A quantitative review of relationships between ecosystem services

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Abstract

Each decision in natural resources management can generate trade-offs with respect to the provisioning of ecosystem services. If the increase of one ecosystem service happens directly or indirectly at the cost of another ecosystem service, an attempt to maximize the provision of a single ecosystem service might lead to sub-optimal results. The research on trade-offs between ecosystem services has recently gained increasing attention in the scientific community. However, a synthesis on existing knowledge and knowledge gaps is missing so far. We aim at closing that gap by a quantitative review of 385 pairwise combinations of ecosystem services that have been studied in 60 case studies that report on relationships between ecosystem services. We categorized relationships between these pairs of ecosystem services into the categories "trade-off", "synergy" or "no-effect" . A synergistic relationship was dominant between different regulating services and between different cultural services, whereas the relationship between regulating and provision-

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ing services was trade-off dominated. Increases in cultural services did not influence provisioning services ("no-effect"). We further analyzed the pattern of relationships between ecosystem services across scales, land system archetypes and methods used to determine the relationship. Our analysis showed that the overall pattern of relationships between ecosystem services did not change significantly with scale and land system archetypes. However, some pairs of ecosystem services showed changes in relationships with scale. The choice of methods used to determine the relationship had an effect on the direction of the relationship insofar as multivariate approaches did underestimate "no-effect" relationships. More than half of the case studies were conducted at the regional scale, and case studies were biased towards Europe, North America and Australia, which might affect our ability to find the effect of scale or land system archetypes on the pattern of relationships. Our results provide helpful information of which services to include in ecosystem services assessments for the scientific community as well as for practitioners. Furthermore, they allow a first check if critical trade-offs have been considered in an analysis.

Keywords: ecosystem services, trade-offs, synergies, relationship of ecosystem services, quantitative review, pair of ecosystem services

1. Introduction

A common goal in natural resource management has been the control of nature to obtain its goods and services and to reduce its threats to the benefit of humanity (Holling and Meffe, 1995). However, the effort to control nature often results in unexpected and undesirable consequences due to multi-functionality of landscapes and ecosystems (Holling, 1996; Bennett et al., 2009).

These undesired consequences can be assessed and incorporated into decision-making within the concept of ecosystem services (ES) (MA, 2005; de Groot et al., 2010). The concept aims at capturing both the provisioning of and the demand for a multitude of ES simultaneously (Haines-Young and Potschin, 2010; de Groot et al., 2010). 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). A key aspect of the ES research is the stimulation of communication between scientific disciplines and decision-makers in order to avoid undesired impacts on ecosystems and to enhance human well-being (TEEB, 2010; Peér et al., 2013). Linking the ES supply and demand thereby plays an important role as it connects the ES providers and the users. ES supply illustrates the capacity of the biophysical structure and process of an ecosystem, whereas ES demand captures the amount of services required by society or by groups of stakeholders (Burkharda et al., 2012; Harrison et al., 2014; Mouchet et al., 2014). This connection between the ES supply and demand has been conceptualized, for example, in the ES cascade model highlighting the intermediate position of ES, which links ecological and biophysical structures (i.e. the supply side of ES) and elements of human well-being (i.e. the demand side of ES). Furthermore, feedback between the supply and the demand of ES has been investigated by several scientific groups (e.g. Lautenbach et al., 2011; Burkharda et al., 2012; Bagstad et al., 2014; Schulp et al., 2014). Trade-offs between ES are partly results of such feedback.

Trade-offs between ES have to be faced in the decision making process if the available options affect ES differently. Decisions in natural resources management are, however, often made without considering such trade-offs and can cause extensive degradation of nature (MA, 2005). A key challenge that decision makers face is, therefore, 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). To support their decisions, explicit information on trade-offs between ES is required.

The term 'trade-off' in ES research has been used when one ES responds to a change of another ES (MA, 2005). An attempt to maximize the provision of a single service will lead to suboptimal 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). However, the use of the term 'trade-off' in the literature often implies not only opposing trends between two ES but also general relationships including synergistic and neutral relationships (TEEB, 2010; Mouchet et al., 2014). In our analysis, we used the term "trade-off" when one service increased with reduction of another service in the supply side of ES. When both services changed positively in the same direction, we used "synergy" to describe the relationship between the two ES, whereas for the neutral relationship "no-effect" was used.

The generic term of 'trade-offs' has been used in various dimensions in ES researches from the supply to the demand side of ES. Trade-offs have been addressed within the biophysical process and structure by focusing on the supply side of ES. This research tends to focus on ecosystem processes and functions that underpin ES rather than quantifying ES themselves (Dickie et al., 2011; Lavorel et al., 2011). The trade-offs are either identified by statistical analysis of field data or by the analysis of the output process models such as LPJ-GUESS (Smith et al., 2001) or SWAT (Arnold et al., 1999) (e.g. Lautenbach et al., 2013). A second line of research focuses on trade-offs between different beneficiaries and policy analysis (Feagin et al., 2010; Zia et al., 2011). Examples include the trade-offs caused by the different benefits perceived by public and private stakeholders (Feagin et al., 2010) or the effect of the scale of an organization on perceived benefits (Zia et al., 2011). A third line of research is the analysis of bundles of ES that has been applied both on the supply (Raudsepp-Hearne et al., 2010) and on the demand (Martín-López et al., 2013) side of ES. The bundles approach tries to identify groups of ES that co-occur repeatedly in landscapes (Raudsepp-Hearne et al., 2010). It is commonly based on a GIS overlay at the landscape or the regional scale. Often complementary statistical or descriptive analysis is conducted to identify the bundles.

In order to address emerging interests in trade-offs between ES across the various ES research communities, several review studies have been conducted. Rodríguez et al. (2006) focused on relative changes at the supply side of ES. These authors studied trade-offs across space and time as well as trade-offs between ES. Bennett et al. (2009) discussed underlying direct and indirect relationships between ES on a selected number of case studies. Howe et al. (2014) investigated trade-offs and synergies between ES with a focus on the characteristics of beneficiaries and conditions. Mouchet et al. (2014) grouped the various types of ES relationships into three categories: supply-supply, supply-demand, demand-demand, and proposed the methodological framework to analyze relationships between ES. However, a comprehensive review of pairwise relationships between ES was hardly done so far, even though understanding relationships between pairs of ES is the first step to investigate further relationships among multiple ES in general (Chan et al., 2006; Raudsepp-Hearne et al., 2010; Jopke et al., 2014).

Our review tackles the research questions raised by above mentioned previous studies and extends the existing work by analyzing pairwise relationships between ES to identify dominant empirical relationships. We extend existing work further by considering the spatial scale and the location of the studies to test whether the pattern of dominant relationships differs in scale and with the land system. Since the variety of approaches used in research on trade-offs of ES makes it hard to determine empirical patterns in the relationships between ES, we decided to tailor our review to trade-offs between ES at the supply side - i.e. supply-supply in the definition of Mouchet et al. (2014). Our study aims at a synthesis of current knowledge on relationships between ES pairs through a quantitative review. We investigate thereby the following hypotheses:

(1) Pairs of ES show a preferred interaction and relationship with each other,

(2) The scale of investigation and the study location affect the relationship defined from (1),

(3) This relationship is further influenced by the method applied to characterize this relationship.

Our analysis includes studies that used the bundles approach as well as studies of trade-offs based on bio-physical relationships.

2. Material and methods

2.1. Literature search

We carried out a literature search in the ISI Web of Knowledge database using the following keywords: 'trade-off* ecosystem service*' or 'trade off* ecosystem service*' or tradeoff* ecosystem service*' or 'tradeoff* environmental service*' or 'ecological service* trade off*' in 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 389 scientific papers. We only included studies that represented case studies including quantitative measure of ES and were written in English. Studies that did not analyze the relationships between ES pairs 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 we analyzed 60 case studies - with 385 pairs of ES.

2.2. Database and classification

The ES categories were defined according to the CICES classification V4.3 (Haines-Young and Potschin, 2013). CICES is a classification tool of ES, which contains a nested hierarchical structure (Haines-Young and Potschin, 2013). The highest level of CICES includes three services 'Section' of provisioning, regulating and maintenance, and cultural services. Below the 'Section' level, 'Division', 'Group', 'Class' levels are nested (Fig 1). The analysis was mainly based on the group level of ES in CICES (Fig 1, see Supplementary table ST1 for the detailed list).

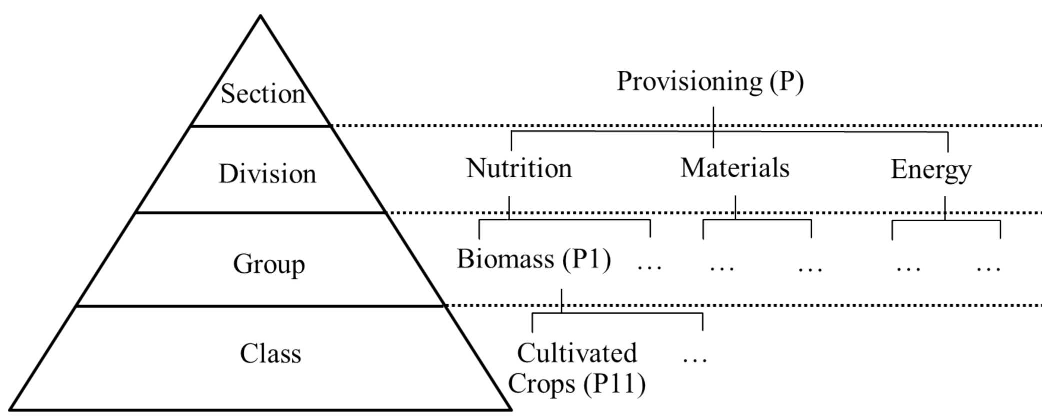

Figure 1: CICES nested hierarchy structure (left) and example of provisioning section and ES code in brackets (adapted from Haines-Young and Potschin (2013))

According to results presented in the case studies, the relationship between each pair of ES was classified either into "trade-off", "synergy" or “no-effect”. ”Trade-offs” was assigned when one service increased with reduction of another service, whereas when both services changed positively in the same direction, ”synergy” was assigned. When there was no interaction between two services, we assigned ”no-effect”. When the relationship was calculated quantitatively within a range between -1 and 1 (e.g. Pearson correlation coefficient), the relationship in the range between -0.25 and 0.25 was assigned as ”no-effect”. If the direction of the relationship between the pair of ES was not clearly described, it was classified as ”other”.

The dominant relationship for each pair of ES was determined based on the ratio of each relationship category 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 ”supporting ratio” to describe the percentage of studies in the dominant relationship category (Eq. 1).

$$Supporting\ ratio_{i,j} = Max(obs_{i,j,k}) / \sum_{k} (obs_{i,j,k}) \tag{1}$$

where $obs_{i,j,k}$ is the number of observations for the pair of ES_i and ES_j in the relationship category k. The higher the supporting ratio is, the higher the percentage of studies on the pair of ES that showed the same direction of relationship is. If there was a tie between two or three categories for a pair or if the supporting ratio 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 1). The land system in which a case study took place was assigned according to the map of land system archetypes (LSA) of Václavík et al. (2013) that matched the location of the study site. When several LSA overlapped within a study area, a dominant LSA that covered more than 50% of the study area was assigned. Otherwise, all LSA was considered. At maximum three LSA were assigned to one pair of ES.

The method used in the study was categorized into five groups: "descriptive", "correlation", "statistical modeling", "multivariate statistics", and "other" (Table 1). We differentiated between the method used to quantify ES (preparation of the data) and the method used to define the relationship between the ES (analysis of the data). 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".

2.3. Analysis

To test our hypotheses that the scale of investigation, the study location and the method used to determine the relationship between ES affect the dominant relationship, subsets of the data set were prepared for each category of the spatial scales, LSAs, and the groups of methods (Table 1). The pattern of the relationships between pairs of ES was compared across subsets in each category. The minimum threshold of the number of case studies to

Table 1: Criteria used for classification

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[a]	$> 10^6$ km^2	
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 developing world	
	LSA 12	Barren lands n 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 correlation coefficient or Spearman's rank correlation coefficient	
	Statistical modeling	Regression analysis such as (generalized) linear models	
	Multivariate statistics	Analysis of pattern in multidimensional data without assuming a dependent variable such as PCA and cluster analysis	
	Other	The relationship between ES was already built in the quantifying ES process	

[a] When a study considered a certain continent (e.g. Europe), we considered it as a continental scale.

participate in the comparison was 10 for subsets of scale and LSA, whereas all case studies in the subset of methods were analyzed. 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.

To compare the outcomes of different subsets of the data set, a bootstrap approach was used (Efron and Tibshirani, 1994). The subset membership was permuted for the case studies during the bootstrap. A measure of similarity was calculated based on the original data and for permutation of the subsets in order to test the similarity of the pattern of the relationships between ES pairs in two subsets. As a measure of similarity the Euclidean distance between the two ES relationship subsets 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.

3. Results

3.1. Dominant relationships of ES pairs

Among the 48 types of ES defined at the class level in CICES, 30 - including one abiotic service (i.e. renewable abiotic energy source) - were found in our data set (Fig 1, Supplementary table ST1). The most studied service was "global climate regulation service" (n = 97) followed by "cultivated crops" (n = 79), "physical use of landscape" such as hiking (n = 77), and "maintaining nursery population and habitats" (n = 75). We found 173 different combinations of ES at the CICES class level (Fig 1). More than half of those combinations at the class level (n = 93) were, however, recorded only one time. Since this did not provide enough support for patterns emerging from an analysis, we decided to drop the analysis at the class level. At the group level in CICES 82 types of ES pair combinations were analyzed (Fig 1, Supplementary table ST1). A pair of two ES that belonged to a common group of ES was considered as well. Figure 2 shows the empirical patterns of relationships between the ES pair – non-empty cells at the main diagonal refer to pairs of ES classes that belong to the same CICES group.

The relationship between regulating services was dominated by a synergistic relationship, which means that regulating services are likely to increase if a management action increases other regulating services. On the other hand, provisioning services and regulating services tended to trade-offs (Fig 2), which means that when a provisioning service increases, a regulating service is likely to decrease. Cultural services showed a trend for synergistic effects mainly with other cultural services (80%) and for no-effect with provisioning services (36%). Even though the number of observations for cultural services was relatively large in our data (40%), the types of cultural services that were covered in the analysis were rather limited; 67% of those cultural services focused on "physical and experimental interactions" (C1), whereas "spiritual services" (C3) were not considered at all in the studies analyzed. The relationship between regulating services and other groups of services was most diverse – trade-offs and synergies could be found as well as no-effect relationships.

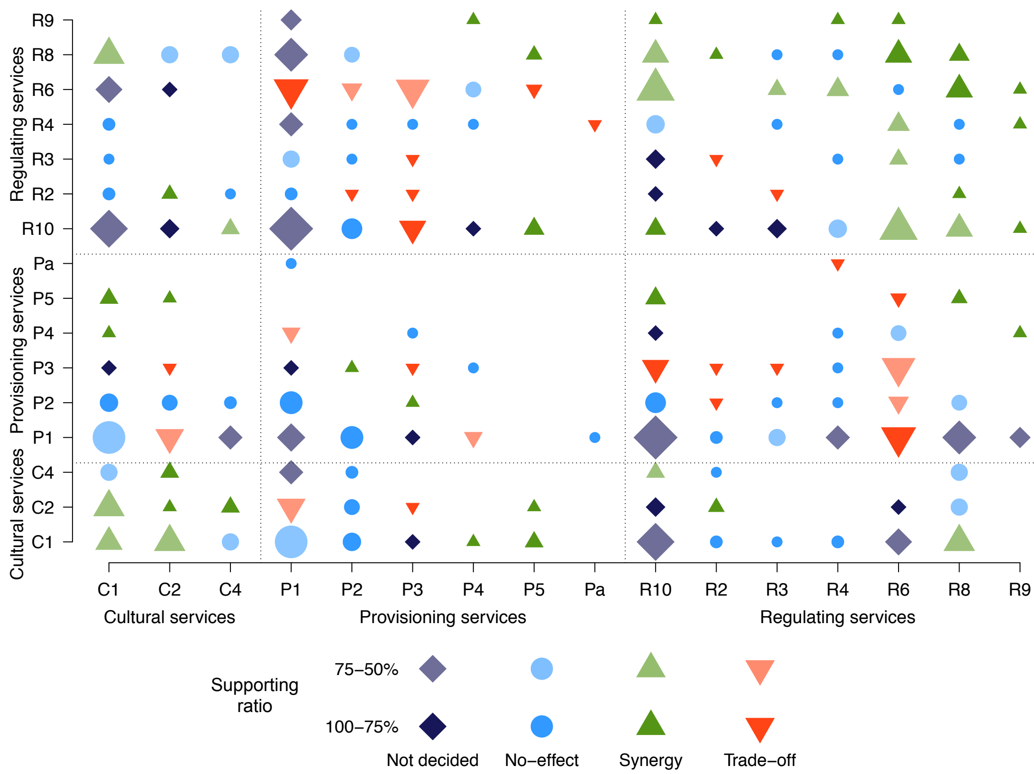

Figure 2: Result from analysis of 60 case studies with 385 pairs of ES, showing the empirical pattern of relationships between ES. X and Y axis represent the ES classification code used in the analysis. The size of the symbol indicates the square root scaled study number. The color intensity represents the support ratio. C: Cultural services, P: Provisioning services, R: Regulating services. C1: Physical and experiential interactions, C2: Intellectual and representative interactions, C4: Existence and bequest, P1: Biomass provisioning, P2: Water provisioning , P3: Materials for production and agricultural uses, P4: Water provisioning (i.e. non-drinking purpose), P5: Energy, Pa: Abiotic provisioning , R10: Atmospheric composition and climate regulation, R2: Mediation by ecosystems, R3: Mass flows regulation, R4: Liquid flows regulation, R6: Life cycle maintenance, habitat and gene pool protection, R8: Soil formation and composition regulation, R9: Water condition

The number of observations available to identify the dominant relationship ranged between 1 and 26. Twenty-eight types of pairs were observed only one time and more than half of the pairs (n = 54) were supported by

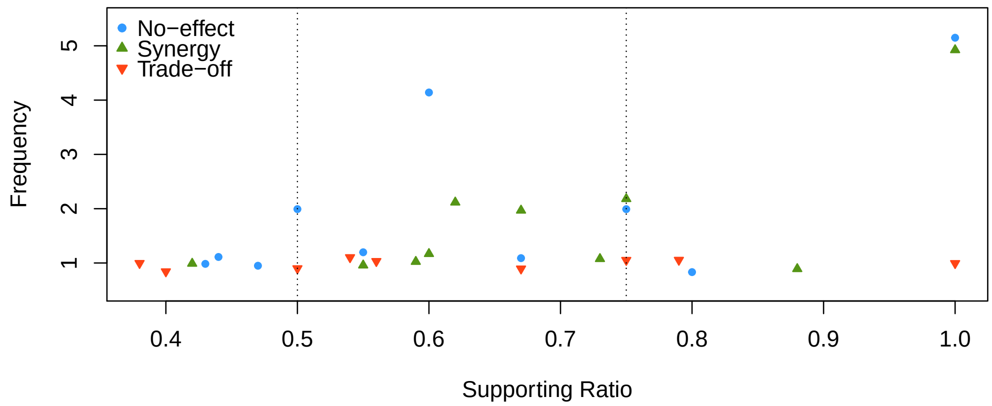

Figure 3: The distribution of the supporting ratio to determine the dominant relationship excluding pairs with a single observation. The shape of symbols indicates the dominant relationship.

less than 5 observations. Only nine pairs among 82 were supported by more than 10 observations. The most studied pair was a pair of "atmospheric composition and climate regulating" (R10) and "biomass provisioning" (P1) services with 26 observations. The supporting ratio ranged from 38% to 100% (Fig 3). For 82% of the ES pairs, the supporting ratio to determine the dominant relationship was higher than 50% - the other ES pairs were assigned to the "not decided" category. For the pair with the largest number of observations, R10 and P1, the dominant relationship had the lowest level of support (38%), therefore the "not decided" category was assigned. The highest supporting ratio for ES pairs with more than 5 observations was observed for the pair of "drinking water provisioning" (P2) and "physical and experiential interactions" (C1) services with the no-effect relationship (100%; n=6). The pair of "life cycle maintenance, habitat and gene pool protection" services (R6) and "soil formation and composition" (R8) followed with a supporting ratio of 88% for the synergistic relationship (n=8). The pair of "life cycle maintenance, habitat and gene pool protection" (R6) and "biomass provisioning" (P1), and the pair of "atmospheric composition and climate regulating" (R10) and "biomass for production such as timber and fodder" (P3) had a strong support for the trade-off relationship with a supporting ratio of 79% (n=14) and 75% (n=8), respectively.

3.2. Scale and Land system archetypes of ES pairs

We used the bootstrap approach in order to test whether the pattern of dominant relationships was different at each scale and in each LSA. The bootstrap approach did not reveal any significant difference between subgroups of the case studies. Neither spatial scale nor LSA membership had a significant influence on the pattern of the relationships between the services – p-values for each test are given in the Supplementary table ST3 and ST4.

The spatial scale of the studies was spread unevenly. The regional scale was most frequently studied (51.4%), followed by the continental scale (17.1%) and the plot scale (15.8%). The global scale was the least studied (2%) (Supplementary figure SF2). Thirty-eight pairs of ES (46%) were studied at only a single type of scale, which hindered the comparison of the relationship pattern among scales. Even though our test from the bootstrap approach showed no significant influence of scale on the overall relationship pattern, a couple of pairs were observed with different dominant relationships at each scale, which led to an assignment to the "not decided" category for those pairs. The pair of "atmospheric composition and climate regulation" (R10) and "biomass provisioning" (P1) was considered at every scale: at a small scale (i.e. the plot, local scale) the dominant result was synergy (43%; n=3), whereas it was trade-off (60%; n=6) at the regional scale and no-effect (56%; n=5) at the large scale. The pair of "soil formation regulating services" (R8) and "biomass provisioning" (P1) showed synergy (100%; n=4) at the small scale (i.e. the plot, local scale), whereas no-effect (64%; n=7) at the larger scale such as regional and continental scales.

The case studies were also unevenly distributed across LSAs (Supplementary figure SF3). Only three among 12 LSAs had more than 10 case studies: "boreal systems of the western world" (LSA3), "extensive cropping systems" (LSA7), and "intensive cropping systems" (LSA10). 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. Twenty-eight 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). The dominant relationship of this pair was synergy (59%),

Table 2: P-values for H0 that different subsets of methods 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 were presented

Methods	Description (18/44)	Correlation (14/290)	Multivariate Statistics (4/18)	Statistical Modeling (10/14)
Description	-	0.01*	0.19	0.35
Correlation		-	0.03*	0.001*
Multivariate Statistics			-	0.33
Statistical Modeling				-

*indicates p-value <0.05

however, the relationship of this pair was different in different LSAs: synergy in LSA1 (n=1), LSA7 (n=4) and LSA10 (n=8), whereas it was no-effect in LSA9 (n=1) and LSA11 (n=2), not-decided in LSA3 (n=2 synergy, n=2 trade-off) and ”other” in LSA8 (n=1).

3.3. Methods used to determine the relationship

The results from the bootstrap approach showed that the pattern of the relationships between the ES defined by the ”correlation” method was significantly different from other methods (Table 2). The ”correlation” method was most frequently used to determine the relationship between two ES (76%) (Fig 4). While 97% of the no-effect pairs were determined by using ”correlation” methods, ”multivariate statistics” approaches did not identify a single no-effect relationship. Among studies that determined a trade-off relationship, the ”correlation” was used most frequently, followed by the ”descriptive” method. However, methods were evenly distributed across the types of ES pairs and across the scale. In other word, the decision on which types of method to use to define the relationship was influenced by neither the type of ES nor the scale of the study.

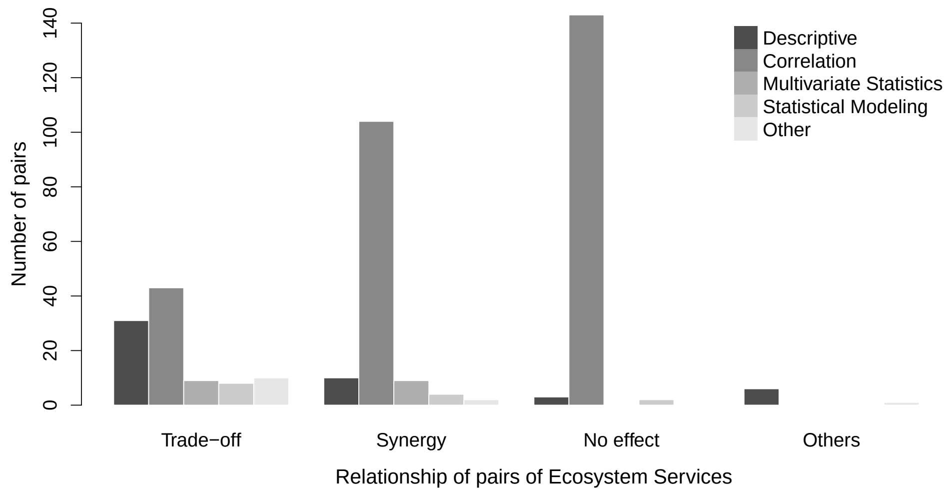

Figure 4: The frequency of method used in different results of the relationship between two ES

4. Discussion

4.1. Relationships between ES

Figure 2 provides a good overview of pairwise relationships between ES - however, it is necessary to look into more detail on the mechanisms that explain the relationships. In the following, we provide additional information on the most important pairs of ES.

4.1.1. Trade-off dominated relationships

The strongest trade-off relationship with more than 5 observations was found in a pair of "life cycle maintenance, habitat and gene pool protection" (R6) and "food provisioning" services (P1) with the supporting ratio, 79%. In general farming management types directly influence these services. This trade-off between R6 and P1 is in line with the debate on the contribution of organic farming, which promises to increase ES nursery and habitat protection but it is doubtful whether this can produce sufficient food to feed the world population (Bengtsson et al., 2005; Zhang et al., 2007; de Ponti et al., 2012). Organic farming generally contributes to increase species richness by providing better habitats and nursing ES (Bengtsson et al., 2005), but it can lower crop yield by up to 20-34% compared to conventional farming (de Ponti et al., 2012; Seufert et al., 2012). However, it should be also noted that 35% of the global production comes from crops that depend on animal pollinators (Klein et al., 2007), thus the positive relationship between food provisioning and habitat protection should be considered further (Aizen et al., 2008; Lautenbach et al., 2012; Garibaldi et al., 2013).

Another ES pair with a strong trade-off relationship was "biomass for production such as timber and fodder" (P3) and "atmospheric composition and climate regulation" (R10) with a supporting ratio of 75%. On the one hand forests are important in terms of carbon fixation and storage, but on the other hand they could also be used for timber production. In this case, a decision on whether forests remain as a source for carbon sink or 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).

4.1.2. Synergy dominated relationships

The strongest synergistic relationship was found in the group of regulating services. The supporting ratio for synergistic relationships varies between 42% and 100% (Fig. 3). Especially "habitat and gene pool protection services" (R6) showed a clear synergistic relationship with most other regulating services. Regulating services are generally associated with ecosystem processes and functions (Kremen, 2005; Bennett et al., 2009; de Groot et al., 2010) and have been described as mostly positively related with 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 might explain its 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 supporting ratio (88%) has been reported by previous studies that emphasized the interactions between soil functions and the role of soils in living habitats (Young and Ritz, 2000; Crawford et al., 2005; de Groot et al., 2010; Larvelle, 2012, e.g.).

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.

4.1.3. No-effect dominated relationships

The dominant no-effect relationship between cultural and provisioning services could be explained by 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. As shown in their 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 the common driver, therefore the relationship between them is no-effect.

Another explanation 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, Rodríguez et al. (2006) confirmed that the relationship between cultural and provisioning services is trade-off, as forest management for timber production could discourage people to visit this forest for recreation. Therefore, it might depend on the types of ES whether they share a common driver to derive synergies or trade-offs.

4.2. Relationship patterns across scales and land system archetypes (LSA)

The overall pattern of relationships was sensitive neither to scale nor to LSA in our test (see Supplementary table ST3 and ST4). This could be due to a biased spread of the spatial scale of case studies and their locations. More than half of the case studies in our data set were conducted at the regional scale (51.4%), whereas analyses at the global scale were rarely done. In addition, 46% of pairs such as C4 and C1, were only studied at one scale, which might hinder a comparison among scales.

Case studies were also unevenly distributed across LSA: only three types of LSA (i.e. "boreal systems of the western world" (LSA3), "extensive cropping systems" (LSA7), and "intensive cropping systems" (LSA10)) among 12 had more than 10 case studies. These three LSA are mainly located in Europe, North America, and Australia, which led a strong bias towards developed countries. This geographical bias of the case studies was already stressed by Seppelt et al. (2011). However, a few ES pairs showed interesting differences across LSAs. The pair of "life cycle maintenance, habitat and gene pool protection" (R6) and "atmospheric composition and climate regulating" (R10), for example, showed different relationships across different LSAs: synergy in "forest systems in the tropics" (LSA1), "boreal systems of the western world" (LSA3), "extensive cropping systems" (LSA7), and "intensive cropping systems" (LSA10) and no-effect in "irrigated cropping system" (LSA9) and "marginal lands in the developed world" (LSA11). 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 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 strong gradient is missing.

Different relationships at different scales were found for the pair of "food provisioning" services (P1) and "atmospheric composition and climate regulating" (R10): synergy at the plot and local scale, trade-off at the regional scale, whilst no-effect at the larger scales (national, continental and global). A possible explanation is that which different indicators were used. At the local or smaller scale carbon sequestration by crops was used as an indicator together with the amount of nutrients that people obtained from crops (e.g. Felipe-Lucia et al., 2014). High plant biomass in crops is typically associated with high food production (Reynolds et al., 2005; Zhang et al., 2009) as well as high carbon sequestration (Moors et al., 2010) in agricultural land. Therefor, a synergy between the two ES has to be expected at this scale and for this land system. At the regional scale the trade-off between P1 and R10 is caused due to competition for land e.g. forest vs. crop land (e.g. Laterra et al., 2012; Paterson and Bryan, 2012). Conversion of forest to agricultural land decreases thereby soil carbon sink up to 30% (Murty et al., 2002), which generates the trade-off between increasing crop production but decreasing carbon sequestration at the regional scale.

The pair of "food provisioning" services (P1) and "soil formation and composition" (R8) also showed different relationships at different scales. Soil organic matters were equally measured to quantify R8 at each scale, whereas nutrient provided by food at the smaller scale (Felipe-Lucia et al., 2014) and cultivated land area were measured at the larger scale (Raudsepp-Hearne et al., 2010; Jopke et al., 2014) to quantify P1. The synergistic relationship at the smaller scale could be explained by that soil organic matters in agricultural land are highly related to soil quality and can therefore be expected to be positively related to crop yield (Reeves, 1997; Loveland and Webb, 2003; Lal, 2004), whereas at the larger scale, this relationship diminishes if the analysis is only based on land cover data such as it is often done at the regional scale analyses.

4.3. Methods applied to determine the relationship

Our result showed that the choice of methods used to determine the relationship between ES influenced the result. Especially, the pattern of relationships defined by correlation methods were significantly different compared to other methods (Table 2). Multivariate statistic did not detect any no-effect relationship for pairs of ES (Fig 4). Multivariate statistics are frequently applied in ES trade-off research to identify bundles of ES by analyzing clusters of ES how similar to each other in a cluster from another, or 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). In this circumstance, this might lead to ignorance of variables that have no influence to each other. Since the assignment of ES to the different bundles does typically not include neither the strength of the association nor the attached uncertainty, it is not possible to detect no-effect relationships. Correlation approaches make it easy to define no-effect relationships based on the absolute strength of the correlation and/or a p-value - if corrected for nuisances such as spatial autocorrelation.

In statistical modeling, regression model was frequently used. From a theoretical point of view the use of a regression model seems questionable to describe relationships between ES since it distinguishes ES into dependent and independent variables. Only regression type II model - which have not been used - seem appropriate.

As already reported in previous studies (Vatn and Bromley, 1994; Jacobs, 1997; Martín-López et al., 2013), the choice of methodological approach for valuation of 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.

4.4. Limitations and Uncertainty

Although our review was comprehensive and thoroughly conducted, we imposed constraints on our review that might have biased our result. First, we only considered peer-reviewed scientific articles written in English found in Web of Knowledge for our analysis. This might have excluded some pairs of ES that are only 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). Second, we used 'trade-offs' as a main search term in refer to the ES relationship studies and did not use "synergy" or "relationship" or "association" as additional search phrases. The use of the term "trade-off" in scientific literature is ambiguous. Within our literature review, we found not only studies dealing with ES trade-offs also examinations of synergies and no-effects studies, thus there is support for the assumption that "trade-offs" as a search term covers relationship between ES in general. Since we observed trade-offs, synergies and no-effect relationships with similar frequencies, we assume therefore that our sample was not biased by this decision.

4.4.1. Defining the dominated relationships

To determine the dominant relationship, we used 50% as a threshold for the supporting ratio (Eq. 1). If the threshold lowers by 40% or rises up to 60%, about 10% of pairs of ES would change the dominant relationship into "not decided" in each case (Fig 3). However, the overall direction of the dominant relationships between groups of ES (i.e. the "section" level of ES (Fig 1) did not change thereby.

We assume that only a single "not-decoded" pair has to be considered as an artifact from the aggregation of ES at the CICES group level (Fig 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 1).

Except this one case 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 82 pairs of ES. Furthermore, to our knowledge, the analysis of relationships between ES at the group level was rarely done. 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).

5. Conclusions

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. This is of importance since it helps during the design of research programs and gives important hints for decision makers and reviewers to check research plans and to ask critical questions with respect to research outcomes. 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 this. 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 good modeling practice or analyze their data properly, reporting uncertainties along with point estimates, more evenly spread across the scales and land systems 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.

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