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Analyzing Spatial Congruencies and Mismatches between Supply, Demand and Flow of Ecosystem Services and Sustainable Development

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Abstract: Ecosystem services (ESs) are increasingly included into decision-making to achieve Sustainable Development Goals (SDGs). Although both concepts consider the interactions between humans and the environment, spatial relationships between ESs and sustainability have been rarely addressed. Therefore, this study aims at analyzing spatial congruencies and mismatches between ESs and sustainability in the greater Alpine region. Using hot spot and overlap analyses, we overlaid maps of supply, demand and flow of eight key ESs with the spatial distribution of sustainability based on 24 indicators. Our results reveal that, in most cases, supply of and demand for ESs are greatly dislocated. These mismatches are reflected also in the spatial distribution of sustainability. In contrast to ES demand hot spots, supply hot spots are generally characterized by high sustainability levels, especially in relation to the environment. However, due to discrepancies in the social and economic dimensions, it cannot be assumed that ES supply hot spots always correspond to high sustainability. Hence, using ES indicators for measuring sustainability provides rather limited insights. We conclude that both concepts should be applied in a complementary way to maximize ecological, social and economic benefits in land management and planning processes.

Keywords: sustainability indicators; ecosystem services mapping; socio-ecological system; European Alps; spatial analysis; supply-demand mismatches; hot spot analysis; overlap analysis

1. Introduction

It is increasingly recognized that the integration of ecosystem services (ESs) into landscape management, decision-making and policy development may support a responsible use of natural resources and contribute to sustainable development [1,2]. ESs are broadly defined as the benefits that humans obtain from ecosystems, mostly co-produced through human interventions [3]. ES provision, however, is highly determined by the spatial characteristics of ESs and environmental conditions [4–6]. This may cause trade-offs and synergies among ESs [7,8], or lead to dependencies of people from certain areas (e.g., lowland populations depending on fresh water from mountain regions) [9]. Moreover, interactions among stakeholders influence whether people actually obtain the benefits from ESs, as these power relationships determine access, management and use of ESs [10,11]. As the concept of ESs originally focused on the consequences of biodiversity loss for future human well-being [12], they would seem to be well aligned with a sustainable use of natural resources [13], but this largely disregards norms of sustainable use such as social equity and justice [11,14]. According to the Brundtland report in 1987, sustainability is defined as a development that meets human needs of current and future generations without overexploiting natural resources [15]. This overall goal can only be realized through the integration of environmental, social and economic aspects and the acknowledgement of related values in decision-making and the development of policies [16]. Recent strategies towards sustainability have often been based on a secure supply of ESs to fulfil the essential needs of people and to strengthen human well-being on the long term [17]. ES indicators may provide a useful approach to monitor and evaluate the progress made towards sustainability goals (e.g., UN Sustainable Development Goals (SDGs) and the Convention on Biological Diversity (CBD) Aichi Targets) [18,19]. In particular, knowledge of the consequences for people as ESs change (i.e., who will be positively and who will be negatively affected), can contribute to finding the right balance between nature conservation and socio-economic development [20].

Although both concepts assess and evaluate the relationship between humans and the environment, there is a need to include ESs into broader sustainability goals and to re-orientate ESs towards the normative goal of sustainability [14,21]. This will enhance an understanding of the contribution of ESs in accordance with the broader SDGs [13,21]. Despite emphasizing the need for a common understanding and proposing possible strategies, studies highlighting spatial congruencies between ESs and sustainability based on indicators are still lacking. After a period of elaborating rather theoretical concepts [6,22–24], the recent focus of research on the implementation and operational use of ESs [25–27] may support an evaluation of the assumed linkages with sustainability. However, several issues still need to be addressed. These include enhancing indicators based on ecological functions and processes to evaluate the consequences of management choices or changes in the demand for ESs [28–30]. This requires a comprehensive view on supply, demand and flow to assess spatial interactions and trade-offs [31,32], as several studies have emphasized that spatial mismatches between demand and supply occur at various scales [4,5,33–35]. Consequently, goods and services may need to be transported to beneficiaries, or people need to move to supply areas (e.g., to benefit from recreational opportunities) [4,36,37]. An increased understanding of these interactions can reveal dependencies of beneficiaries from ecosystems that are located in other regions or countries, allowing decision-makers to adopt sustainable solutions [36,38]. However, it remains unclear how supply, demand and flow of ESs are related to the level of sustainability, and whether a high ES provision indicates a high level of sustainability at the local and regional scale. Hence, to monitor the outcomes of policies and management strategies to enhance the provision of ESs and foster a sustainable development, clear measures are required to map and quantify the economic, environmental and social dimensions of sustainability [39–41]. Although general frameworks and indicators exist to monitor changes in sustainability [18,38,42], the local- and region-specific environmental and socio-economic characteristics need to be taken into account, which often requires an adaptation of existing indicators or the development of new context-specific indicators [43].

To contribute to an understanding of the linkages between ESs and sustainability, this study aims to analyze spatial congruencies and mismatches between spatial patterns of ESs and sustainability, focusing on the European Alps and surrounding lowlands. We address this objective by first providing a conceptual framework (Section 2.1) to explain the linkages between ESs and sustainability within a socio-ecological system (SES). In Section 2.2, we provide a description of how we mapped supply, demand and flow of eight key ESs. Section 2.3 explains the calculation of a cumulative sustainability index based on 24 indicators referring to environment, society and economy. In Section 2.4, we describe the spatial analyses, which we carried out to assess spatial patterns and dependencies, including hot spot and overlap analyses. The results section first presents spatial patterns of the various ESs (Section 3.1), and then illustrates the spatial congruencies and mismatches with sustainability (Section 3.2). We discuss our results pointing out their relevance for decision-making and indicating the limitations of the study (Section 4). Finally, we draw conclusions on the usefulness of our findings for decision-making and point out further research needs (Section 5).

2. Materials and Methods

2.1. Conceptual Framework

To analyze spatial congruencies and mismatches between ESs and sustainability, we used a conceptual framework (Figure 1), which was adapted from other theoretical frameworks [10,44]. An SES generates ESs that are crucial to human well-being [12,44]. Ecological functions and processes of ecosystems (ES supply) generate goods and services that are demanded by society (ES demand) (i.e., there is a directional flow from the ecosystems to the beneficiaries) [37,45]. The capacity of the ecosystems to provide ESs is influenced by environmental assets such as climate, land-use/cover and topography [45], but stakeholders and land managers may alter the ecosystems to increase the provision of desired ESs through environmental management [30,46–48]. Actors of the SES with their social and economic relations determine furthermore the type and level of use of the ecosystems (ES flow) [10,49], which may result in an unequal distribution of ESs, or prevent people from having access to ESs. The regional SES (our study area) is embedded into the global SES, and interacts with it through the import or export of ESs.

In this study, we follow the definition of the Brundtland report, which refers to sustainability in terms of a sustainable development [15]. This concept, which considers the three dimensions of environment, society and economy as equally important [15], aims at supporting long-term socio-economic progress while protecting the environment, i.e., human well-being and social equity of current and future generations can only be assured when environmental limits are respected [50]. In the regional SES, the three dimensions are located in both the supply-side and the demand-side of ESs (Figure 1). Sustainability indicators, which are specific indicators related to the three dimensions of sustainability [40], can indicate linkages of ESs with sustainability.

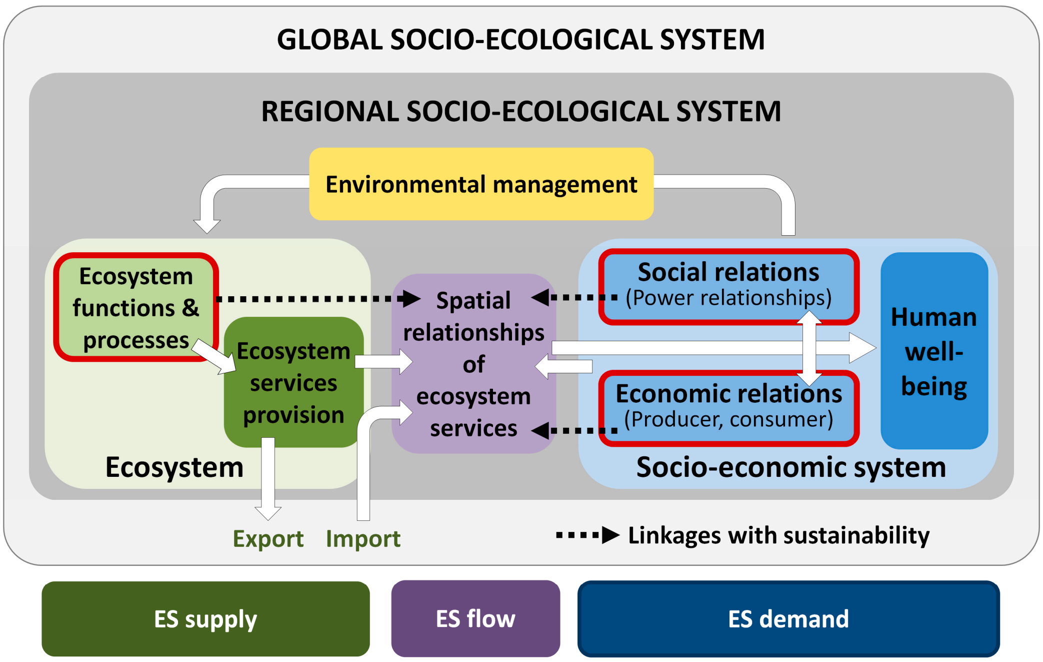

Figure 1. Conceptual framework to analyze spatial relationships between ESs and sustainability (adapted from [10,44]). White arrows represent the linkages between the ecosystems and the socio-economic system, influencing ES provision and spatial relationships of ESs. The spatial dependencies between ES supply and ES demand determine the flow (actual use) of ESs. The three dimensions of sustainability are indicated by red frames. The linkages of ESs with sustainability (black dotted lines) are measured by sustainability indicators.

In this study, we first mapped the supply, demand and flow of eight key ESs based on biophysical indicators. We conducted hot spot analyses to quantitatively describe spatial patterns and dependencies among the supply, demand and flow for each ES. To relate supply, demand and flow of ESs to the level of sustainability, we derived a cumulative sustainability index based on 24 sustainability indicators. By carrying out overlap analyses, we finally identified and analyzed spatial congruencies and mismatches between ESs and sustainability.

2.2. Study Area and Ecosystem Services

We carried out our analyses in the Alpine Space Programme cooperation area, which includes the European Alps and surrounding lowlands (Figure 2). It extends over an area of approximately 390,000 km^2 and comprises Austria, Switzerland, Liechtenstein and Slovenia, as well as several regions of France, Germany and Italy. Natural and semi-natural ecosystems including forests, grasslands, rocks and glaciers, are located mainly in mountainous municipalities, whereas intensive agriculture and urbanized areas are situated mainly in the main Alpine valleys and surrounding lowlands [8]. Almost 70 million people live in the study area, most of them in urbanized areas in the surrounding regions of the European Alps or large Alpine valleys. Tourism plays an important role, especially in mountainous areas and along the coastline.

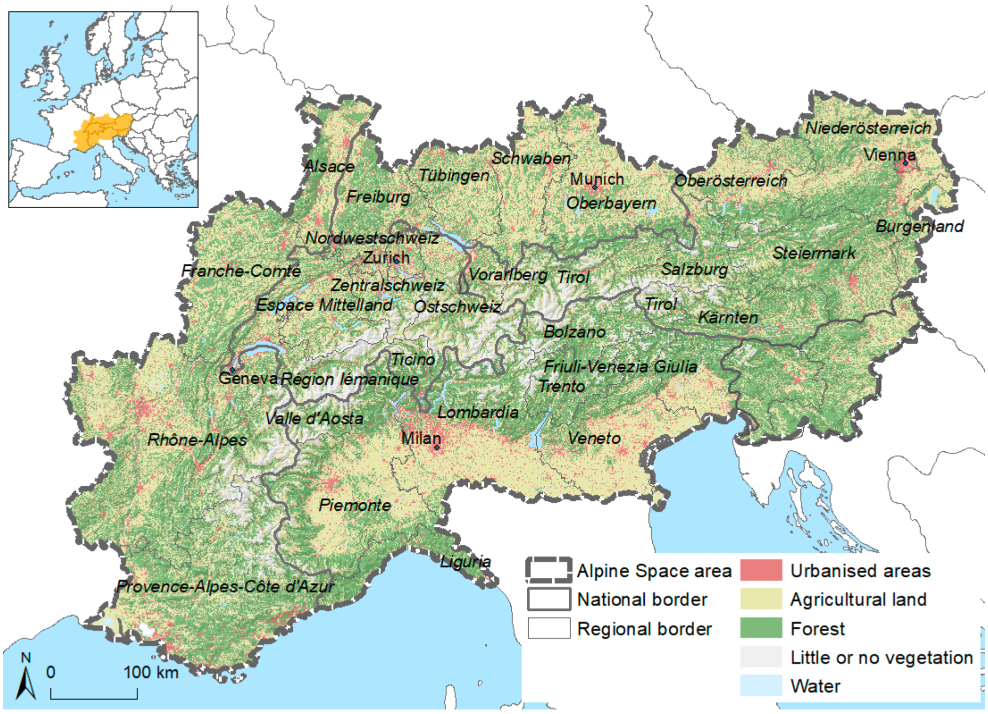

Figure 2. Location of the Alpine Space area, and national as well as regional administrative boundaries.

Numerous ESs were provided by mountain ecosystems, including fresh water provision, climate regulation and outdoor recreation [51]. In a previous study, we mapped eight ESs [8], which we used as the ES information in this study (Table 1). These ESs were identified as key ESs for our study area based on an extensive literature review, workshops with experts and a survey of users [8]. For all ESs, indicators included supply, demand and flow (Table 1), with the exception of the demand for symbolic plants and animals that could not be assessed in spatial terms. Further details on the indicators and assessment methods are reported in Table S1 in the Supplementary Materials. The selection of the indicators was based on their scientific soundness, as well as comprehensibility for stakeholders and decision-makers, but it was largely influenced by data availability and the possibility to harmonize the data (i.e., to obtain datasets with a common thematic and spatial resolution for the whole study area). All indicators were mapped at the landscape level using raster data with a resolution of 25 m (grassland biomass, fuel wood, filtration of surface water, protection against mountain hazards, carbon sequestration) or 100 m (fresh water, outdoor recreation, symbolic plants and animals), except for some indicators of ES demand (e.g., fresh water, grassland biomass, outdoor recreation), for which we used data from population or agricultural censuses that were only available at the municipality level.

Table 1. Ecosystem services (ESs) and indicators used for mapping [8].

Category	ES	Supply	Demand	Flow
Provisioning service	Fresh water	Water availability	Water abstraction	Water use
	Grassland biomass	Gross fodder production	Feed energy requirements	Net fodder energy content
	Fuel wood	Wood biomass increment	Potential fuel wood requirements	Wood removals
Regulating service	Filtration of surface water	Potential nitrogen removals	Nitrogen loads	Effective nitrogen removals
	Protection against mountain hazards	Site-protecting forest [1]	Infrastructure in hazard zones	Object-protecting forest [2]
	Carbon sequestration	CO_2 sequestration by forests	CO_2 emissions	CO_2 sequestration by forests
Cultural service	Outdoor recreation	Outdoor recreation availability	Potential beneficiaries	Visitation rates
	Symbolic plants and animals	Habitats of symbolic species	-	Occurrence in hotel names

[1] Forest area with a protective effect against potential avalanches, rockfalls and channel processes. [2] Forest area with a protective effect for human infrastructure against potential avalanches and rockfalls.

2.3. Measuring Sustainability

To assess the level of sustainability in each municipality, we used 24 indicators, with each indicator representing one of the three dimensions of environment, society or economy (Table 2; for further details see Table S2 in the Supplementary Materials). These indicators were furthermore related to several topics such as biodiversity, land use, population, households and the labor market. They were implemented within the Sustainability Monitoring Program South Tyrol (www.sustainability.bz.it), which has been an ongoing project for almost 20 years that informs decision-makers and supports political and planning decisions [43]. Furthermore, these indicators were presented in the book *Mapping the Alps* [52], to provide an overview of the status of the entire European Alps at the municipal level and inform social and political actors. The initial selection of indicators was determined within the Sustainability Monitoring Program South Tyrol [43], based on various international and national frameworks and indictor sets which were developed, for example, by the United Nations Commission on Sustainable Development [42], or projects like SUSTALP [53] and MARS [54], to best represent the underlying theories and integrate practical experiences. In addition, to be linked to international frameworks, the indicators had to be relevant at the municipal level and reflect the specific needs of mountain regions [43]. Unfortunately, the initial selection of indicators had to be revised due to data constraints, and other indicators would have been more desirable from a theoretical point of view (e.g., social indicators related to poverty, health and security). However, this revision assured the quality of the data and allowed the mapping of all indicators at the municipal level after harmonizing all data across the different countries.

To derive a total sustainability index, each indicator was first min–max standardized to a scale ranging from 0 to 1. Then, we evaluated whether high values had a positive or negative influence on the respective dimension of sustainability (Table 2) (i.e., social indicators were only evaluated in relation to their social performance and environmental indicators in terms of ecological performance).

This evaluation was based on the outcomes of a Delphi-survey among experts (*n* = 13) that was carried out within the Sustainability Monitoring Program South Tyrol, and that was adopted for each indicator as described by Tappeiner et al. [43,52]. We inverted the values of those with negative influence in order to obtain the same direction for all indicators (i.e., high values of all indicators mean positive influence on the level of sustainability). Finally, a total sustainability index was calculated for each municipality by summing all indicators and dividing the sum by the total number of indicators, as all three dimensions were equally represented.

Table 2. Sustainability indicators related to environmental, social and economic dimensions as well as their influence (+ = positive, − = negative) on the level of sustainability (adapted from [43,52]).

Dimension	Indicator	Unit	Influence of High Values on Sustainability	
Environment	Artificial areas	%	−	Negative impacts on the environment
	Forest areas	%	+	Positive impacts on the environment
	Near-natural and natural open areas	%	+	Positive impacts on the environment
	Land-cover diversity of agricultural areas	n km^{-2}	+	Higher agricultural diversity
	Land-cover diversity of near-natural and natural areas	n km^{-2}	+	Higher biological diversity
	Road density	m km^{-2}	−	Negative impacts on the environment (e.g., fragmentation)
	Special protected areas	%	+	More environmental benefits
	Natura 2000 areas	%	+	More environmental benefits
Society	Population	%	−	Higher demand for living space and environmental goods, higher pressure on the environment
	Natural population growth	%	+	Positive influence on the dynamics and structure of society
	Youth rate	%	+	Higher socio-economic future viability
	Old age rate	%	−	Negative influence on the dynamics and structure of society
	Old to young age ratio	%	−	Negative influence on the dynamics and structure of society
	Single-person households	%	−	Higher social exclusion and isolation, higher demand for living space
	Average household size	%	+	Lower social exclusion and isolation, less demand for living space
	Divorced residents	%	−	Less stable social structures
Economy	Total employment rate	%	+	Higher socio-economic stability
	Cultural and recreational facilities	n	+	More economic activities related to increased leisure and tourism offers
	Farm density	n. of farms km^{-1}	−	Less economic benefits and lower productivity per farmer
	Enterprise density	n	+	More dynamic economic development
	Out-commuters ratio	%	−	Lower concentrations of businesses and a backward local economy
	In-commuters ratio	%	+	Higher concentration of businesses and a vibrant economy
	Commuter balance	%	+	Increasing productivity by improving employees' work–life balance
	Livestock size units (LSUs) per farm	n	+	Higher economic benefits due to higher productivity per farm

2.4. Analyzing Spatial Pattern and Congruencies

To analyze spatial patterns and relationships among the eight ESs and sustainability, we aggregated all indicators to the municipal level as a common spatial unit. Each indicator was max-standardized to a scale ranging from 0 to 1 to make them dimensionless and comparable. Higher indicator values correspond to greater supply, demand or flow of services.

In the first step, we applied the Getis-Ord Gi* statistic to explore the spatial patterns of individual ESs, as well as the sustainability index. The Getis-Ord Gi* statistic measures the degree of association between neighboring municipalities, and identifies statistically significant hot spots [55]. A hot spot arises when a municipality with a high ES value or sustainability index is surrounded by other municipalities that also have high values and the local sum for this municipality and its neighbors is higher compared to the sum of all municipalities of the entire study area, resulting in statistically significant z-scores [55]. This statistical method is suitable to capture large-scale contiguous areas providing valuable information on spatially autocorrelating areas for landscape planning and management [56]. Accordingly, we identified statistically significant hot and cold spots (i.e., regions with significantly high or low levels of ESs or sustainability), and created maps of spatial clusters with either high or low values of each ES indicator or sustainability.

In the second step, we used the resulting hot spots for an overlap analysis [57,58] to quantify spatial congruencies and relationships between ESs and sustainability, as it can be assumed that interactions are of flexible spatial range and not limited to one municipality. For example, in some cases farmers used meadows and pastures distributed over different municipalities to provide fodder for their livestock at their farm location in a specific municipality, while tourists usually stay overnight in a selected municipality, but move to adjacent municipalities to perform outdoor recreational activities. The second step included the following analyses:

- We calculated mean sustainability values for the three single dimensions (economy, society, environment) and a total sustainability value (mean of the single dimensions) distinguishing between the areas within and outside the hot spots of each ES to evaluate whether ES hot spots correspond to higher levels of sustainability. We used a *t*-test (equal variances not assumed; sig. level = 99%, bootstrapping: n = 200) to check whether the ES hot spots differed significantly in terms of sustainability.
- We mapped and calculated the percentage of spatial overlap between hot spots of each ES and the sustainability index to assess spatial congruencies and mismatches between them in spatial and quantitative terms.
- To analyze mismatches between ES hot spots and sustainability hot spots, we applied stepwise logistic regressions using the forward selection method. This procedure analyses the dependence of a dichotomic variable on explanatory variables. In all cases of multiple regression, it is recommended to analyze the independent variables according to multicollinearity, which is defined as the mutual linear dependence of variables in the context of multivariate procedures [59]. This was proven by using collinearity diagnosis, which helped us to discover and eliminate multicollinearities via variance factors and tolerance values. In the present case, the dichotomic variables were the spatial mismatches (1) and congruencies (0), and the explanatory variables were the sustainability indicators (see Table 2).

All analyses were performed in ArcGIS 10.4 (ESRI Inc., Redlands, CA, USA) using the Spatial Statistics extension and SPSS 24 10.0 (IBM Corp., Armonk, NY, USA).

3. Results

3.1. Spatial Pattern of Ecosystem Services

The spatial distribution of hot and cold spots of ES supply, demand and flow differed greatly for the different ESs (Figure 3). In the following, we shortly describe spatial patterns as well as spatial congruencies between supply, demand and flow for each ES separately.

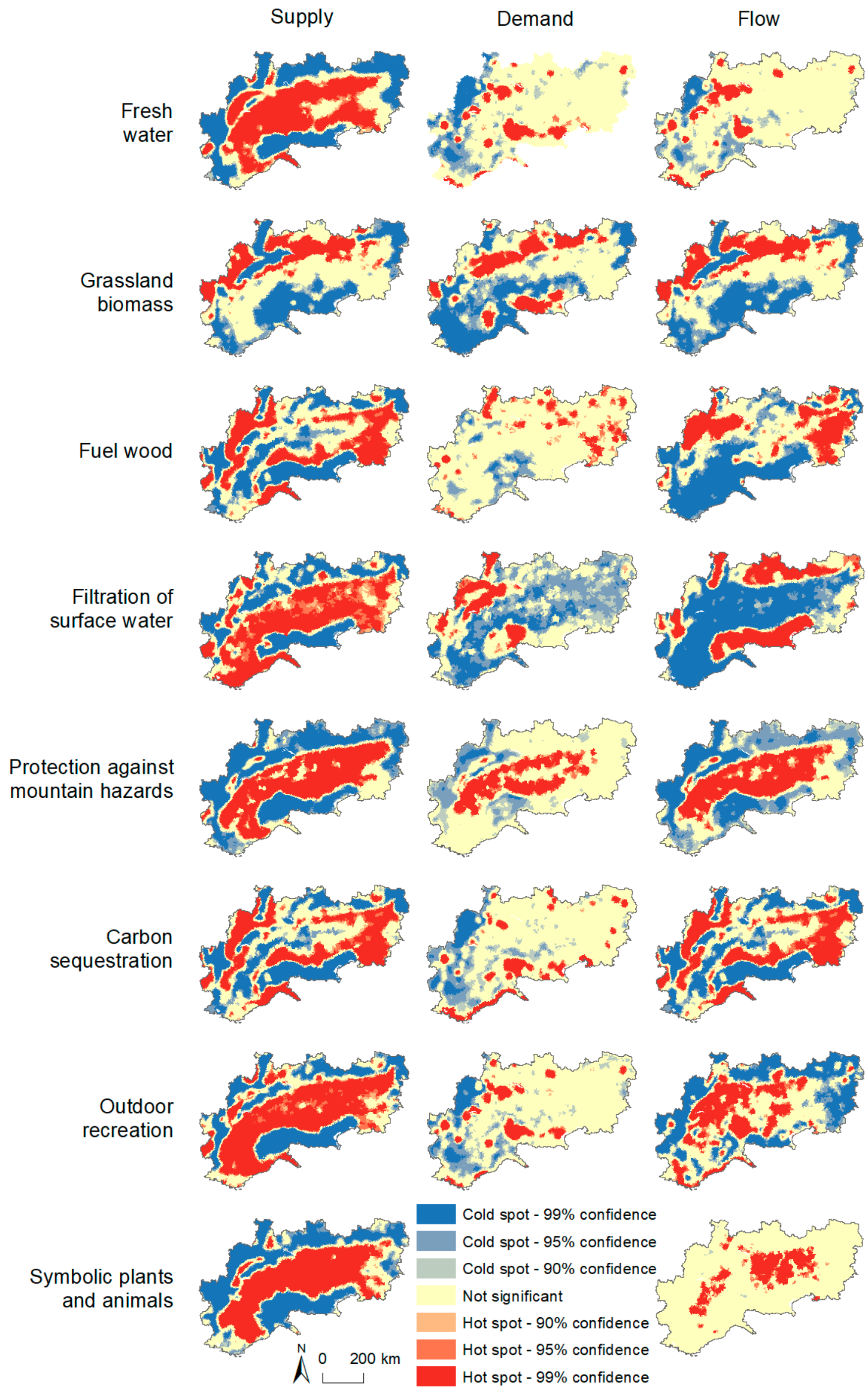

Figure 3. Hot and cold spots of eight key ESs distinguished by supply, demand and flow.

3.1.1. Fresh Water

Fresh water supply had its highest values within the Alps, whereas the lowlands were characterized by lower water yields. Demand for and flow of fresh water declined with increasing altitude and decreasing population density, and both were highest in urban agglomerations of the pre-Alpine lowlands. Furthermore, hot spots of flow greatly matched those of demand, with the highest discrepancies in the Italian pre-Alpine lowlands.

3.1.2. Grassland Biomass

Hot spots of both supply and flow of grassland biomass were located in the northern range of the Alps and adjacent lowlands, with the highest yields in the foothills of Bavaria and Switzerland due to favorable climate conditions. Demand hot spots in these regions corresponded largely to the distribution of the supply, but further important demand hot spots in the Italian lowlands, such as the Po Valley and Italian foothills, were located in supply cold spots. Accordingly, flow overlapped greatly with supply and demand in the northern part of the study area, whereas flow in the Italian lowlands was influenced by demand, and did not include a high amount of grassland biomass.

3.1.3. Fuel Wood

Hot spots of supply were mainly located in Franche-Compté, Liguria, along the Italian, Austrian and German foothills of the Alps, and in Slovenia, corresponding to forested areas at rather low and medium elevations. Cold spots were located in intensively used agricultural areas (e.g., the Po Valley) and high elevations (e.g., core zone of the Alps). Spatial patterns of flow overlapped largely with those of supply, but hot spots were limited to Franche-Compté and the eastern parts of the Alps. In contrast, demand for fuel wood had little influence on flow, and high values of demand were located mainly in Rhône-Alpes as well as some smaller regions distributed over the whole study area.

3.1.4. Filtration of Surface Water

Supply hot spots were mainly located in mountainous areas, whereas cold spots corresponded generally to the lowlands. Flow showed opposite spatial patterns. Demand hot spots concentrated on some regions in France, Switzerland and Austria, matching some supply hot spots as well as flow. The spatial distribution of flow was mainly influenced by supply.

3.1.5. Protection Against Mountain Hazards

Supply hot spots of these regulating services were strongly linked to the potential occurrence of gravitational hazards, which was highest in areas with higher elevation gradients and steep slopes (i.e., in the mountainous areas of the Alps, the Apennine in Liguria and the Vosges in Alsace). Most demand hot spots corresponded to supply hot spots, except for a core region of the Alps due to a relatively low settlement and infrastructure density. Flow hot spots overlapped greatly with supply as well as demand, and were rather restricted to the Alps due to a lower damage potential in the other mountain ranges.

3.1.6. Carbon Sequestration

Supply hot spots of carbon sequestration corresponded to rather low- and medium-elevation areas, with a high proportion of forested area (e.g., in Franche-Compté, Liguria, along the Italian, Austrian and German foothills of the Alps, and in Slovenia). In contrast, cold spots were located in intensively used agricultural areas (e.g., the Po Valley) and high elevations (e.g., core zone of the Alps). Spatial distribution of supply was rather independent from demand for carbon sequestration, and high demand values occurred especially in densely populated areas.

3.1.7. Outdoor Recreation

Supply hot spots of outdoor recreation were concentrated in mountainous areas, whereas areas of high demand were located in urban agglomerations in the surrounding lowlands. Flow hot spots were found in some specific mountain locations (e.g., the Dolomites), close to great lakes (e.g., Zurich lake, Garda lake) and urban agglomerations (e.g., Milan, Munich, Basel), and along the coastline of the Mediterranean Sea. The overlap analysis indicated a spatial mismatch between supply and demand. Some spatial overlap was found between supply and flow, but flow hot spots corresponded rather to demand hot spots.

3.1.8. Symbolic Plants and Animals

Most mountainous areas were supply hot spots of symbolic plants and animals. Flow hot spots were mainly located in supply hot spots, but were concentrated only in specific regions (e.g., Tyrol and Salzburg in Austria, the Dolomites in Italy and some mountain ranges in the Western Alps). The demand for this cultural service could not be mapped.

3.2. Spatial Overlap with Sustainability

Hot spots of most ESs (Figure 3) had significantly higher levels of sustainability than the areas outside the hot spots (Table 3, Figure 4a). Exceptions were the supply and flow of grassland biomass, as well as the flow of fuel wood and outdoor recreation. The hot spots differed significantly in sustainability from other areas in more than 82% of the ESs, mainly due to differences in environmental dimensions (87%), whereas, in only about 50% of the ESs, hot spots differed from other areas in economic and social dimensions (see Table S3 in the Supplementary Materials for mean values related to environment, society and economy).

Sustainability hot spots were mainly located in the high-mountain areas of the Alps (Figure 4b), whereas cold spots included the south of the Alps the Po Valley in Italy, and extended from the northern lowlands from France, over northern Switzerland and Bavaria (Germany), to eastern Austria.

The overlap analysis between ESs and sustainability indicated great differences between supply, demand and flow, as well as among ESs (Figures 5 and 6). For the supply of ESs, more than half of the hot spot areas matched hot spots of sustainability. In contrast, demand and flow hot spots reached generally lower levels of spatial congruencies with sustainability hot spots. The highest percentage of overlap occurred for fresh water supply, protection against mountain hazards (supply, demand and flow), outdoor recreation supply and supply as well as flow of symbolic plants and animals.

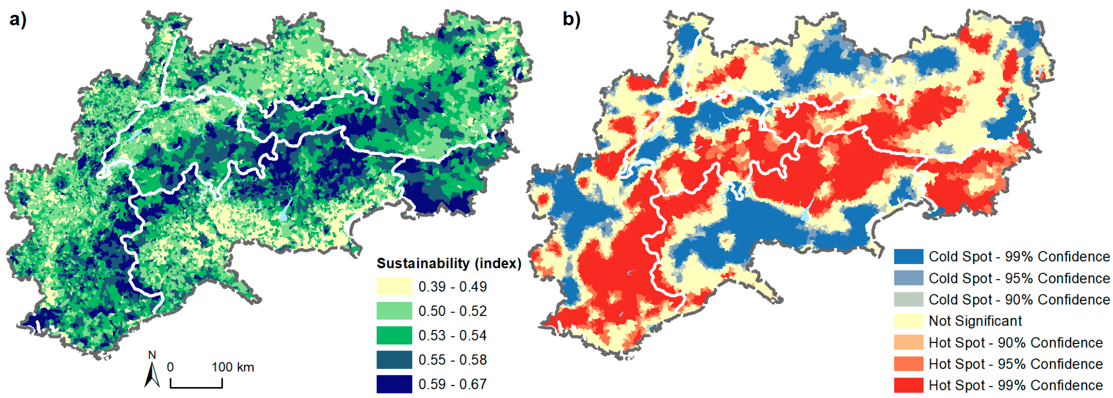

Figure 4. (**a**) Spatial distribution of sustainability at the municipal level, and (**b**) hot and cold spots of sustainability.

Table 3. Mean sustainability values (±*s.e*) for municipalities within or outside ES hot spots; bold = $p < 0.05$ (t-test with bootstrapping, equal variances not assumed; significance level = 99%).

		Number of Municipalities		Sustainability Index	
	ES	Hot Spot	Other	Hot Spot	Other
Supply	Fresh water	6068	10,717	**0.528 (±0.036)**	**0.512 (±0.032)**
	Grassland biomass	4168	12,617	0.519 (±0.029)	0.518 (±0.036)
	Fuel wood	6025	10,760	**0.525 (±0.031)**	**0.514 (±0.036)**
	Filtration of surface water	6339	10,446	**0.531 (±0.038)**	**0.510 (±0.030)**
	Protection against mountain hazards	4072	12,713	**0.537 (±0.033)**	**0.512 (±0.032)**
	Carbon sequestration	6053	10,732	**0.526 (±0.032)**	**0.513 (±0.035)**
	Outdoor recreation	6019	10,766	**0.536 (±0.035)**	**0.508 (±0.030)**
	Symbolic plants and animals	4015	12,770	**0.538 (±0.035)**	**0.512 (±0.032)**
Demand	Fresh water	3337	13,448	**0.505 (±0.032)**	**0.521 (±0.034)**
	Grassland biomass	4577	12,208	**0.508 (±0.025)**	**0.522 (±0.037)**
	Fuel wood	2118	14,667	**0.508 (±0.043)**	**0.519 (±0.033)**
	Filtration of surface water	5276	11,509	**0.508 (±0.027)**	**0.523 (±0.036)**
	Protection against mountain hazards	2686	14,099	**0.535 (±0.035)**	**0.515 (±0.033)**
	Carbon sequestration	2737	14,048	**0.505 (±0.037)**	**0.520 (±0.033)**
	Outdoor recreation	3368	13,417	**0.503 (±0.031)**	**0.522 (±0.034)**
Flow	Fresh water	3391	13,394	**0.505 (±0.030)**	**0.521 (±0.035)**
	Grassland biomass	4177	12,608	0.518 (±0.028)	0.518 (±0.036)
	Fuel wood	5072	11,713	0.519 (±0.035)	0.517 (±0.034)
	Filtration of surface water	5008	11,777	**0.505 (±0.025)**	**0.523 (±0.036)**
	Protection against mountain hazards	3314	13,471	**0.538 (±0.034)**	**0.513 (±0.033)**
	Carbon sequestration	6053	10,732	**0.526 (±0.032)**	**0.513 (±0.035)**
	Outdoor recreation	5564	11,221	0.518 (±0.036)	0.518 (±0.034)
	Symbolic plants and animals	1162	15,623	**0.546 (±0.042)**	**0.516 (±0.033)**

ES hot spots that did not overlap with sustainability hotspots could be mainly found in areas with a higher share of forest areas, and often in areas with protected alpine habitats (Figure 7). This applied to supply, demand and flow. For ES supply, spatial mismatches also included areas with intensive grassland management in addition to more natural areas. Although these areas had above-average values in the environmental dimension, some social or economic indicators had lower values compared to sustainability hot spots. Differences in demand occurred in cases of a high total employment rate, a negative out-commuters ratio and a small household size, which were represented by highly urbanized regions. Spatial divergences related to flow included mostly rural areas (with high livestock size units (LSUs) and high old-age rates), representing rather economically weak regions.

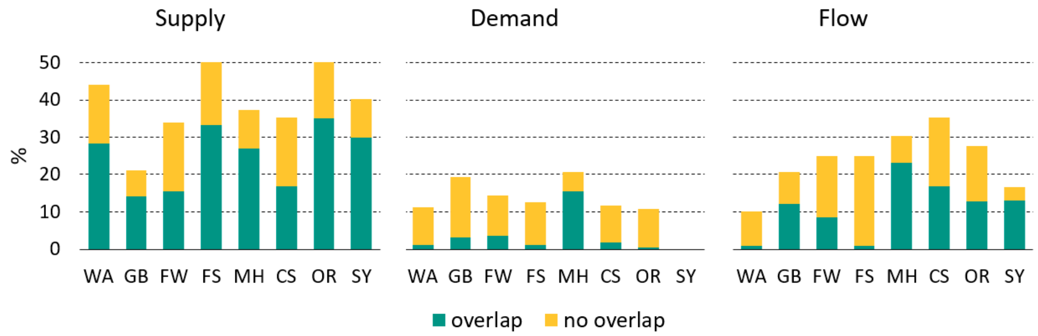

Figure 5. Area of hot spots related to the entire study area for each ES, and spatial overlap (% area) between ES and sustainability hot spots. Fresh water (WA), grassland biomass (GB), fuel wood (FW), filtration of surface water (FS), protection against mountain hazards (MH), carbon sequestration (CS), outdoor recreation (OR), symbolic plants and animals (SY).

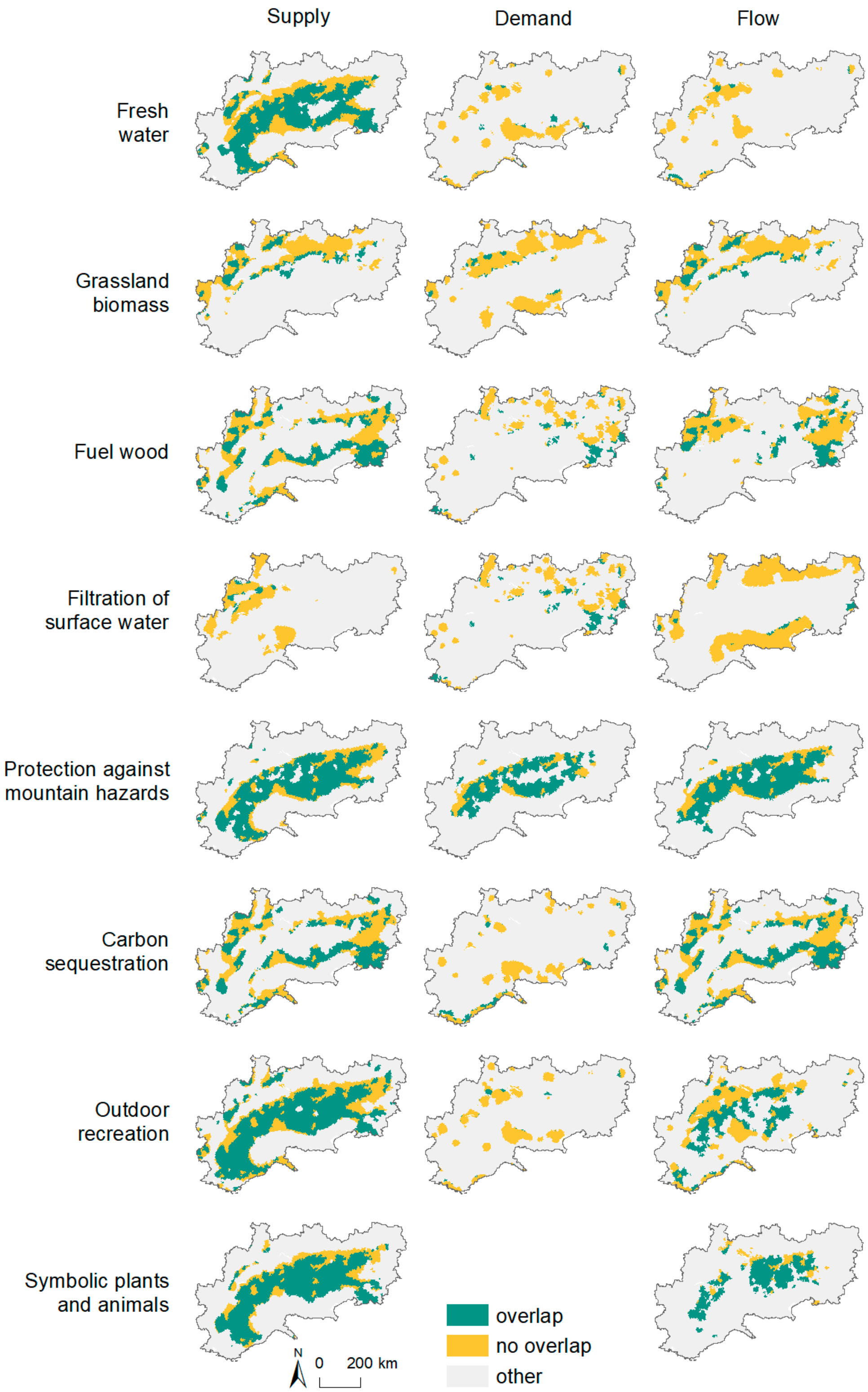

Figure 6. Spatial overlap between ES and sustainability hot spots.

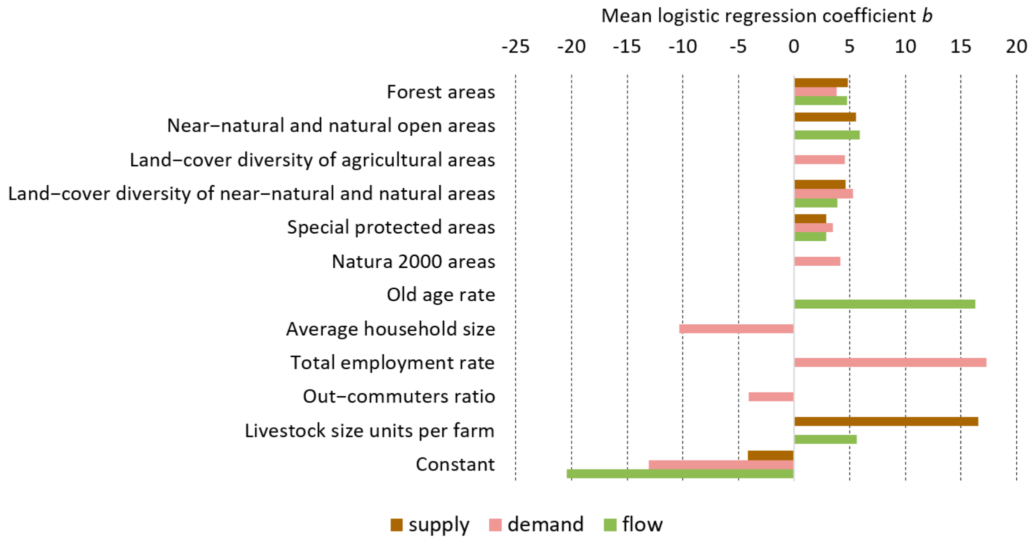

Figure 7. Mean logistic regression coefficient *b* indicating the influence (direction and strength) of individual sustainability indicators on the distribution of ES hot spots that do not match sustainability hot spots. Sustainability indicators with a continuity <45% were excluded.

4. Discussion

4.1. Spatial Patterns of ESs and Linkages with Sustainability

Similar to other studies [4,5,34,35], the first step of our analyses, the mapping of ESs, revealed spatial congruencies as well as mismatches between supply, demand and flow. Although spatial relationships were rather heterogeneous for the analyzed ESs, the results of the hot spot analysis suggest some general findings. In line with other studies [35,45,60–62], areas of high supply and those of high demand, corresponding to service-provisioning and -benefiting areas, were greatly dislocated due to the spatial divergence between natural or semi-natural ecosystems and human dominated environments. Indeed, our results demonstrate that natural mountain regions are hot spots of ES supply [51], whereas high demand is mostly associated with highly urbanized areas or intensively used agricultural areas in the lowlands [33]. Our results from the overlap analyses indicate that spatial patterns of ES flow may depend on the spatial distribution of supply or demand to varying degrees, but can be also independent. We found the highest levels of dependency on the supply for services that are produced or consumed in situ [6] (e.g., partly grassland biomass, protection against mountain hazards). For services that could be delivered to beneficiaries (e.g., freshwater), the flow matched significantly with the demand areas. Flow of outdoor recreation was influenced by both natural assets and the proximity to benefitting areas in cases of green urban areas [63], but this greatly depended on touristic infrastructure and the promotion and popularity of destinations [64,65].

These spatial divergences were also reflected in the results from our second step, the overlap analysis between ES and sustainability hot spots. Areas with high levels of ES supply matched quite well with sustainability hot spots, but it cannot be assumed that ES supply hot spots always correspond to high sustainability, due to discrepancies in the social and/or economic dimensions. Especially rural areas with a high levels of ES supply and a high level of the environmental dimension of sustainability may include municipalities with a rather weak economy or lower levels of social indicators. These results are in accordance with other studies that emphasize trade-offs between the three dimensions of sustainability [66–68]. In contrast to the supply, ES demand hot spots were characterized by low sustainability levels, and corresponded to urbanized areas with a high population density. With increasing urbanization, agriculturally-used landscapes become more fragmented and isolated, which has had negative impacts on local and regional levels of sustainability [69]. With regard to the spatial distribution of flow, the degree of overlap was largely influenced by the spatial pattern of ESs (i.e., whether the flow depended on the supply or the demand.

These results suggest that ESs and sustainability may be related, but there exist considerable imbalances between rather rural or urban municipalities, which becomes apparent in the differences in overlap and in the distinctions between supply, demand and flow. By focusing only on ES supply or even ES potential, as done by most of the ES assessments [31], our results indicate that the environmental dimension of sustainability may be well presented, but the social and economic dimensions have been widely neglected. Moreover, a high provision of ESs does not always imply the use of the environment in a sustainable manner (i.e., fodder or timber production may be maximized using unsustainable measures [47,70], or a high recreational use may have negative impacts on ecosystems [71]).

4.2. Implications for Management and Decision-Making

The heterogeneity in the spatial distribution of ESs as well as sustainability needs to be considered adequately in landscape management and planning not only at the local level, but in particular at the regional level that comprises service-provisioning and -benefiting areas across different landscapes [60] (i.e., in our case, mountainous areas with adjacent lowland regions). Based on our results, society can actively intervene in an SES to optimize it and achieve a balance between the use of natural resources for socio-economic development and the maintenance of ESs by developing management strategies and policies [38,72]. Moreover, social actors need to account for power relationships between stakeholders during the decision-making process to avoid the exclusion of people from access to crucial ESs [10,11]. There are many ways of exerting these influences; above all, these include spatial planning policies, conservation policies, resource management strategies and ecological engineering [10,73].

However, indicators that are measurable and interpretable are needed to effectively implement these different possibilities of environmental management [41]. In this study, the analysis of the sustainability indicators suggests, for example, that regions with a higher share of forest areas and/or protected areas are ES supply, demand and flow hot spots, but sustainability cold spots. Intensively used grassland regions have high values in the environmental dimension, but social or economic values are lower compared to sustainability hot spots. Economically weak regions (high LSUs and high old-age rates) are often characterized by lower ES flow. Based on this knowledge, different management strategies can be developed at different levels, including higher governance levels (national, regional) as well as at the local level (single plot, municipality). At the local level, it may be easier to implement well-defined measures for an increase of forest areas or near-natural areas, as well as to increase land-cover diversity. At the regional or national level, measures and actions can be taken to designate protected areas, and to foster the labor market. The effectiveness of these measures can be promptly identified by monitoring the changes in sustainability indicators and, in the case of failure, it can be reacted to accordingly [41,47].

Finally, the sustainability indicators are partly linked to the UN SDGs, especially to eight SDGs (Goals 2, 4, 8, 9, 11, 12, 13 and 15). The indicators from the environmental dimension concentrate on Goal 15 (Protect, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss), while the indicators belonging to the economic dimension are strongly linked to Goal 8 (Promote sustained, inclusive and sustainable economic growth, full and productive employment and decent work for all). Decision- and policy-makers may take advantage from these linkages for the monitoring of sustainable development across different levels, and for identifying appropriate development strategies.

4.3. Limitations of the Study

The interpretation of our results must consider some limitations. For some ES indicators, such as fresh water demand, we had to downscale available data from the regional to the municipal level, which may not have always properly reflected local conditions. For other indicators, we used spatial modeling approaches, assuming similar or simplified ecological processes throughout the study area.

For example, although we distinguished four climatic regions to model fresh water supplies, local heterogeneities are not depicted and need more sophisticated hydrological modeling approaches [9]. We employed significant effort to harmonize data and use Europe-wide datasets, which nonetheless limited the selection of indicators. Consequently, some important indicators (e.g., related to health) could not be quantified over the entire study area. Different indicators sometimes referred to different years, but we did not expect important effects on general spatial patterns, as we used only standardized data for the hot spot and overlay analyses. Moreover, data on land use, demographics and human activities are usually representative for several years or even decades. Of course, the analyses need to be repeated in the future to provide continually updated information for decision-making, and to identify spatio-temporal dynamics. A more-important issue is related to the aggregation of the raster data from the landscape to the municipality scale, which we used to jointly analyze ESs and sustainability. During the aggregation process, variation in the original scale of data may lose validity, because small clusters of high or low values are likely to disappear, in particular when municipalities include highly heterogeneous areas [74]. Our results are therefore most useful for identifying broad-scale patterns, whereas the raster data with a resolution of least 100 m should be used for analyses at the local level to capture also small-scale heterogeneities.

Finally, the linkages between our sustainability indicators with the SDGs may be improved, as they relate only to eight out of 17 SDGs. There were two main reasons for this. First, some SDGs such as Goals 1, 6, 7, 10, 14, 16 or 17 were less relevant to our study areas due to the general high development level of the Central European countries. Second, we focused on a smaller spatial extent, using indicators at the municipal level, where other indicators are needed to describe sustainable development [43] (i.e., the ratio of commuters may provide important insights at the local level, but has no importance at the national level). Nevertheless, indicators should be integrated related to Goal 3 (Ensure healthy lives and promote well-being for all at all ages) and Goal 5 (Achieve gender equality and empower all women and girls). Moreover, our cumulative sustainability index is additive and linear, as the specific contribution of single sustainability indicators to overall human well-being is still poorly understood. Future assessment should therefore consider trade-offs and interactions between indicators to improve the understanding of the linkages between ESs and sustainability.

5. Conclusions

Using ES indicators for measuring sustainability provides a rather limited understanding, especially since the social and economic dimensions are not adequately depicted. This is particularly true for rural and highly urbanized municipalities, where we found the greatest imbalances between ESs and sustainability. ES hot spots may indicate a high level of the environmental dimension of sustainability, but ES indicators alone do not provide information on whether the ecosystems are used in a sustainable manner with positive effects on local or regional socio-economic well-being. Our results from the overlap analyses, therefore, provide valuable information for decision-making from the local to the trans-national level. Although strengthening ESs aims to improve human well-being, the benefits often remain unclear or unaddressed in ES assessments [20,31]. Hence, not only is a better alignment of ESs with SDGs needed [13,18,19], but also an enhancement of ES assessments is necessary to better represent the human dimension, and to include norms of sustainability.

Supplementary Materials: The following are available online at http://www.mdpi.com/2071-1050/11/8/2227/s1, Table S1: ES indicators, Table S2: Sustainability indicators, Table S3: Mean sustainability values for municipalities within or outside ES hot spots.

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