How much do we know about trade-offs in ecosystem services? A systematic review of empirical research observations

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Abstract

As an important domain of sustainability science, trade-offs in ecosystem services (ES) is crucial for spatial planning to sustainably manage natural resources while satisfying the needs of local and non-local beneficiaries. However, there is still a growing debate in understanding, characterization, and visualization of the trade-off relationships. This paper systematically reviews a total of 473 articles, published in the last 16 years (2005-2020) through 135 academic journals, based on empirical studies conducted in over 80 countries, and led by the researcher from over 50 countries. Trade-off relationships are often visualized as spatial associations of ES, but very few articles have characterized trade-offs as the causal interaction among ES. More than two-thirds of the studies were carried out in temperate and sub-tropical regions, but we depicted an under-representation of the critical ecosystems in tropics. About 90% of the articles were based on funded research but the involvement of government institutions was very low (<10%). Trade-off analysis was based only on biophysical constraints of the ecosystem, as observed in more than 80% of the selected articles, without due regards of the divergence in utility functions of different stakeholders and ecosystem beneficiaries. This study identifies a total of 198 pairs of conflicting ES, of which the trade-off between crop production and carbon/climate services has the highest records of observation (i.e., as identified by 20% of the total studies). Further, this study identifies the major drivers (i.e., ecological and social) and stakeholders (i.e., land users and government agencies) of trade-off in ES, and major gaps in the analytical approach to understand the trade-off relationships. Based on our findings, we have discussed and recommended a number of research trajectories, including trans-disciplinary research considering both biophysical constraints and utility functions, in order to guide the future direction of sustainability science through the creation of win-win scenarios.

Keywords
Ecosystem services; trade-offs; sustainability framework; production possibility frontiers; utility functions

1. Introduction

Ecosystem services (ES) are the attributes, processes and functions of nature that directly or indirectly benefit human beings, through the functioning of ecosystem and natural assets (Costanza et al., 2017; MEA, 2005). Growing demands for food, fresh water, and forest products, and increasing urbanization and industrialization have resulted in irreversible loss of ecosystems (Aryal et al., 2019a; MEA, 2005; Valencia Torres et al., 2021). The concept of ES is popularly used in recent decades to halt the loss of ecosystems and to fulfill human needs without compromising the ability of ecosystems for sustainable supply of various goods and services, such as provisioning, regulating, cultural and supporting ES (Cavender-Bares et al., 2015a; Mengist et al., 2020b). Sustainability framework, at the broader level, has articulated the inter-dependence of economic development and ecosystem conservation (Fang et al., 2018; Holden et al., 2014). Yet, the relationship among various services provided by ecosystems at spatial and temporal scales is merely discussed in sustainability science (Cavender-Bares et al., 2015a; Sun et al., 2018).

ES differ based on land use types, as well as on the pattern of occurrence within the land use type (i.e., synergy, compatibility and trade-off) (Liu et al., 2020). Negative relationship among various ES is called the trade-off situation which occurs when the increase in one ES leads to the decrease in the other ES and vice versa (Feng et al., 2021; Zhang et al., 2020). Trade-off occurs at both spatial and temporal scale (Howe et al., 2014; Sun et al., 2018), and is prominent among provisioning and non-provisioning ES (Rodríguez-Ortega et al., 2014), which is also considered through the supply (natural capital) and demand (beneficiaries) perspective (Vallet et al., 2018). Spatially exclusive ES can be observed at the landscapes level (Palacios-Agundez et al., 2015). Periodic assessment of the changes in the occurrence of ES explains the trade-off at the temporal scale (Rodríguez et al., 2006).

From the sustainability framework of ES, the trade-off in ES can be observed from two perspectives: (1) biophysical constraints: which indicate the optimum capacity of natural capital stocks to produce two or more ES simultaneously, and (2) utility functions: which signify the highest possible welfare of the concerned stakeholder groups and individuals (Cavender-Bares et al., 2015b; King et al., 2015; Mastrangelo and Laterra, 2015). Biophysical constraints define the production possibility frontiers (PPF) of the ecosystem to provide goods and services now and in the future (Ager et al., 2017; Cavender-Bares et al., 2015a). PPF, also understood as efficiency frontiers, is the basic concept in trade-off analysis because it explains the maximum rendering of one ES at each level of the other ES simultaneously, indicating the optimal balance between two conflicting ES (Cavender-Bares et al., 2015b; King et al., 2015; Vallet et al., 2018). Ecological functioning of the earth does not follow a uniform gradient elsewhere, and it varies with the geographical location, climatic characteristics, and biotic interference including those of humans (Dronova, 2017; Huang et al., 2015). PPF therefore depends on various biological, ecological and climatic characteristics, along with the context of resource use and management prescriptions (Bagdon et al., 2017; Lafond et al., 2017; Pohjanmies et al., 2017).

Besides, ecosystem is not valued unless it benefits to whole or parts of the society, be it local or non-local benefit, or for the individuals or groups of the society (Dawson and Martin, 2015; Howe et al., 2014). The utility function of the ES is hence another important consideration for the sustainable framework of ES. Various stakeholders, ranging from primary land users to the global communities, might have divergent values to the same ES which imply the trade-off in consumption and/or valuation of the ES (Cavender-Bares et al., 2015b). For instance, land users are concerned with the optimization of local ES, however landscape manager opt for the co-occurrence of global ES (i.e., carbon and climate services, biodiversity, nutrient cycle, and water regimes) (Drake et al., 2013; Laudari et al., 2021). Moreover, utility functions vary due to the differentiations in socio-economic and cultural factors, as well as the spatial proximity of the resources (Naidoo and Ricketts, 2006).

Understanding and analysis of trade-off among ES is of great importance for spatial planning to sustainably manage natural resources while satisfying the needs of local and non-local beneficiaries (Chen et al., 2021; Lu et al., 2021; Turkelboom et al., 2018). However, studies on the ES, including interaction among ES, was negligible until the inception of Millennium Ecosystem Assessment (MEA) in 2005 (Mengist et al., 2020a). Afterwards, a growing number of publications can be found about the general assessment of ES (Acharya et al., 2019; Costanza et al., 2017; Dang et al., 2021; Hølleland et al., 2017; Malinauskaite et al., 2019; McDonough et al., 2017; Mengist et al., 2020b; Valencia Torres et al., 2021; Wang et al., 2021). Nevertheless, only few studies have been carried out to support the framework of ES relationship (especially trade-off) that resulted from human and nature interactions (Aryal et al., 2021b; Khosravi Mashizi and Sharafatmandrad, 2021; Mengist et al., 2020b; Spake et al., 2017). Besides, most of the studies on the trade-off assessments are based on the estimates rather than empirical observation and evidence based (Mach et al., 2015).

Although few literature have reviewed studies on ES interactions (Howe et al., 2014; Lee and Lautenbach, 2016; Obiang Ndong et al., 2020), they were not comprehensive but observed sporadically at sectoral level. To illustrate, systematic mapping of ES relationship (Howe et al., 2014; Lee and Lautenbach, 2016), drivers of ES interaction (Obiang Ndong et al., 2020), regulatory ES focused studies (Mengist et al., 2020a), and mountain focused studies (Mengist et al., 2020b) have been carried out in the past. However, those studies lack comprehensive findings and applicability to the policy communities and scholars for sustainable ecosystem management (Mengist et al., 2020a; Zhao et al., 2020). Documentation and analysis of global trends of publications that are based on empirical observation (i.e., having specific data location), which focus on understanding the competing interactions among ES, is lacking. A composite overview of the studies on trade-off in ES is hence deemed important to reflect on the wave of research trend and to set priority for future studies on trade-off analysis.

In this paper, we aim to characterize the trade-offs in ES through the adoption of systematic literature review of research articles over the last 16 years (2005-2020). The main purpose of this review was to assess the research trend and global outlook of trade-off among ES through the assessment and analysis of (1) geographical distribution, land use categories and types of ES trade-offs, (2) methodological and analytical framework of the trade-off analysis, and (3) major drivers of trade-off recommended response measures. The findings of this review will help decision makers in articulating a new or revised policy instrument to solve complex yet uncertain ecosystem functioning at regional and global scale.

2. Methods

2.1 Review protocol and literature search

We adopted a qualitative content analysis, as well as quantitative tools, to carry out the systematic literature review. Question formulation, protocol and framework of searching, article screening and data extraction, synthesis and data analysis were the major steps we followed during the systematic literature review (Haddaway et al., 2020; Pant et al., 2020). We adopted the steps of systematic literature review to overcome the drawbacks of traditional approaches of literature review, which also helped in avoiding biases (Haddaway et al., 2020). The transparency and replicability of the literature review was ensured by developing and applying a robust review protocol (Mengist et al., 2020b). After the identification of study objectives, we formulated review questions and selected the key words in consultation with few key experts (n=3) in the field of research. The use of keywords was made in defining the criteria of the search string. The search string of the literature review was: [*("ecosystem service" OR "ecosystem services" OR "environmental services" OR "environmental service") AND (tradeoff OR tradeoffs OR trade-off OR trade-offs OR "trade off")*].

[Figure 1 here]

We searched for peer-reviewed articles that were published from 2005 to 2020, from 'Scopus' and 'Web of Science Core Collection'. Only empirical research articles were accessed. We selected 2005 as the reference year because the global attention to ES was derived by the MEA in 2005, and not only the relationship among ES but also studies on ecosystem dynamics were rare then (McDonough et al., 2017; Valencia Torres et al., 2021). We found a total of 1,951 records from 'Scopus' and 2,915 records from 'Web of Science Core Collection' database. After the removal of duplicates (i.e., 33% records were common in both database), 3,239 records were selected for article screening. A flow chart of the articles selection processes, including the search criteria and inclusion criteria, is presented in Figure 1.

2.2 Article screening

Article screening was done at three levels. First, title screening was done by excluding the articles which were not explicit about the relationship of ES (i.e., interaction, association, relationship, bundling, trade-off). In addition, theoretical papers, project evaluation reports, and meta-analysis papers were removed. From the total records of articles, 25% of the articles were selected for inclusion based on title screening. Second, at the abstract level, all non-empirical research papers, non-representative of at least one ecosystem type, and opinion papers were excluded from the review. From the total records, 20% of them were included for full-text screening after screening at the abstract level. Third, we followed population-exposure-comparator-outcome (PECO) approach as the inclusion criteria while full-text screening (Cimino et al., 2017; Cohen Hubal et al., 2020). While doing so, we adopted ecosystem types or land use types or the spatial scope of the research as the population; natural processes or human interface to the ES were explained through the exposure; comparators were the drivers and stakeholders defining relationship among ES; and outcomes were the conflicting pairs of ES. Finally, 473 research articles (i.e., 15% of the total records) were selected for data extraction after the full-text screening.

2.3 Data extraction and data analysis

After the article screening, we selected 473 articles for data extraction. Data extraction was carried out in two stages. First, we extracted meta-data and defined (categorical) coding of the data. Meta-data included data location, study time period, date and journal of publication, ecosystem types, ecosystem unit for analysis, ES, study methods and others. Secondly, after doing the critical appraisal, we extracted the variables of interest and information in a predefined category for common data frame. The data frame with the variable of interests, along with the data from selected 473 articles is presented in detail in supplementary file A. As an assumption of this study, we built our data frame to capture a maximum five pairs of ES per article which was based on the observations made by previous studies such as, Seppelt et al. (2011), which recorded an average of 2-4 ES per study and Obiang Ndong et al. (2020) which recorded 3-6 ES per study. While documenting the typologies of ecosystem services, we adopted the broader classification framework of MEA (i.e., provisioning, regulating, cultural and supporting services). Being within the classification framework, we further put the names of ES that resemble the same type of ES in the corresponding literature because of the variations in naming of ES in the global literature, employing an inductive approach. Moreover, to avoid confusion, we elaborated the ES to capture the variability in the use of such terminology in various literature. Data analysis was done through both quantitative and qualitative tools. Qualitative data were synthesized using configurative synthesis by which we could explain and interpret the interactions and/or trade-offs in ES, including its visualization, knowledge clusters and knowledge gaps.

3. Results

3.1 Trends and current status of literature on trade-offs in ES

As noted, 473 research articles published between 2005 and 2020 met our inclusion criteria (Figure 2). A very few number of articles were published in the initial 7 years after MEA (i.e., only 22 articles between 2005 and 2011), however 27 articles were published in a single year (i.e., 2012). The number of publications was continuously increasing afterwards. A total of 75 articles were published in 2020 (Figure 2).

[Figure 2 here]

A total of 135 academic journals were involved in publishing the selected 473 research articles about trade-offs in ES. The names of the top ten journals that have published the highest number of articles are presented in supplementary file B. The journal- 'Ecosystem Services' has published 49 articles about trade-offs in ES, followed by 'Ecological Indicators', 'Science of the Total Environment', 'Ecology and Society', and 'Ecological Economics' (with the respective records of 40, 21, 21 and 16). Those five top journals published about one-third of the total research articles. Likewise, the top ten academic journals published ≥10 articles each between 2005 and 2020, while the rest published ≤ 9 articles each in that period of time.

Studies about trade-offs in ES have been carried out over 80 countries in the last 16 years, led by authors from more than 50 countries. Fifteen articles each were based on the data collection from ≥2 countries and 23 studies were carried out at the European scale. China has become the highest country in carrying out research on the trade-off analysis (>120 studies), followed by the United States of America (>50 studies) (Figure 3). Interestingly, the third highest research about trade-offs in ES was carried out at the continental level (i.e., Europe). None of the developing countries, except China, was listed among the top 10 highest research countries for trade-off in ES. Regarding the belongingness of the lead author to the country of research, 83% of the studies were carried out where the lead author of the articles also belongs to.

[Figure 3 here]

Various actors and stakeholders from multiple disciplines have been involved in research about trade-offs in ES. Out of the selected 473 articles, academic institutions (i.e., universities and colleges), research centers, government agencies, and others (i.e., non-governmental organization and companies) were involved in the publication of 461 (97%), 119 (25%), 42 (9%), and 30 (6%) articles respectively. A total of 1096 academic institutions, 172 research centers, 48 government institutions, and 38 other organizations were involved in the publication of the selected articles. Despite the lowest level of engagement of government agencies and companies in publication, 89% of the articles were based on the studies that received funding for research. Four percent of the articles received no funding, and about 7% articles did not mention any information about funding.

Highest number of studies can be found in temperate climatic region which accounted for almost half of the total research (i.e., 48%) carried out globally, followed by subtropical, tropical and semi-arid climatic zones. The sub-alpine region is the least studied climatic zone for understanding the trade-offs in ES. More details about the climatic zones of the trade-offs studies can be found in supplementary file C. Regarding land use types, most of the studies were carried out at the mixed land use types (45%), followed by forestland (25%), farmland (15%), rangelands/grasslands (5%), and others (10%). Other land use types include urban agglomerates, orchards, coastal area, floodplains, barren land and brown fields. Within the mixed land use types, the frequency of occurrence of farmland is highest (89%), followed by forestland (81%), rangeland (51%), wetlands (12%), and others (21%).

3.2 Methodological approaches and modes of the trade-off analysis

From the broader perspective, four categories of methodological approaches are popular in analyzing the trade-off relations, namely, statistical analysis, spatial analysis and ecosystem mapping, scenario analysis and model simulation, and descriptive analysis (Li et al., 2018; Liu et al., 2019; Zhou et al., 2019). Although the methods used in the trade-off analysis were not mutually exclusive and substantial number of research papers used two or more methods simultaneously, we picked up the main approaches that were considered in the trade-off analysis. More than half of the selected articles (54%) used statistical analysis to assess the trade-offs in ES (Figure 4). The use of descriptive analysis, spatial analysis and ecosystem mapping, and scenario analysis and model simulation was done in 17%, 15% and 14% of the published papers, respectively. Among the studies that used statistical analysis, 43% was based on correlation and regression analysis, followed by multivariate statistics and cluster analysis (34%), production possibility frontiers (14%), Bayesian belief network (4%) and root mean square error (4%).

[Figure 4 here]

Two-thirds of the selected studies were solely based on the spatial analysis of trade-offs in ES, while the remaining one-third were based on both spatial and temporal analysis. At the spatial scope, most of the studies were carried out at the landscape level (39%) and basin scale (22%) (Figure 5a). Regarding those studies that considered temporal analysis, most majority was based on historical observation (>70%). The temporal scope of the studies, including the time range of the observation, is presented in Figure 5b. About 12% of the total literature were based on the historical observation of the time range from 11-30 years, followed by the historical observation of 1-10 years (6%). Only about 3% of the total studies were based on the temporal observation of both historical observation and prediction modeling. The proportion of the temporal observation of the studies that considered more than 50 years of observation is very low (<7%).

[Figure 5 here]

From the perspective of sustainability science, studies have been focusing on the biophysical constraints of the ecosystem. Consideration of the divergence in valuation of the ES by different stakeholders through utility funtions has rarely been considered in the past literature. To illustrate, 84% of the selected literature explained the trade-off relations based on the biophysical constraints alone, 10 % of the studies considered utility functions alone, and only 6% of the articles were based on the consideration of both biophysical constraints and utility functions.

3.3 Major ES and trade-off relationships

Regarding the frequency of observation of various ES, regulating ES were the highest studied (37%), followed by provisioning, supporting and cultural services which constituted 34%, 19%, and 10% of the selected articles. We categorized various ES that were identified in the selected literature into 33 commonly used categories of ES (Table 1). Carbon and climate services was the most frequently observed ES (i.e., studied in >53% of the selected literature). This was followed by crops and grains (50%), biodiversity (34%), water conservation and regulation (32%).

[Table 1 here]

Trade-off in ES was found to occur among and within all four categories of ES (i.e., provisioning, regulating, cultural and supporting ES). The frequency of occurrence of trade-off relationship is highest between provisioning and regulating services (62%), followed by provisioning and supporting (45%), and provisioning and cultural ES (25%). Similarly, substantial number of literature (i.e., about 15%) showed that the trade-off relationship occurred between the regulating and supporting ES. Nonetheless, the results showed that trade-off relationship is possible even within supporting services and cultural services themselves (Figure 6).

[Figure 6 here]

A total of 198 pairs of ES possessed conflicting interaction and/or trade-off relationship. Among them, 28 pairs of ES were reported as the conflicting pair of ES at least 10 times. From the selected literature, about 90 pairs of ES were reported only once as having the trade-off relationship between each other. The top 10 most frequently observed pair of ES is presented in Figure 7. The most frequently observed trade-off relationship was found between Crop and Grains (CG) and Carbon and Climate Services (94 cases), followed by CG and Water Conservation (85 cases), CG and Soil Retention (72 cases), CG and Recreation and Tourism (65 cases), and CG and Biodiversity conservation (56 cases). Out of the top ten most frequent trade-off relationships, CG appeared 8 times with other various regulating, cultural and supporting ES.

[Figure 7 here]

3.4 Drivers and stakeholders related to the trade-off in ES

Various drivers were responsible for the presence of trade-off among ES. Among others, ecological drivers were the most prominent (65%), followed by social (55%), economic (23%)

and institutional drivers (7%). The factors responsible for the trade-off in ES were categorized in four major archetypes: change in land use, change in management objectives, use of natural resources, and climate change. Forty three percent of the trade-off studies have identified change in land use as the major factor responsible for trade-offs in ES. Similarly, change in management objectives and intervention was found responsible for the occurrence of trade-offs in ES, representing 34% of the total studies. The existing pattern of using natural resources is responsible for 17% of trade-off relationship whereas climate change has also been regarded as the major factor responsible for the trade-off as mentioned by 6% of the selected articles.

[Figure 8 here]

Various actors and stakeholders are concerned with the trade-offs in ES. Based on this review analysis, 96% of the literature showed that land users are primarily concerned with the trade-off, followed by government agencies (68%), companies (16%), recreationists (15%), citizens (14), and others (3%). About 85% of the total articles directly or indirectly recommended measures to mitigate trade-off analysis. About two-thirds of the articles recommended management interventions as the best measure to mitigate trade-off in ES (Figure 8). Other recommended measures include allocation of incentives, advancement and adoption of technologies, empowerment of resource managers and land users, and compensation mechanisms to deal with the trade-offs in ES.

4. Discussion

4.1 Reflecting on the current research observations

4.1.1 Publication trend: number of publications, journals, contributors and geographical coverage

The concept and structural assessment of ES was institutionalized only after the MEA in 2005 (Laudari et al., 2019; Mengist et al., 2020a; Valencia Torres et al., 2021). Over the last 16 years, scientific communities have been growingly involved in studying ES, which is reflected through the trend of publication. For instance, the rise in publication about trade-off studies has increased from a single article in 2005 to 5 articles in 2010, which then increased to 75 articles in the year 2020. A study by Howe et al. (2014) found only 96 records of publications that were explicit about the trade-offs in ES between the year 2000 and 2013. Afterwards, the number of publications has increased substantially to reach 473 in 2020. However, in comparison to publications about broader aspect of ES, which was approximately 3,000 publications in 2016 (McDonough et al., 2017), the proportion of publications about the trade-off analysis is very low.

Although the selection of search string and database might differ in collecting the publication records, studies regarding trade-off assessment are still not adequate. Some researchers believe that the lack of evidence-based research and methodological uncertainties are responsible for the under-representation of the publications about trade-off analysis (Bai et al., 2020; Mach et al., 2015; Mengist et al., 2020a). Nonetheless, the coverage of publications by a wide range of academic journals shows that the concept is popularly accepted by many disciplines of conservation and development. Moreover, the top ten publishing journals, all being listed in quartile 1 ranking, covered more than 40% of the total publications. The acceptance of the research theme by broader categories of journals, and the growing uptake by high quality journals, indicate that studies on trade-off analysis are of high importance to both academic communities and funding organizations. Nevertheless, we observed the need for more rigorous empirical observation and sophisticated research methodologies for the research projects.

The trade-offs studies from more than 80 countries have shown that the emerging issue about the interaction of ES is widely acknowledged. However, those studies were mainly concentrated in developed countries and countries with growing economies. For example, 75% of the total studies were based in China, USA, UK, Canada, Australia, and European Countries. A study by McDonough et al. (2017) found that more than 70% of the ES publications were from USA and European countries. But in our case, China has led the publications in trade-off analysis. One of the reasons for this could be the priority of concerned stakeholders to assess and evaluate the impact of China's largest ecological restoration program, i.e., the Grain for Green Program, which has been implemented over the last two decades (He et al., 2020; Li et al., 2020; Zheng et al., 2014). Accordingly, two-thirds of the studies were concentrated in temperate and sub-tropical climatic zones. The tropical region, which is critical with respect to the trend of resource extraction and economic performance (Aryal et al., 2021a; Barlow et al., 2018), has only a few representations in the current literature (i.e., 12%). Similarly, alpine and sub-alpine regions and poles are underrepresented in the literature, which are disproportionately impacted by climate change. Although we did not restrict our literature review to the lands and landscape, as evident through the article screening criteria, the representation of the ecosystems has been dominated by agricultural land and landscapes. Very few representations of oceans, soils and other ES are depicted in the literature. This implies that ES from the ecosystem below land is underrepresented which might be because of the difficulties in the assessment of ES or the minimum interaction among ES in those environments. Unavailability of long-term research stations, data gaps, and lack of technical and financial resources are cited as the reasons for the minimum representation of ES publications from the tropics, alpine, sub-alpine, and poles (Buechley et al., 2019; Dang et al., 2021; Muenchow et al., 2018).

About 90% of the selected literature acknowledged that the studies received funding which implies that studies on trade-off analysis is objective-specific and have a growing interest to policy makers and funding organizations. Nevertheless, the involvement of government institutions in research publication is very low as compared to that of academic institutions. For example, researchers from government institutions engaged only in 9% of the studies, while researchers from academic institutions and research centers were involved in more than 97% and 25% of the publications, respectively. The current scenario of the availability of funding for research on trade-offs is optimistic, however, in order to connect the findings of the research to policy decisions, the involvement of researchers from government institutions is crucial (Costanza et al., 2017; Liu et al., 2021; Phillipson et al., 2012; Tallis et al., 2011). More than two-thirds of studies were concentrated in the developed countries of the temperate region and about 90% of the studies on trade-off analysis received research funding. This portrays a small yet important argument that donors from developed countries or the funding organizations are unwilling to allocate budgets for undertaking ES research in globally important ecosystem hotspots in the tropics. Perhaps, difficulty in data collection in different parts of the world (i.e., tropics and poles) is also likely to affect the geographical distribution of the recorded studies about trade-offs in ES.

4.1.2 Reflection of methods used to characterize trade-offs in ES

The interactions of ES can be explained in various ways, such as through descriptive analysis, mapping, bundling, valuation, simulation and modeling, and statistical analysis (Mengist et al., 2020b; Sieber et al., 2021; Valencia Torres et al., 2021). Correlation analysis between ES has been popular in explaining the relationship of the ES, followed by the multivariate statistics (i.e., principal component analysis, multi-criterion analysis, clustering, and redundancy analysis). For example, principal component analysis was done in more than 40 articles from the selected literature. Our assessment corroborates with the findings of Lee and Lautenbach (2016), indicating that correlation coefficient and multivariate statistics are the popular tools to assess the relationship among ES. Statistical analysis clarifies the linear and non-linear relationship among ES through statistical inferences but it is likely to overlook the logic of relationship and its causal interaction and phenomenon (Liu et al., 2019; Zhou et al., 2019). Some of the previous literature (Acharya et al., 2019; Aryal et al., 2021b; Garcia et al., 2018; Lara-Pulido et al., 2018; Naime et al., 2020) articulated economic valuation as the popular method in assessment of ES; however, our study found biophysical indicators as the most prominent methods in understanding relationship among ES, as observed in one-third of the selected literature. This indicates that economic valuation is not the only measure to guide the optimal management of ES, but the assessment of ecological parameters and biophysical constraints also provides a framework for sustainable ecosystem management (Capriolo et al., 2020; King et al., 2015; Paudyal et al., 2020).

Similarly, spatial analysis and mapping of ES has also been popular in the selected literature. Various spatial tools (i.e., Land Utilization and Capability Indicator-LUCI, Soil and Water Assessment Tool-SWAT, Integrated Valuation of Ecosystem Service and Trade-offs-Invest, and Artificial Intelligence for ES-ARIES) are being used in the assessment of relationship of ES (Cong et al., 2020; Sharps et al., 2017). Our review however shows that InVEST tool was predominantly used in more than 60 studies. Although ARIES is being preferred due to its flexibility in data management, transparency, and replicability (Capriolo et al., 2020), the reason for the use of InVEST might be due to the availability of comprehensive user manual and provision of example data model for easy use (Agudelo et al., 2020; Sharps et al., 2017). Further, research trends yet are limited to a single spatial scale which is insufficient to capture the telecoupling phenomena and cross-spatial relationships among various ES (Qiu et al., 2018). Although few studies (i.e., Dick et al., 2014; Fagerholm et al., 2019; Martín-López et al., 2019) have analyzed cross-scale assessment of ES, the analysis of trade-offs in ES at one landscape and its direct or indirect impacts on ES dynamics to the other in different geographic locations has not been critically examined yet.

Spatial analysis and mapping is good at visualization of spatial associations of ES (Zhou et al., 2019). However, ecosystem functioning of nature varies over time (Acharya et al., 2020a; Koch et al., 2009) as well as spatial analysis is being criticized for being static and ignoring the landscape history of the ecosystem functioning (Vallet et al., 2018). In this regard, regular monitoring and systematic appraisal of temporal changes in ES is crucial for designing sustainable policy solutions (Braun et al., 2018; Jaligot et al., 2019; Rau et al., 2018). Our findings reveal that only one-third of the total studies have considered temporal analysis while assessing the trade-off relationship, in which most of the studies were based on historical observation of 11-30 years. Only about 10% of the total studies were based on the analysis of time consideration of more than 30 years. Temporal analysis of natural processes is the only way to investigate linear and non-linear (i.e., periodic or event based) dynamics of ecosystem functioning (Rau et al., 2018), but we found a lack of such studies in trade-off analysis which might be due to data gaps and uncertainties in available methodologies to explore such dynamics (Muenchow et al., 2018). A review by Obiang Ndong et al. (2020) also found that less than 10% of the studies about relationship of ES considered temporal analysis, which is less than our findings probably because their review was based on the article before 2017, and studies on temporal analysis might have increased in the last few years.

In order to characterize the interaction of ES, the fitting of the production possibility frontiers (PPF) from a macroeconomic perspective, is highly recommended in recent literature (Ager et al., 2016; Lang and Song, 2018; Vallet et al., 2018). In our review analysis the concept of PPF was used by only 8% of the total studies. The research trend indicates that studies are more focused on assessing the static spatial correlation among ES. Few studies also considered temporal dynamics of trade-offs in ES, by analyzing the changes in spatial correlation over time (i.e., temporal variations). However, studies were insufficient to capture the multifunctional dynamics of landscape structure and heterogeneity, as well as policy preferences and management interventions with regards to the ecosystem management. Scenario analysis and model simulation builds on simulated data and estimation of the parameters which merely reflect the real world situation (Zhou et al., 2019). Similarly, descriptive analysis explains the logics and narratives of emerging ES relationship but largely based on the qualitative judgment and limited applicability (Liu et al., 2019).

Because ES are intertwined with human welfare, not only the biophysical constraints (explained through PPF), but also the utility functions, which integrate divergent valuation by differing stakeholders, of the ecosystem should be considered while assessing trade-off relationship (Cabral et al., 2017; King et al., 2015; Stosch et al., 2019). Research trend shows that only 6% of the total studies have considered both biophysical constraints and utility functions, and about 84% of the studies were based on biophysical constraints only. Optimal allocation of ES and creation of win-win situation among the competing users is only possible through the consideration of utility functions of different stakeholders groups (Rieb et al., 2017; Stosch et al., 2019). Having considered the policy implications of the studies, analysis of the mere biophysical constraints could be limited to the academic repositories unless it is accompanied with utility functions of the competing stakeholders' group when analyzing trade-off in ES.

4.1.3 ES interaction, drivers and stakeholders

Carbon and climate service of the ecosystem was the most studied ES in the selected literature, followed by crops and grains, and biodiversity. The inclusion of those three ES implies that trade-off analysis is crucial to balance provisioning and non-provisioning ES, ranging from local users to the global communities (Muldowney et al., 2013; Zhu et al., 2019). A high number of conflicting pairs of ES (i.e., 198 pairs of conflicting ES) indicates that most of the ES are spatially exclusive and need to be dealt with caution while managing ES. A study by Lee and Lautenbach (2016) revealed that 74% of the pairs of ES are spatially associated. Further, Howe et al. (2014) recorded that trade-off relationships are three times higher than synergistic relationship among ES. In this regard, trade-offs are highly critical for ecosystem management. Out of the top ten pairs of ES, crops and grains was repeated eight times as having trade-off relationship with other ES. Trade-off between 'crops and grains' and 'carbon and climate service' has the highest record of observation in our review, which was also identified by other previous literature (i.e., Dang et al., 2021; Howe et al., 2014; Mengist et al., 2020b; Valencia Torres et al., 2021). This implies that agricultural production measures at the local level is challenging especially when international communities are opted for ensuring ES of the global importance. And, future course of action must consider the climate friendly approach to the production of crops and grains. Unlike the previous literature, our review reveals that 'crops and grains' have 2nd and 3rd highest records of conflicting interaction (i.e., trade-offs) with 'water conservation and regulation', and 'soil retention', respectively. This indicates that there is a growing competition over agricultural production and productive capacity of the landscape (i.e., water regulation and soil retention) which seems to be further exacerbated by the impact of climate change and land use change. Besides, only one cultural ES (i.e., recreation and tourism) has been listed in the top ten trade-off pairs of ES. This indicates that there is a tendency of trade-off assessment mostly in biophysical terms, in which various other cultural ES are overlooked because of difficulties in its measurement in biophysical or monetary terms.

Not only the social and economic drivers are responsible for trade-off among ES, but also the ecological characteristics of the landscape in itself is responsible (Turkelboom et al., 2018). Ecological processes of landscapes, such as biophysical and chemical processes, collectively drive primary production and distribution of biodiversity. Further, such ecological processes are influenced by various natural and human interferences (i.e., land use change, management intervention, chemical use, and technological experimentation) (MEA, 2005; US EPA, 2017). Intrinsic ecological dynamics, as well as spatial and temporal changes in the ecological processes due to various natural stressors (i.e., temperature and precipitation extremes) and human activities, and limited productive capacity per unit area of the landscape, determine trade-offs in ES (Andersson et al., 2007; Hansson et al., 2012). Our findings show that the highest occurrence of trade-off (i.e., >60% of the total cases) is explained by ecological drivers (i.e., multifunctional capacity/constraints of the ecosystem). Although, it depends on whether the study solely focused on biophysical parameters of the ecosystem or it also encompasses changing social preferences, we found substantial records of ecological trade-offs and environmental variability in spatial planning for conservation and development, which is also supported by other literature (i.e., Dade et al., 2019; Turkelboom et al., 2018). Nevertheless, we believe in the use of socio-ecological system in understanding the drivers of trade-offs as mentioned by Lu et al. (2021).

A study by Obiang Ndong et al. (2020) found that land use change is the major drivers of trade-offs in ES. However, our findings reveal that in addition to land use change, the change in management objectives of the landscape drives the trade-off relationship among ES. In this regard, we stress the need of understanding utility functions of the ecosystem while analyzing trade-off relation to guide the future pathways of sustainable ecosystem management. Moreover, the highest concern of local resource users (>95%), followed by agencies (68%) implies that the trade-off is prone to the changing land use practices of local land users, followed by various policy shifts or management interventions by government agencies.

Regarding recommended measures to address the trade-off relationship, instead of blueprint prescription of incentives and compensation (Naime et al., 2020), we found that 75% of the selected publications indicated for correction in management intervention to address the trade-off relation and to create sustainable solutions. This finding reinforces on the need of identification and analysis of landscape-specific interaction among ES, and exploration of the optimal site-specific management prescription considering both biophysical constraints and utility functions of ES. Nonetheless, incentive and compensation for ecosystem management (i.e., payment for ecosystem services) have also been successful in some regions because of the sound institutional arrangement (Aryal et al., 2019; Grima et al., 2016), while others advocate for empowerment and capacity building of the ecosystem beneficiaries (Davis and Goldman, 2019; Tampubolon, 2020). The findings will support in program articulation of UN Sustainable Development Goals, institutionalization of UN Decade on Ecosystem Restoration, and implementation of the post-2020 Global Biodiversity Framework.

4.2 Future trajectories of research on trade-offs in ES

The discourse of ES has been at the core of environmental affairs after MEA, however the concept of interaction and/or associations among various ES is yet to bring to the frontline of discussion in sustainability science (Obiang Ndong et al., 2020). The archetypes of the relationship among ES is barely discussed, for example, whether it is causal relationship (i.e., interaction) or correlations (i.e., associations) (Obiang Ndong et al., 2020; Vallet et al., 2018). A forested landscape may not produce grains and we may not call it a trade-off relationship between timber and food production, so a snapshot approach to the assessment of ES association, as quoted by Obiang Ndong et al. (2020), should not be the priority. Instead, the causal relationship among the ES, abide by the influence of policy scenarios or management interventions and also reflected through the lens of beneficiaries (local and non-local stakeholders) should be the future concern of trade-off analysis.

Remarkable shifts in research priorities can be observed in ES. For example, the impact of rapid urbanization and industrial development on ecosystem assets had been the research priority until the end of 20th century (Costanza et al., 1997). Although environment conservation and economic development were the two extremes of discursive struggle in academia, research were concentrated to analyze the trade-offs between direct use value of ES (i.e., for economic development) and its indirect use (i.e., sustainable and wise use) (Dang et al., 2021; Seppelt et al., 2011). In the beginning of 21st century, research priorities were shifted towards quantification and economic valuation of ES which mounted the focus of research in articulating a notion that indirect benefits of ES are much higher than the economic gains from direct use benefits of ES (Acharya et al., 2019; Costanza et al., 2017). Since MEA-2005, research topic in ES has been moved towards assessing the relationships among ES and how they interact with the stressors (i.e., climate change, extreme events, and human interference) (Obiang Ndong et al., 2020; Valencia Torres et al., 2021; Wen et al., 2020).

Recently, research arena in ES has embraced the sustainable framework of ES management, which includes both biophysical and social aspects of ES management (Cavender-Bares et al., 2015b; King et al., 2015). While observing the research trends and current practice of ES studies, the next step is to satisfy the growing and diversified need of various ecosystem beneficiaries through optimization of ES while sustaining the production and productive capacity of ecosystem assets to supply various provisioning and non-provisioning ES. In this regard, future research trajectory should embrace biophysical interaction of ES, including cross-spatial and cross-temporal dynamics, as well as diversified needs of local and non-local ecosystem beneficiaries (Dick et al., 2014; Harmáčková and Vačkář, 2018; Martín-López et al., 2019). Further, institutional dynamics of ecosystem management, drivers of change in ES interaction, and responses to the contemporary management intervention should be the future concern of research in ES trade-offs (Costanza et al., 2017; Khosravi Mashizi and Sharafatmandrad, 2021). Comprehensive assessment of socio-ecological trade-offs in ES, including drivers of change and management responses would be a promising framework to policy makers for decision making in sustainable ecosystem management to satisfy both local and global needs of ES.

The proportion of availability of funding for ES research (i.e., about 90%) shows that the trade-off in ES is a pertinent issue to the decision maker. However, in order to link the science of the research to policy and society, the engagement of government institution and empowerment of management practitioners in scientific arena (i.e., practitioner-cum-scholar) should be the priority of funding organizations (Costanza et al., 2017; Phillipson et al., 2012). Similarly, tropical region with the hotspot of biodiversity and climate service globally is under-represented in the currently available literature (Muenchow et al., 2018). Moreover, climate sensitive ecosystem in the alpines regions and poles are not studied adequately. The future course of research should be directed to the hyper-diverse tropical region and climate sensitive alpine zones, and accordingly, adequate technical and financial support should be directed to the developing countries in these areas.

Simple descriptive analysis, mapping of spatially explicit ES and correlation analysis provide the coarse indication of ES association (Obiang Ndong et al., 2020). Moreover, the influence of management interventions and causal inferences are largely unknown in the previous literature on trade-off in ES (Ikematsu and Quintanilha, 2020; Vallet et al., 2018). Therefore, the interaction of ES should be diagnosed using multivariate methods while considering the multidimensional production possibility (i.e., Pareto optimal) of the ecosystem. PPF embrace the economic concept of production possibility with due consideration of natural capital, ecosystem functioning, and management inputs while defining the optimal land use decision for sustainable ecosystem functioning (Cabral et al., 2017; Cavender-Bares et al., 2015b). Determination of utility functions through the identification of value preferences of land users and other stakeholders guides policy and management prescriptions for decision makers (Cabral et al., 2017). Accordingly, future trade-off research should be focused on comprehensive analysis of PPF of the ecosystem and utility functions of the stakeholders at multifunctional landscape level. Moreover, to cope with the interconnectedness among ES, landscape multifunctionality, and uncertainties of climatic scenarios, future course of trade-off analysis should embrace alternative policy simulations and future scenario analysis. The use of long-term data sets (i.e., >30 years) and comprehensive understanding of ecosystem gradient at broader landscape or river basin scale (integrating upstream-downstream linkages of ES) must the priority of future research on trade-off in ES.

Be it a developed or developing country, agricultural production is the most frequently observed ES to have negative interaction with other ES (Power, 2010; Valencia Torres et al., 2021). In addition, projected double demand of food production by the middle of the century further highlights the need for sustainable framework of ecosystem management (Cavender-Bares et al., 2015b; Chabert and Sarthou, 2020). In such scenario, biophysical constraints of the ecosystems in terms of supplying other critical ES (i.e., water regulation, soil retention, carbon, and biodiversity) should be on the priority to examine its trade-off relationship with agricultural production under future policy alternatives. Consideration of how the trade-off relationship among ES impact on livelihoods of local resource users and on the overall sustainable development goals must be made in future studies on ES (Schirpke et al., 2019; Wood et al., 2018). Incentives for ecosystem conservation and compensation for the potential loss of ES could be the immediate tools for minimizing the stress of the trade-offs; in the long run however, capacity building of the local resource users, innovation and upscaling of technologies, and management interventions should be the priority of both scholars and policy makers for creating sustainable solutions through the optimization of desired ES.

We cannot have all the desired ES simultaneously, and thus trade-offs exist while making the choice of ES. To deal with the trade-offs, policy makers should focus on multifunctional landscape management in accordance with the choice of local and non-local stakeholders, and within the biophysical capacity of the landscape (Acharya et al., 2020b; Aryal et al., 2021b). Further, capacity building and financial backstopping to the developing countries in the tropics should be the priority of action for global community to reverse the current state of ecosystem degradation. In addition, we recommend trans-disciplinary approach to trade-off analysis through the engagement of government institutions and community people to support the policy adoption of research findings. As a limitation of our review methods, we performed our analysis based on articles enlisted in Scopus and Web of Science; consideration of other databases, inclusion of grey literature and articles published in languages other than English might further clarify our findings.

5. Conclusions

We selected and examined 473 research articles based on empirical observation of the trade-offs in ES globally. Our finding shows that the number of publications about trade-off analysis is substantially increasing; however, snapshot assessment of spatial association is dominating the literature. Most of the studies were concentrated in temperate regions while the tropical regions in developing countries are under-represented. Despite the high proportion of funded research (i.e., about 90%) low engagement of government institutions (<10%) weakens the policy linkage of the research findings. On one hand, two-thirds of the studies were solely based on spatial analysis without depicting the temporal changes, and on the other hand, interpretation of the trade-off relationship was predominantly based on the correlation analysis. For that reason, it is important to carry out multi-criterion analysis of trade-offs in ES, embracing causal relationship and interactions both at spatial and temporal scale.

Further, the interpretation of trade-offs in ES from the perspective of biophysical constraints only (>80% articles) outlays that the utility functions, which explain the divergent values of ES to the different stakeholders, was the most forgotten aspect of the trade-off analysis. Out of the total observation of 198 pairs of conflicting ES, crops and grains was the most frequently occurring ES that showed trade-off relationship with carbon and climate services (94 cases), followed by water conservation and regulation (85 cases), and others. Ecological drivers were prominent in characterizing the trade-off relationship. Nevertheless, land use change and change in management objectives of the landscape were found as the causal factors for most cases of trade-off relationships, highlighting the major role of land users and management agencies in trade-offs in ES. In addition to the immediate measures to minimize trade-offs in ES (i.e., incentives and compensation), our review shows that correction in management intervention is the highly recommended measures to create win-win situation among ES and accordingly the beneficiaries.

Based on our review assessment, we found some critical yet important research gaps that need to be considered for future studies: (1) trade-off analysis should be directed towards analyzing causal interaction among ES rather than the spatial assessment of associations of ES, (2) more studies are needed to represent the tropical ecosystem in developing counties which are under immense socio-economic pressure and climatic uncertainties, (3) trade-off analysis should be built upon the multi-criterion analysis to outlay the production possibility frontiers, considering both spatial and temporal dynamics of ecological and social drivers of trade-offs, (4) trade-off studies should be carried out to capture integrated ecosystem gradient at the broader landscape level or at the river basin level, for comprehensive understanding of the interactions among ES, (5) in addition to the assessment of biophysical constraints of the ecosystem, varying preferences and valuation to different beneficiaries should be mainstreamed in the trade-off analysis to create win-win solutions to ecosystem management, and (6) policy (alternative) scenarios and uncertainties must be adjusted to the trade-off analysis to ensure sustainable flow of ES under complex land use dynamics and future climate change scenarios.

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