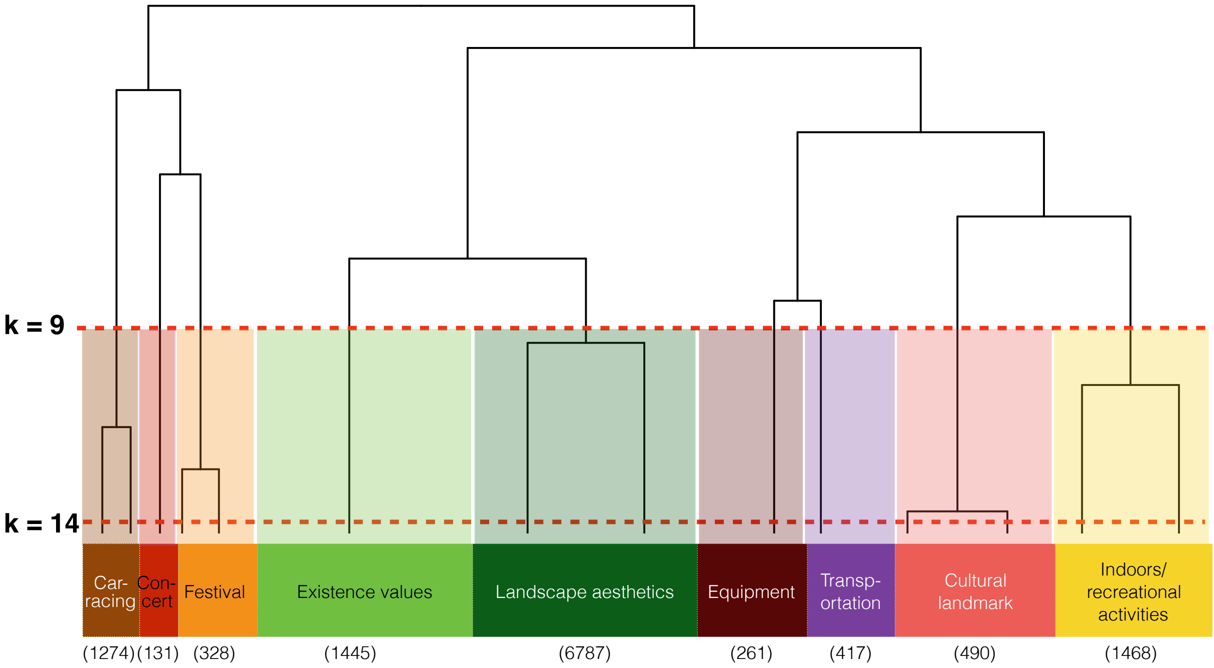

Figure 5.5: The dendrogram of the hierarchically clustered tags cut at the number of clusters (k) is 14. The dashed line in the middle and the colors in the bottom line and the boxes refer to the nine clusters (k=9) as used in this study. Numbers in the parentheses are the total number of the photos of the clusters.

To visually identify CES hotspots, we mapped the spatial distributions of the clusters. In Figure 5.7, the average proportion of each cluster in the photos within each cell of the 2.5 × 2.5 km base grid are presented. Particularly high proportions of the CES clusters "landscape aesthetics" and "existence values" were identified in proximity to the Ore mountains in the southern part of the basin. This area is well known for outdoor activities (Hodeck and Hovemann, 2016). The proportion of the "car racing" cluster was high in the western part of the basin where the popular racing circuit 'Sachsenring' is located between Zwickau and Chemnitz (Fig. 5.1). Proportions of "equipment" and "transportation" clusters were high in the northern part of the basin.

Since photos were frequently assigned tags from multiple clusters, we assigned a dominant cluster to each photo using a weighted majority voting. Regarding the dominant cluster, 65.1% of the photos belong to CES-related clusters: 53.7% of the photos to the cluster "landscape aesthetics" and 11.4% to "existence values" (Fig. 5.5). The dominant clusters of the rest of 34.9% of the photos were non-CES-related. The supporting ratio of the dominant cluster is the largest proportion in each photo (Eq. 2.6). The highest supporting ratio was for the cluster "car racing" (60-80%) (Fig. 5.10). Photos from the CES-related clusters had mostly a supporting ratio in the range of 40-60%; these photos may have been involved in multiple clusters - a photo with a car on the unpaved road might involve trees and therefore get also tags from the "landscape aesthetics" cluster. For the CES clusters that are all taken in natural environments, some overlap between the clusters

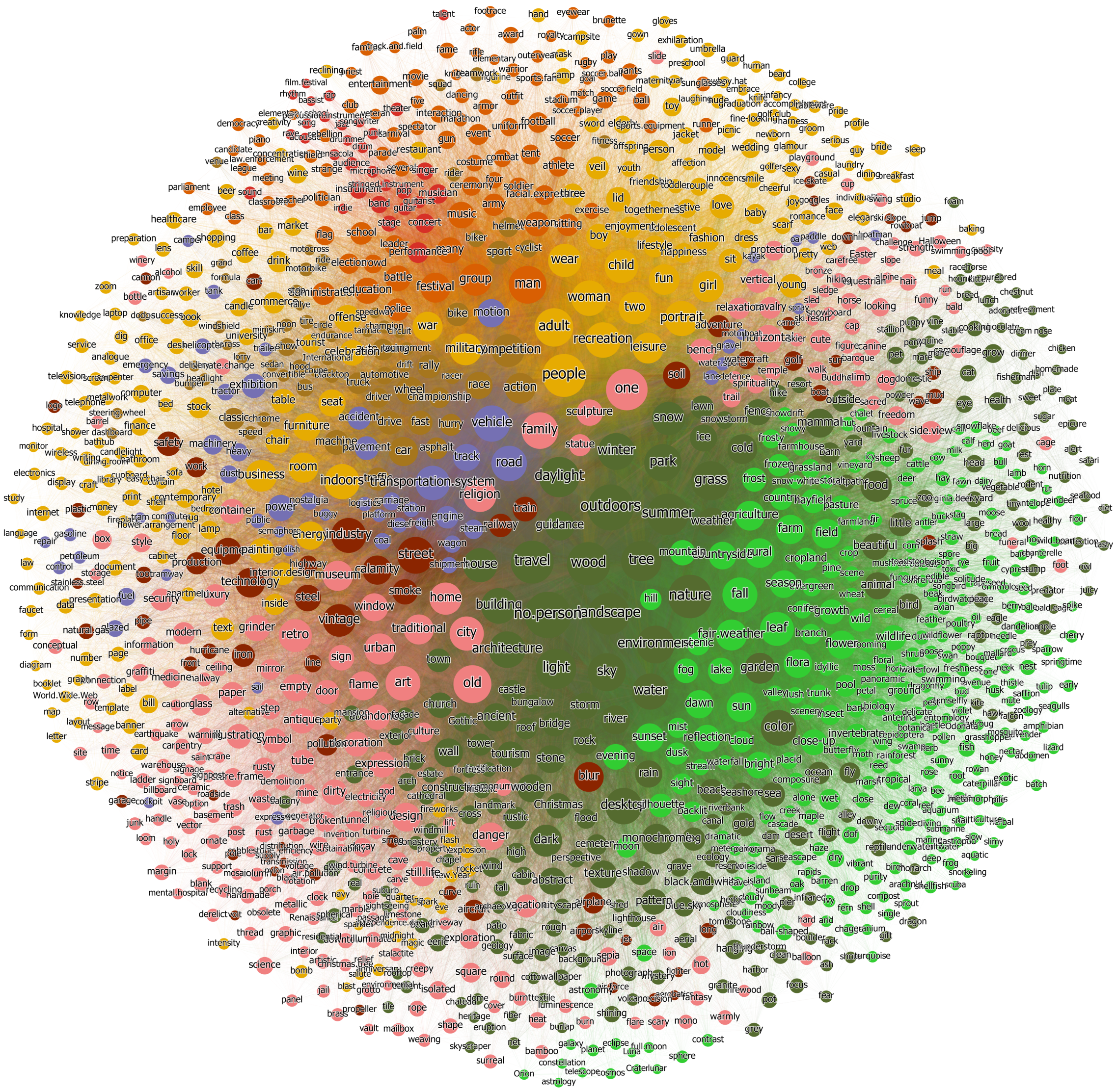

Figure 5.6: The tag-network of the Flickr photos. Nodes represent the machine-learned tags (n = 1,316) and links represent co-occurrence of tags in the photos. The size of a node and a label is scaled by eigenvector centrality, i.e., larger nodes were higher in centrality in the tag-network (Table 5.2). The position of the nodes was determined by *Force Atlas2 multi-gravity algorithm* via the software Gephi (Bastian et al., 2009, Jacomy et al., 2014). The colors indicate the tag clusters determined by Walktrap algorithm ($k = 9$) (Pons and Latapy, 2006): (a) dark green: landscape aesthetic, (b) green: existence values, (c) dark yellow: indoors/recreational activities, (d) brown: car racing, (e) orange: festival, (f) pink: cultural landmark, (g) purple: transportation, (h) red: concerts, (i) dark red: equipment; this color scheme is applied to all following graphics.

Table 5.1: The top 10 tags with high eigenvector centrality in each cluster. The clusters "landscape aesthetics" and "existence values" are considered as CES-related. Numbers in the parentheses are the total number of the tags of the clusters.

landscape aesthetic (248)	**existence value (296)**	**indoors/recreational activities (230)**	**car racing (66)**	**festival (92)**
no person	leaf	people	fast	man
outdoors	flora	adult	drive	group
nature	fall	indoors	wheel	festival
wood	season	woman	race	education
summer	fair weather	portrait	driver	many
tree	bright	wear	car	election
travel	wild	child	hurry	battle
landscape	growth	room	action	music
grass	sun	girl	competition	administration
daylight	rural	furniture	machine	school
cultural landmark (231)	**transportation (56)**	**concert (31)**	**equipment (66)**	
old	transportation system	band	industry	
art	vehicle	performance	technology	
one	engine	musician	equipment	
family	road	pop	steel	
retro	track	concert	street	
religion	steam	singer	pollution	
traditional	power	instrument	vintage	
design	diesel	guitarist	production	
antique	shipment	guitar	train	
museum	carriage	stringed instrument	calamity	

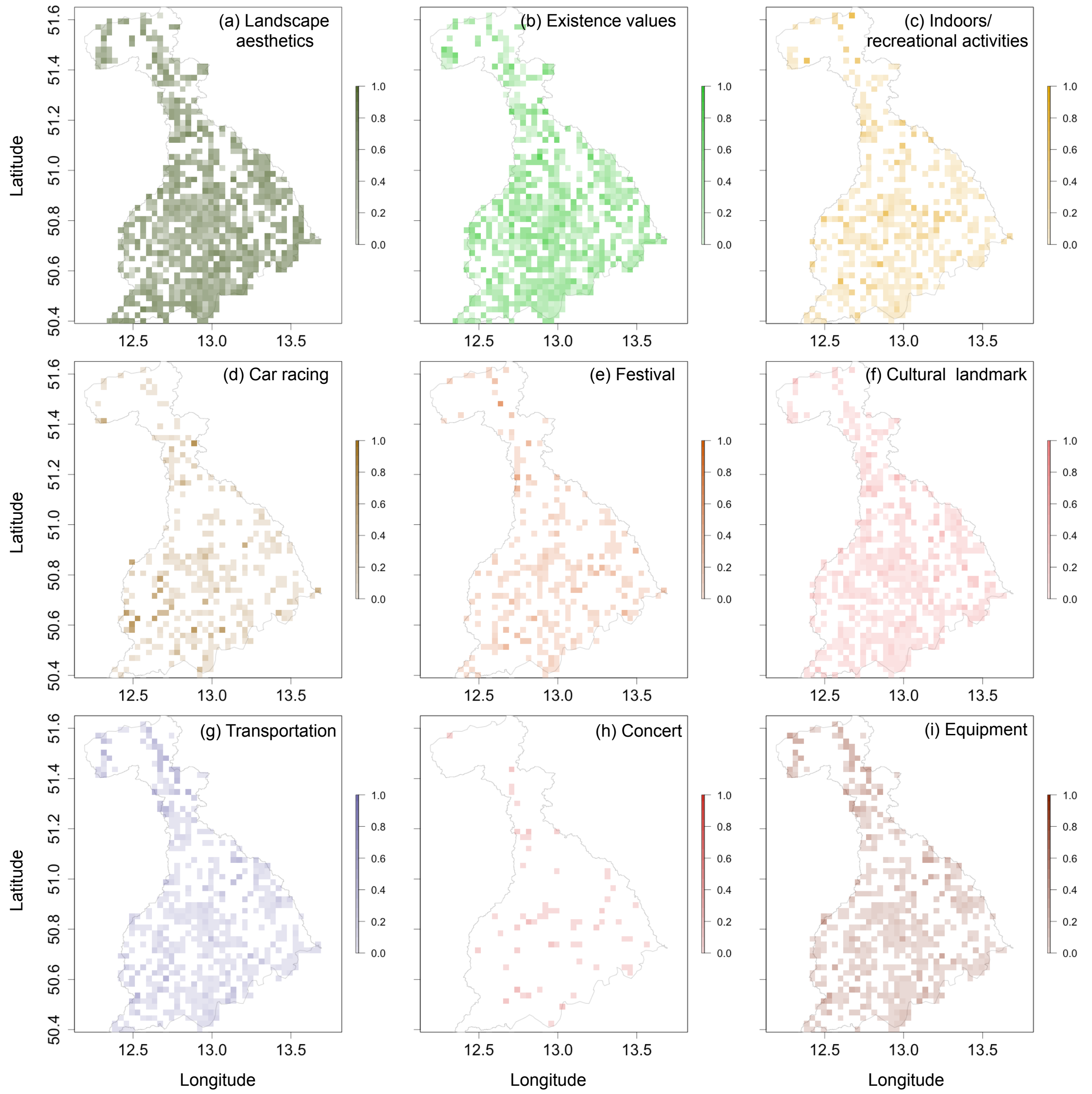

Figure 5.7: The average proportion of each cluster ($k = 9$) in the photos per cell (2.5 km×2.5 km). Vivid colors indicate the higher proportion of a cluster in the photos of the cells.

seems logical. A photo of a butterfly taken outdoor would likely to contain tags from both “landscape aesthetics” (e.g., nature) and “existence values” clusters (e.g., butterfly, insect).

We calculated the photo-user-days to identify CES hotspots given the strongly skewed distribution of the number of photos per user on the $1km$ grid. For each cell, we compared the photo-user-days based on all the photos with the CES-related photo-user-days in clusters “landscape aesthetics” and “existence values” (Fig. 5.9). The correlation between the photo-user-days of the total photos and the CES photos was high ($r = 0.92$). However, the correlation differed strongly by the different CES types: the “landscape aesthetics” cluster was strongly correlated with the number of total photos ($r = 0.91$), while the “existence values” cluster showed a different distribution ($r = 0.51$).

The presence of protected areas had a significant positive effect on the photo-user days for both “existence values” and “landscape aesthetics” (Table 5.3). Interestingly, the presence of protected areas had also a significant positive effect on the photo-user days of the non-CES related photos. The number of photo-user-days increased with the share of protected areas around the location. The explanatory power of protected area for photo-user-days was however low for all clusters: “landscape aesthetics” (5.5%), “existence values” (1.1%), and non-CES related photos (1.7%).

5.4 Discussions

Geotagged photos obtained from social media data have received increasing attentions in ES quantification and identifying CES hotspots (Wood et al., 2013, Pastur et al., 2016, Tenerelli et al., 2016). However, the contents of the photos have often been disregarded due to time and resource limitations (e.g., Richards and Friess, 2015, Thiagarajah et al., 2015, Pastur et al., 2016). The combination of automatic tagging and tag-network analysis proposed in this study opens up a feasible way to analyze contents of a large volume of photos. With the proposed method, we were able to distinguish detailed themes of photos (i.e., CES-related vs. non-CES-related themes (Table.5.1)) and to reproduce patterns in accordance with the ecological and cultural characteristics of the Mulde water basin in short time. This approach can improve the commonly used ES evaluation tool InVEST (Sharp et al., 2016), which calculates the photo-user-days based on the total number of geotagged photos with no consideration of the contents.

The content analysis of the crowd sourced photos has a high potential to improve our understanding of the cultural usage of the landscape. Indeed, concerns remain regarding the representativeness of populations who uploaded photos in social media databases (Ruths and Pfeffer, 2014). However, given the limitations of geotagged real-time data collection within a limited time at a large scale based on other sources (e.g., surveys and interviews) (Ford et al., 2016), the use of photo archives offers an important opportunity to derive the additional information on CES hotspots and detailed motivations of those hotspots. Through the content analysis, land managers can be served not only information on hotspots where more conservation plans are needed, but also information on the activities performed by landscape users. Our approach offers a huge potential for the management of landscapes used for outdoor recreation given a large number of crowd sourced photos available over the globe.

A major benefit of using automatic tagging is time efficiency in characterizing the contents of photos. The tagging of the 12,635 photos took approximately 3 hours, which is several orders of magnitude faster than the manual labeling (e.g., Richards and Friess, 2015). In our study, we used an externally trained classifier by machine-learning algorithms, Clarifai, instead of user-provided tags from Flickr since these were inconsistent and subjective. If we would have used the Flickr tags, 20.2% of the photos would have been ignored. Furthermore, the unrestricted and non-standard characteristics of Flickr tagging (e.g., number of tags per photo and language for tagging) potentially hinders interpretation of tags (Anderson et al., 2008, Tisselli, 2010). We therefore question the use of user-provided tags e.g., for the pre-selection of photos (e.g., van Zanten et al., 2016).

For interpretation of tags, it is important to consider that the content is represented by the combination of tags and not by a single tag. A co-occurrence of the tags “fall” and “winter”, for instance, needs to be interpreted as “cold season of the year”. It should also be kept in mind that photography might have been motivated by a combination of different objectives. This will be reflected by the different semantic tags of the photo (Boutell et al., 2004). When landscape photos contained a house without a person, the automatic tagging often suggested both ‘no person’ and ‘people’. Presumably a house is likely to be associated with ‘people’, therefore, the trained model suggested ‘people’ as well even though there was no person in the photo. Manual validation of tags showed that automatic tagging is reliable - the 20% of tags were incorrect (Hamming loss = 0.20). The Hamming loss differed across the different clusters: The lowest Hamming loss was found for photos associated with the cluster “landscape aesthetics” (0.13), whereas the highest Hamming loss (0.42) was associated with the photos related to the cluster “festival”. Increasing tagging accuracy is expected due to the recent development of the research on artificial intelligence, for example, considering spatial and temporal contexts of photos (Weyand et al., 2016).

The identified importance of landscape aesthetics as the main content of photos taken is in line with the recognition of landscape scenic beauty as the most popular motivation of photography (e.g., Richards and Friess, 2015), and the observation that tourists tend to value especially aesthetic values and recreation opportunities (Zoderer et al., 2016). We have distinguished different CES themes in the basis of unlabeled photos and shown that the spatial pattern of the different CES-related photos differs. However, we should note here that photo taking is limited in some recreation activities such as skiing (Wood et al., 2013, Tenerelli et al., 2016). Therefore, importance of outdoor activities cannot be directly compared on the number of photos taken or the photo-user-days. Our analysis also revealed that non-CES motivations were important for 34.9% of photos taken even we excluded photos taken in the urban area.

Further research will analyze how strongly CES-related activities differ in space in relationship to the landscape and socio-cultural settings. The nine clusters selected in our case may not be directly applicable to other regions where different activities might be dominant. The decision about the number of clusters based on co-occurrence of tags determines the scale of the further analysis. By increasing the number of clusters, one could get a more detailed list of CES as it breaks the large cluster into several sub-groups (Fig. 5.5). If the number of the clusters in our case study was changed to fourteen instead of nine, the cluster “landscape aesthetics” would be further divided into two sub-groups (“agricultural land based scenery” and “non-agricultural land based scenery”), and the cluster “indoors/recreational activities” related with human activities in general was divided into “recreational activities” and “indoors activities” (Fig. 5.5). If the number of cluster was reduced to five, only a single CES would be present. Relying on a technical criterion such as modularity provides some guidance but needs to be thoroughly investigated.

Furthermore, specific CES should be further analyzed with relation to landscape properties - such as terrain, a presence of water bodies, land use configuration but also accessibility and touristic infrastructure - that co-occur with these activities in space. It should also be explored how CES types differ with landscape types and cultural settings as well as with user groups such as tourists, elderly visitors, hiker, biker, skier, and visitors with kids. This information would enable a better representation of CES in landscape planning and spatially explicit trade-off analysis.

Supplementary materials

cluster	Photographs	20 tags assigned by *Clarifai*	*The Hamming loss*
Landscape aesthetic		Fall (o), wood (o), nature (o), no person (o), landscape (o), lake (o), water (o), tree (o), outdoors (o), scenic (o), sky (o), reflection (o), river (o), dawn (x), leaf (o), composure (o), season (o), travel (a), park (a), scenery (o)	0.05
Existence values		Butterfly (o), insect (o), nature (o), wing (o), lepidoptera (o), wildlife (o), summer (o), animal (o), wild (o), monarch (o), entomology (o), outdoors (o), moth (o), delicate (o), antenna (o), fly (a), nectar (a), flower (o), biology (a), invertebrate (o)	0.00
Indoors/ recreational activities	 Flickr © Photostream from the Meanwhile Exhibition.	Indoors (o), people (o), grinder (x), room (o), industry (a), building (o), offense (x), business (a), light (o), production (x), battle (x), tube (x), election (x), architecture (a), festival (x), adult (o), city (x), police (x), urban (x), calamity (x)	0.5
Car racing		Race (o), competition (a), vehicle (o), action (o), hurry (o), fast (o), track (o), championship (a), car (o), rally (o), drive (o), racer (o), driver (o), wheel (o), tournament (a), transportation system (x), road (o), auto racing (o), motion (o), endurance (a)	0.05

Figure 5.8: Example of photos with the Clarifai-assigned tags of the clusters: “landscape aesthetics”, “existence values”, “indoor/ recreational activities” and “car racing”. Image courtesy of Flickr, user names of each photo are presented on the photos. The symbols in the parentheses are the example of manual validation of tags: ‘o’ represents ‘relevant’, ‘a’ represents ‘’possibly relevant’ (i.e., the tag was not directly but indirectly related to the content of the photo), and ‘x’ represents ‘irrelevant’. The Hamming loss equals to the fraction of the irrelevantly assigned tags to the total number of tags.

cluster	Photographs	20 tags assigned by *Clarifai*	*The Hamming loss*
Festival	 Flickr © Freilicht-Theater Waldenburg e.V.	Festival (o), people (o), many (o), group (o), action (o), religion (x), competition (x), strange (x), man (o), military (x), performance (o), crowd (o), adult (o), rally (x), police (x), war (x), music (x), costume (o), motion (o), rally (x)	0.4
Cultural landmark	 Flickr © karlheinzmarschner-kama	Sculpture (o), statue (o), travel (a), no person (o), sky (o), art (o), monument (o), religion (x), architecture (o), ancient (a), cavalry (o), bronze (x), culture (o), outdoors (o), tourism (a), traditional (a), square (a), two (a), dragon (x), man (a)	0.15
Transportation	 Flickr © stefanmueller83	Train (o), railway (o), train (o), transportation system (o), railway (o), track (o), no person (o), engine (a), road (o), travel (x), daylight (o), outdoors (o), vehicle (o), shipment (o), guidance (x), freight (o), carriage (o), line (o), wagon (o), station (x)	0.15
Concert	 Flickr © Adina Scharfenberg	Performance (o), festival (o), music (o), concert (o), energy (a), light (o), musician (o), people (a), stage (o), band (o), singer (o), city (x), modern (o), entertainment (o), business (a), recreation (o), show (o), party (o), motion (o), pop (o)	0.05
Equipment	 Flickr © Neuwieser	Industry (a), transportation system (x), no person (o), machine (o), machinery (o), vehicle (x), heavy (o), train (x), old (o), abandoned, steel (o), vintage (o), wheel (o), truck (x), rusty (o), equipment (o), grinder (a), retro (x), dirty (o), work (a)	0.25

Figure 5.8: Example of photos and the 20 assigned tags for each photo in the clusters: "festival", "cultural landmarks", "transportation", "concert and equipment". Image courtesy of Flickr, user names of each photo are presented on the photos. Note that we made a blur effect on the faces in the photo of the "festival" cluster to make them unrecognizable due to the privacy reason. The symbols in the parentheses are the example of manual validation of tags: 'o' represents 'relevant', 'a' represents 'possibly relevant' (i.e., the tag was not directly but indirectly related to the content of the photo), and 'x' represents 'irrelevant'. The Hamming loss equals to the fraction of the irrelevantly assigned tags to the total number of tags.

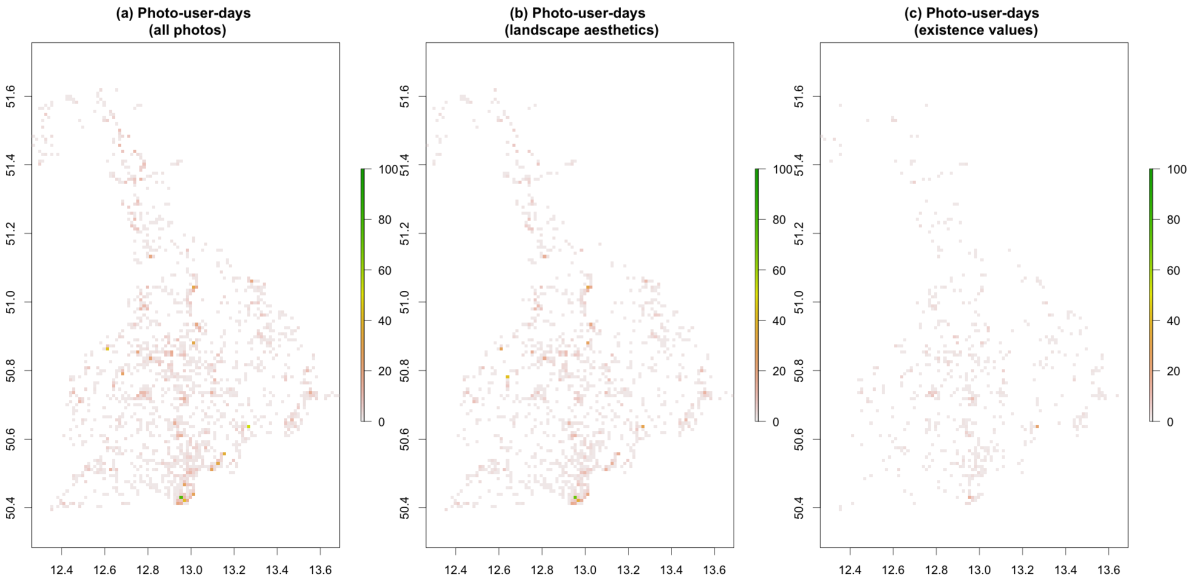

Figure 5.9: The photo user days for 2005-2016 (1 km by 1 km). (a) Photo-user-days based on all the photos, (b) Photo-user-days based on the photos from the 'landscape aesthetics' cluster, (c) Photo-user-days based on the photos from the 'existence values' cluster.

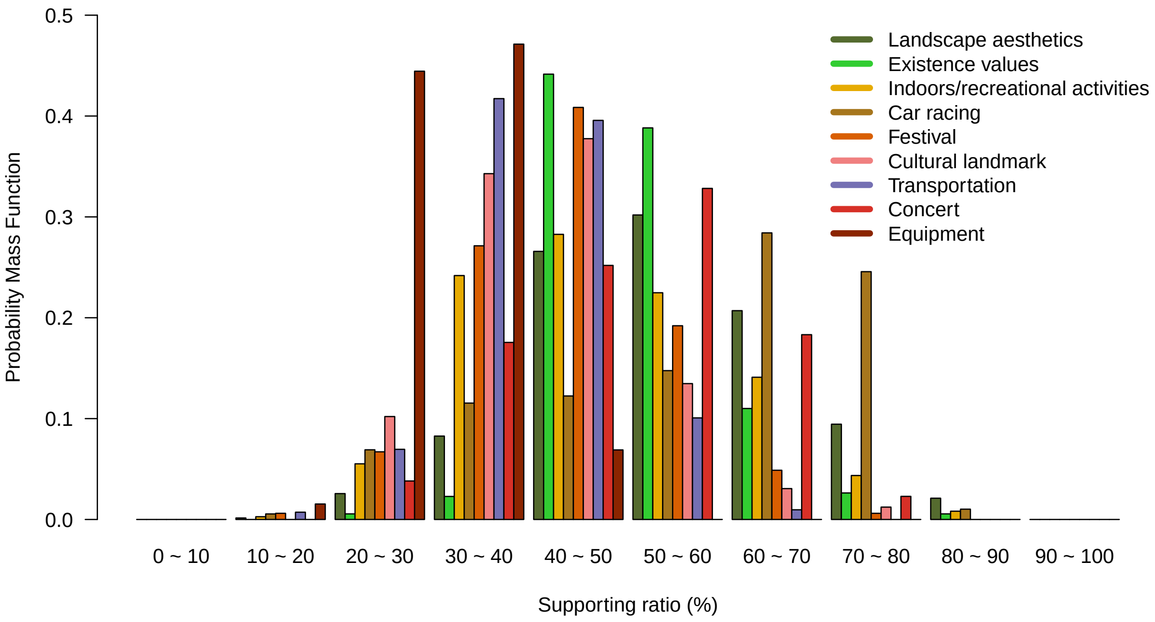

Figure 5.10: The distributions of the supporting ratios by cluster; the nine color represents the different clusters.

Table 5.2: The 20 most frequently assigned tags to the Flickr photos with the centrality measures

Rank	Tag	Frequency	Eigenvector centrality	Degree
1	no.person	9445	1.00	1215
2	outdoors	8550	0.97	1140
3	nature	6362	0.80	1026
4	landscape	6181	0.81	877
5	travel	5861	0.72	929
6	tree	5608	0.77	824
7	wood	5142	0.67	966
8	sky	3948	0.54	738
9	summer	3849	0.52	891
10	grass	3162	0.43	808
11	road	3078	0.31	607
12	people	2965	0.18	952
13	daylight	2911	0.39	809
14	vehicle	2771	0.22	653
15	park	2630	0.37	695
16	transportation.system	2569	0.21	588
17	architecture	2414	0.28	652
18	environment	2405	0.34	738
19	water	2228	0.31	659
20	leaf	2182	0.31	609

Table 5.3: Results of the quasi-poisson regression models with a log-link testing the effect of area covered by protected areas on the photo-user days (PUD) for three cluster types.

Model	Predictor	Coefficient	Standard error	p-value
PUD (existence values cluster)	intercept	-2.397	0.08899	$< 2e\text{-}16$
	protected area (km^2)	0.6465	0.1246	$< 2e\text{-}06$
PUD (landscape aesthetics cluster)	intercept	-1.586	0.0941	$< 2e\text{-}16$
	protected area (km^2)	1.13	0.1205	$< 2e\text{-}16$
PUD (non-CES clusters)	intercept	2.212	0.0941	$< 2e\text{-}16$
	protected area (km^2)	0.7494	0.2341	0.00138

Table 5.4: The full list of tags in each cluster

	landscape aesthetics	indoors/recreational activities	car racing	festival	cultural landmark	existence values	transportation	concert	equipment
1	abstract	accomplishment	action	actor	abandoned	abdomen	accident	acoustic	adventure
2	adorable	active	asphalt	administration	air	agriculture	boatman	audience	aerobatics
3	aerial	adolescent	auto.racing	armor	alcohol	alone	buggy	band	air.force
4	alert	adult	automotive	army	alpine	amphibian	camper	bassist	air.pollution
5	alley	affection	bike	athlete	antique	antelope	carriage	concert	aircraft
6	ancient	alternative	biker	award	arrow	antenna	coal	drum	airplane
7	animal	analogue	blacktop	ball	art	antler	cockpit	drummer	airport
8	apple	anniversary	bumper	battle	artistic	aquarium	commuter	film.festival	blur
9	arch	apartment	bus	brunette	bald	aquatic	control	guitar	boat
10	archaeology	artisan	car	candidate	balloon	arachnid	diesel	guitarist	calamity
11	architecture	baby	champion	carnival	bamboo	arid	dust	indie	cannon
12	ash	baking	championship	ceremony	baroque	astrology	emergency	instrument	canoe
13	background	bang	chrome	class	barrel	astronomy	engine	jazz	cart
14	backyard	banner	circle	classroom	basement	atmosphere	exhibition	microphone	curve
15	balcony	bar	circuit	club	bench	avenue	expressway	musician	distribution
16	bald.eagle	bathroom	classic	combat	billboard	avian	freight	Pensacola	downhill
17	barn	bathtub	competition	costume	blade	backlit	fuel	percussion.instrument	equipment
18	beach	beard	convertible	crowd	blank	bale	gasoline	performance	fighter
19	beautiful	bed	coupe	dancing	bottle	ball-shaped	glazed	pop	front
20	big	bedroom	cyclist	democracy	box	bark	gravel	punk	garage
21	bird	beer	dashboard	education	brass	barley	heavy	rap	goggles
22	black.and.white	bill	delivery	election	broken	barren	helicopter	rave	golf
23	blue.sky	blast	dodge	elementary	bronze	batch	kayak	rhythm	highway
24	board	bomb	drift	elementary.school	Buddha	beak	lane	singer	hurricane
25	boulder	book	drive	employee	burn	bee	logistics	song	ice.skate
26	breed	booklet	driver	entertainment	burnt	beef	machinery	songwriter	industry
27	brick	boy	endurance	event	cage	beetle	motion	sound	iron
28	bridge	breakfast	fast	exercise	camouflage	berry	motorboat	stage	jet
29	building	bride	fitness	eyewear	canine	biology	nostalgia	stringed.instrument	jump
30	bungalow	business	formula	facial.expression	cap	birch	oar	talent	line
31	burlap	cabinet	grand	fame	carefree	birdwatching	paddle	theater	logo
32	cabin	camp	harass	famous	carpentry	blooming	pavement		long
33	canal	campsite	headlight	festival	carve	Boletus	petroleum		mud
34	canvas	candle	helmet	five	caution	botanical	platform		natural.gas
35	castle	candlelight	hood	flag	cavalry	bouquet	polish		pipe
36	cat	card	hurry	football	cave	branch	power		plastic
37	cathedral	carpenter	International	footrace	ceiling	bread	public		pole
38	cement	casual	lorry	four	ceramic	bright	repair		pollution
39	cemetery	celebration	machine	game	challenge	buck	road		precision
40	chapel	chair	miniskirt	goal	christmas.tree	bud	sail		production
41	chateau	cheerful	motocross	group	city	bull	savings		propeller
42	chestnut	child	motorbike	gun	climate.change	butterfly	semaphore		pylon
43	chicken	coat	noon	interaction	climb	calf	shipment		railway
44	chocolate	coffee	race	knight	clock	cascade	spray		roadside
45	Christmas	college	racer	law.enforcement	cobblestone	caterpillar	station		rowboat
46	church	commerce	rally	leader	column	cattle	steam		safety
47	cityscape	communication	rallye	league	conceptual	cereal	tank		ship
48	clean	computer	ride	man	concrete	chalet	track		ski.slope
49	cold	concentration	rider	many	connection	change	tractor		smog
50	color	contemporary	sedan	marathon	container	chanterelle	trailer		smoke

Table 5.4: The full list of tags in each cluster (cont.)

	landscape aesthetics	indoors/recreational activities	car racing	festival	cultural landmark	existence values	transportation	concert	equipment
51	confection	couple	show	match	cover	cherry	tram		soil
52	construction	cowboy.hat	speed	meeting	crane	chill	tramway		splash
53	cooking	craft	speedway	movie	creepy	close	transportation.system		stainless.steel
54	cotton	creativity	sport	music	culture	close-up	vehicle		steel
55	cream	cupboard	squad	outerwear	cup	cloud	wagon		street
56	cross	curtain	steering.wheel	outfit	curiosity	cloudiness	water.sports		supply
57	dam	data	stop	palm	cute	cloudy			surf
58	dark	desk	tarmac	pants	danger	compost			technology
59	daylight	diagram	teamwork	parade	decay	composure			tool
60	delicious	dig	tire	parliament	decoration	cone			train
61	desert	dining	tournament	piano	defence	conifer			transmission
62	desktop	dining.room	traffic	play	demolition	coniferous			vintage
63	diet	display	truck	police	derelict	constellation			volt
64	dinner	document	venue	politician	design	contrast			watercraft
65	dish	dress	wheel	priest	dirty	coral			wave
66	dome	drink	windshield	rebellion	dog	corn			work
67	domestic	easy.chair		rifle	door	cosmos			
68	downy	elderly		royalty	downtown	country			
69	dragon	electronics		rugby	driveway	countryside			
70	eagle	elegant		runner	earthquake	cow			
71	ecology	embrace		school	Easter	Crater			
72	eerie	energy		several	efficiency	creek			
73	entrance	enjoyment		shield	electricity	crocus			
74	environment	eve		sitting	empty	crop			
75	epicure	exhilaration		soccer	environmental	cropland			
76	equine	explosion		soccer.ball	equestrian	cypress			
77	eruption	face		soccer.field	exploration	dairy			
78	estate	fashion		soccer.player	expression	damselfly			
79	exterior	faucet		soldier	family	dandelion			
80	eye	figurine		spectator	fantasy	dawn			
81	fabric	finance		sports.equipment	figure	deep			
82	facade	fine-looking		sports.fan	firewood	deer			
83	falcon	fireplace		stadium	flame	delicate			
84	fear	fireworks		strange	flare	dew			
85	fence	flash		sunglasses	foot	diving			
86	fiber	floor		teacher	freedom	dof			
87	fisherman	flower.arrangement		tent	funeral	dragonfly			
88	flight	form		track.and.field	funny	dramatic			
89	flood	friendship		uniform	garbage	drop			
90	fly	fun		veteran	generator	dry			
91	foam	furniture		warrior	glass	duck			
92	focus	girl		weapon	god	dusk			
93	food	glamour			graffiti	early			
94	footpath	gloves			graphic	eclipse			
95	fortification	golf.club			grinder	edible			
96	fortress	golfer			grotto	entomology			
97	fountain	gown			hair	evening			
98	fur	graduation			Halloween	evergreen			
99	garden	graph			hallway	exotic			
100	gate	groom			handle	fair.weather			

Table 5.4: The full list of tags in each cluster (cont.)

	landscape aesthetics	indoors/recreational activities	car racing	festival	cultural landmark	existence values	transportation	concert	equipment
101	geology	guard			handmade	fall			
102	gift	guy			hard	farm			
103	gold	hand			heat	farmhouse			
104	Gothic	happiness			hiking	farmland			
105	granite	harness			hole	fawn			
106	grass	healthcare			holy	feather			
107	grave	hospital			home	fern			
108	grey	hotel			horizontal	field			
109	grow	human			horse	fir			
110	guidance	independence.day			hot	fish			
111	hanging	individuality			illuminated	flora			
112	harbor	indoors			illustration	floral			
113	hawk	infancy			information	flour			
114	head	innocence			interior	flow			
115	health	inside			invention	flower			
116	healthy	intensity			isolated	fog			
117	hedge	interior.design			jail	freshness			
118	heritage	internet			junk	frog			
119	high	jacket			ladder	frost			
120	hike	joy			lift	frosty			
121	historic	knife			limestone	frozen			
122	homemade	knowledge			lion	fruit			
123	hound	label			lock	full.moon			
124	house	lamp			looking	fungus			
125	ice	language			loom	galaxy			
126	image	laptop			luminescence	gastropod			
127	infrared	laughing			luxury	geranium			
128	juicy	laundry			mailbox	goat			
129	kite	law			marble	goose			
130	kitten	layout			margin	grasshopper			
131	landmark	leisure			medicine	grassland			
132	landscape	lens			mental.hospital	ground			
133	large	letter			message	growth			
134	lawn	library			metallic	hay			
135	light	lid			mine	hayfield			
136	lighthouse	lifestyle			mirror	haze			
137	little	love			modern	Heaven			
138	log	magic			mono	herb			
139	lunch	map			monument	herbal			
140	mammal	market			mosaic	herd			
141	mane	mask			museum	hill			
142	mansion	maternity			notice	hog			
143	mare	meal			obsolete	honey			
144	meat	metalwork			old	horizon			
145	monarch	midnight			one	horn			
146	monastery	military			option	horticulture			
147	monochrome	model			ornate	husk			
148	mystery	money			panel	hut			
149	nature	monitor			paper	icy			
150	net	navy			passage	idyllic			

Table 5.4: The full list of tags in each cluster (cont.)

	landscape aesthetics	indoors/recreational activities	car racing	festival	cultural landmark	existence values	transportation	concert	equipment
151	no.person	New.Year			picture.frame	insect			
152	nose	newborn			playground	invertebrate			
153	nutrition	nude			porch	island			
154	ocean	number			post	ivy			
155	outdoors	offense			protection	jungle			
156	outside	office			recycling	ladybug			
157	owl	offspring			relaxation	lake			
158	park	page			relief	lakeside			
159	patio	painting			religion	lamb			
160	pattern	party			religious	larva			
161	peace	people			Renaissance	lavender			
162	perspective	person			retro	leaf			
163	pet	picnic			rope	Lepidoptera			
164	photograph	portrait			rotation	livestock			
165	pier	preparation			round	lizard			
166	plate	preschool			row	Luna			
167	pony	presentation			run	lunar			
168	pot	pretty			rust	lush			
169	powder	pride			rusty	mallard			
170	predator	print			sacred	maple			
171	prey	profile			saint	marine			
172	property	quarter			scary	marsh			
173	puppy	reclining			science	metamorphosis			
174	purebred	recreation			sculpture	meteorology			
175	racehorse	restaurant			security	milk			
176	rack	rocket			sepia	mist			
177	rain	romance			shape	moody			
178	raptor	room			side.view	moon			
179	real	rug			sign	moose			
180	refreshment	salute			signage	mosquito			
181	reptile	scarf			signboard	moss			
182	reservoir	screen			signpost	moth			
183	residential	seat			site	mountain			
184	resort	serious			ski.resort	mushroom			
185	rest	service			skier	mute			
186	river	sexy			sled	neck			
187	riverbank	shelf			sledge	nectar			
188	rock	shopping			slide	needle			
189	rodent	shower			slope	nest			
190	roof	sit			snowboard	oak			
191	rooftop	skill			spirituality	Odonata			
192	rough	sleep			square	oil			
193	ruin	smile			stalactite	Orion			
194	rustic	sofa			statue	ornithology			
195	safari	spark			step	panorama			
196	sand	sparkler			still.life	panoramic			
197	sea	stock			storage	pastoral			
198	seafood	stripe			strength	pasture			
199	seashore	studio			style	pest			
200	shadow	study			support	petal			

Table 5.4: The full list of tags in each cluster (cont.)

	landscape aesthetics	indoors/recreational activities	car racing	festival	cultural landmark	existence values	transportation	concert	equipment
201	shed	success			surreal	pile			
202	shining	sword			sustainability	pine			
203	shore	table			swimming.pool	placid			
204	sightseeing	tableware			swing	planet			
205	sky	telephone			symbol	poison			
206	skyline	television			temple	pollen			
207	skyscraper	template			thread	pool			
208	snow	text			time	poppy			
209	snowstorm	three			traditional	poultry			
210	spherical	toddler			trail	purity			
211	stable	togetherness			trash	rainbow			
212	stallion	tourist			tube	rainforest			
213	stone	toy			tunnel	rapeseed			
214	storm	two			turbine	rapids			
215	stump	umbrella			urban	reed			
216	suburb	university			vacation	reef			
217	sugar	veil			vase	reflection			
218	summer	war			vault	reindeer			
219	surface	wear			vector	root			
220	sweet	web			vertical	rose			
221	tall	wedding			voltage	rowan			
222	tasty	wine			walk	rural			
223	textile	wireless			warehouse	rut			
224	texture	woman			warmly	rye			
225	thunderstorm	worker			warning	saffron			
226	tile	World.Wide.Web			waste	saltwater			
227	tiny	writing			weaving	scene			
228	tombstone	young			wind.turbine	scenery			
229	tourism	youth			window	scenic			
230	tower	zoom			winery	scuba			
231	town				wire	seagulls			
232	travel					seascape			
233	tree					season			
234	vegetable					seed			
235	vine					sequoia			
236	volcano					sheep			
237	wall					shell			
238	wallpaper					shellfish			
239	water					shrub			
240	weather					sight			
241	wind					silhouette			
242	windmill					single			
243	winter					slimy			
244	wood					slow			
245	wooden					snail			
246	wool					snorkeling			
247	yard					snow-white			
248	zoo					snowdrift			
249						snowflake			
250						snowy			

Table 5.4: The full list of tags in each cluster (cont.)

	landscape aesthetics	indoors/recreational activities	car racing	festival	cultural landmark	existence values	transportation	concert	equipment
251						solitude			
252						songbird			
253						space			
254						sparrow			
255						sphere			
256						spider			
257						spike			
258						spore			
259						springtime			
260						sprout			
261						spruce			
262						stag			
263						straw			
264						stream			
265						submarine			
266						sun			
267						sunbeam			
268						sunny			
269						sunset			
270						swamp			
271						swan			
272						swimming			
273						telescope			
274						thistle			
275						toadstool			
276						toxic			
277						tropical			
278						trunk			
279						tulip			
280						turquoise			
281						underwater			
282						valley			
283						vibrant			
284						vineyard			
285						violet			
286						Virginia.deer			
287						waterfall			
288						waterfowl			
289						wet			
290						wheat			
291						wild			
292						wild.boar			
293						wildflower			
294						wildlife			
295						wing			
296						zoology			

6. Trade-off between cultural services and carbon storage, and cultural services and species richness (following chapter 5)

6.1 Introduction

The Free State of Saxony aims at expanding the forest cover by afforestation programs (Lautenbach et al., 2017a). The effect of such afforestation programs on multiple ecosystem services (ES) generated in this region is unavoidable. Also, the effect can differ across different types of ES. The effects on the relationship between carbon storage and biodiversity in the Mulde river basin in Saxony was investigated in Lautenbach et al. (2017a). In their study, they revealed that the afforestation programs affect both carbon storage and plant species richness positively on average. Also, the relationship between carbon storage and plant species richness was overall positive, but it varies across the region. Based on their results, it is recommended that the afforestation programs in Saxony should consider a spatial specific recommendation to avoid unexpected trade-offs between carbon storage and plant species richness.

In this chapter, the relationship investigated in Lautenbach et al. (2017a) is extended to cultural ecosystem services (CES). As outdoor recreation activities and landscape aesthetics are important for the local economy in this region, the quantification of relationships between CES and other ES is crucial to provide a comprehensive understanding of the effects of the afforestation programs. Furthermore, as CES were spatially various across the region (chapter 5), the spatial context needs to be further investigated to avoid spatial trade-offs. CES were generally independent, or at least not obviously synergistic to the other services (chapter 3); however, the relationship between CES and carbon storage or life cycle maintenance was not decided as the case studies showed contradictory results, which requires further investigation (chapter 3). The results of chapter 3 suggested that the method used to determine the relationship between ES affects the results (i.e., directions of relationships). Specifically, Pearson's correlation coefficient identified more 'no-effect' relationships than descriptive methods. In contrast, descriptive methods identified more trade-off relationships. To quantify relationships robustly, it is necessary to use a multitude of methods and its ensembles. In this chapter, the relationships between CES and carbon storage, and between CES and biodiversity in the Mulde river basin are extensively examined using a number of methods.

6.2 Material and methods

6.2.1 Data

In addition to the Flickr photos and machine-learned tags used in chapter 5, biodiversity indicators, and carbon stock data were used for the comparative analysis in the Mulde river basin, Saxony, Germany. The data sets and their characteristics are summarized in the following. For spatial analysis, all the data were reprojected into a 2.8 km base grid in DHDN/Gauss-Kruger zone 4 (EPSG:31468) using a bilinear filter.

6.2.1.1 Cultural ecosystem services (CES) indicators

As a spatially explicit proxy of CES, we used numbers and contents of crowd-sourced images. We used Flickr photos available in the Flickr archive for 2005-2016 in the study site ($n = 12,635$). The photos were processed and tagged using a machine learning algorithm (See details in chapter 5). The contents of the photos were identified by an unsupervised hierarchical clustering using the machine-learned tags. The tags were clustered by a hierarchical clustering algorithm which led to nine clusters. Then we identified the dominant cluster of each photo based on the proportions of the clusters of the assigned tags. In this chapter, we re-categorized the nine clusters into three groups: ‘Landscape aesthetics cluster (53.7%)’, ‘Existence values cluster (11.4%)’, and ‘Other clusters (35%)’; the first two groups were considered as CES related (65%) and the last non CES-related photos (35%) (from chapter 5).

We calculated photo-user-days per cell in the 2.8 km base grid. The metric was calculated for 1) all photos (100%), 2) photos related to aesthetic values (i.e., ‘Aesthetic’ cluster (53.7%)), and 3) photos related to existence values (i.e., ‘Existence’ cluster (11.4%) (chapter 5). The photo-user-days (PUD) is defined as the total annual days that a photographer took at least one photo within a cell in the study area (chapter 2). Note that it is used to measure the frequency of photos taken after controlling often exceptionally high numbers of photos taken by a single photographer in the area at the same day.

6.2.1.2 Other ecosystem services (i.e., carbon storage, biodiversity) indicators

Indicators for carbon storage and biodiversity were compared with the CES indicators. We used the biodiversity database for the study site established in Lautenbach et al. (2017a), which is based on the vascular flora database for Saxony (Zentrale Artdatenbank (ZenA) Sachsen, 2017a), and the carbon storage estimated using the LPJ-GUESS simulation model (Lautenbach et al., 2017a). The database provides the total number of plant species (all plants), indigenous species, archaeophytes (i.e., introduced before A.D. 1500), neophytes (i.e., introduced after A.D. 1500), threatened (Red List) species, and species grouped by three pollination types (i.e., wind-, self- or insect-pollinated species). The butterfly species richness data was obtained from the database established by the environmental agency of the Free State of Saxony (Zentrale Artdatenbank (ZenA) Sachsen, 2017b). All these data sets were prepared at a 2.8 × 2.8 km base grid. The total number of the pixels is 811.

6.2.2 Analysis

Hotspots of the provision of ES refers to areas where produce multiple ES (Eigenbrod et al., 2010). To identify hotspots and quantify trade-offs robustly, we utilized five different methods in parallel: percentile, mutual information, correlation coefficient, principal component analysis, and hierarchical clustering. Details of the metrics are described in Table 3.1. As a descriptive method, percentile approach was used to assign high, mid, and low indicator values across the study region. Although it does not compute statistical significance, it is adopted as it is a simplistic way to identify areas with high and low indicator values. Mutual information shows how much information is shared between two variables in a multidimensional space. Using this metric, we tried to figure out how pairs of ES share information, thus whether they are meaningful to each other. Pearson's correlation coefficient method was used to analyze how strongly two variables are related. Multivariate analyses (i.e., Principal Component Analysis (PCA) and cluster analysis) were primarily used to analyze patterns in the multidimensional indicator data. Note that in the multivariate analyses, the pixels with no butterfly data were excluded ($n = 158$) out of the all 811 pixels. All calculations were done in R version 3.3.1 (R Core Team, 2016).

Percentile analysis In the percentile approach, all indicators are classified in percentile groups to look for regions with many high or low class pixels aggregated. All indicators were classified in three groups using percentiles, high ($> 66\%$), medium ($33\% \sim 66\%$), and low ($< 33\%$). We used square-root transformed PUD values as the PUD values were strongly skewed; the percentile approach may be inappropriate if used for skewed variables directly. Note the square-root transformation is applicable only to positive values.

Pairwise information between indicators To quantify bivariate correlations between the indicators, Pearson's correlation was calculated pair-wisely between the 12 indicators. In addition to that, we calculated mutual information of the indicator data set. The mutual information of two random variables measures the information content that is shared between two variables (Eq. 6.1), which can be used to quantify arbitrary dependency between the variables (Battiti, 1994). Pearson's correlation can be misleading if the relationship between a pair of variables are non-linear. The major advantage of the mutual information over the correlation coefficient is that it can measure a general dependence between two variables (Battiti, 1994). The general dependence is a broader concept than a linear dependence as it considers non-linear relationships as well.

$$MI(X, Y) = H(X) + H(Y) - H(X, Y), \tag{6.1}$$

where *H(X)* and *H(Y)* are the Shannon entropy of the random variables X and Y, respectively, and *H(X, Y)* is the joint Shannon entropy of X and Y (Shannon, 1948). The mutual information approaches '1' for increasing mutual information *(X, Y)*, and equals '1' if there is a perfect functional relationship between X and Y. The mutual information is non-negative, but has no upper bound. To facilitate comparisons between different data sets, the normalized mutual information proposed by Numata et al. (2008) was used. We estimated the mutual information by the method of k nearest neighbors using the R package `parmigene` (Margolin et al., 2006). Note that we calculated the mutual information for 100 times iteratively and took the mean values.

Cluster analysis To characterize groups of the pixels in the study area, we applied a hierarchical clustering for the pixels across the region. A hierarchical clustering algorithm is primarily searching for group. In this study, Ward's method (Ward, 1963), which is generally utilized to identify groups, was adopted. Thus, it can be used to identify indicators that tend to occur frequently together and map those. The algorithm calculates sum-of-square errors considering variance, then it uses these to group the data rows in k-groups. In our case, all the pixels were classified into n-groups. The number of the clusters (k^*) was chosen based on the mantel correlation. We used Euclidean distance for the predictors as input attributes for the Ward algorithm.

Principal Component Analysis (PCA) Principal Component Analysis (PCA) was used to analyze the multivariate relationships among these indicators. It is especially for the relationships between indicators for CES (photo-user days of existence value, and of landscape aesthetics) and indicators for species richness, and between indicators for CES and carbon storage. PCA reduces the dimension of the data by finding linear combinations of original variables (i.e., principal components (PCs)), which can best explain the variance of the data. To obtain an appropriate representation of the indicators, all indicators were z-transformed in the PCA analysis. Note that we closely looked at the PCs with eigenvalues (λ) > 1 (i.e., Kaiser–Guttman criterion) (Cliff, 1988). Note that in score plots, the principal component scores were normalized following Gabriel (1971).

6.3 Results

6.3.1 Percentile approach

In the percentile analysis, the hotspot areas were identified based on three percentile groups; trivially, the distribution of the 'high' category was different in each indicator (Fig. 6.1). Overall high plant species richness areas were located in the western Mulde watershed, whereas the high carbon pool areas were concentrated in southern areas in the Mulde watershed. The areas with the high photo-user-days for both existence values and landscape aesthetics were found in southern areas, which did not match with the high plant species richness areas (Fig. 6.1).

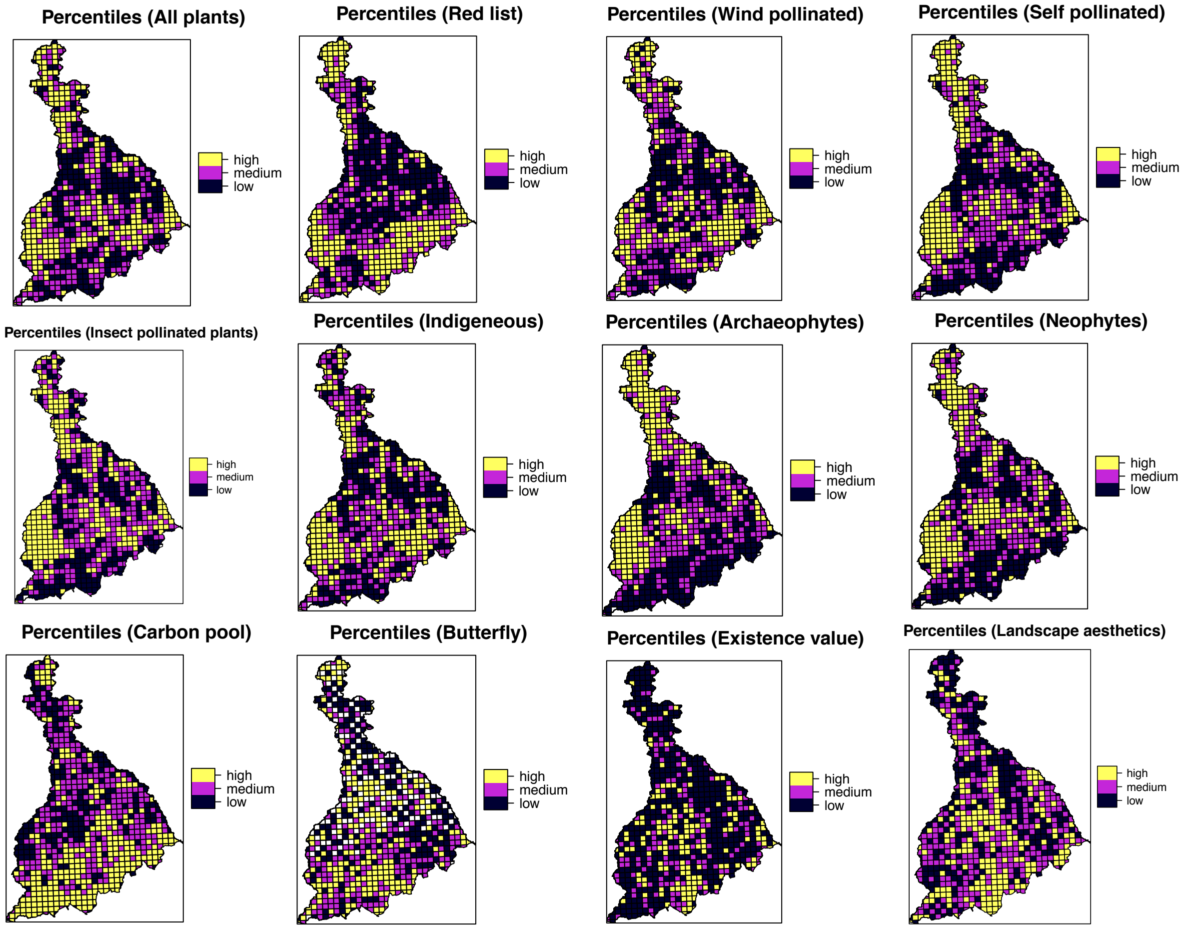

Figure 6.1: The hotspots identified based on three groups of percentiles, high ($> 66\%$), medium ($33\% \sim 66\%$), and low ($< 33\%$). For the photo-user-days, the square root transformed values were used as they were strongly skewed.

6.3.2 Correlation Coefficient

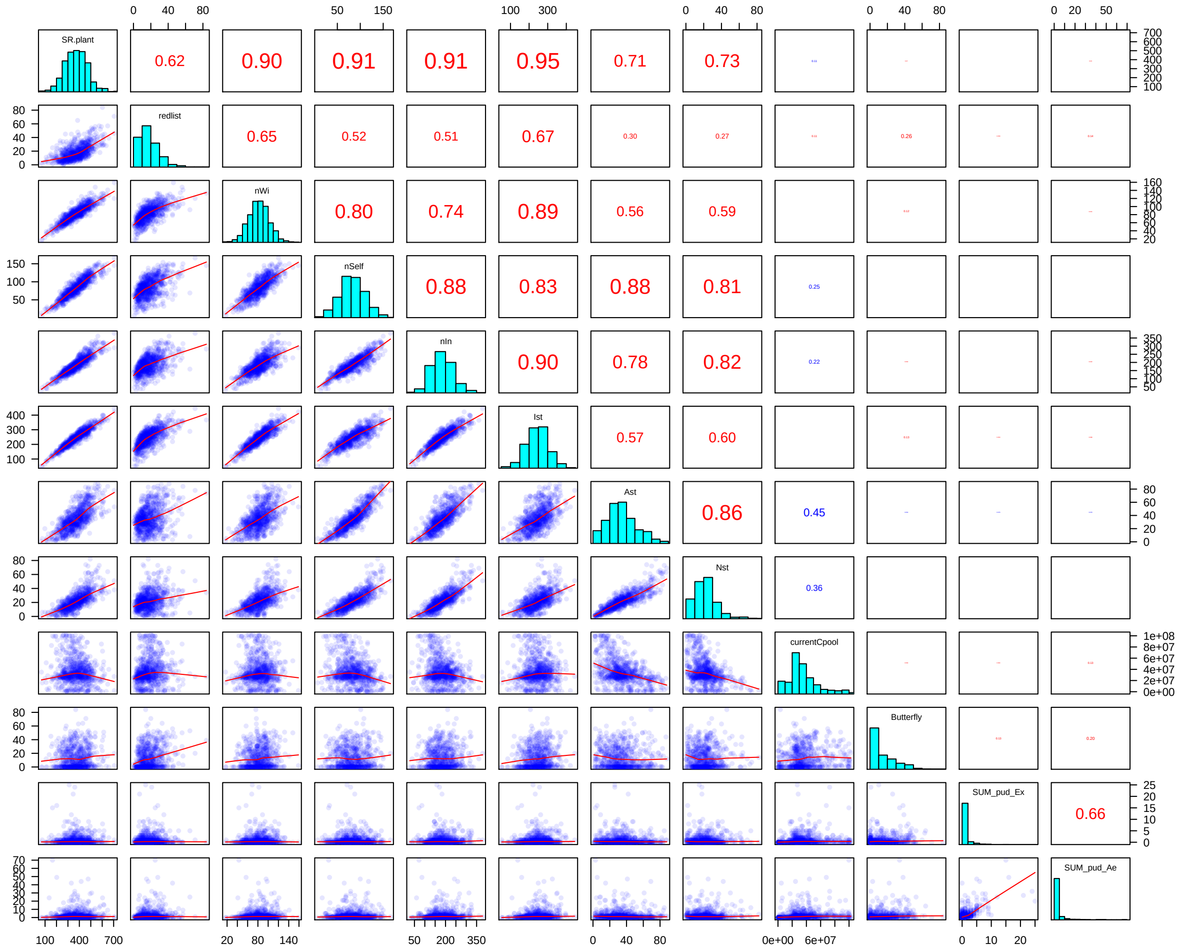

Figure 6.2: Pairwise scatter plots of the indicators: SRplant (all plant species), redlist (endangered species list), nWi (wind pollinated plant species), nSelf (self pollinated plant species), nIn (insect pollinated plant species), Ast (archaeophytes), Nst (neophytes), currentCpool (simulated carbon pool), SUMpudEx (photo-user-days of existence values), SUMpudAe (photo-user-days of landscape aesthetics). In the upper triangle the Pearson's correlation coefficients are presented. Blue color refers to a negative correlation and red refers to a positive. The font size is proportional to the absolute value of the correlation coefficients. Note that a lowess smoother was added to each scatter plot.

In Fig. 6.2, the scatter plots illustrate the pairwise relationships between indicators. The correlations between different plant species richness or between two CES indicators were high, however correlations were relatively low between CES indicators and plant species richness. Among other species richness, the butterfly richness showed a relatively higher positive correlation with CES indicators for the existence value (0.13) and the landscape aesthetics (0.20). The current carbon pool showed low correlations with CES indicators (0.084 and 0.13 for existence value and landscape aesthetics, respectively), and a negative correlation with plant species richness. The butterfly richness showed a low correlation with plant species richness. The highest correlation among relationships between butterfly and plant species richness was found with the endangered species (redlist; 0.26).

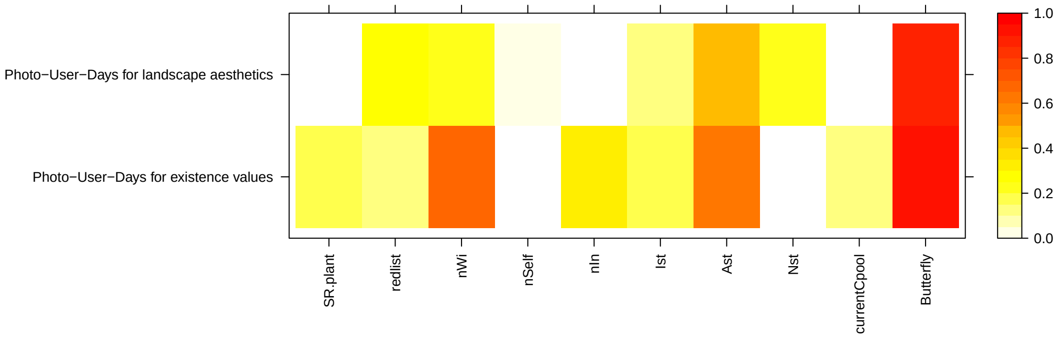

Figure 6.3: Normalized mutual information between CES indicators (i.e., photo-user-days of existence values and photo-user-days of landscape aesthetics) and the other diversity and carbon indicators: SRplant (all plant species), redlist (endangered species list), nWi (wind pollinated plant species), nSelf (self pollinated plant species), nIn (insect pollinated plant species), Ist (indigenous species), Ast (archaeophytes), Nst (neophytes), currentCpool (simulated carbon pool). The values are mean from the 100 repetitions.

The normalized mutual information between the butterfly richness and CES had the highest mutual information (MI) (avg. MI > 0.8) among other variables (Fig. 6.3). Wind pollinated plant species (nWi) and archaeophytes (Ast) also showed relatively high mutual information (avg. MI > 0.6) with the photo-user-days of the existence values. With the photo-user-days of the aesthetic values, Ast appeared to be informative as well (avg. MI $= 0.46$). Note that these relationships were not found in the naive correlation analysis.

6.3.3 Hierarchical clustering

The Mulde river basin was spatially classified based on the hierarchical clustering method. The optimal number of the clusters $k^* = 5$ suggested by the Mantel correlation (=0.395). The characteristics of the clusters are shown in Fig. 6.4. All plant species richness indicators showed higher mean values in cluster 1, whereas the carbon pool indicator showed the minimum mean value in the cluster. Cluster 5 contains higher values of the both CES indicators, namely existence values and landscape aesthetics. The butterfly richness was relatively similar in the clusters, with its lowest value in cluster 4.

To display spatial distributions of the indicators, the assigned cluster for each pixel was shown by colors (Fig. 6.5). Cluster 5 was concentrated in southern areas where Ore mountains are located (Fig. 5.1).

6.3.4 Principal Component Analysis

The relationships were further analyzed using the PCA analysis. PC1 (eigenvalue= 6.13) explained the most (51.1%) of variance, which represents all plant species richness. CES

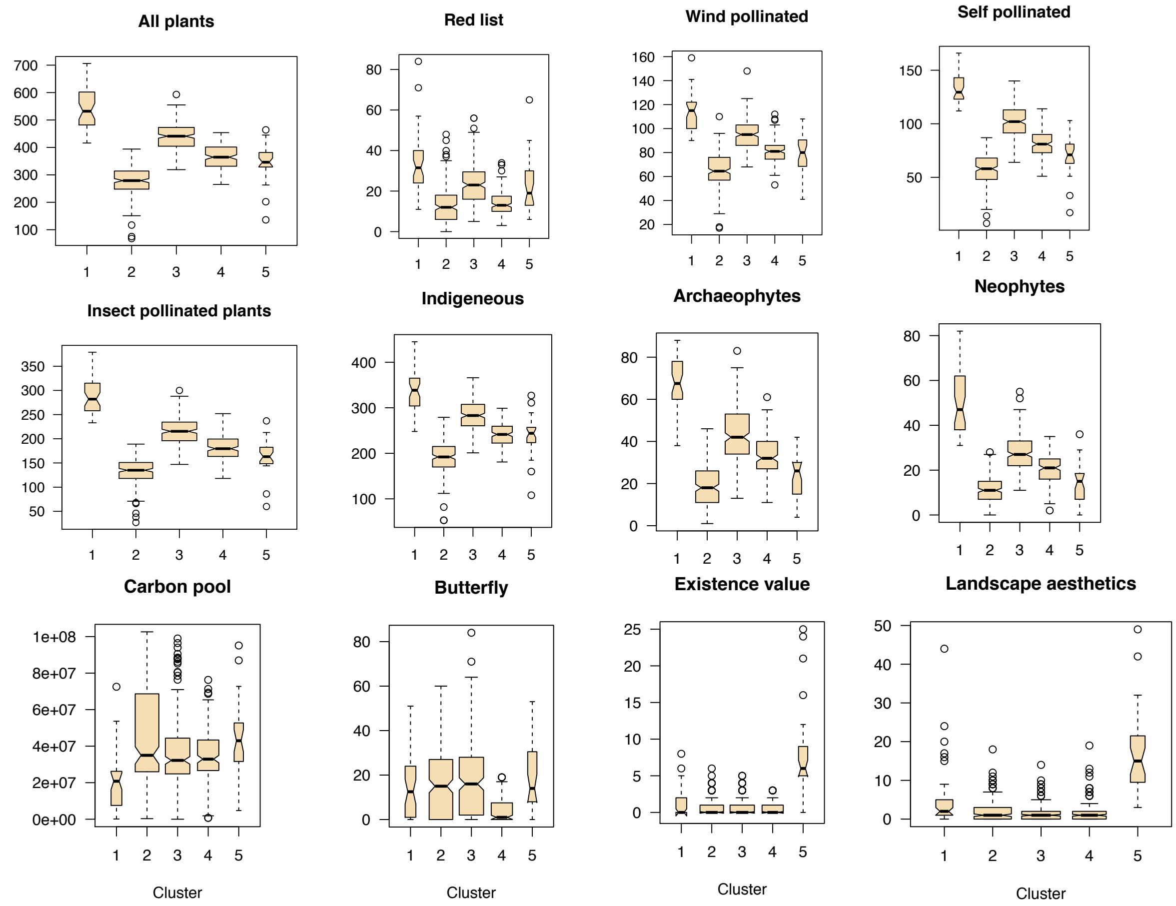

Figure 6.4: Distributions of the indicator values (y-lab) in the five clusters (x-label) for the 2.8 km pixels in the Mulde basin ($n = 658$). Out of the total 811 pixels, the 158 pixels with no butterfly data were excluded.

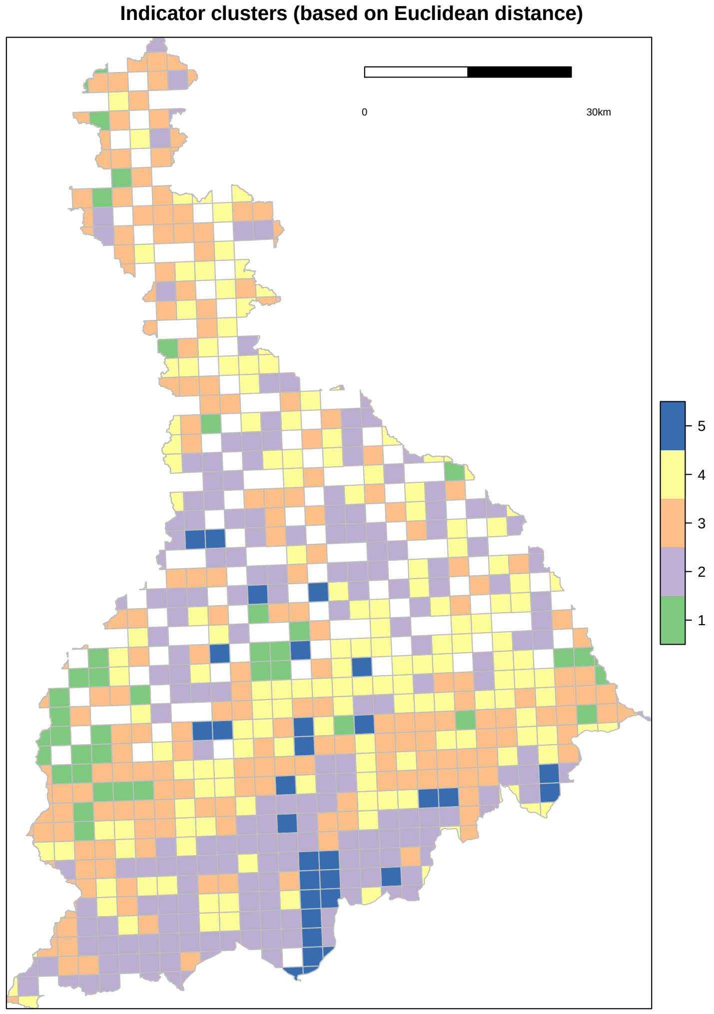

Figure 6.5: The spatial cluster in the Mulde watershed (2.8 km by 2.8 km). Colors refer to the different cluster number. White colors represent pixels with no cluster determination due to the lack of the butterfly database.

indicators, the butterfly richness and the carbon pool showed an opposite direction to all plant species richness (Fig. 6.6, left, Table 6.1). PC2 (eigenvalue= 1.94) explained 16.2 % of variance and PC3 (eigenvalue=1.39) explained 11.1% of variance. The loading plot shows the biggest and positive values for butterfly, existence values and landscape aesthetics in PC2 (Table 6.1). Overall, the CES values were almost orthogonal to the flora diversities.

The clusters assigned in the above were apparently distinguished in the score plots (Fig. 6.6). Especially in the score plot with PC1 and PC2 (left), cluster 1 and 5 are characterised by high flora diversities and cultural ecosystem values, respectively.

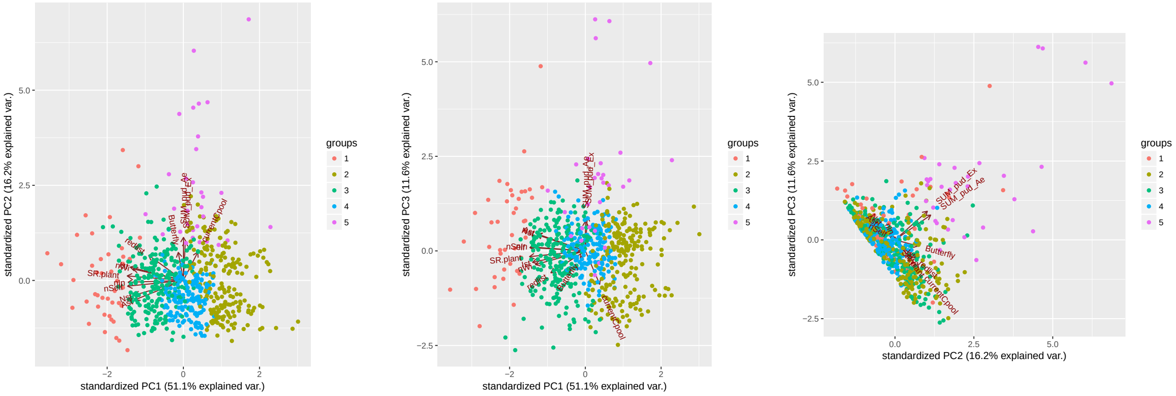

Figure 6.6: Principal Component Analysis score plots for the input indicators. Arrows represent the ES predictors. The direction and the length of the arrows show the correlation between the original variables and the principal components (PC). Three biplots show PC1 and PC2 (left), PC1 and PC3 (middle), and PC2 and PC3 (right). The color of symbols refers to the clusters identified by the Ward algorithm.

Table 6.1: Loadings of the first seven PCs from the PCA analysis. The color of symbols refers to the clusters . Explained variance (%) are shown in parentheses next to PC names. Note that the only PCs explained more than 2% of the variance are presented, for simplicity. Note that in score plots, the principal component scores were normalized (Gabriel, 1971).

Indicator	PC1 (51.1%)	PC2 (16.2%)	PC3 (11.1%)	PC4 (7.4%)	PC5 (4.6%)	PC6 (2.9%)	PC7 (2.6%)
SR.plant	-0.39	0.06	-0.08	0.09	-0.02	-0.10	-0.20
redlist	-0.24	0.31	-0.32	-0.06	0.59	0.21	0.56
nWi	-0.35	0.14	-0.20	0.09	0.10	-0.20	-0.34
nSelf	-0.39	-0.07	0.05	0.01	-0.09	-0.01	0.12
nIn	-0.38	-0.02	0.06	0.03	-0.12	0.03	-0.07
Ist	-0.37	0.16	-0.17	0.12	0.04	-0.14	-0.30
Ast	-0.33	-0.24	0.25	-0.07	-0.16	0.16	0.39
Nst	-0.34	-0.18	0.24	-0.06	-0.32	0.19	0.16
currentCpool	0.10	0.35	-0.49	0.36	-0.64	0.15	0.25
Butterfly	-0.04	0.35	-0.11	-0.89	-0.26	-0.09	-0.04
SUM_pud_Ex	0.01	0.48	0.50	0.18	-0.04	-0.62	0.30
SUM_pud_Ae	0.00	0.53	0.44	0.10	0.05	0.64	-0.29

In the spatial plots for PCs (Fig. 6.7, we displayed the spatial distributions of the PCs with eigenvalue > 1. PC1, which represents all plant species richness, showed higher concentrations of values in southern and middle of the Mulde river basin, whereas PC2, which represents high CES and butterfly, concentrated in southern area. PC3 spread evenly all over the region, except for the southern areas, which was opposite to the PC2 distribution.

Overall, our results showed that crowd-sourced photos as an indicator for existence value and landscape aesthetics were related with the butterfly richness with a marginally positive

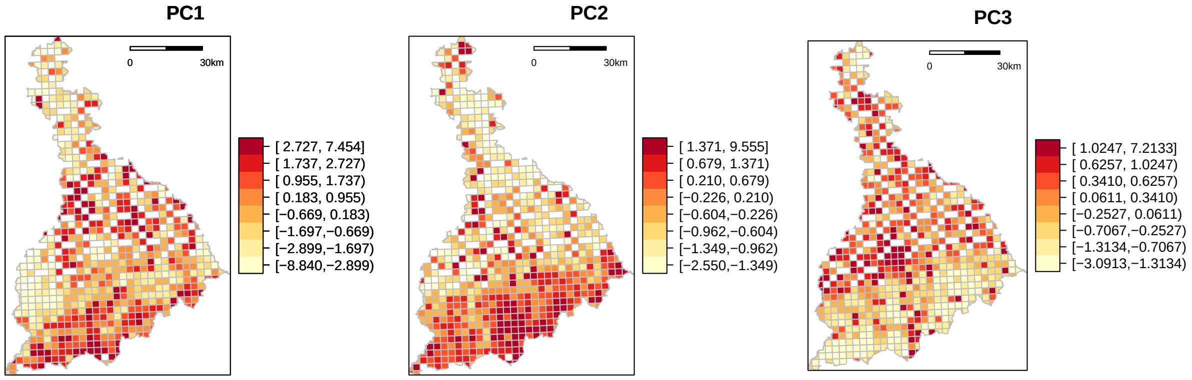

Figure 6.7: Spatial distributions of the principal components (PCs) in the Mulde watershed. White colors represent pixels with no data due to the lack of the butterfly database. Note that the PCs with eigenvalue larger than 1 are displayed.

correlation and overlapped hotspot areas. With carbon storage and plant species richness, the relationship was rather no-effect.

6.4 Discussions

Whilst relationships between biodiversity and ES have been extensively studied, the analyzed services included mainly provisioning or regulating services (Balvanera et al., 2006, Benayas et al., 2009, Cardinale et al., 2012, Quijas et al., 2012, Lautenbach et al., 2017a). The relationship between CES and biodiversity has rarely been pushed forward compared to other groups of ES (Quijas et al., 2012, Milcu et al., 2013, Harrison et al., 2014). It is partly due to a lack of spatially explicit CES data (Hernández-Morcilloa et al., 2013). CES identified in chapter 5 can provide a new possibility to investigate relationships between CES and other services. In this study, we tried to fill this knowledge gap by analyzing relationships between CES and biodiversity, and between CES and carbon sequestration in the Mulde river basin. Species richness was used as the main indicator for biodiversity in this region.

Our results showed mixed relationships between biodiversity and CES. Existence values are supposed to depend on the existence of certain species (Gee and Burkhard, 2010, Milcu et al., 2013). However, our results showed that plant species were not clearly related to the existence values identified by photo contents. Butterfly species richness appeared to be positively related with both CES (i.e., landscape aesthetics and existence values) in the Mulde river basin. The fauna diversity has been of importance for recreation in previous studies as well, such as bird watching, butterfly watching and also wildlife watching (López-Hoffman et al., 2010, Nahuelhual et al., 2013). However, it should also be noted that the human-induced recreation can affect the fauna habitat negatively (Buckley, 2004, Kangas et al., 2010), therefore, a management threshold should be carefully applied. Plant species richness showed 'no-effect' relationships with CES in our study. The no-effect relationship between plant species richness and CES was also found in Anderson et al. (2009). In their study, the overlap rate between hotspots of biodiversity and recreation was poor, which indicates a poor association between services. There was a contrast result as well. Quijas et al. (2012) showed a positive effect of plant diversity on CES from an expert knowledge assessment.

We used five different methods; descriptive (quantile approach), correlation coefficient (Pearson correlation coefficient), multivariate statistics (PCA, cluster), and mutual information. Mutual information analysis can be used when considering non-linear relationships as well. In our analysis, mutual information analysis revealed more related pairs that were not revealed by correlation coefficient measures. However, mutual information does not identify the direction of the relationships. For the direction of the relationships, correlation coefficient or multivariate statistics are more appropriate. Generally speaking, the ordination with the more dimensions leads to smaller errors, however it is more difficult to interpret the results. In other words, with the more dimensions, the better statistical fit will be required. It is shown in the results that the intrinsic dimensions of the indicator data sets are three (PCA) to five (Ward clustering). Therefore, it may be inappropriate to surrogate ES using an one-dimensional indicator. At least, it would be difficult to account for the second and the third axes of the variations, which would include carbon pool, fauna diversity, and CES. For spatial planning, we suggest mapping the results of the cluster analysis or PCA for a spatial pattern and statically explicit applications. These maps can be of help for spatial planning as it shows spatial distributions of clustered features.

Future studies should consider geographical settings as well. Especially, road connections and accessibility would be beneficial to understand the distribution of photos as well as related species. Also, the land cover data can provide how species can be related to the spatial distribution. For example, Loos et al. (2014) found a higher butterfly diversity in arable and grassland. It should also be noted that some variances among species exist. Some species such as butterfly would be more preferred in photography among others, hence those species are more appropriate to be predicted based on photos as an indicator. This limitation can be potentially reduced by combining with other types of data, such as interviews of photographers (Stedman et al., 2004, Beckley et al., 2007). In this way, photographers can directly express their feeling on specific species and preference, hence can improve the usefulness of the photo data.

7. Conclusions and Outlook

The concept of Ecosystem Services (ES) is an emerging concept which influences environmental discourse at many levels in the global community. Since the MA was published in 2005, the ES research community has grown rapidly. In many ways, the concept of ES will shape environmental regimes as IPCC and the global CO_2 emission trade did. It will be a crucial medium by which we can diagnose and project a socio-economic-ecological system from a multitude of perspectives. The international community agreed on a need to develop a global ES consensus to take a step further. The Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) was established to bridge between the scientific findings and decision-making processes in a manner similar to how IPCC has contributed. However, we still face difficulties in making use of the ES concept in practical applications. Synthesized evidence is missing for informed decision-making to secure multiple ES. Also, less studied services such as cultural ecosystem services (CES) still lack a standardized approach to improve data acquisition and quantification.

In this PhD thesis, which evolved as a part of the OPERAs project, conceptual and methodologic aspects of the ES quantification are examined based on the large number of published literature and “big-data” using cutting-edge analysis techniques at three spatial scales: global (chapter 3), landscape (chapter 4), and regional (chapter 5 and 6). For refining the concept of trade-offs and synergies between ES, an exhaustive review study was implemented (chapter 3). For a detailed measure of agricultural practices on ES, chapter 4 was dedicated to a meta-analysis in the Mediterranean area.

Chapter 3 identified a general pattern of relationships between ES. Trade-offs were dominant between provisioning and regulating services, whereas synergistic relationships were dominant between regulating services, or between cultural services. This pattern can be a standard conversion table when considering multiple ES in a decision-making process in practice. However, the scale effect on the relationship could not be addressed due to a geographical bias in the case studies. The results in chapter 3 also revealed the importance of methods used to determine the relationship, which should be considered when conducting a case study. This global review helps to build a common trend of trade-offs research. The results of this thesis emphasize that trade-off and synergy effects need to be evaluated to successfully assess multiple ES.

Subsequently, impacts of conservation agricultural practices on ES in the Mediterranean basin are examined from the extensive literature using a meta-analysis (chapter 4). For this purpose, conservation management options in the Mediterranean region were compared with the pair-wise conventional management options regarding major ES studies in the last 20 years. It is shown in the study that 1) conservation agricultural practices are significantly beneficial to local ES, 2) conservation practices are generally positively correlated with soil and soil microbial community structure (soil formation regulating services). These patterns were generally valid for the sites spread over the Mediterranean basin, even though site-specific behavior was observed. The noteworthy remark was that conservatively managed fields were less susceptible to water and heat stress, which may be due to the undisturbed soil and microbial communities in it. However, the impacts of different management options may require different time scales to be effective; some services may experience an immediate change, whereas some services need more time to be affected. It implies that decision-makers (i.e., farmers) should consider different time frames to cope with changes. I recommend for future research a comparison of the valid time scales in order to apply, effectively and efficiently, different management options.

Finally, for rapid and efficient quantification of ES, I estimated the spatial distribution of CES using a crowd-sourced image database. Crowd-sourced photos were successfully clustered according to their contents surrogated by machine-learned tags and interpreted in ES terms. To my knowledge, this study is the first study in which a coupling of the tag-network analysis was done with the ES concept, which shows a huge potential to apply at large scales, where data acquisition is limited. Furthermore, it validated its usability on the CES quantification by comparing with the ground observed ES and carbon storage indicators. The identified CES hotspot areas were related with butterfly richness, whereas carbon storage was not related with identified CES hotspots. This analysis implies possible applications of crowd-sourced photos beyond CES, to fauna biodiversity and habitat richness indicators. On the other hand, since such ES that are less recognizable by photos (e.g., carbon storage) are also substantial in regional ES studies, we would need to improve this approach toward the automatized and rapid processing of big data sources. Furthermore, I recommend for future research that new information sources such as remote and proximity image sensors must be considered for modeling the less recognizable ES, especially at large scales.

Toward future ES studies, the results of this thesis need to be integrated in terms of model development, scientific findings, and practical lessons for the rapid monitoring of ES, especially at large scales. In this PhD thesis, I tackled the two major obstacles in the current ES monitoring mentioned above: a lack of standard impact tables from a number of case studies and the difficulty of large-scale ES monitoring. I would argue that adequately analyzing the public big data sources is important for appropriate and timely quantification of ES for decision-making and policies.

Finally, I hope that this thesis can contribute to a consistent and timely approximation of ES at local to global scales. Also, it can lead to development of ES studies as well as future global environmental studies in order to secure our biodiversity and ES through the IPBES process.

A. List of Articles prepared during the preparation period of the thesis

During the preparation period of this thesis several scientific papers were prepared and partially published.

Peer-reviewed articles

Lee, H. and Lautenbach, S (2016) A quantitative review of relationships between ecosystem services, Ecological Indicators 66, 340-351. DOI: 10.1016/j.ecolind.2016.02.004

Lee, H., Bogner, C., Lee, S. and Koellner, T. 2016. Crop selection under price and yield fluctuation: Analysis of ago-economic data from South Korea, *Agricultural Systems* 148, 1-11

Schetke, S., Lee, H., Graf, W., and Lautenbach, S. 2016. Demand for ecosystem services – an analysis of the application of the ecosystem service concept in German urban land use planning and climate mitigation strategies, *Ecosystem Services* (in press) doi: 10.1016/j.ecoser.2016.12.017

Lautenbach, S., Mupepele, A.-C.,Dormann, C. F., Lee, H., Schmidt, S., Scholte, S. S.K., Seppelt, R., van Teeffelen, A.J.A., Verhagen, W., Volk, M.: Blind spots in ecosystem services research and implementation, *Regional Environmental Change*, under review

Lee, H., Seo, B., Koellner, T. and Lautenbach, S. 2017. Big data analysis to map cultural ecosystem services from unlabeled crowd sourced images, *Ecological Indicators*, under review

Others

The Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES), Thematic assessment, the Land Degradation and Restoration Assessment (LDRA), Chapter 5: Land degradation and restoration associated with changes in ecosystem services and functions, and human well-being and good quality of life. (Contributing author for the cultural ecosystem services part)

B. Presentations of research related to this thesis at scientific conferences

Oral Presentations

Lee, H., Lautenbach, S. 2014. A quantitative review of relationships between ecosystem services, ACES (A Community on Ecosystem Services Linking Science, Practice and Decision Making), 8-12 Dec 2014, Washington DC, USA

Lee, H. and Lautenbach, S. 2016. A quantitative review of relationships between ecosystem services, ESP Europe 2016, 19-23 Sep 2016, Antwerp, Belgium

Lee, H., Seo, B., Koellner, T., and Lautenbach, S., 2017. Automatic tagging of crowdsourced image for quantifying cultural ecosystem services – a case study in Saxony, Germany, Natural Capital Symposium 2017, 20-24 Mar 2017, Stanford University, CA, USA

Poster Presentations

Lee, H., Lautenbach, S. 2015. The effect of afforestation on recreational services - a case study in Saxony, Germany, IALE-D annual Conference, 20-23 Oct 2015, Bonn, Germany – *Best Poster award*

Lee, H., Seo, B., Koellner, T. and Lautenbach, S., 2016. Machine-learning-based tagging of crowdsourced image for quantifying cultural ecosystem services – a case study in Saxony, Germany, ESP Europe 2016, 9-23 Sep 2016, Antwerp, Belgium

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I hereby declare, to the best of my knowledge and belief, that this thesis does not contain any material previously published or written by another person, except where due reference has been made in the text. This thesis contains no material, which has been previously accepted or definitely rejected for award of any other doctoral degree at any university or equivalent institution.

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Heera Lee

Hiermit erkläre ich, dass ich die vorliegende Promotionsarbeit selbständig verfasst und keine anderen als die angegebenen Quellen und Hilfsmittel benutzt habe.

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Hiermit erkläre ich, dass ich nicht bereits anderweitig versucht habe, diese Dissertation ohne Erfolg einzureichen oder mich einer Doktorprüfung zu unterziehen.

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