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Integrating supply, flow and demand to enhance the understanding of interactions among multiple ecosystem services

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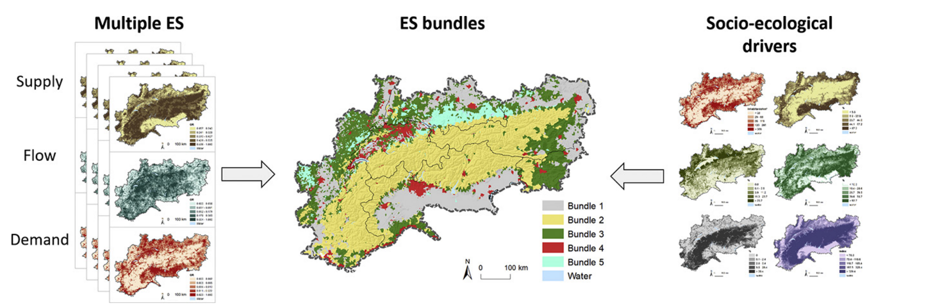
HIGHLIGHTS

- The complexity of relationships among multiple ES is not fully understood.
- We analysed eight key ES assessing supply, flow and demand.
- We applied a multistep approach including various statistical analyses.
- Five ES bundles revealed spatial linkages between major supply and demand areas.
- Socio-ecological variables effectively predicted the distribution of bundles (81%).

GRAPHICAL ABSTRACT



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ABSTRACT

A comprehensive understanding of the relationships among ecosystem services (ES) is important for landscape management, decision-making and policy development, but interactions among multiple ES remain under-researched. In particular, earlier studies often did not clearly distinguish between supply, flow and demand. Furthermore, the underlying mechanisms in complex socio-ecological systems remain less examined. In this study, we therefore aimed to assess interactions among eight key ES, adopting a multistep approach. For all ES, we mapped ES supply, flow and demand at the municipality level in the Alpine Space area. We applied correlation analysis and cluster analysis in order to analyse the linkages between ES and to identify bundles of ES. We used random forest analysis to explain the distribution of the ES bundles and to identify important drivers based on socio-ecological variables (e.g. land use/cover, climate, topography and population density). Our results demonstrate that trade-offs and synergies varied greatly for supply, flow and demand. We identified five ES bundles, distinguishing hotspots of ES supply and demand. Twelve socio-ecological variables correctly predicted the membership of 81% of the municipalities to the ES bundles. Our results suggest that a limited number of socio-ecological variables can explain the majority of the distribution of ES bundles in the landscape. Considering the spatial relationships between mountain regions and their surrounding lowlands, regional and transnational governance frameworks need to connect areas of multiple ES supply to areas of ES demand, and should account for the different levels and types of ES relationships.

1. Introduction

Understanding the relationships among ecosystem services (ES) represents one of the key challenges for efficiently managing multiple

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ES and integrating them into landscape management, decision-making and policy development (Howe et al., 2014; Mach et al., 2015; Raudsepp-Hearne et al., 2010). In particular, knowledge of the relationships between ES is decisive in discerning situations where an increase in one service may cause a decrease in others (trade-offs), or where synergetic relationships between services may lead to their concurrent enhancement (synergies) (Bennett et al., 2009). Management actions aiming to improve selected ES may consequently have positive or negative effects on other ES, as underlying direct or indirect mechanisms often influence several ES at various spatial and temporal scales (Cord et al., 2017). In the past, the increase of ES provision, such as food and fibre, has often reduced regulating and cultural services such as water regulation and carbon sequestration, as well as aesthetic, recreational and cultural values (Egarter Vigl et al., 2016; Locatelli et al., 2017; Raudsepp-Hearne et al., 2010). A trade-off may be a deliberative decision, but trade-offs also often arise unintended or unexpected (Rodríguez et al., 2006). Hence, decision-makers today face the challenge of considering multiple ES rather than concentrating on selected ES (Polasky et al., 2011).

While the number of studies addressing ES trade-offs and synergies is growing, there has been an increasing recognition of the relevance of conducting dedicated studies focusing on mountain areas both for science and decision-making (Locatelli et al., 2017; Sil et al., 2016; Howe et al., 2014). Mountain regions are, in fact, key supply areas for several ES, such as water regulation, timber production, grazing and recreation (Grêt-Regamey et al., 2012). These areas provide benefits not only to their inhabitants and tourists, but also to those living in the adjacent lowlands, which are usually more highly populated (Marston, 2008). Moreover, mountain ecosystems and associated ES are especially vulnerable to land-use and climate change (Bürgi et al., 2015; Schröter et al., 2005). In particular, agricultural intensification has degraded regulating and cultural ES (Locatelli et al., 2017), whereas recent landscape developments, i.e. the abandonment of marginal grassland areas, have resulted in a shift in ES from provisioning to regulating services due to natural reforestation processes (Egarter Vigl et al., 2016; Schirpke et al., 2017). Land-use policies and management decisions that account for interconnections among multiple ES can therefore enhance regulating and cultural services as well as support a high level of biodiversity (Briner et al., 2013; Crouzat et al., 2015; Kirchner et al., 2015), and thus connect areas of multiple ES supply to specific beneficiary groups (Schirpke et al., 2014; Wolff et al., 2015).

The relationships among multiple ES are highly complex and context-specific (Howe et al., 2014). In spite of an increasing number of studies, knowledge regarding common patterns in ES relationships are inchoate due to several reasons. Earlier studies often provided limited insights owing to a low number of ES (Ring et al., 2010). More recent studies have assessed multiple ES and their relationships mostly within respective regions or countries (Mouchet et al., 2017; Schröter et al., 2016), and may therefore fail to include ES that are important in other landscapes or socio-ecological systems. Analysing interregional relationships between multiple ES allows to capture distant interdependencies and impacts (Schröter et al., 2018), but only a few studies have addressed multiple ES over large geographical scales and often limited their analysis to ES supply (Mouchet et al., 2017). Despite the increasing number of studies comparing the supply, flow and demand of single ES (Schröter et al., 2016), a precise distinction between the indicators is rarely applied in the analysis of relationships between multiple ES, and indicators for ES supply and flow are often used indistinctively (Spake et al., 2017). Recent literature advances multiple definitions of ES supply, flow and demand (Burkhard and Maes, 2017; Wolff et al., 2015; Burkhard et al., 2014; Villamagna et al., 2013) and varying understandings of the relationships between these components (Schröter et al., 2017; Burkhard et al., 2014; Burkhard et al., 2012). Following Burkhard and Maes (2017), in our study, we define ES supply as the capacity of ecosystems to provide ES regardless of their being used, whereas ES flow refers to the actual level of use. Demand for ES instead represents the amount of a service required or desired by society, expressed through stated preferences and values or direct use (Wolff et al., 2015). A clear separation of these different aspects of ES is the first step to understanding not only their spatial relationships, but the potential results of trade-off analysis (Mouchet et al., 2014). Given that the outcomes of trade-off analysis can be biased by the method of assessment used (Martín-López et al., 2014), a combination of different methods may more effectively account for the different characteristics of supply and demand (Mouchet et al., 2014). Finally, underlying mechanisms have rarely been examined owing to a lack of data and the complexity of socio-ecological systems (Meacham et al., 2016; Mouchet et al., 2017). Hence, comparisons across studies are difficult due to diverse scales and methodologies, hampering generalisations of local or regional outcomes and the separation of context-dependent drivers from actual interactions between multiple ES (Queiroz et al., 2015).

Given the aforementioned challenges in understanding the relationships among multiple ES, this study aimed to assess interactions among eight key ES in the Alpine Space area. The area comprises the European Alps as well as the adjacent lowlands, facilitating analysis of the complex relationships between areas of high ES demand and areas of high ES supply (Grêt-Regamey et al., 2012). We extended earlier studies on multiple ES (e.g. Crouzat et al., 2015; Raudsepp-Hearne et al., 2010; Spake et al., 2017) by integrating and clearly distinguishing among ES supply, flow and demand, enabling identification of the differences in relationships and dependencies among the three components. In order to systematically assess the relationships between multiple ES, we adopted a multistep approach, with three specific objectives (Fig. 1):

(1) to analyse trade-offs and synergies between ES;
(2) to identify ES bundles across different landscapes;
(3) to identify the socio-ecological drivers that determine ES bundles.

These analyses provide a comprehensive picture of the interactions among multiple ES, and are intended to contribute to the understanding of the dynamics between multiple ES and to support decision-making at the regional as well as cross-national level.

2. Materials and methods

2.1. Study area

The 'Alpine Space Programme' cooperation area is a region in Europe that covers the European Alps and surrounding foothills and lowlands (Fig. S1 of the supplementary material). It comprises an area of approximately 390,000 km^2 across Austria, Switzerland, Liechtenstein and Slovenia, as well as several regions of France, Germany and Italy. Due to its scale, significant topographical and climate variations and different cultures, the landscape is very heterogeneous. The Alps are characterised by a diversified cultural landscape, strongly influenced by traditional small-scale farming practices (Flury et al., 2013), and in spite of the intensive use of their valley bottoms, represent one of the largest continuous near-natural areas in Europe (Alpine Convention, 2016). In contrast, the surrounding lowlands and foothills are dominated by large-scale intensive agriculture and economically very active metropolitan regions (Dematteis, 2009). The Alpine Space area comprises a population of about 70 million, concentrated in urban agglomerations in the lowlands. Furthermore, the Alps are highly appreciated for tourism and receive about 500 million visitors per year (Bartaletti, 2007).

2.2. Mapping ES

This study focused on eight ES that were identified as relevant for the study area, including three provisioning services (drinking water