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RESEARCH ARTICLE

Enhancing understanding of ecosystem multifunctionality in mountain regions

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Abstract

1. Mountain landscapes that are managed to provide several ecosystem services (ES) have the potential to sustain high levels of biodiversity while also meeting multiple human needs. The promotion of multifunctional landscapes has become an important policy target in land management and has gained research traction under the definition of ES-multifunctionality. However, scale dynamics and patterns of ES-multifunctionality remain poorly understood and are rarely integrated into land management and policy recommendations.
2. To address this gap, we used two diversity indices to quantify ES-multifunctionality based on 11 ES indicators at different spatial scales in a case-study region in the European Alps. The approach used captures the diversity of ES provided at patch and landscape levels (α-multifunctionality) as well as unique ES contributions of ecosystems to the regional ES diversity (β-multifunctionality).
3. Results show that ES-multifunctionality generally decreases from low to high land use intensities and increases from high to low elevations. While forest-dominated landscapes are hotspots of ES diversity, the more specialized ES supply in landscapes above the tree line and on valley floors enhances regional ES-multifunctionality.
4. This study highlights how understanding ES-multifunctionality and its incorporation into policy and landscape management requires adopting a multi-scale approach. Patch-scale analyses are necessary to identify the environmental characteristics underpinning ES-multifunctionality with a fine level of detail. However, looking at the distribution of ES at landscape and regional scales uncovers the benefits originating from interacting ecosystems, and can support the identification of areas that should be protected, restored, or sustainably managed.

KEYWORDS
ecosystem management, ecosystem services, spatial scales, α-diversity, β-diversity

1 | INTRODUCTION

Mountain ecosystems provide a variety of services that are essential for local inhabitants as well as people living in adjacent lowlands (Grêt-Regamey et al., 2012; Schirpke et al., 2019). For example, mountain regions are hotspots of biodiversity, and often represent important water suppliers for large cities in the surrounding plains, while also acting as important tourism and recreation destinations (Schirpke et al., 2018). Conceptual advances have been made in how humans relate to nature, mainly using the concepts of Ecosystem Services (hereafter ES) and Nature's Contributions to People (NCP), to refer to the various benefits that nature provides to us all (Daily et al., 1997; Díaz et al., 2018). However, mountain areas are also vulnerable to rapid global changes, such as rising temperatures, infrastructure development, habitat fragmentation, and unsustainable tourism, which are undermining the ability of these ecosystems to provide ES (Schröter et al., 2005).

Recently, the scientific community has shown growing interest in the concept of ecosystem multifunctionality, defined as the capacity of ecosystems to supply multiple functions (EF-multifunctionality) and services (ES-multifunctionality) within the same spatial unit (Manning et al., 2018). The concept of ecosystem multifunctionality has been embraced by global (IPBES, FAO, TEEB) and European institutions (EU Commission, DC AGRI) to promote the sustainable management of natural resources. Ecosystem multifunctionality is also highly relevant to efforts to put biodiversity on the path to recovery by 2030 by establishing a network of protected areas and developing an EU Nature Restoration Plan (European Commission, 2020). ES-multifunctionality has, therefore, become an important policy target for landscape management and policy makers have called for spatial assessments on which to base their decisions (Manning et al., 2018; Mastrangelo et al., 2014). In fact, the quantification of multifunctionality in a particular area is seen as a new integrated way to study land use and landscape dynamics and to consciously reflect on the influence of different management practices on the provision of multiple ES, and on the synergies and trade-offs among different ES (Queiroz et al., 2015; Rodríguez-Loinaz et al., 2015). Monofunctional land use systems are indeed still often considered to be economically efficient because the provision of one or a few ES is maximized (Stürck & Verburg, 2017). However, such approaches often result in diseconomies in the form of environmental problems, such as the depletion of the natural resources on which humans depend (e.g. reduced soil and water quality; Brandt & Veijre, 2004; Fischer et al., 2017; Kulcsar et al., 2016). The Millennium Ecosystem Assessment (MEA) has raised awareness about the negative effects of biodiversity loss on human wellbeing and addresses the importance of protecting and safeguarding ecosystems and the multiple services they provide for future generations (Maes et al., 2011). Working to enhance ES-multifunctionality has the potential to sustain high levels of biodiversity while also meeting multiple human needs (Maestre et al., 2012; Pasari et al., 2013; Soliveres et al., 2016).

However, while multifunctionality is not a new concept (Vos & Meekes, 1999) and recent work has made remarkable advances clarifying terminology (Manning et al., 2018), there is still not a common way to understand and conceptualize ES-multifunctionality (Brandt & Veijre, 2004; Hölting, Beckmann, et al., 2019; Stürck & Verburg, 2017). This lack of clarity is one reason why practical implementation of the concept is still lacking (de Groot et al., 2010; Jarvis et al., 2020; Mastrangelo et al., 2014). Some of the most pressing challenges when assessing ES-multifunctionality include a lack of relevant data and suitable approaches for the quantification and mapping of ES. These gaps often determine the number and type of ES indicators included in assessments and the degree of comparability of multifunctionality metrics across studies (Hölting, Beckmann, et al., 2019). Moreover, spatial patterns of ES are determined using a mix of environmental and sociological factors that are still being explored. Land use represents the major unit of inquiry in ES assessments (de Groot et al., 2010; Tasser et al., 2020), because it also allows exploration of the complex relationships within socio-ecological systems, which are of particular importance for the maintenance and enhancement of landscape functionalities (Egarter Vigl et al., 2017; Stotten et al., 2021). Despite this focus on land use, an open debate exists on the possibility to directly link land use diversity to landscape multifunctionality (Crouzat et al., 2015; Huber et al., 2020). Felipe-Lucia et al. (2018) provided a comprehensive view of the effect of forest attributes (e.g. vertical heterogeneity, understorey richness) on stand-scale forest multifunctionality. A study by Haberman and Bennett (2019) showed that socio-economic variables such as population size and wealth are important factors determining the provision of different ES in the rural areas surrounding metropolitan cities around the world. Several, mostly large scale, studies have demonstrated that the provision of multiple ES follows climate-related spatial gradients (e.g. south–north; Hölting, Jacobs, et al., 2019; Mouchet et al., 2017). However, the effects of environmental characteristics such as topography and land use/cover on ES-multifunctionality at high spatial resolution remain unclear. A better understanding of such patterns could improve our ability to predict the consequences of specific policy and management decisions on ES provision and interactions (synergies and trade-offs; Egarter Vigl et al., 2017; Geneletti et al., 2018; Hölting, Jacobs, et al., 2019).

Several methods to quantify ES-multifunctionality have been proposed (Hölting, Beckmann, et al., 2019; Rodríguez-Loinaz et al., 2015; Stürck & Verburg, 2017), which makes harmonization of the findings a challenging task (Pilogallo & Scorza, 2022; Queiroz et al., 2015). Methods include the "threshold" approach, which calculates the number of ES above a certain threshold value, or the "averaging" approach, which computes the average value of multiple normalized ES indicators. Some studies have also employed richness and diversity indices originating from biodiversity research (Crouzat et al., 2015; Mouchet et al., 2017), such as the α-diversity index (α-multifunctionality), which favours a balanced supply of different ES (Hölting, Jacobs, et al., 2019). Given the assumption that higher ecosystem multifunctionality values are more desirable, such metrics allow the identification of ES hotspots at defined spatial scales. Hölting, Jacobs, et al. (2019) were among the first to also account for the unique ES contributions of municipalities within a regional context by employing the β-diversity index (β-multifunctionality).

As a matter of fact, it may not always be possible for landscape planners to satisfy disparate societal requirements, such as the needs of farmers, citizens, and tourism, alongside environmental viability, quality and biodiversity conservation (Turkelboom et al., 2018). Decision makers are often asked to find compromises among the needs of different actors with conflicting land use demands and practices. Compromise is particularly needed when ecosystems have a limited capacity to meet multiple demands or when land use change dynamics (e.g. urban sprawl, agricultural ex- and intensification, land abandonment, reforestation, or tourism development) affect the provision of specific ES (Raudsepp-Hearne et al., 2010; Turkelboom et al., 2018). Given that ecosystem functions become ES if humans benefit from them (Boyd & Banzhaf, 2007; Fisher et al., 2009), we need to better understand where ES-multifunctionality is needed and at what scale (Fischer et al., 2017). In fact, according to Felipe-Lucia et al. (2018), enhancing the supply of a smaller number of ES may also be important, if the provided services are needed but not supplied within the larger region, thus enhancing ES-multifunctionality at larger spatial scales. (Hölting, Jacobs, et al., 2019; van der Plas et al., 2018).

The aims of this study are to enhance the understanding of ES-multifunctionality in mountain regions and to contribute to mainstreaming concepts and methodological advancements among researchers, policymakers, and landscape managers. Building on previous studies, we developed an ES-based approach to investigate the factors underpinning ES-multifunctionality in a cross-border region in the European Alps using two diversity indices, namely α- and β-multifunctionality. The following specific objectives were addressed: (i) identification of ES-multifunctionality patterns across land use types and elevational gradients at high spatial resolution; (ii) increased understanding of ES-multifunctionality at patch and landscape levels to inform land management strategies and policy goals.

2 | MATERIALS AND METHODS

2.1 | Study area

The study area is located in the eastern European Alps and comprises the two Italian autonomous provinces of South Tyrol and Trentino and the Austrian federal state of Tyrol, which together form the transboundary cooperation area named EUREGIO. The region covers a total area of 26,253 km^2, divided into 605 municipalities, with elevations ranging from 61 to 3905 m a.s.l. (Table 1 provides information on surface area distribution, and population size and density across the three regions). The region is predominantly covered by forests, permanent grassland, alpine grassland, sparsely vegetated areas, rocks and glaciers. Valley floors are often intensively used for agriculture (Figure 1; Tasser et al., 2020). The diversified cultural landscape influenced by small-scale farming systems, makes the area an attractive tourism destination (Flury et al., 2013), which registers about 100 million overnight stays per year (data source: EUREGIO Tyrol-South Tyrol-Trentino, 2019).

TABLE 1 Surface area, number of municipalities, mean municipality size, total population and population density in Trentino, South Tyrol, and Tyrol (data source: EUREGIO Tyrol-South Tyrol-Trentino).

Attribute	Trentino	South Tyrol	Tyrol
Surface (km^2)	6207.12	7398.38	12,648.0
Municipalities	210	116	279
Mean municipality size (km^2)	30	63	45
Total population	541,098	532,010	754,705
Population density (inhabitants/km^2)	87	72	59.9

2.2 | Study concept

Based on the guidelines proposed by Mastrangelo et al. (2014), we applied a spatiofunctional approach to assess the ES-multifunctionality of terrestrial ecosystems using 11 ES indicators. We assessed ES-multifunctionality at different spatial scales using two metrics: α-multifunctionality and β-multifunctionality (Hölting, Jacobs, et al., 2019). α-multifunctionality is defined as the diversity of ES supplied in terms of ES richness and abundance and accounts for service evenness, favouring a balanced supply of ES (Raudsepp-Hearne et al., 2010; Stürck & Verburg, 2017). β-multifunctionality is defined as the unique ES contribution of spatial units (e.g. ecosystems, landscape) to ES-multifunctionality at bigger spatial scales (e.g. region). A landscape is considered unique when it supplies specific ES at a higher level compared to other sites in the region (Hölting, Jacobs, et al., 2019). Figure 2 simplifies our methodological approach. We first calculated α-multifunctionality at the patch scale to understand how the supply of multiple ES responds to environmental characteristics. We then measured α- and β-multifunctionality at the landscape scale (i.e. Administrative level), based on the approach presented by Hölting, Jacobs, et al. (2019). The latter analysis was conducted to better understand how ES distribution affects ES-multifunctionality at the regional level, which can inform landscape policy and management.

2.3 | Ecosystem service indicators

The ES indicators (including six regulating, two provisioning and three cultural ES) included in this study build on the Common International Classification of Ecosystem Services (CICES v5.1; Haines-Young & Potschin, 2018) and describe either the actual use or the potential supply of ES across the study region. Potential supply represents the amount of an ES that can be delivered by an ecosystem and is strongly linked to natural conditions such as land

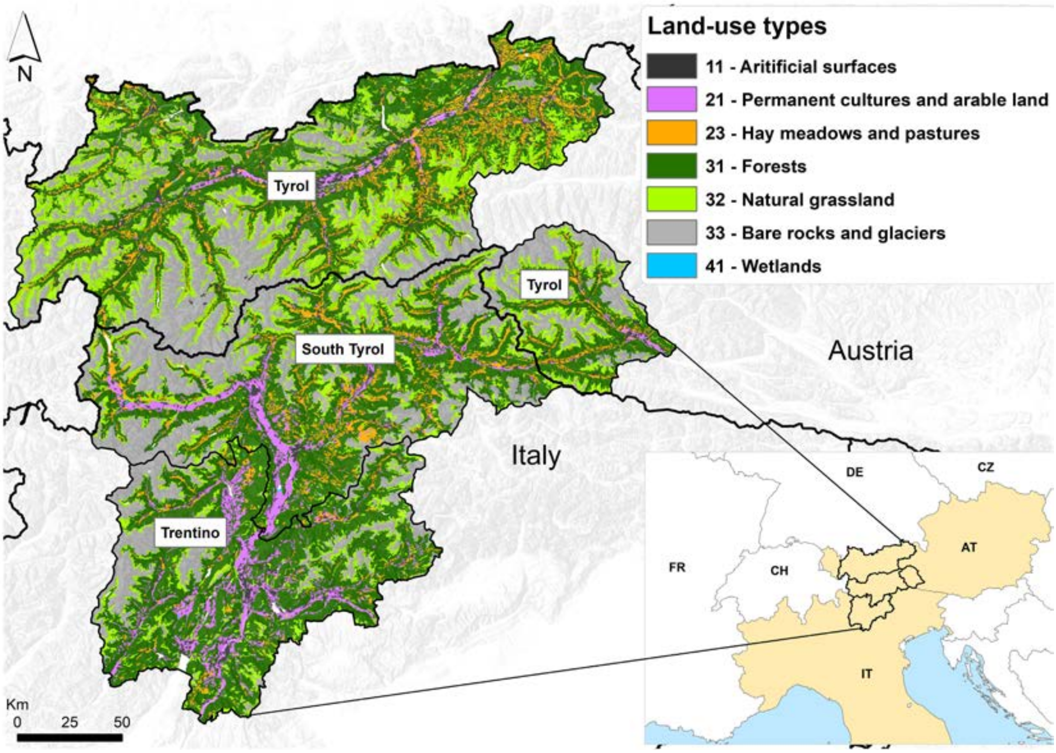

FIGURE 1 Study area showing the land use/land cover distribution in Trentino, South Tyrol and Tyrol.

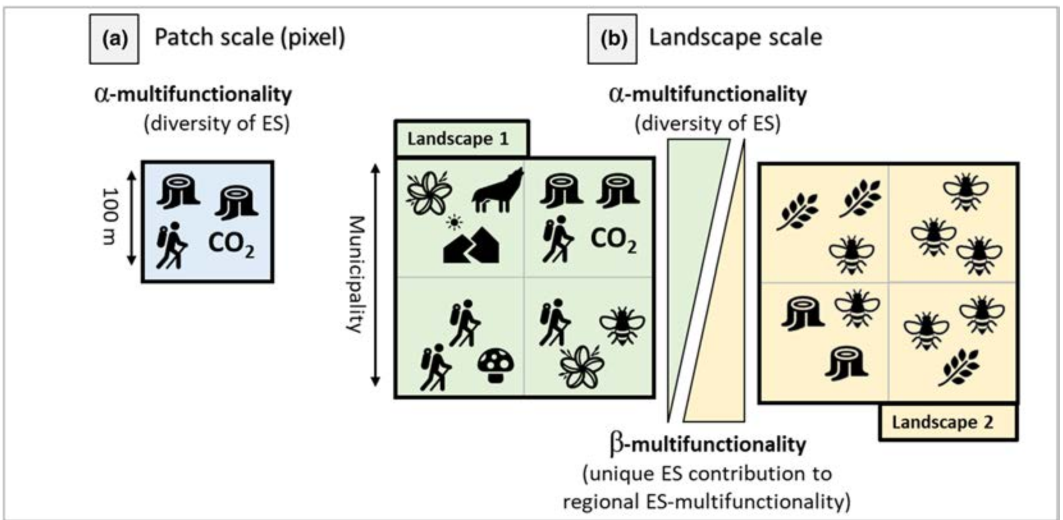

FIGURE 2 Conceptual approach for measuring ecosystem services ES-multifunctionality across the two scales of analyses. At the patch scale (a), ES-multifunctionality is quantified as the Gini- Simpson diversity index (α-multifunctionality), while at the landscape scale (b) ES-multifunctionality is assessed as both, the Gini-Simpson diversity index, and the average dissimilarity between landscapes (β-multifunctionality). α-Multifunctionality favours a balanced supply between single ES, therefore landscape 1, which serves 8 ES simultaneously, has a higher diversity index compared to landscape 2. In contrast, β-multifunctionality accounts for ES identity and abundance and therefore landscape 2, which serves one specific ES (i.e. pollination) at high levels, has a higher β-multifunctionality compared to landscape 1.

use/ cover, hydrology, soil conditions, biodiversity, elevation, slope and climate (Burkhard et al., 2012). We obtained data for seven ES indicators from the results of the Interreg Alpine Space project AlpES (Alpine Ecosystem Services—mapping, maintenance and management, https://www.alpine-space.eu/project/alpes/) and calculated four new ones: lifecycle maintenance, gene pool protection, land use integrity and quality, and foraging practices. Table 2 provides a full overview of the ES indicators used in this study. ES indicators were originally mapped at a pixel resolution of either 25 or 100 m. Therefore, some ES indicators were upscaled to the same spatial

TABLE 2 Overview of ES included in this study.

Category	Ecosystem service (ES)	Indicator description and units	References
Regulation	Carbon sequestration	Annual rate of CO_2 sequestration (t CO_2 ha^{-1}year^{-1}) by forest biomass based on IPCC equations. The indicator was originally mapped at a pixel resolution of 25 m	IPCC (2006)
Regulation	Filtration of surface water by ecosystem types	Potential nitrogen removal capability of ecosystem types based on the InVEST NDR model (kg ha^{-1}year^{-1}). The indicator was originally mapped at a pixel resolution of 25 m	Natural Capital Project (2020)
Regulation	Forest protection against natural hazards	Capability of forests to deliver a protective function against avalanches, rock falls and channel processes (index between 0 and 1). The indicator was originally mapped at a pixel resolution of 25 m	Bauerhansl et al. (2010)
Regulation	Lifecycle maintenance	Pollination potential as total pollinator abundance based on the InVEST pollination model (index). The indicator was originally mapped at a pixel resolution of 100 m	Lonsdorf et al. (2009) and Natural Capital Project (2020)
Regulation	Gene pool protection	Habitat quality as an indicator for plant diversity (index) approximated as mean number of vascular plant species per ecosystem. The indicator was originally mapped at a pixel resolution of 100 m	Tasser et al. (2008)
Regulation	Land use integrity and quality	Distance to nature (index) calculated by multiplying the degree of land naturalness by the average Euclidean distance to the next natural or near natural habitat. The indicator values were then transformed to indicate that a higher land use integrity and quality is reached when the indicator value is low. The indicator was originally mapped at a pixel resolution of 100 m	Rüdisser et al. (2012)
Provisioning	Fuelwood production	Amount of timber that can be removed from forests for fuelwood production (m^{3}ha^{-1}year^{-1}) considering both forests accessibility and topographical site conditions. The indicator was originally mapped at a pixel resolution of 25 m	Clouet and Berger (2009)
Provisioning	Biomass production from grassland	Grassland fodder dry mass (DM) production (t DM ha^{-1} y^{-1}) on permanent grassland estimated depending on management type, growing season length, temperature, precipitation and topographical parameters. The indicator was originally mapped at a pixel resolution of 25 m	Jäger et al. (2020)
Cultural	Outdoor recreation	Recreation opportunities (index) provided by ecosystems based on six landscape indicators (naturalness, protected areas, presence of water, landscape diversity, terrain ruggedness, density of mountain peaks) weighted by accessibility. The indicator was originally mapped at a pixel resolution of 100 m	Schirpke, Meisch, Marsoner, and Tappeiner (2018)
Cultural	Symbolic species	Spatial distribution of habitats of symbolic species (plants and animals) using habitat models and distribution maps (index). The indicator was originally mapped at a pixel resolution of 100 m	Schirpke, Meisch, and Tappeiner (2018)
Cultural	Foraging practices	Accessibility of forest areas at low elevations (<2000 m a.sl.) and slope angles (<80%), with consideration of forest density, estimated as the inversed least accumulative cost distance index from paths and roads. The indicator was originally mapped at a pixel resolution of 100 m	Egarter Vigl et al. (2017)

resolution of 100 m and then normalized using a min-max standardization between 0 and 1 to facilitate further analysis and comparison using ArcGIS version 10.7.1 (ESRI, 2019; Paracchini et al., 2011).

2.4 | ES-multifunctionality assessment across scales

We measured α-multifunctionality at the patch scale at the pixel resolution of 100 m (~1 ha) using the Gini-Simpson diversity index (Simpson, 1949) for the 11 ES across the study region. The following formula was used:

$$\alpha = 1 - \sum_{i=1}^{N} pi^2$$

where N is the total number of ES considered, pi is the supply of each ES (i) in proportion to the supply of all ES in the site (i.e. pixel in our case). The value of α ranges between 0 and 1, the greater the value, the higher the diversity of ES supplied (van der Plas et al., 2016). We calculated the Pearson's correlation between α-multifunctionality and elevation to understand how ES-multifunctionality responds to environmental characteristics. In addition, we explored the distribution of α-multifunctionality values across elevation zones where we defined colline zone as: <500 m, montane zone as: 500–1500 m, sub-alpine zone as: 1500–2400 m, alpine zone as: 2400–3000 m, nival zone as: >3000 (EU, European Copernicus Programme, 2016). We also analysed the distribution across a land use/land cover (LULC) map with seven macro-classes (Figure 1; EU, Copernicus Land Monitoring Service, 2019). A one-way ANOVA and a Tukey's Post-hoc test were used to check statistically significant differences in α-multifunctionality between LULC macro-classes and elevation zones.

For landscape units we used the municipality boundaries (EuroGeographics, 2019), corresponding to the Local Administrative Level (LAU Level 2). We calculated the area weighted mean values for all normalized ES for each municipality. We then calculated α-multifunctionality as the Gini-Simpson's index of diversity for the 11 aggregated ES using the function diversity in the R package "vegan" (Oksanen, 2013). β-multifunctionality was assessed by calculating the total ES abundance-based dissimilarity matrix between landscape units using the beta.pair.abund function in the "betapart" package in R (Baselga & Orme, 2012; R Core Team, 2020). The dissimilarity matrix was calculated using the Bray Curtis Index (BCI):

$$BCI_{ij} = 1 - \left(2C_{ij} / S_i + S_j\right)$$

where i and j are the two landscape units (i.e. municipalities); S_i is the summed supply ES supplied in site i; S_j is the summed supply ES supplied in site j; C_{ij} is the sum of only the lesser ES supplies for each ES found in both sites (Bray & Curtis, 1957). β-multifunctionality for each landscape unit was then quantified as the average dissimilarity between one landscape unit and all the others (Hölting, Jacobs, et al., 2019). The value of β ranges between 0 and 1, the greater the value, the higher the level of dissimilarity between different landscape units, and the higher the unique ES contribution (van der Plas et al., 2016). We then calculated the Pearson's correlation coefficient between the two indices to further quantify the relationship between α- and β-multifunctionality across the study region. Next, we identified landscape units with lower or higher levels of α- and β-multifunctionality by reclassifying the two indices into three classes using quantile classification. Finally, we merged α- and β-multifunctionality into a bivariate composite map to identify pattern combinations of the two diversity indices.

3 | RESULTS

The distribution of α-multifunctionality in different LULC (Figure 3a) showed increasing values moving from urban-artificial areas, to agricultural areas, and peaking in forests. Lower α-multifunctionality values were apparent in more natural and open spaces, where the landscape is mainly characterized by sparse vegetation, bare rocks and glaciers, as well as in wetlands. There was a significant negative correlation between α-multifunctionality and elevation ($r = -0.561$; $p < 0.001$). The distribution of α-multifunctionality in different elevation zone (Figure 3b) showed lower values above 2400 m a.s.l. Higher α-multifunctionality values could be observed below 2400 m a.s.l., particularly between 500 and 1500 m a.s.l. The ANOVA results revealed significant differences in α-multifunctionality among LULC types (Table S1) and between elevation zones (Table S2). A map displaying the α-multifunctionality index values at the patch scale across the study region can be found in the Supplementary Information (Figure S1).

Analysis at the landscape scale showed high values of α-multifunctionality in municipalities at lower elevations across the entire study region (darker colour in Figure 4a). We observed lower α-multifunctionality values in municipalities located at higher elevations (lighter colour in Figure 4a), in sites where high β-multifunctionality values were reached, in particular in the border municipalities between Italy and Austria (darker colour in Figure 4b). α- and β-multifunctionality were negatively correlated ($r = -0.597$, $p < 0.001$; Figure S2). Figure 5 presents a composite map of both α- and β-multifunctionality and the distribution of the 11 ES in nine municipalities characterized by

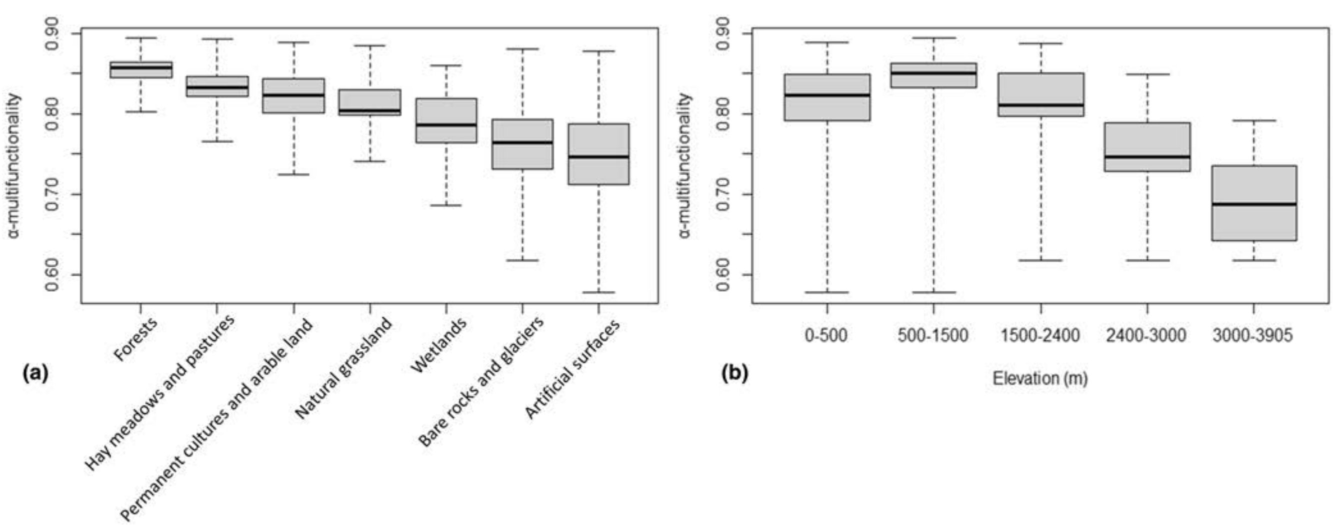

FIGURE 3 (a) Boxplots showing the distribution of α multifunctionality in different land use/land cover classes, ordered from higher to lower α multifunctionality. (b) Boxplots showing the distribution of α-multifunctionality across elevation zones: colline zone (<500 m), montane zone (500–1500 m), sub-alpine zone (1500–2400 m), alpine zone (2400–3000 m), nival zone (>3000 m).

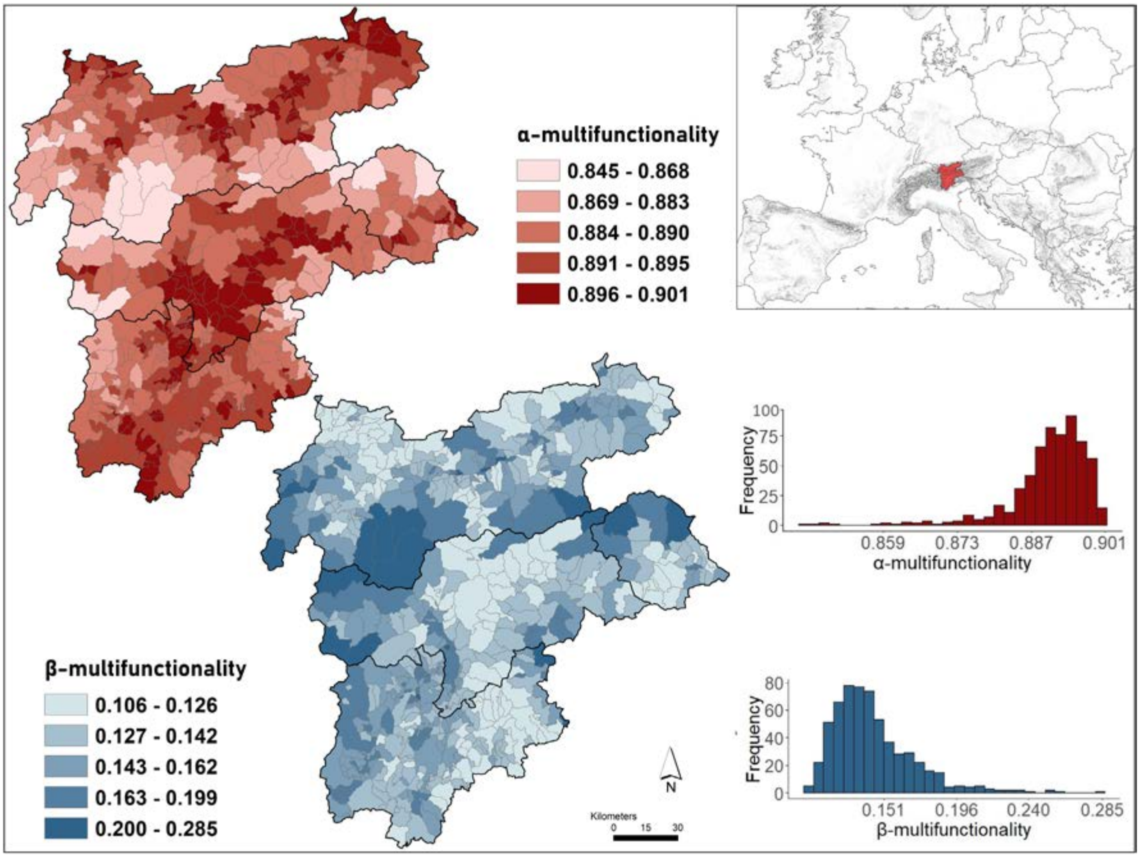

FIGURE 4 α-Multifunctionality, measured as the diversity of ecosystem services (ES) based on the Simpson Diversity Index at the LAU2 level, and β-multifunctionality, calculated as the total abundance-based dissimilarity of ES supply at the LAU2 level, and frequency distribution of α- and β-multifunctionality.

different combinations of α- and β-multifunctionality. For example, the Tyrolean municipalities of Sölden, and the Italian municipalities of Predoi/Prettau (South Tyrol) and Sagron Mis (Trentino) showed low α-multifunctionality values ($\alpha<0.890$) and high β-multifunctionality values ($\beta>0.148$) and are therefore characterized by a unique ES supply. The municipalities of Vipiteno/Sterzing (South Tyrol), Kössen (Tyrol), and Imer (Trentino) were characterized by high α-multifunctionality ($\alpha>0.894$) and low β -multifunctionality values ($\beta<0.132$) and are therefore characterized by a balanced ES supply. The municipalities of Andriano/Andrian, located along the valley floor of the Adige Valley (South Tyrol), as well as the municipalities of Lienz (Tyrol), and Fai della Paganella (Trentino), located at elevations between 200 and 1500 m, were characterized by high α -multifunctionality ($\alpha>0.894$) and high β -multifunctionality ($\beta>0.148$) and are therefore characterized by a more generalized ES supply.

4 | DISCUSSION

4.1 | Overview

In line with previous assessments (Brandt & Veijre, 2004; Mouchet et al., 2017), our results indicate that the supply of multiple ES is largely driven by different land use types and topography, generally increasing following a gradient from high to low land use intensity and/or high to low elevation, respectively. However, understanding ES-multifunctionality and incorporating it into land use policy and management requires adopting a multi-scale approach (Le Provost et al., 2022). While patch-scale analyses are necessary to identify the environmental characteristics underpinning ES-multifunctionality with a fine level of detail, assessments at the landscape and regional levels can shed light on the benefits received from interacting ecosystems. Different management scenarios may emerge at the landscape scale, reflecting the necessity to target landscape policy and management strategies according to the specific capacities of ecosystems to supply multiple ES (i.e. balanced, unique, generalized ES supply), by also including spatial patterns and scale considerations.

4.2 | ES-multifunctionality patterns at different spatial scales

4.2.1 | Balanced ecosystem service supply

Landscapes that are characterized by a high diversity of ES (i.e. high α-multifunctionality, red colour in Figure 5) should be sustainably managed to increase the resilience of socio-ecological systems. Our

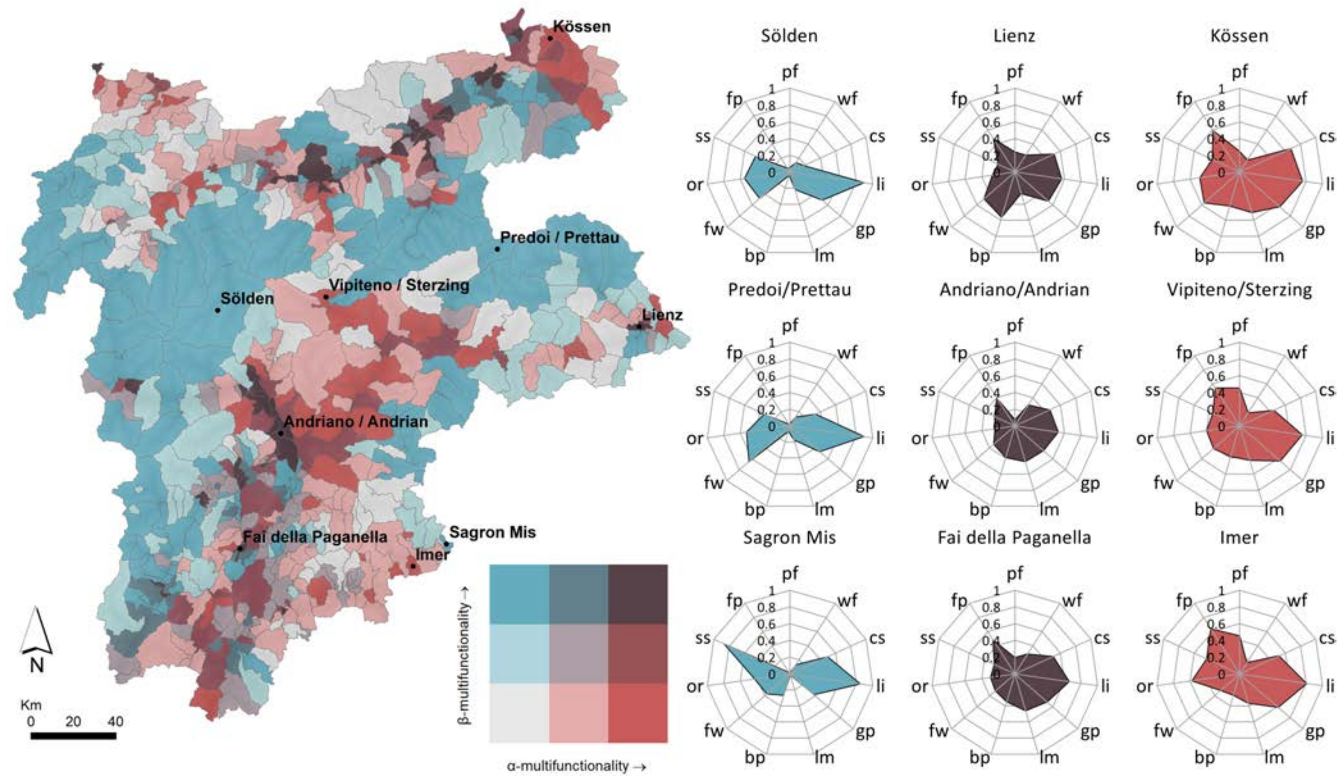

FIGURE 5 Bivariate map of α- and β-multifunctionality based on quantiles (class intervals of α: [0–0.889], [0.890–0.894], [0.895–0.901]; class intervals of β: [0–0.131], [0.132–0.148], [0.149–0.285]). Spider charts display the distribution of the 11 ES (pf, forest protection against natural hazards; wf, surface water filtration by ecosystem types; cs, carbon sequestration; li, land use integrity and quality; gp, gene pool protection; lm, lifecycle manteinance; gp, biomass production from grassland; fw, fuelwood production; or, outdoor recreation; ss, symbolic species; fp, foraging practices) in three municipalities taken as an example for the Italian provinces of South Tyrol and Trentino and the Austrian federal state of Tyrol in the top quantile combinations [high α and low β (red, balanced ES supply); low α and high β (light blue, unique ES contributions); high α and high β (brown, generalized ES supply)].

study shows that forest-dominated landscapes of the mountain and sub-alpine belts are ES diversity hotpots, reflecting their ability to provide several ES simultaneously (e.g. carbon sequestration, protection, and outdoor recreation), which was also acknowledged in other studies (Crouzat et al., 2015; van der Plas et al., 2016). Managers should aim to ensure that ES synergies are enhanced and potential land conflicts among different ES (e.g. timber production and gene pool protection) are mitigated (Mastrangelo et al., 2014; Tscharntke et al., 2012). Previous works (Felipe-Lucia et al., 2018; Gamfeldt et al., 2013) have highlighted that managing forests to increase structural heterogeneity, maintaining large trees, and canopy gaps, for example, are valuable strategies to pursue this goal and promote forest multifunctionality. However, maintaining the provision of multiple ES simultaneously in small plots of land, that is at the patch scale, may be hard when ecosystems do not have the necessary biophysical attributes to provide them all (e.g. structural heterogenity; Turkelboom et al., 2018) or if landscape dynamics, such as land use changes or rural abandonment influence their provision (Egarter Vigl et al., 2016). In such cases, the aim should be to achieve ES-multifunctionality at larger spatial scales (Hölting, Jacobs, et al., 2019).

4.2.2 | Unique ecosystem service contributions

When maximum ES diversity cannot be reached, sites targeted for specific purposes can provide greater value to society by ensuring ES that are needed, but lacking, within larger regions (β-multifunctionality, light blue colour in Figure 5; Felipe-Lucia et al., 2018; Hölting, Jacobs, et al., 2019). Significantly lower levels of ES-diversity were apparent in the more natural areas of the alpine and nival zones where landscapes are dominated by sparse vegetation, rocks, and permanent snow cover (Grêt-Regamey et al., 2012). Indeed, the provision of ES at these elevations is largely based on climate. For example, ES such as insect pollination and carbon sequestration, which are largely dependent on primary productivity and on heat accumulation (Haberman & Bennett, 2019; Mouchet et al., 2017), are less abundant. Nevertheless, similar to the findings of Crouzat et al. (2015), these sites were characterized by the highest levels of land use integrity and quality (i.e. naturalness), and cultural ES (i.e. outdoor recreation and presence of symbolic species). These sites should, therefore, be considered unique due to their narrow and more specialized ES contribution to the region (Hölting, Jacobs, et al., 2019;

van der Plas et al., 2018). Moreover, since a large proportion of alpine areas lies within the Natura 2000 network of protected areas and human intervention is limited, landscape managers should not only manage for ES in these areas, but also consider that these sites are intrinsically worth preserving, independently of the benefits they provide to people.

4.2.3 | Generalized ecosystem service supply

Our results indicated that landscapes on valley floors at lower elevations were often characterized by high ES diversity, although intensive land use types found at this elevation (e.g. permanent cultures and urban areas) featured a lower capacity to supply multiple ES, as also described in Egarter Vigl et al. (2017) and in Hölting, Jacobs, et al. (2019). In fact, the administrative boundaries of low-mountain municipalities typically include not only the valley floor but also the valley slopes covered by land uses with high ES potential (e.g. managed forests). At these elevations (<750 m a.s.l.), in cases where high ES diversity levels were coupled with high dissimilarity scores (i.e. high β-multifunctionality, brown colour in Figure 5), the ES supply is not particularly specialized, but rather generalized, meaning that the landscape supply lower or moderate levels over multiple ES compared to other sites (Hölting, Jacobs, et al., 2019; van der Plas et al., 2018). The results obtained by Hölting, Jacobs, et al. (2019) attribute the combination of high α- and β-multifunctionality to low intensity management systems (e.g. fallow farmland). In our case, however, these landscapes were highly different from others in the region because of the high concentration of many different land use types in small areas, in addition to the fact that much of the land in the valley floor is used for intensive permanent crops. Such land use composition results in a lower degree of land use integrity and fewer opportunities for outdoor recreation, but overall increases the regional ES-multifunctionality through contributions from agriculture. Similar considerations have been made by Egarter Vigl et al. (2021) and in van der Plas et al. (2018). While agricultural expansion advances as new areas become suitable due to changing climatic conditions (e.g. moving up in elevation; Tscholl et al., 2022), management decisions should account for the ES trade-offs originating from land sparing strategies (i.e. segregating land for nature from land for production; Tscharntke et al., 2012). In fact, agricultural intensification degrades regulating and cultural ES, while also impairing biodiversity and ecological connectivity (Dainese et al., 2017; Locatelli et al., 2017). Agroforestry systems and increased cover of hedgerows, for instance, have been proposed for sustainable intensification, that is increasing production of goods without degrading natural resources (Dainese et al., 2017; Nerlich et al., 2013). Some landscapes had low ES-diversity but were also not particularly specialized (white colour in Figure 5). We suggest that these sites could be considered as potential candidates for projects that aim at restoring ecosystems and their capacity to provide ES, but more in-depth analyses would be required to better understand the processes at the basis of lower α- and β-multifunctionality.

4.3 | Applicability of the assessment

ES maps are powerful tools for decision-making processes, as they can guide the implementation of the ES-multifunctionality framework for the management of ecosystems and landscapes (Maes et al., 2011; Zen et al., 2019). While achieving high ES-multifunctionality is often a management aim of the landscape level (Manning et al., 2018), information should be available at all scales for ES-multifunctionality to be a common goal across socioeconomic sectors and administrative levels (Nagendra & Ostrom, 2011; O'Farrell & Anderson, 2010). This would allow to perform ES-multifunctionality assessments based on which ES are desired and at the proper scale. In this study, the behaviour of α-multifunctionality patterns at the patch scale was generally confirmed at the landscape scale: we observed higher ES-diversity at middle elevations in forest-dominated landscapes. However, in line with Stürck and Verburg (2017), the correspondence of α-multifunctionality hotspots decreased at increasing scales of analysis. In fact, landscape scale results made it difficult to identify the specific land uses where ES hotspots formed, for example in forests at middle elevations. This occurred because higher levels of data aggregation (e.g. from 25 to 100 m resolution and to the landscape scale, as in this study) often result in a loss of information and therefore in a lower level of detail, highlighting the importance of employing multiple scales of analysis (Zen et al., 2019). According to Raudsepp-Hearne and Peterson (2016), scale mismatches do not invalidate the results of these types of analysis, but rather they should be conveyed to administrative bodies and stakeholder groups at different scales of governance. The distinctive comparison of patches at the patch scale allows a better interpretation of the results at the landscape scale while providing detailed spatial information on ES diversity to landscape managers. Such information could be used to identify and prioritize areas that should be sustainably managed, protected or restored in the planning and management of regional and cross-border Green Infrastructure networks (Benedict & McMahon, 2002). Additionally, detailed spatial information could be integrated into the co-design of conservation measures by farmers and other stakeholders (e.g. agricultural advisors, scientists; Hölting et al., 2022). On the other hand, information at the landscape scale can be harnessed at higher governmental levels. Potential applications include establishing restoration targets, design of agri-environmental schemes, and the allocation of subsidies or payment schemes for ecosystem services (PES). These tools can promote sustainable land use through financial incentives for ES providers, which ultimately encourages the long-term conservation of natural resources (Nelson et al., 2009; Turner & Daily, 2008). Choosing appropriate scales of analysis is, thus, crucial to convey the relevant information according to the management applications at stake (Raudsepp-Hearne & Peterson, 2016).

4.4 | Methodological considerations

Given that there is no unified approach to the quantification of ES-multifunctionality (Hölting, Beckmann, et al., 2019), metrics should be chosen based on the type of information desired. We decided not to take the simple sum of ES indicators to avoid overestimating patches with few ES at high levels. This approach risks ignoring ES richness, which is very much associated with the concept of ecosystem multifunctionality (Stürck & Verburg, 2017). The "averaging" approach would have also been suitable for the identification of ES hotpots and coldspots. However, the use of diversity indices allowed us to take into account the identity of ES, while also evaluating whether different ES are equally balanced across different spatial units, or whether there are a few dominant ones, thus allowing us to assess unique ES contributions of smaller areas to a larger region. In this study, we defined landscape units through municipality boundaries. However, we cannot fully exclude boundary effects when deriving multifunctional metrics at the landscape level. Moreover, the choice of the ES indicators included in the assessment should also be carefully considered when interpreting the results. As a matter of fact, the number and the spatial distribution of ES clusters is sensitive to the individual ES selected and the input data available to define them (Mouchet et al., 2017). For example, the fact that ES indicators are often calculated and mapped based on land use classes can involve circular reasoning (Kuemmerle et al., 2013), which may hide the variety of factors that shapes land use distribution and the sustainable provision of multiple ES (de Groot et al., 2010; Tasser et al., 2009). Thus, we cannot ignore the fact that the results could have been influenced by the ES considered and that the scenarios produced could change by including different ES in the analysis and by choosing different landscape boundaries (e.g. altitudinal belts). The integration of valuation and validation by stakeholders into ES-multifunctionality analysis can translate the actual benefits that people derive from nature into different weightings for ES (Manning et al., 2018), thus increasing the value of policy and management recommendations (Kurle et al., 2022). Finally, the present study did not include any temporal component, which would enable monitoring of changes in ES-multifunctionality.

5 | CONCLUSIONS

ES-multifunctionality is a fundamental property of sustainable landscape systems that builds upon healthy and interacting ecosystems. Our findings suggest that the use of diversity metrics is a promising approach to enhance understanding of ES-multifunctionality in mountain regions and to operationalize it into land use policy and management. In fact, the approach allows to account for dynamics in the supply of multiple ES at different spatial scales, and to shed light on the benefits originating from interacting ecosystems, as well as unique ES contributions by small areas to larger regions. While at the landscape scale the supply of multiple ES is shaped by structural heterogeneity and biophysical characteristics, at the patch level, ES-multifunctionality is largely driven by the diversity of ecosystem processes and functions that determine the supply of individual ES. We advocate that landscape policy and management need to account for such scale effects and need to encompass the structural, functional, and social complexity of ecosystems and their benefits. Ultimately, this will contribute to identifying areas that should be protected, restored, or sustainably managed.

AUTHOR CONTRIBUTIONS

Heidi Simion and Lukas Egarter Vigl conceived the idea. Heidi Simion, Lukas Egarter Vigl, Valentina Giombini and Erich Tasser designed the methodology. Heidi Simion and Thomas Marsoner collected and harmonized the data. Heidi Simion analysed the data and led the writing of the manuscript. All authors contributed critically to the drafts and gave final approval for publication.

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CONFLICT OF INTEREST STATEMENT

Lukas Egarter Vigl is an Associate Editor of Ecological Solutions and Evidence but took no part in the peer review and decision-making processes for this paper. The authors declare no competing interests.

DATA AVAILABILITY STATEMENT

The dataset containing the records of α- and β-multifunctionality for each municipality and the map of α-multifunctionality at the pixel resolution of 100 m are available at the open digital Zenodo Repository: https://doi.org/10.5281/zenodo.8198968 (Simion et al., 2023).

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

Figure S1. α-multifunctionality.

Figure S2. Relationghisp between α- and β-multifunctionality.

Table S1. Results of one-way ANOVA between α-multifunctionality and LULC.

Table S2. Results of one-way ANOVA between α-multifunctionality and elevation zones.

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