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# A multi-pressure analysis of ecosystem services for conservation planning in the Alps

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ABSTRACT

Increasing anthropogenic pressures such as pollution, climate change or invasive species can have multiple impacts on ecosystems and the services (ES) they provide. To address the potential effects on ES provision, we propose a geospatial framework to identify and analyze the cumulative effects on terrestrial and freshwater ES. The framework includs an impact chain analysis based on ten pressures grouped into six categories (pollution, climate change, land-use change, overexploitation, land fragmentation, invasive species) and their single or multiple effects on five key ES of the Alpine environment (recreation, forest protection, $CO_2$ sequestration, habitat maintenance, grassland biomass). Results show that the areas most affected by cumulative effects were located in major urban centers, in the Po Valley, Germany, Slovenia, and in coastal areas of the Adriatic Sea. The spatial coincidence analysis of pressure P-ES on IUCN protected sites showed that protection categories IV and V mostly had high P/high ES scores. Our approach will help in management and planning for mountain conservation aimed at reducing multi-pressure occurrences in transboundary environments. The framework can be used to identify areas with the highest ES provision, characterize areas with high stress from anthropogenic pressures, and examine the effects of pressures on protected areas.

## 1. Introduction

Global and European frameworks have highlighted the need to address the effects of human and nature-based phenomena on ecosystem services (ES) and human wellbeing (Maron et al., 2017). For instance, the Millennium Assessment (MA) explicitly identifies global drivers of change as the agents for modification of ES provision (MA, 2005). In Europe, the Mapping and Assessment of Ecosystems and their Services (MAES) initiative identified six ecosystem threats that can impair ES flow and affect human wellbeing (BISE, 2019). While the frameworks were designed to guide researchers in developing instruments to analyze ES with the final aim of supporting ES management of socio-ecological resources, the analysis of how to address the drivers of change or ES threats has only shown small advances in the last decade. In the context of ES research drivers for change can be found in a first place in the Millennium Assessment, where a set of direct and indirect drivers for environmental and socio-economic change and their future trends were described. Drivers were defined as the natural and human-induced factor that directly or indirectly causes a change to an ecosystem and include climate, plant nutrient use, land conversion, and diseases and invasive species (MA, 2005). Within the analysis of drivers, the term threats (Farella et al., 2020), pressures (Kuempel et al., 2020) or stressors (Allan et al., 2013) was used interchangeably in the specification of the ecological or physical phenomena exerting the alteration on the environment. An emerging instrument for integrated environmental assessment is the use of cumulative effects assessment (CEA) of human activities on single or multiple ecosystem components (Allan et al., 2013; Depellegrin et al., 2020). The objective of CEA is to ensure that adverse environmental effects are properly considered to foster sustainable development and stimulate public participation. CEA has become a common approach to assess impacts on environmental assets and potential consequences for human well-being (Menegon et al.,

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2018). In recent years, the approach has been extended by incorporating the impact on ecosystems with ES into multiple impact assessments. Most studies addressing cumulative effects on ES refer to freshwater environments (Culhane et al., 2019), wetlands (Evans et al., 2014) or marine environments (Depellegrin et al., 2020). Although ES assessment has proceeded rapidly in terrestrial realms, the analysis of cumulative effects has been neglected by the scientific community. While global and EU level ES assessments, such as the Millennium Assessment (MA, 2005), The Economics of Ecosystems and Biodiversity (TEEB, 2020) or the Mapping and Assessment of Ecosystem Services (MAES, 2013) classification framework provide multiple guidelines for the analysis of ES, the majority of them provide very few guidelines in the analysis of the drivers of change or impacts that ES can be subjected to.

The aim of this research was to analyze the cumulative effects generated by multiple anthropogenic pressures on key ES in the Alpine Space Programme cooperation area (ASPCA). The analysis was based on five key ES of the ASPCA, namely $CO_2$ sequestration, forest protection, outdoor recreation, grassland biomass and habitat maintenance adapted from the AlpES Project (Alpine Ecosystem Services - mapping, maintenance, management, 2018). The multi-pressure dataset was based on nine pressure layers grouped into five categories defined according to threat categories within the Biodiversity Information System for Europe (BISE, 2019), namely climate change, land use change (soil sealing), invasive species (vector-based diseases), pollution (light, noise, air and soil) and landscape fragmentation and exploitation (wood removal and hydropower production). Similar pressure categories can be retrieved from Maes et al. (2018). We aimed to provide a scalable instrument to provide a CEA of key ES of the Alpine Space and to suggest an operational and replicable framework to better incorporate ES knowledge into the cumulative EIA context. A focus in the analysis was on the coincidence of protected areas (PA) in securing ecosystem goods and services through a spatial PA coincidence analysis. Results were discussed for their relevance for EU and macro-regional governance of the Alpine Space, methodological strengths, shortcomings and applicability outside the current study area.

## 2. Methods

### 2.1. Study area

The study area is defined by the transboundary area of the ASPCA (Fig. 1). It covers about 390,000 km$^2$ and includes seven countries (France, Italy, Switzerland, Liechtenstein, Austria, Slovenia and Germany). About 70 million people live in the ASPCA, mainly in urban agglomerations in the peri-Alpine belt. The Alps, offering various outdoor recreation opportunities in summer and winter, are a very popular tourist destination with around 120 million tourists annually, which come mostly from European countries but also from all over the world (Schirpke et al., 2019b). Tourism hotspots in the ASPCA include, among others, various mountain locations, the coastline of the Mediterranean Sea, the great lakes in the Italian Alps as well as big cities such as Zurich, Milano, Munich or Vienna (Schirpke et al. 2018).

Land cover in the whole ASPCA is dominated by forests (40%), agricultural land (29%) and grassland (15%). For details on land cover distribution and recent changes, see Appendix A of the supplementary material. While arable land, permanent cultures as well as urban and industrial surfaces concentrate on the lowland areas, forest, grassland, rocks and sparsely vegetated areas can be principally found in the core mountain area. In particular, the Alpine arc is home to unique flora (over 4,500 vascular plants) and fauna (about 30,000 species) and with an outstanding cultural landscape (WWF, 2019). However, the ASPCA is a fragile environment facing a number of threats mostly related to biodiversity loss, pollution (WWF, 2019), mass tourism (Alpconv, 2013) and climate change (EEA, 2010).

In 1994, the International Union of Conservation of Nature (IUCN) defined standardized guidelines for designating PA using six distinct categories: about 77,330 km$^2$ of land in the study area is under six different IUCN categories (Ia, Ib to VI). The aim was to apply different levels of legislative or regulatory protection and control the nature and intensity of permissible land uses (IUCN, 1994). Appendix B in the supplementary material provides an overview of the IUCN categories present in the study areas, including their description and extent (in km$^2$

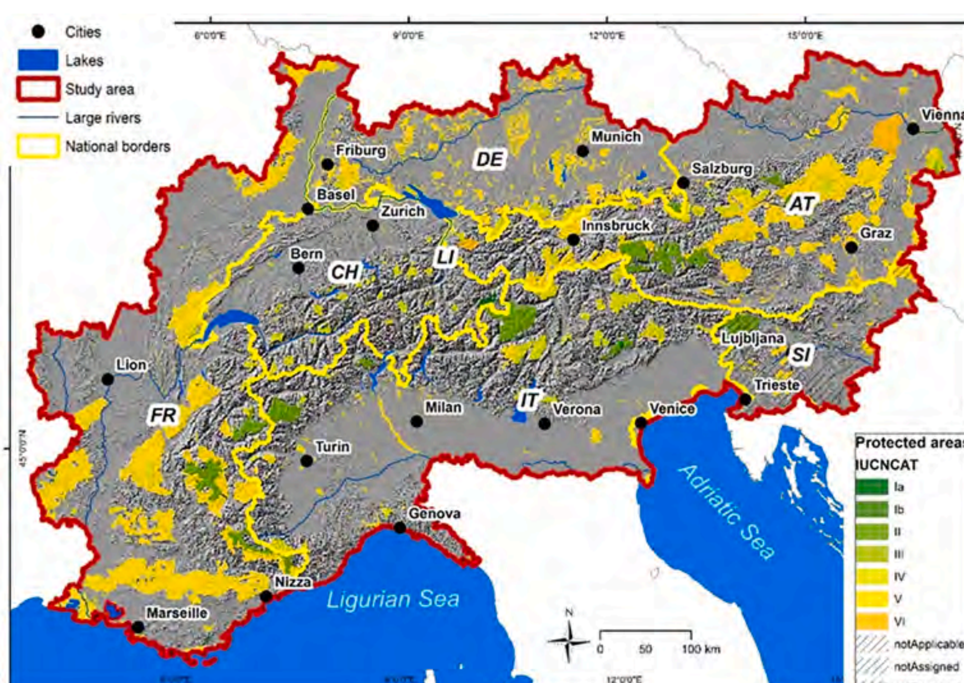


**Fig. 1.** The study area of the Alpine Space Programme cooperation area and respective protected areas with IUCN categories (I to VI). Note: IUCN areas that are notApplicable, notAssigned and notReported are not taken into consideration in the assessment presented in this research. Note: FR – France, CH – Switzerland, IT – Italy, DE – Germany, AT – Austria and SI – Slovenia.

and %).

### 2.2. Linking multiple pressures to ES: The impact chain model

To assess the cumulative impacts of anthropogenic pressure (P) on ES, we used an impact chain approach (e.g. Drius et al., 2019; Menegon et al., 2018; Vanbergen, 2013) to develop a cumulative P-ES effect assessment model ($C_{P\text{-}ES}$) as presented in Fig. 2. The aim of the impact chain model was to provide a conceptual and operative framework that describes the causal links among the *i-th* pressure ($P_i$) affecting the *j-th* ecosystem service ($ES_j$). The single or multiple pressures $P_{1\ to\ i}$ exerted by human activities or natural phenomena ($n = 9$) can affect single or multiple $ES_{1\ to\ j}$ ($n = 5$ (Fig. 2). Each of the P-ES combinations results in an ES specific pressure assessment model and map, with the final aim of producing a cumulative P-ES impact model. The outputs of the framework include ES and P maps, the cumulative pressure ecosystem services assessment ($C_{P\text{-}ES}$) and a spatial coincidence analysis of P and ES in IUCN PA.3

The algorithm used to describe $C_{P\text{-}ES}$ is composed of $P_i$ (the *i-th* pressure affecting the *j-th* ES); $ES_j$ (the *j-th* ecosystem service) and *n* (the number of pressures present). The algorithm can be described as follows:

$$C_{P-ES} = \sum\nolimits_{i=1}^{n} P_i x ES_j$$

All datasets for P and ES were subjected to a normalization procedure based on $x/x_{max}$ to enable harmonization of inputs and applicability of the $C_{P\text{-}ES}$ algorithm. The raster grid cell resolution applied to all datasets was 1 km using the EEA reference grid resulting in over 402,500 pixels (EEA, 2019). Depending on the input dataset resolution, datasets were upscaled or downscaled to fit the reference grid. In the following sections a detailed description of the P and ES involved in the cumulative effects assessment and their data sources is presented.

### 2.3. Pressures

The definition of P was aligned to the MAES threat categories provided within the Biodiversity Information System for Europe (Table 1, BISE, 2019). Using an existing threats nomenclature to operationalize the P on ES within an EU-wide assessment framework facilitated replicability and comparison with other applications across Europe. In the following sections a detailed description of the P comprising the multiple-pressure dataset are described.

#### 2.3.1. Climate change (CC)

CC can have multiple effects on biodiversity and human wellbeing (Nelson et al., 2013; van der Geest et al., 2019). In recent years there has been increasing analysis of the effects of CC on ES and the development of frameworks capable of considering the CC phenomena in ES-driven

**Table 1**
MAES threat categories, explicit pressures and indicators applied.

| Threat | Pressure | Indicator |
|---|---|---|
| Climate Change | Precipitation trend | mm (years 1982–2010) |
| | Temperature trend | Celsius (years 1982–2010) |
| Pollution | $CO_2$ emissions | $CO_2$ emissions (t $CO_2$ km$^2$, for the year 2010) |
| | Noise | Noise index (Day-Evening-Night-Level Lden in db(A)) |
| | Light pollution | Light pollution index |
| | Eutrophication | Nitrogen load (kg ha$^{-1}$y$^{-1}$) |
| | Soil pollution | Eight heavy metals: As Arsenic, Cd Cadmium, Cr Chromium, Cu Copper, Hg Mercury, Ni Nickel, Pb Lead, Zn Zinc (in kg/m$^3$) |
| Invasive species | *Ixodus ricinus* ticks | Degree of presence (Established – Introduced – Not recorded) |
| | West Nile Virus infections (Projection 2025) | Probability of presence (0.5 to 0.02) |
| | Tiger mosquito (*Aedes albopictus*) | Degree of presence (Established – Introduced – Not recorded) |
| Overexploitation | Timber removal | m$^3$ / year (2012) |
| Fragmentation | Landscape fragmentation | Edge |
| | | Patch |
| | | Perforated natural landscape |
| | | Core (<250 acres) |
| | | Core (250–500 acres) |
| | | Core (>500 acres) |
| | Freshwater fragmentation | Fragmentation index (% of area (in km$^2$) of catchment fragmented in total catchment) |
| Land use change | Soil sealing | Area (ha) of land use converted to urban LU and incorporated in the 1 km grid |

approaches (Chiabai et al., 2018). The CC effects included temperature (degree Celsius) and precipitation (mm) patterns for the years 1981–2010. Datasets used for the analysis were retrieved from the Historical instrumental climatological surface time series of the Greater Alpine Region (HISTALP) (Auer et al., 2007) and represented gridded data of monthly average temperature and total monthly precipitation at 5 min spatial resolution.

#### 2.3.2. Pollution (POL)

POL phenomena are a major source of biodiversity loss and risks to human health (MA, 2005). The P dataset incorporated five POL phenomena: (1) the noise pollution layer was represented by a day-evening-night noise level (Lden) from road, rail, and air traffic as well as industrial sites. The data was retrieved from the EIONET data repository of the EEA based on the EU National Reporting Obligations DF4 and DF8 Strategic Noise Maps according to the Environmental Noise Directive

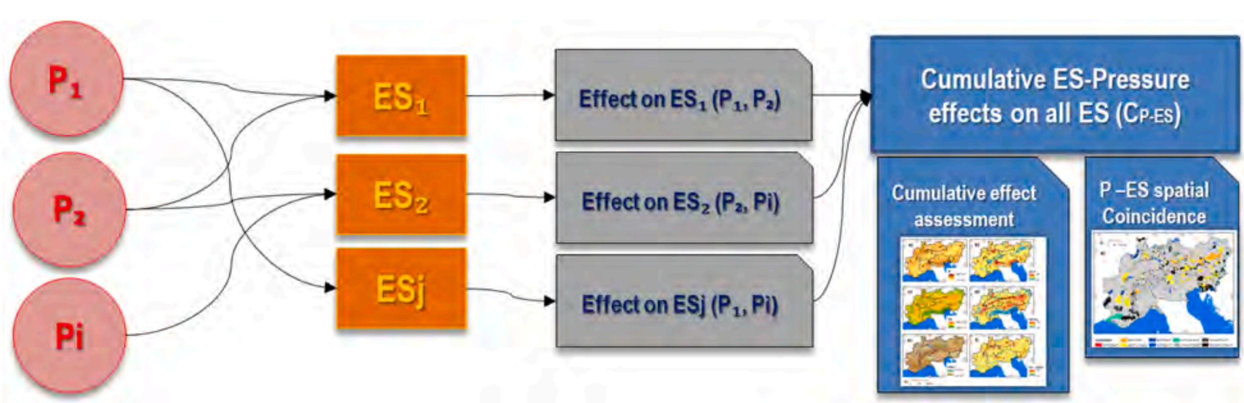


**Fig. 2.** Conceptual representation of the cumulative impact chain model: anthropogenic activities exert single or multiple Pressures (P) on one or multiple ecosystem services (ES) resulting in a cumulative effect assessment model ($C_{P\text{-}ES}$).

(Eionet, 2019). The dataset was provided in A-Weighted Decibel (dB(A)) units. (2) Light pollution data was retrieved from NOAA (NCEI) Earth Observation Group and represents the annual average radiance composite (VIIRS, 2016). (3) Air pollution was represented by $CO_2$ emissions in tons per square kilometer per year retrieved from JRC (Air and Climate unit Directorate C - Energy, Transport and Climate (Trombetti et al., 2019) and (4) soil pollution was composed of eight heavy metals (As Arsenic, Cd Cadmium, Cr Chromium, Cu Copper, Hg Mercury, Ni Nickel, Pb Lead, and Zn Zinc) in kg/$m^3$ (5 km resolution) for surface soil retrieved from the European Soil Data Centre (ESDAC, 2008). (5) Eutrophication effects were modelled using the InVEST Nutrient Delivery Ratio model (Sharp et al., 2016) calculating the N load (kg $ha^1$ $y^{-1}$) in the study area based on the nitrogen emitted in the atmosphere and then deposited in the landscape, including the nitrogen used for fertilization in agriculture.

#### 2.3.3. Invasive species (IVS)

IVS can be vectors for diseases and pathogens that can affect biodiversity and human health (Crowl et al., 2008). In this study we used a spatial dataset of three vector-based diseases retrieved from the European Centre for Disease Prevention and Control (ECDC): *Ixodus ricinus* ticks, West Nile Virus infections (Projection 2025), and Tiger mosquitos in Europe (*Aedes albopictus*). *Ixodes ricinus* can transmit some of the most important tick-borne diseases, namely Encephalitis (TBE) and Lyme borreliosis (Lyme disease; ECDC, 2019). The Tiger mosquito can transmit viral diseases such Zika, chikungunya and dengue (e.g., Li et al., 2019). The IVS were selected, because study area evidences of increasing incidence of vector-based diseases in the population of study area in recent years (AGES, 2020; ECDC, 2020).

#### 2.3.4. Overexploitation (OXP)

Resource extraction activities such as wood harvesting belongs to the most traditional industrial activities in the Alpine Space (Modica, 2019; Alpconv, 2015). We apply an proximity-based indicator named Forest removal that describes the total timber removals considering forest accessibility and in-site conditions measured as $m^3\ ha^{-1}\ y^{-1}$ (Clouet and Berger, 2009). The layer was produced by disaggregating regional timber harvest statistics, using a general accessibility and terrain analysis to simulate potential wood harvest conditions and estimate the average removal from each forest area. The Copernicus High Resolution Layers and the EU Digital Elevation Model v1.1 were used as data sources at a resolution of 25 m (EEA, 2016a, 2016b, 2018c). The indicator is limited to localized exploitation of wood resources, while for instance under-exploited areas, such as un-managed forest that may can have negative effects on species richness (Plieninger et al. (2014); Paillet et al. (2010)) was omitted in this research.

#### 2.3.5. Fragmentation (FRAG)

Phenomena like urban sprawl, transportation and energy network development can induce fragmentation of ecosystems. This weakens the resilience of ecosystems. Landscape fragmentation analysis was performed using the Landscape Fragmentation Tools (LFT) v2.0 provided as an ArcGIS toolbox by the Center for Land Use Education and Research (CLEAR; University of Connecticut). The input dataset for land use was provided by CORINE 2018. The tool can be freely downloaded from the Center for Land Use Education and Research website (CLEAR, 2020). Fragmentation of freshwater ecosystems is mainly caused by dam structures (Grill et al., 2015). For the spatial analysis of fragmented freshwater bodies, we adapted the freshwater fragmentation index proposed by Grill et al. (2015). The index corresponded to the ratio of the percentage of fragmented sub-catchments to the percentage of total area of the catchment within a study area. The input was the Global Reservoir and Dam (GRanD) dataset retrieved from the Socioeconomic Data and Applications Center (SEDAC, 2011) and sub-catchments for the study area were taken from the European catchment and river network (Ecrins, 2012).

#### 2.3.6. Land use change (LUC)

LUC and its effects on ES belong to the most studied anthropogenic drivers for ES change and modification (Bryan et al., 2018; Yang et al., 2018). The analysis was based on the CORINE 2018 dataset retrieved from the Copernicus land monitoring systems (Copernicus, 2019). The LUC pressure layer represented the land patches converted from natural/semi-natural to urbanized land use (in ha) from 1990 to 2018.

### 2.4. Ecosystem services

Eight key ES were identified within the AlpES Project (Interreg Alpine Space Programme AlpES, 2019), which provides reference ES assessments and methods for theASPCA. These were derived from a literature review, expert workshops and a user survey and selected accounting for specificity and representativeness, easiness of communication, and influenceability at different policy levels (Schirpke et al., 2019a). The geospatial datasets of the Es can be explored and downloaded in the dedicated webGIS (www.alpes-webgis.eu) at the municipality level. To quantify ES provision at the landscape level, we selected five ES, which were available as raster data with sufficient spatial resolution: forest protection, $CO_2$ sequestration, habitat maintenance (terrestrial and freshwater), outdoor recreation and grassland biomass (Table 2).

#### 2.4.1. Forest protection

This ES represented the protection function of forests towards mountain hazards. Forest areas that have a protective function against avalanches, rockfalls and channel processes were identified, and their level of protection was scored on an index ranging from 3 (sufficient) to 1 (negligible).

The protective effect for each natural hazard was calculated using ArcGIS (ESRI, 2020) and the following input data (DEM, Copernicus HRL, Ecrins). Avalanches and rockfall paths were modeled by delineating potential release areas, transition and runout zones using threshold values from literature, ArcGIS Cost path analysis and energy line angle calculations (Bauerhansl et al., 2009). The protective effect on channel processes was based on distance and slope steepness around river channels (Schwitter and Bucher, 2009). For further details on the model development we refer to WikiAlps (2020).

#### 2.4.2. $CO_2$ sequestration

This ES was calculated by estimating above- and below- ground biomass increase in forests based on IPCC equations (IPCC, 2006). The biomass increase was converted into (t $CO_2\ ha^{-1}y^{-1}$) to calculate the annual increment in the carbon pool represented by forest. Regional

**Table 2**
Ecosystem services and pressure dataset applied in this research. Note: P-provisioning, R-regulating, C-cultural ES.

| ES of the Alpine Space | Service provided | Indicator |
|---|---|---|
| Outdoor recreation (C) | Recreational potential based on 6 landscape factors | Index from 0 to 100 (with 100 having highest contribution) |
| Forest Protection (R) | Avalanche, rockfall and water channel risks lood | Index (3 = sufficient to 1 = negligible) |
| $CO_2$ Sequestration (R) | $CO_2$ sequestration by above and below ground biomass in forests | t $CO_2$ $ha^{-1}$ $y^{-1}$ |
| Habitat maintenance (R) | Terrestrial mammals and freshwater fish species habitats | Number of species per 1 $km^2$ for terrestrial mammals and freshwater fish species (*Vulpus vulpus, Ursus arctos , Sciurus vulgaris, Rupicapra rupicapra, Rhinolophus hipposideros, Dama dama, Cervus elaphus*) |
| Grassland biomass (P) | Forage production on permanent grassland | T DM $hg^{-1}$ $yr^{-1}$ |

factors for above-ground biomass were derived from the dataset of Busetto et al. (2014) and integrated with information from national forest inventories, forest typology, elevation and climatic macro-area. Factors for below-ground biomass were derived from the Swiss National Forest Inventory and adapted based on forest typology, elevation and climatic macro-area.

#### 2.4.3. Habitat maintenance

The dataset was developed using the IUCN red list geospatial dataset available from the IUCN's spatial data and mapping resources section (IUCN, 2019). Datasets included seven terrestrial mammals and 33 freshwater fish species polygons. Both habitats were represented by species abundance (Dunbar et al., 2013) in species/km$^2$. A detailed list of the species incorporated in the analysis is shown in Appendix B in the supplementary material.

#### 2.4.4. Outdoor recreation

This ES was calculated as the recreational potential according to the study of Schirpke et al., 2018. The index identified outdoor recreation provision based on six landscape features (naturalness, PA, presence of water, landscape diversity, terrain ruggedness, density of mountain peaks), weighted by accessibility. For further information, please refer to Schirpke et al. (2018).

#### 2.4.5. Grassland biomass

This ES referred to forage production in T DM hg$^{-1}$/yr$^{-1}$ on permanent grassland estimated based on growth functions for different grassland management types depending on the length of the growing season and with consideration of site parameters such as precipitation and sum of radiation. For further information please refer to Schirpke et al. (2019a) and Schirpke et al. (2019b)).

### 2.5. Outputs

The application of the cumulative P-ES assessment model enabled the production of multiple outputs analyzed and discussed in this section: (1) an overview of the impact chain characterizing P and ES linkages in the Alpine Space based on a Sankey diagram; (2) geospatial analysis of P and ES distribution and the resulting cumulative impact assessment ($C_{P\text{-}ES}$) based on eq. 1 including the identification of hot and cold spots, and (3) a spatial coincidence analysis of the three outputs in respect to PA in the study area to address relevant aspects for management.

## 3. Results

### 3.1. Impact chain

Fig. 3 shows the explicit conceptual impact chain applied to the study area using a Sankey diagram. The chain is composed of six threat categories (left column), the respective ten P indicators (middle column) and the five key ES (right column) affected by a single or multiple P relationship. In summary, pollution phenomena presented in form of five distinct agents (air, noise, light pollution, heavy metals and eutrophication) had effects on habitats and recreational ES. Fragmentation may be a primary cause of physical obstruction in reaching recreational areas (Mitchel et al., 2015) and overexploitation had important effects on terrestrial habitats. CC was identified as affecting all ES assessed (Nelson et al., 2013). Invasive species in the form of vector-based diseases primarily influenced areas of high recreational potential and attractiveness due to the high probability of people being available as infection recipients (Mazza et al., 2013). For further details on the linkages among P and ES, and an overview of effects please refer to the literature review in supplementary material (Appendix C).

### 3.2. Pressures, ecosystem services and cumulative effect assessment

The cumulative P index registered a maximum score of 8.2 (Fig. 4a–b). Application results showed that the highest pressures were concentrated in the main urbanized land uses of the study area (Milan, Vienna, Lyon and Munich). The eastern coastal areas of the Veneto and Friuli-Venezia-Giulia region (Adriatic Sea) registered higher pressure

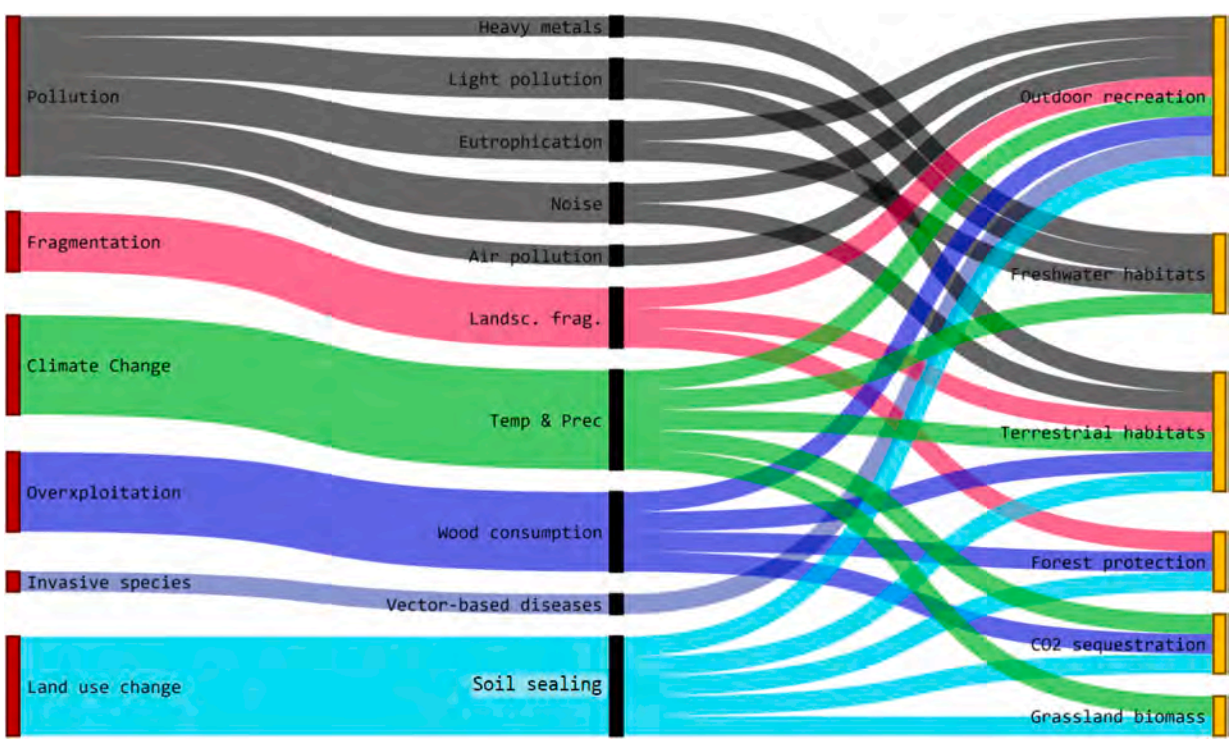


Fig. 3. Explicit impact chain application for the study area. Note: threat categories (left); explicit pressures (middle) and key ecosystem services affected (right). A literature review addressing the linkages and effects of the pressures is provided in the supplementary material (Appendix B).

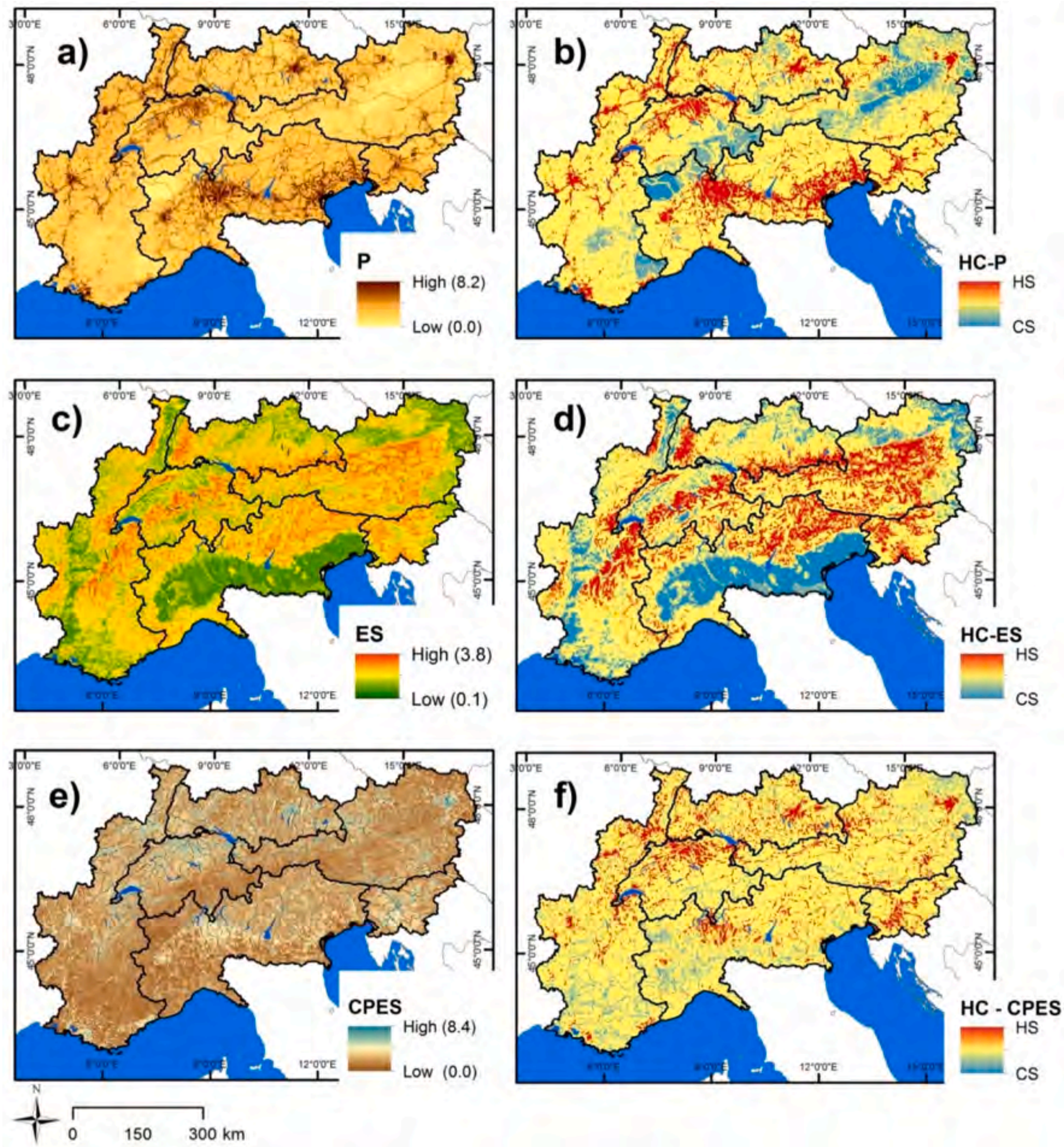


**Fig. 4.** Geospatial representation of $C_{PES}$ for the study area: (a) cumulative P application in the study area; (b) hot–cold spot analysis on cumulative P; (c) cumulative ES provision in the study area; (d) hot–cold spot analysis on cumulative ES provision; (e) cumulative effect assessment application according to $C_{P\text{-}ES}$ and (f) hot–cold spot analysis of $C_{P\text{-}ES}$.

intensity than the western coastal areas of the Ligurian Sea (Liguria and Provence-Alpes-Côte d'Azur). Coastal areas of the Veneto region are among the most highly industrialized areas of the Mediterranean (Depellegrin et al., 2017). The main reasons included the presence of multiple river outlets into the Northern Adriatic Sea, coastal urbanization phenomena causing fragmentation, noise and air pollution and the presence of vector-based diseases. Areas that registered the lowest pressure intensity were concentrated in Val D'Aosta region (IT) and Jura (CH) in the north-western Alpine Space. or northern Styria (AT) in the north-eastern Alpine Space.

Areas with the highest ES scores were located in the central part of the study area (Switzerland and Slovenia; see supplementary material Appendix D, Fig. 4c–d). The Po Valley covering the regions of Piedmont, Lombardia, Veneto and Friuli-Venezia-Giulia registered lower ES provisioning. The regions of Niederösterreich (AU), Provence-Alpes-Cote-d'Azur (FR) and Auvergne-Rhone-Alpes (FR) also registered as areas of low ES provisioning. The analysis showed that core ES provisioning bundles scoring 2.2 times the median value were located in the French Alps, Switzerland (supplementary material Appendix D).

Fig. 4e–f shows the geospatial results from the cumulative effect assessment of P on ES. The $C_{P\text{-}ES}$ highlighted particular areas that had larger combined cumulative scores, which reflected high provision of ES and high anthropogenic pressures. Areas with the highest scores were located close to urbanized settlements. However, the Po Valley had lower scores, because of the lower level of ES provisioning (supplementary material Appendix E).

### 3.3. Spatial coincidence analysis

Fig. 5a presents the aggregated spatial coincidence of P and ES hot and cold spots within IUCN PA in the study area. The relative spatial coincidence was divided into nine categories (high ES/P to not significant ES/P). There was a spatial gradient reflecting high ES hot spots combined with low or not significant P located within the central

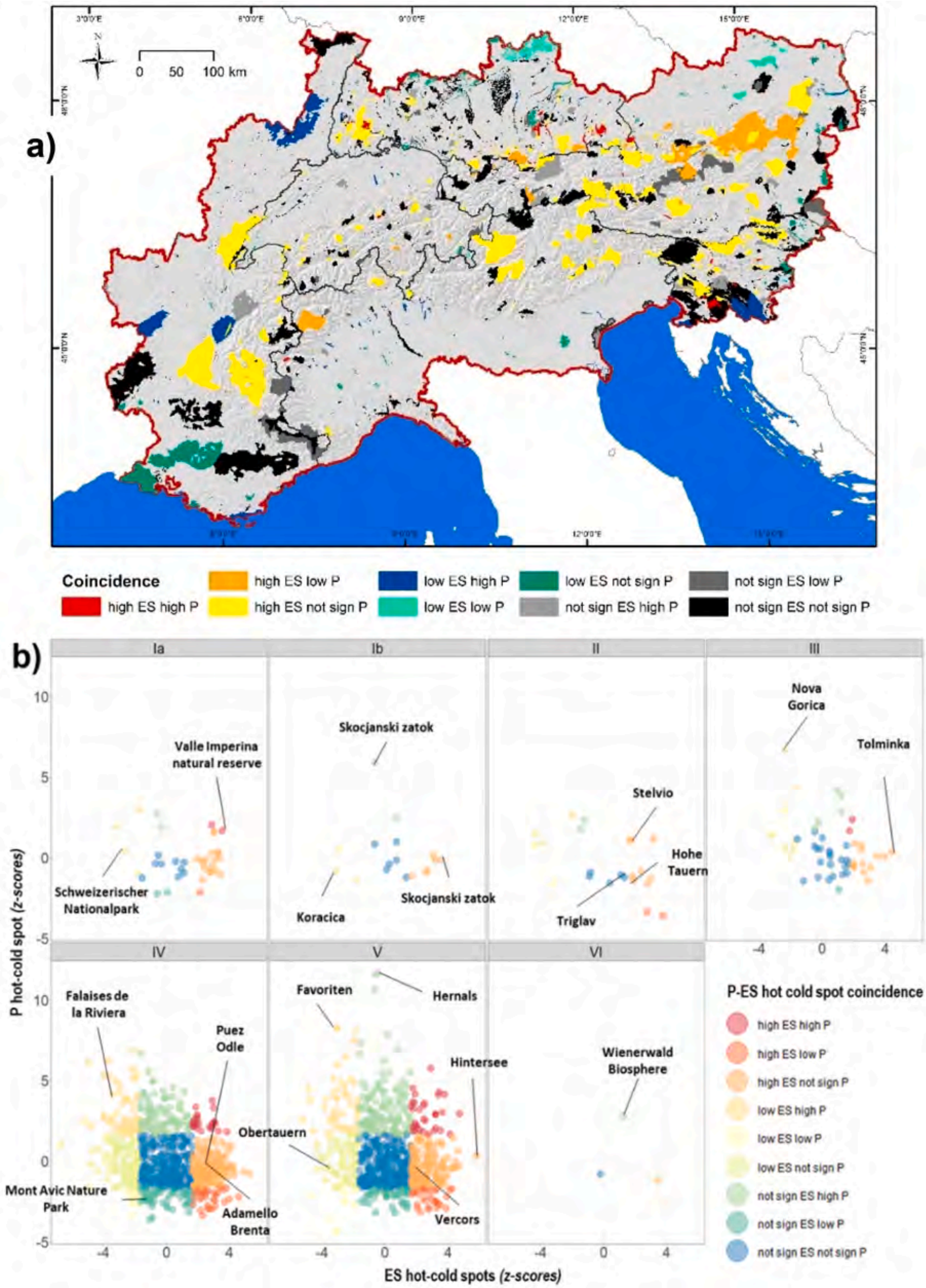


**Fig. 5.** (a) Geospatial coincidence of P and ES hot and cold spots within IUCN protected areas in the study area and (b) aggregated P-ES coincidence-based z-scores for P and ES in the IUCN protected sites. The legend (bottom right) defines the coincidence categories resulting from the analysis in each single IUCN protected area represented by dots.

segment of the Alpine Space. Notably, there was a relatively low number of PA coinciding with high ES and high P (926 $km^2$; 1.1%), mostly located in south-eastern Slovenia and Germany. Protected sites with not significant P and ES were the most preponderant (23,553 $km^2$; 30.5%). These areas were in the peripheral parts of the study area (south-west France and south-east Slovenia). In the central segment of the study area, PA had high ES and not significant P (22,082 $km^2$; 28.6%). In the northern sections of the Alpine Space several PA occurred that showed low ES/high P (Forêt des Volcans de Wegscheid - France and Schutzzone mit Naturpark Altmuehltal - Germany). Fig. 5b provides a comparative analysis of the P and ES z-scores from the H-C analysis within PA grouped into the six IUCN categories. The study area had a very limited number (n = 3) of category VI sites (sites with sustainable use of resources), while the most common categories were IV and V that designate sites of habitat and landscape protection. In terms of the spatial coincidence of P-ES hot spots, category IV and V provided multiple ES hot spots with low P cold spots (Fig. 5b).

## 4. Discussion

### *4.1. Overall considerations*

The methodology used here provides a conceptual and operational modelling framework for the assessment of multiple P and their cumulative effects on key ES in the Alpine Space. The method can firstly be used for an initial assessment of areas with the highest ES provision, through an ES hot–cold spot analysis. Secondly the method can be used to characterize areas of high stress from multiple or single anthropogenic P through the multi-pressure analyses. Finally, the method can be used to analyze the effects on potential PA through spatial P-ES coincidence.

The method is flexible as cumulative effects can be modelled against any of the ES presented here. Both datasets (ES and P) can be further complemented, as follows. (1) The integration of a supply-flow-demand ES cascade would allow investigation of how single or multiple P may affect different components of the cascade. This is essential to understand the sustainability of human activities and how they impair ES capacity and flow in certain geographic areas (Schirpke et al., 2019c). Advancements in the integration of impact assessment into the ES cascade are provided for certain pressure categories already such as landscape fragmentation (Mitchel et al., 2015) and eutrophication (Clark et al., 2017). (2) Our approach for analyzing P needs to be further extended towards a better spatialization of the P behavior across their spatio-temporal dimension. From a temporal point of view, P intensities vary through seasonal domains, such invasive species proliferation, eutrophication, air pollution, and noise pollution from mass tourism flows and, therefore, techniques that enable a differentiation of pressure intensity over time need to be examined. A first methodological advancement can be considered by incorporating expert knowledge in the P intensity of seasons and addressing the temporal coincidence with the temporal resolution of ES provision. From a spatial point of view, the existing pressure model considers P that have varying spatial propagation over time that are relevant for different compartments (air–soil–freshwater).

At the current stage, the model represents both local P (e.g. soil sealing) and P propagation. In the future, progressively more P specific spatial models need to be included. This would allow understanding of potential cross-country or cross-regional impacts in the study area, and supplement the analysis with transboundary impact assessment information for authorities. Specifically, transboundary P in this study address climate change (Benzie et al., 2016), air pollution, and freshwater fragmentation across transboundary catchment areas, while local P assessments are mostly related to mountain community development, such as soil sealing from urbanization at metropolitan and rural level and overexploitation of timber resources. The effects of climate change remain particularly challenging to address in the context of habitat functioning, as they may cause mass extinction phenomena (Bässler et al., 2010a, 2010b) and affect species distribution and abundance (Sirami et al., 2017). In this sense, the presented model should more strongly incorporate a temporal component of the analysis ideally using predictive species distribution models for mountain areas (Tang et al., 2018).

The application of the cumulative pressure model illustrated the difference in anthropogenic activities and resource management at a national level. This was the case in relation to forest consumption, where different management practices existed. For example, differences were visible between Italy and Austria. Forests in the Italian Alpine Space were managed very extensively or not at all in the last decades, mostly to ensure an optimal protective function through a very dense crown cover by applying a more naturalistic approach to forestry (Iovino et al., 2009). In Austria, forests were mostly held by private owners. They were still being managed with an agronomic approach where the economic benefit was an important factor. Even though both nations followed the guidelines of multifunctional forest management, they had different approaches, which were clearly visible in our data.

### *4.2. Challenges for the analysis*

A major challenge for ES assessment remains the definition of ES indicators suitable for the analysis and harmonization of ES assessment and mapping across EU. Starting from a consolidated ES indicator spectrum provided through the AlpES Project, we advanced the dataset towards an impact assessment-oriented analysis of the anthropogenic drivers of alpine ES change. Major shortcomings of the existing approach include: (1) the absence of guidelines on how to construct ES threat-relevant pressure indicators that can be spatially represented. In some cases, multiple pressure indicators may need to be implemented in a single MAES threat such as, for instance, pollution. This requires a more comprehensive review of pollution phenomena that directly and indirectly affect ES provision. (2) The current application of the $C_{P\text{-}ES}$ algorithm considers a linear relation between the P intensity and the ES provision. This may not be relevant in all the P-ES linkages identified, in as far as multiple pressures may have synergetic or antagonistic effects on target ES and their ecosystem components. (3) ES tipping points that may cause abrupt changes in ecological status that can impair or lead to failure of ES provision are not considered (BISE, 2019). Information on the ecological status is essential to complement the existing model with a calibration approach, as the model currently does not provide insights whether pressure(s) are responsible for a low ES on a pixel level. (4) Pressures may affect with different intensity different ES. The variability in ES sensitivity needs to be further aligned to archetypal cumulative effects assessment (Allan et al., 2013; Depellegrin et al., 2017), ideally incorporating expert elicitation procedures into the conceptualization of the impact chain framework that can be implemented in the proposed spatial cumulative effects assessment model. (5) The analysis is limited to five key ES, but further ES are also of great importance to mountain regions including water-related ES, agricultural food production, aesthetic value (Egarter Vigl et al., 2017) or cultural heritage (Tasser et al. 2020). Study results indicate that climate change as well as ongoing land use changes can have positive effects on agricultural food production and some forest-related ES, but many regulating ES and most cultural ES are negatively affected (Braun et al., 2019; Briner et al., 2013; Schirpke et al., 2020). It would therefore important to extend our analysis with further ES. A major strength of the method is the integration of a causal relationship among P and ES components into a single analysis complemented by comprehensive spatial datasets. The approach can be a useful tool for risk assessment of ES provision. We suggest that our method can be used for an initial screening of critical areas in management contexts, and to identify territories of high ES importance that have the highest impact risk. In terms of conservation management, the proposed study can provide valuable information on ecological corridor planning in regional and trans-regional level, by taking into account socio-ecological hot-spots and environmental pressure can have multiple origins and distribution patterns (Liang et al., 2018).

The results of this research are highly dependent on the scale of the case study area and the resolution of the grid applied. The applied EEA grid of 1 km resolution was designed to provide users with a suitable spatial framework for up or down scaling of geospatial analysis while preserving its unique code identifiers (EEA, 2019). These types of spatial harmonization have already been implemented successfully in other studies (Menegon et al., 2018; Zen et al., 2019) and should be further progressed to facilitate operationalization of the assessment and foster complementarity with other studies applying similar data treatment.

### 4.3. Data sources

The datasets incorporated in this research illustrate the substantial diversity of data sources needed to build a spatial impact chain model: the ES datasets benefitted from a harmonized dataset developed within a spatially comprehensive study area, while the P datasets that were applied to spatially represent MAES threats had to be developed from scratch. While there is substantial literature available for ES indicators assessment and mapping, guidelines for an ES-oriented impact assessment framework are substantially lacking in operational details that clearly address pressures on ES. This is reflected by the diversity and multitude of datasets, formats and providers required to build the pressure indicators. A comparison with the marine realm that includes the Marine Strategy Framework Directive list of 15 pressures exerted by human activities (EC, 2020), shows that terrestrial environments have a considerable amount of literature on the impacts of different anthropogenic activities (e.g. land-use change), but they do not provide an operational list of pressures that can be used to deduce spatial indicators relevant for management and planning for P application.

### 4.4. Pressure-ecosystem services coincidence analysis

The spatial coincidence analysis (Fig. 5) performed on PA illustrated the flexibility of the approach in relation to conservation planning priorities on a large spatial scale and in the conservation effectiveness of the IUCN categories (Joppa et al., 2008; Geldmann et al., 2019). The coincidence analysis assumes that there is a congruence of the assessed P-ES taking place in a PA and that these stressors that may have a wider distribution e.g. air pollution or climate change effects inhibit the ES provided within the PA. Stressor categories that are related to physical loss of a natural resource such as land use conversion are easier to monitor and usually relate to localized effects.

There is an overall lack of information on the quality of ES provision and how the anthropogenic pressures may affect the ecological status that may, in turn, impair the conservation effectiveness of the PA. An essential advance in the analysis of the effects of anthropogenic activities on PA is the need to have monitoring and observation campaigns producing in-situ data on the pressure intensities in the PA that can be used to calibrate the presented cumulative effects assessment model. This would also enable the definition of adaptive management strategies and dynamic buffer zones that could be designed around different PA based on their socio-ecological conditions, seasonality, P types and intensity.

PA that coincide with high P and low ES require particular investigation and monitoring, to understand whether the low ES provision is related to the intensification of pressures that deplete the ES provision. In this sense, the analysis could contribute to the design of restoration priorities in the study area that can systematically target multiple stressors. However, PA that are ES hot spots would require further investigation of the ecological and socio-economic conditions that enable high ES provision within different IUCN categories. In this sense, exchange of experience and knowledge sharing mechanisms among national responsible authorities would facilitate a wider investigation of the study area and a more comprehensive management approach to specific PA.

## 5. Conclusion

The methodology presented here can support decision-makers and planners in the analysis of current impact risk areas in the transboundary regions of the Alpine Space combined multi-pressure-ES assessment models. From an operational viewpoint, the model can be used to identify management priorities in the study area and in specific IUCN PA highlighted through the approach. We believe that the research provides a methodological advance in the assessment of terrestrial cumulative impact assessment and can provide substantial support in the further implementation of operational instruments for a pressure-aware ES cascade assessment aligned to the MAES approach. The model faces a set of methodological and data-driven gaps that need to be addressed in the near future: The set of five alpine key ecosystem services for the study area need to be further complemented with species-specific distribution models and water provisioning services or landscape aesthetics. The threat categories identified in the study should be further complemented by incorporating other invasive species or freshwater pollutants (e.g. eutrophication, heavy metals, fertilizers, litter). The propagation model based on a multi-buffer distance approach should be complement with threat specific propagation simulations, such as atmospheric circulation or models for water quality assessment. This future research needs can support the development of decision-support instruments for the analysis of environmental restoration needs and guide investments towards ES flow enhancement to ensure human wellbeing and resilience of the ES use. The model presented provides an overview of complex relationships of P and ES. Conservation prioritization needs to be further addressed on a single P-ES level, as the complexity of the interactions proposed in the impact chain may require different restoration actions at a single P-ES chain level, suggesting a more integrated conservation and restoration approach.

## CRediT authorship contribution statement

**Lukas Egarter Vigl:** Conceptualization, Methodology, Investigation, Data curation, Writing - original draft, Writing - review & editing, Project administration, Funding acquisition. **Thomas Marsoner:** Methodology, Investigation, Data curation, Writing - original draft, Writing - review & editing. **Uta Schirpke:** Methodology, Investigation, Writing - original draft, Writing - review & editing. **Simon Tscholl:** Methodology, Investigation, Data curation, Writing - original draft, Writing - review & editing. **Sebastian Candiago:** Methodology, Investigation, Data curation, Writing - original draft, Writing - review & editing. **Daniel Depellegrin:** Conceptualization, Methodology, Formal analysis, Investigation, Data curation, Writing - original draft, Writing - review & editing.

## Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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## Appendix A. Supplementary data

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