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How to integrate nature's value within spatial conservation prioritization

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How to integrate nature’s value within spatial conservation prioritization

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Abstract

Degradation of ecosystems due to anthropogenic actions has increased in the last decades, inducing a decrease in ecosystem services supply. Since most of the benefits provided by nature to people are essential for human well-being, ecosystem services should be integrated into conservation planning. Here, we selected ten services to be quantified, economically valued and mapped for the study area of the *Alpes Vaudoises*. Value maps were integrated with spatialized biodiversity data (i.e. model predictions) into a spatial conservation prioritization (SCP) software, to identify areas allowing to align conservation goals for biodiversity and targeted ecosystem services. Different weighting scenarios for biodiversity and services were used to simulate alternative actions and assess the efficiency of different conservation networks. Solutions were compared to existing protected areas and to SCP analysis focusing on biodiversity only. Including services in conservation planning has shown to maximize their supply in protected areas, and represents a powerful decision support tool. Nevertheless, a threshold must be defined by decision makers for the relative weights assigned to the different biological features targeted in spatial prioritization. The ecosystem service framework proposed here can be used to assess consequences of alternative actions for biodiversity protection and promote communication between scientists and conservation actors.

Keywords

Ecosystem services, conservation planning, economic valuation, spatial prioritization, Decision support tool, Zonation software, Evidence-based conservation

Résumé

L'impact négatif des activités humaines sur les écosystèmes a augmenté ces dernières décennies, ayant pour cause une diminution des services écosystémiques. La majorité des bénéfices fournis par la nature étant indispensables au bien-être de l'être humain, les services écosystémiques devraient être pris en compte dans la planification des zones de conservation. Dix services ont été sélectionnés, quantifiés, économiquement évalués et cartographiés pour la zone d'étude des *Alpes Vaudoises.* Les cartes représentant la valeur monétaire fournie par les différents services ont été jointes à des données spatialisées sur la biodiversité (i.e. prédictions) puis analysées, afin d'identifier les zones permettant de remplir les attentes en matière de protection de la biodiversité et des services ciblés. Plusieurs scénarios faisant varier l'importance donnée à la biodiversité et aux services dans l'analyse ont été appliqués, afin de simuler les décisions potentielles, et d'évaluer l'efficacité des réseaux de conservation en résultant. Les comparaisons de ces solutions potentielles avec les réserves existantes, ainsi qu'avec un réseau de conservation basé sur les données de biodiversité uniquement, ont permis de démontrer l'utilité de la prise en compte des services écosystémiques dans la planification des zones de conservation. Néanmoins, les décideurs doivent définir l'importance relative de chaque élément pris en compte dans l'analyse, de façon à cibler au mieux les besoins en matière de protection. L'outil proposé dans cette étude permet d'estimer les conséquences de certaines décisions pour la biodiversité, et incite à la communication entre scientifiques et acteurs de la conservation.

Table of contents

Introduction

Irreversible losses on Earth's biodiversity have already been induced by anthropogenic actions. The extinction rate was estimated to be 100 times greater over the past 100 years than what had been recorded in fossil records (MEA 2005). The way in which humans have modified the majority of biomes and degraded ecosystems, on which society is highly dependent, was also highlighted in the Millennium Ecosystem Assessment report (MEA 2005). Furthermore, the Cost of Policy Inaction project (COPI) predicts by 2050 an additional loss of biodiversity in the range of 11% to 20% (Braat *et al.* 2008, Vellend *et al.* 2017). Biodiversity represents the living part of natural capital and has a crucial role in the proper functioning of ecosystems (MEA 2005, Diaz *et al.* 2006, Balvanera *et al*. 2006, Harrison *et al.* 2014).

To stop this decline in biodiversity and the degradation of ecosystems, governmental and international policies have been implemented in the last decade. For example, the Convention on Biological Diversity (CBD) proposed a strategic plan in 2010, with 20 time-bound goals (i.e. Aichi Biodiversity Targets) to be met by the year 2020. One of these targets (i.e. Target 11) promoted the expansion of protected areas of terrestrial land (up to 17%) as well as an improved connectivity between protected areas. In 2015, the United Nations proposed 17 Sustainable Development Goals (SDGs) and 169 targets to be reached by 2020 or 2030. One of these goals (i.e. SDG 15) is directly linked to the Aichi target 11, aiming at the promotion of a sustainable management of ecosystems and the halt of biodiversity loss and land degradation.

Compared to previous action plans for biodiversity conservation, both the Aichi biodiversity targets and SDGs include the concept of ecosystem services in their strategies. Ecosystem services are defined by the Millennium Ecosystem Assessment as "*The benefits people obtain from ecosystems*" (MEA 2005). This definition emphasizes all the various gains supplied by ecosystems, comprising food, clean water, pollination, climate regulations and many other services that have an important role in supporting human well-being and survival (De Groot 2010). As reported by the COPI project, land-use changes and environmental pressures induce modifications in biodiversity and ecosystem functions, which lead to loss of services (Braat *et al.* 2008). This concept was introduced in the 1970s, raising great interest in scientific literature in the 1990s (Costanza 1997, Daily 1997). The main typologies used to classify ecosystem services comprise four categories: i) Regulating: the benefits obtained from the regulation of ecosystems, including climate regulation or flood control; ii) Provisioning: all goods and products obtained from ecosystems, comprising food and timber provision; iii) Cultural: spiritual and aesthetic benefits people obtain from ecosystems, including recreation or cognitive development; and iv) Supporting (or Habitat): comprising nutrient cycling and soil formation (MEA 2005, De Groot *et al.* 2010a). The distinction between ecosystem function and service is still debated (Wallace 2007, Boyd & Banzhaf 2007, Fisher et al. 2009). It has been argued that only final services contributing to people's well-being should be considered as such, to avoid double-counting of services (Haines-Young & Potschin 2010). In response to the need of convergence of terminologies, a Common International Classification of Ecosystem Services (CICES), which builds on the TEEB and MEA classifications, was proposed in support to the work developed by the European Environment Agency (Haines-Young & Potschin 2013). This typology distinguishes only three main categories of services: i) Provisioning, ii) Regulating, and iii) Cultural.

The negative effects of globalization and economic growth on natural resources have been widely recognized in the field of ecological economics (Victor 2010, Wijen 2012). One reason for that is the multiple market failures associated with public goods and non-marketed services, leading to a non-efficient use of common-pool resources (Lant *et al.* 2008, Burkhard & Maes 2017). In order to make progress in achieving a sustainable human well-being, one has to ensure the sustainability of the whole ecological system, including services which humanity depends on (Costanza *et al.* 2017). The valuation and inclusion of ecosystem services in policies can be seen as a starting point to highlight nature conservation benefits, giving an anthropogenic justification for preserving biodiversity (Reid *et al.* 2006). There are various types of values, defined as `the contribution of an action or object to user-specified goals, objectives, or conditions' (MEA 2005). Recently, the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) emphasized the importance of a pluralistic valuation approach comprising biophysical, sociocultural, economic, and other types of values (Pascual *et al*. 2017). Another study proposed a multidimensional valuation framework to account for the different types of values (Gunton *et al.* 2017).

Any valuation approach first requires the identification of a purpose, which is determinant to define the most relevant type of values (Pascual *et al.* 2017). Economic valuation of ecosystem services has the advantage to be easily comparable with the value of other consumptive goods through different human societies and cultures. In 1997, the total economic value of the world's ecosystem services was estimated to be around $33 trillion, corresponding to about two times the Global GNP for that period (Costanza *et al.* 1997). More recently, the COPI project measured the social and economic costs due to loss of biodiversity in monetary terms by 2050. The calculated loss of welfare due to the reduction of ecosystem services is around €14 trillion, corresponding to 7% of the projected GDP for 2050 (Braat *et al.* 2008). These results show the importance of ecosystem services for the regional economy, especially for alpine regions which are highly dependent on multiple services supply (Grêt-

Regamey *et al.* 2008b, 2013, Häyhä *et al.* 2015, Rewitzer *et al.* 2017). An initiative called "Mapping and Assessment of Ecosystems and their Services" (MAES), launched in 2013, aims to quantify and value ecosystem services in Europe in order to guide decisions on complex public issues (Maes *et al.* 2013). This project assesses the heterogeneity of services supply to improve conservation planning, supporting also previously mentioned targets (i.e. Aichi and SDG targets/goals).

Conservation actions for biodiversity protection have a cost and strategies are required to invest limited resources efficiently (Margules & Pressey 2000, Naidoo & Ricketts 2006). Decision support tools, such as Spatial Conservation Prioritization (SCP), are used to identify priority areas for conservation planning. This method allows identifying areas or landscapes that are important for the protection of biodiversity and other targeted features. Until now, the majority of priority areas have been identified based on biodiversity hotspots, or the presence of species of interest (Balvanera *et al.* 2001). The decrease in ecosystem services supply and the recognition of their importance to human well-being have raised an interest for their integration into spatial conservation planning. By this way, sustainability of services can be ensured without compromising biodiversity protection.

In this study, we aim to propose alternative conservation networks prioritizing biodiversity and ecosystem services in the study area of the *Alpes Vaudoises,* in Switzerland. A previous study realized in the same study area used SCP analyses to propose an optimal conservation network for biodiversity protection and demonstrated that existing protected areas were not at the optimal locations (Vincent 2017, Vincent *et al.* (submitted)). Here, we integrated the economic value of nature's benefits to people into spatial conservation planning, to see if this changes the priority sites selected for biodiversity protection. To do this, we quantified, valued and mapped a subset of ecosystem services for the study area. First, we reviewed the literature to gather information about ecosystem services and existing methods to integrate nature's value into conservation planning. Following relevant methodologies, we gathered information and spatial data necessary for the quantification and valuation of services from different institutions and sources. In a next step, we selected different services and valuation methods, based on the availability of data. We quantified, mapped and valued the selected services in monetary units. To perform the spatial prioritization analyses, we integrated the maps of services' values with biodiversity data into an SCP software. We applied different weighting scenarios for ecosystem services, to simulate stakeholder's preferences. Finally, we compared the performances and spatial overlap between prioritization solutions.

This study is, to our knowledge, the first SCP analysis that includes ecosystem services at regional scale in Switzerland and has the potential to help decision makers to improve conservation planning in the study area. This tool can help reach the objectives of the new Swiss Biodiversity Strategy for 2020, which aims to achieve a sustainable use and maintenance of biodiversity in Switzerland and in the world. It offers spatial conservation alternatives addressing local people's concerns and supporting regional economy.

Methods

Study area

This project was applied in the western Swiss Alps, located in the Vaud canton (6°60' to 7°10' E; 46°10' to 46°30' N; hereafter *Alpes Vaudoises*). The total surface of the study area covers 71'796 hectares, with altitude ranging from 1300 to 3120 m. From an administrative point of view, the area is divided in two districts (i.e. Aigle and Riviera-Pays-d'Enhaut) and 28 communes. Various ecosystems are present within the study area, comprising different types of forests, grasslands and agricultural lands. The region benefits from great tourism assets, rich natural landscapes, and cultural heritage. More than 60% of the study area is considered important for biodiversity and ecosystems conservation, with 18.12% of the landscape designated as `Strict Nature Reserve' (IUCN Category Ia) or `Habitat/Species Management Area' (IUCN Category IV). The region is also a priority area for interdisciplinary research at the University of Lausanne, where a geo-platform providing all the scientific metadata concerning the area was developed (http://rechalp.unil.ch) and where more information can be found.

Literature review

An extensive literature review was performed to gather information about ecosystem services, their integration into conservation planning and the existing methodologies to quantify, map and value nature's benefits to people. A total of 103 relevant studies and reports were identified using Web of Science as a database. Keywords combined for the search were: "Ecosystem services", "valuation", "Non-monetary valuation", "Mapping", "Conservation planning", "Spatial conservation prioritization" and "Cost-benefit analysis".

Analytical framework

In this study, a subset of ecosystem services was quantified, mapped and valued for the study area, in order to integrate the nature's value into spatial conservation planning. More details about the different steps followed are given below (see also Figure 1).

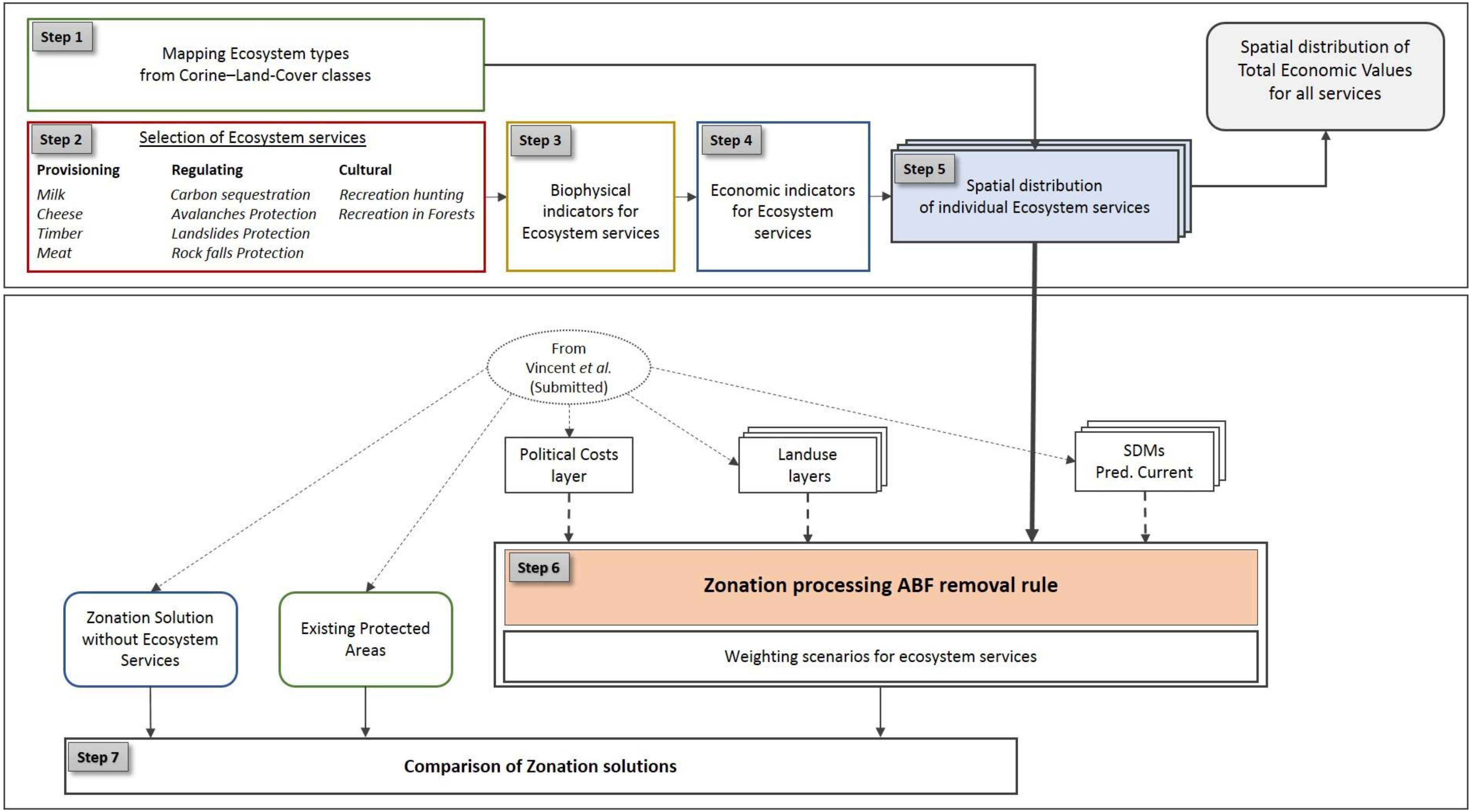

Figure 1. Conceptual framework representing the different steps followed in this case study. Step 1: mapping ecosystem types for the study area using Corine-Land-Cover classes. Step 2: selection of a subset of ecosystem services to be included in the analysis. Step 3: gathering data for biophysical indicators to quantify and map selected services. Step 4: gathering data for economic indicators to value selected services. Step 5: mapping monetary values for ecosystem services. Step 6: spatial conservation prioritization analysis using the Zonation software. Step 7: comparison of Zonation solutions and proposition of spatial conservation alternatives.

Step 1 – Map of ecosystem types

A map of ecosystem types was created using the software ArcGIS 10.2 (ESRI 2014), based on the typology of ecosystems proposed by the European Union in the context of the MAES initiative (Figure 2) (Maes *et al.* 2013). This typology distinguishes 12 main ecosystem types, built from the European Union Nature Information System (EUNIS) habitat classification (Davies *et al.* 2004) and corresponding Corine-land-Cover (CLC) classes. CLC datasets, defined as the main inventory on land cover for terrestrial ecosystems at EU level, were available for the study area. Details about the correspondence between CLC classes and ecosystem types proposed by the MAES initiative are available in Appendix A (Table A1).

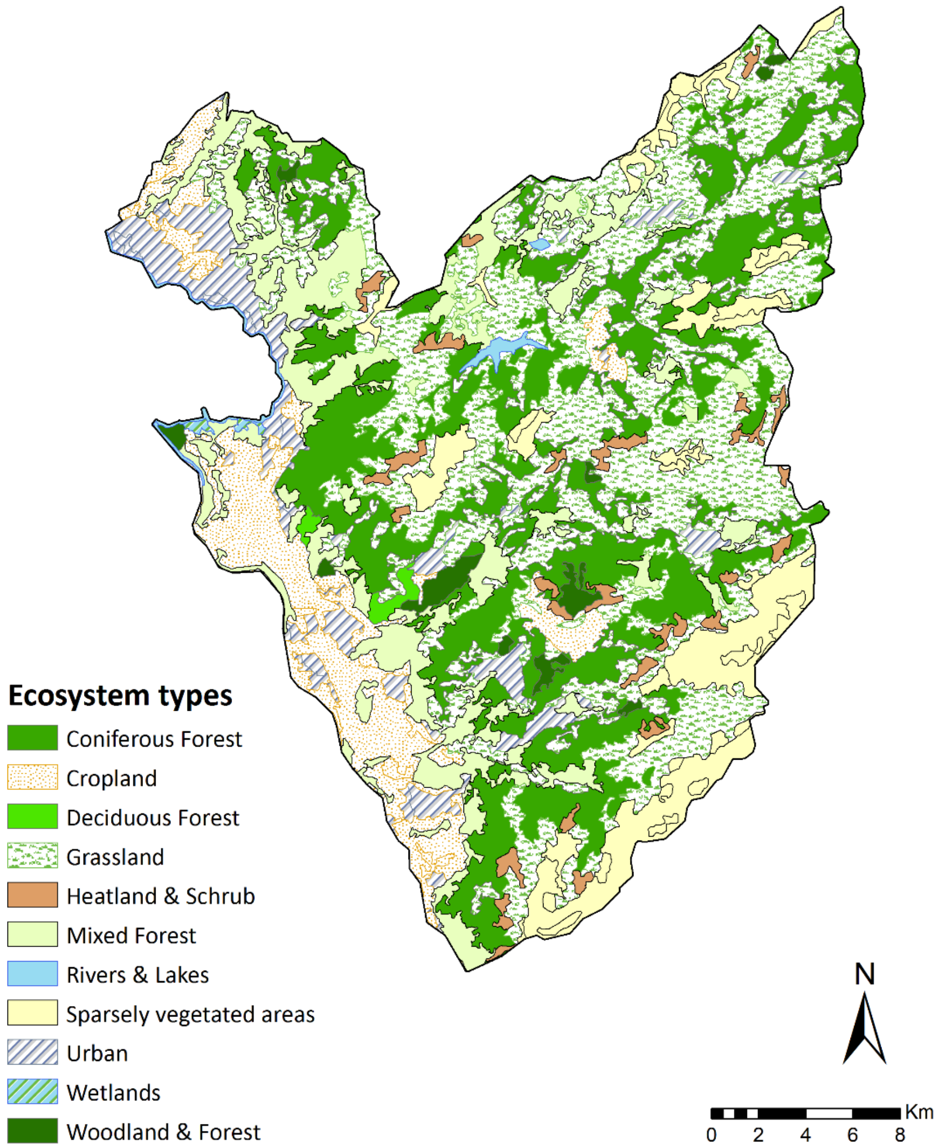

Figure 2. Map of ecosystem types for the study area of the *Alpes Vaudoises* (Switzerland). Ecosystem types were mapped according to their correspondence with Corine-Land-Cover classes, following a typology proposed by the Mapping and Assessment of Ecosystems and their Services (MAES) initiative.

Step 2 – Selection of ecosystem services to quantify and value

A subset of services recognized by the CICES typology was selected to be quantified and valued. The most frequently used services were identified through peer review studies (Schmidt *et al.* 2016, Grêt-Regamey *et al.* 2008a) and additional studies specific to Alpine regions. After this literature review, a subset of services for which data was available for the study area was retained to be quantified and valued. A total of ten services were selected: four provisioning services (*timber, meat, milk, cheese EtivazAOP*), four regulating services (*carbon sequestration, protection against avalanches, landslides and rock falls*) and two cultural services (*recreation in forests and hunting*) (see Table 1). A subset of additional services, for which additional data was required and were not included in this study is available in Appendix A (Table A3).

Step 3 – Biophysical quantification of ecosystem services

Biophysical indicators were used as proxies to quantify the goods and services provided by ecosystems (Czúcz & Arany 2015). Some of the indicators used in this study were taken from a list proposed by the Swiss Federal Office for the Environment (Staub *et al.* 2011). Provisioning services were quantified based on the quantity produced or harvested (see Appendix B, part 1 for more details). To quantify carbon sequestration, a formula adapted from Häyhä *et al.* (2015) was used. This formula translates wood increment into kg of CO_2 sequestrated by trees per hectare/year. The protective role of forests against avalanches, landslides and rock falls was quantified based on roads and buildings considered as protected. Additional details about the quantification of regulating services are available in Appendix B, part 2. Recreation from hunting activity was quantified using the same set of data as for wild meat provision (i.e. the number of animals hunted). Recreation in forests was quantified based on people's preferences for forests' attributes, revealed by the second Switzerland-wide survey on Socio-cultural Monitoring (WaMos 2) and carried out in 2010 (OFEV et WSL 2013). Detailed quantification and valuation of cultural services are available in Appendix B, part 3.

Step 4 – Economic valuation of ecosystem services

A range of monetary and non-monetary valuation approaches to value services have been described and are listed in Appendix A (Table A2). The choice of the valuation technique depends on the type of service to value, as well as the quantity and quality of data available. In this study, different methods were used to estimate the monetary values of selected services. The Market price method (Pascual *et al.* 2010) was used for provisioning services, using the current market price per unit of marketed goods. Hydrogeological protection services were valued by using the avoided damage costs method (Barth & Döll 2016, Brander & Crossman 2017). To value carbon sequestration, the Social Cost of Carbon (SCC) of 40.8 CHF/ton of CO_2 was used. Valuation methods based on people's preferences were used to assess the minimum willingness to pay (WTP) of people for cultural services (Pascual *et al.* 2010). The recreational value of hunting was estimated through a revealed preference valuation method (Tietenberg *et al.* 2016), using the price of hunting licenses for the different species hunted. The recreational value of forests was estimated based on the results of a previous study, which assess the monetary value for recreation in Swiss forests (Von Grünigen *et al*. 2014). Additional details about services valuation are available in Appendix B.

Step 5 – Spatial maps of ecosystem services

Services heterogeneity of supply was spatially represented, using the map of ecosystem types created in step 1. The precision and resolution of services supply maps depend on the availability of data for indicators. For milk and cheese provision, data were available for the different communes within the study area. For timber provision and carbon sequestration, data were available for the different forest districts. Services related to hunting (i.e. *meat provision and recreation*) were mapped according to the different wildlife areas, defined as the spatial unit for hunting statistics. A map of recreation in the forest was created by identifying the presence of forests' attributes that were appreciated by people, such as hiking trails and watersheds. The heterogeneity of recreation was represented by combining these attributes, creating four levels of recreation, which were valued according to people's preferences. To visualize the distribution of the total economic value from ecosystem services in the study area, defined as the aggregate of individual services valued, individual services maps created in step 5 were overlaid as a unique raster layer in ArcGIS 10.2. A summary of indicators, units and valuation methods used to quantify, map and value each service is available in Table 1.

Step 6 – Spatial analysis using the Zonation software

To identify priority areas for biodiversity and ecosystem services in the *Alpes Vaudoises,* the software Zonation 4.0 (Moilanen *et al*. 2005) was used. This software produces a hierarchical prioritization of the landscape, based on input factors and an iterative cell removal rule that allows the retention of only the cells contributing the most to specific conservation goals. Biodiversity information was integrated into the analysis by using predicted species distribution maps, which are increasingly used in conservation planning (Guisan *et al.* 2013). Input factors from a previous prioritization analysis in the same study area were used (Vincent *et al.* (submitted)), with the integration of ecosystem services maps created in previous steps as biodiversity features (Moilanen *et al.* 2014). Included inputs were: i) species prediction maps for plants (n = 627), amphibians (n = 5), reptiles (n = 12) and insects (n = 123) obtained from previous studies (Vincent (2017), Vincent *et al.* (submitted); see Appendix B part 4) ; ii) land use maps (from Swiss land use statistics data from 2009; (SFSO 2013)); and iii) land costs estimated as the average opposition results from political votes that have a direct impact on biodiversity conservation, acquired from Cardoso (2015). To account for ecosystem services in spatial prioritization analysis, raster grids (i.e. 25 x 25m) representing monetary values for services were built in ArcGIS. Values were normalized from 1 to 100 according to the methodology of Casalegno *et al.* (2014). The Additive Benefit Function (ABF) removal rule, used for previous analyses, was applied (Moilanen *et al.* 2014). In Zonation, each input feature can be assigned a positive or negative weight to increase or decrease its relative importance in the prioritization solution. Species were weighted according to their IUCN status and Swiss legislation (Vincent *et al.* (submitted)). The sum of weights for all species in the analysis was equal to 961. Negative weights were assigned to competing land uses included in the analysis, representing opportunity costs for conservation. Since weights allocated to biodiversity features are determinant for the output of spatial prioritization, ten different weighting scenarios were tested for ecosystem services. Weight values ranging from 1 to 10'000 were assigned to each of the ten services selected. Since the sum of weights for species was already fixed to 961, a weight of 1 per service, implying a total weight of 10 for services, means that ecosystem services represent 1% of the total weights in the analysis and biodiversity represent 99% of the total weights. Conversely, a weight of 10'000 per service implied that ecosystem services represent 99% of the total weights in the analysis.

Step 7 – Zonation solutions comparison

Zonation solutions were compared to see if the integration of nature's value changed the locations of prioritized areas and the efficiency of conservation networks for biodiversity protection. A previous study showed that, for a determined subset of species and scenarios, existing protected areas were not at the optimal locations for biodiversity protection and a new conservation network was proposed using the Zonation software (Vincent 2017, Vincent *et al.* (submitted)). For each scenario that includes services with biodiversity, the spatial overlap with existing protected areas (i.e. IUCN protected area categories Ia and IV) and with previous Zonation solution focusing on biodiversity only, was calculated. The top 18.12% of the landscape, corresponding to the cover surface of existing protected areas, was identified for each Zonation output map. Average protected species range and the number of species that have none of their range protected by the new protected areas were calculated for each scenario, to assess the efficiency of each calculated conservation network.

Table 1. Subset of ecosystem services considered in this study, classified according to the CICES typology, with corresponding biophysical and economic indicators used for the quantification and valuation. Units used for biophysical quantification and the valuation method chosen for each service is also specified, as well as the ecosystem type that provide each service.

Category of Service	CICES Division	CICES Group	CICES Class	Class Type	Biophysical Indicator	Unit	Economic indicator	Ecosystem	Resolution	Valuation method
Provisioning	Nutrition	Biomass	Reared animals and their output	**Milk production**	Milk production	Kg	Price of milk	Grasslands	Commune	Market price
				Cheese Etivaz AOP provision	Cheese production	Kg	Price of Etivaz AOP	Grasslands	Commune	Market price
			Wild animals and their output	**Meat from game**	Meat from wild animals	head	Price of meat	Forests	Wildlife area	Market price
	Materials	Biomass	Fibres and materials from plants	**Timber provision**	Timber harvested	m3/ha	Market price of timber	Forests	Forest district	Market price
Regulating	Mediation of flows	Mass flows	Mass stabilisation and control of erosion	**Protection against avalanches**	Protective forest & risk zones	ha	Infrastructures value	Forests	Study area	Avoided damage costs
				Protection against rock falls	Protective forest & risk zones	ha	Infrastructures value	Forests	Study area	Avoided damage costs
				Protection against landslides	Protective forest & risk zones	ha	Infrastructures value	Forests	Study area	Avoided damage costs
	Maintenance of biological conditions	Climate regulation	Reduction of greenhouse gas concentrations	**Carbon sequestration**	Annual wood increment	m3/ha	Market price of carbon	Forests	Forest district	Market price
Cultural	Physical and intellectual interactions	Physical and experimental interactions	Physical use of landscape	**Hunting**	Number of animals killed	head	Price of licences	Forests	Wildlife area	Revealed preference
				Recreation in forest	People's preferences for forest attributes		Willingness to pay (WaMos 2 study)	Forests	Study area	Expenditure method

Results

Literature review and selection of services

Studies considered and reviewed in the literary work were classified by topics and sub-topics to facilitate future information finding and research (see Table 2). This research allowed to identify strengths and weaknesses of existing ecosystem services frameworks. It highlighted what was possible to do and what was not for this case study. Existing gaps in actual knowledge about ecosystem services were: i) overemphasis on monetary values and a lack of non-monetary valuation of ecosystem services; ii) a bias toward services that are simple to quantify and for which a market price or social cost exists (i.e. carbon sequestration, material and food provision, recreation) (see Table C1 in Appendix C); and iii) a lack of knowledge and evidence about connectivity between services and human well-being. For additional/complementary information regarding strengths and weaknesses of ecosystem services studies see Bull *et al.* (2016). The complete list of references cited in Table 2 is available in Appendix C (Table C2).

Services appearing the most often in literature were: i) recreation services, comprising the benefits provided by outdoor activities and aesthetic enjoyment; ii) food and material provision; and iii) regulation of climate and extreme events. More details about the number of studies and services identified in the reviews are available in Appendix C (Table C1).

The majority of services selected for this case study were provided by forests (i.e. *timber, meat, carbon sequestration, hydrogeological protection, recreation in the forest and recreational hunting*). The remaining ones were provided by grasslands (i.e. *milk and cheese provision*).

Ecosystem services distribution maps

The spatial distribution of the total economic value for ecosystem services, created by overlaying individual services maps in a GIS, is represented in Figure 3. Maps of individual services used as input layers for Zonation analyses are available in Appendix C (Figures S1, S2, and S3). The economic value is relatively well spread within the study area. Higher values, represented on the map with red/orange colours, are more present on the western side of the area compared to the north-eastern part, which contains lower values for ecosystem services (i.e. in green on the map). The absence of value for grey areas on the map, which are mostly occupied by urban areas, croplands, and low vegetation zones, is due to the non-exhaustive list of services included in this study, implying that some ecosystems were not assigned any value.

Table 2. Studies considered in the literature review, classified by topics and sub-topics. Complete references are available in Appendix C.

Topic	Sub-topic	References
Definition & classification		(de Groot *et al.* 2002), (Wallace 2007), (Boyd & Banzhaf 2007)(Fisher *et al.* 2008),(Fisher *et al.* 2009), (Roy Haines-Young & Potschin 2013) (La Notte *et al.* 2017), (Schröter *et al.* 2014)
Socio-ecology	Ecosystem services and human well-being \ Why to protect ecosystems?	(Nicholson *et al.* 2009), (Pascual *et al.* 2017), (Chan *et al.* 2016), (Bennett *et al.* 2016), (Costanza *et al.* 2017)
Mapping & valuation	Quantification of services and mapping	(Boerema *et al.* 2017), (Bagstad *et al.* 2013a), (Crossman *et al.* 2013), (Martínez-Harms & Balvanera 2012), (Schägner *et al.* 2013), (Brown & Fagerholm 2014)
	Natural capital accounting & valuation methods	(Goio *et al.* 2008), (Onofri *et al.* 2017), (Hackbart *et al.* 2017)
	Economic valuation	(Gios *et al.* 2006), (Grêt-Regamey *et al.* 2007), (Grêt-Regamey & Kytzia 2007), (Troy & Wilson 2006), (Häyhä *et al.* 2015), (Sumarga *et al.* 2015), (Costanza *et al.* 2014), (Grilli *et al.* 2014), (de Groot *et al.* 2012), (Gómez-Baggethun & Ruiz-Pérez 2011), (Rewitzer *et al.* 2017)
	Non-economic valuation & cultural value	(Walz *et al.* 2016), (Zoderer *et al.* 2016), (Oteros-Rozas *et al.* 2014), (Kelemen *et al.* 2014), (Chan *et al.* 2012)
	Conceptual framework	(Gunton *et al.* 2017), (Maes *et al.* 2016a), (Díaz *et al.* 2015)
	Mountain regions	(Haida *et al.* 2016), (Fuchs *et al.* 2007), (Teich & Bebi 2009), (Walz *et al.* 2016), (Notaro & Paletto 2012)
	Future scenarios	(Gago-Silva *et al.* 2017), (Schägner *et al.* 2013), (Civantos *et al.* 2012)
Conservation planning	Cost benefit analysis	(Chan *et al.* 2011), (Naidoo & Ricketts 2006), (Naidoo *et al.* 2006), (Sarkki *et al.* 2016), (Ingram *et al.* 2012)
	Ecosystem services and biodiversity	(Dee *et al.* 2017), (Crouzat 2015), (Schneiders *et al.* 2012), (Harrison *et al.* 2014), (Cimon-Morin *et al.* 2013)
	Land use planning, Land use change, Management	(Sumarga & Hein 2014), (Ditt *et al.* 2010), (Grêt-Regamey *et al.* 2008), (Ma *et al.* 2016), (Egoh *et al.* 2008), (Chen *et al.* 2009), (Grêt-Regamey *et al.* 2013b), (Burkhard *et al.* 2012), (Sumarga & Hein 2014), (Turner *et al.* 2015),
	Spatial conservation prioritization, Policy support and Decision making	(Maes *et al.* 2012), (Hauck *et al.* 2013), (de Groot *et al.* 2010a), (Chan *et al.* 2006), (Grêt-Regamey *et al.* 2017), (García Márquez *et al.* 2017), (Di Minin *et al.* 2017), (Di Marco *et al.* 2017), (Verhagen *et al.* 2017), (Moilanen *et al.* 2011), (Geneletti 2011)
	Multiple modelling and tools	(Nelson *et al.* 2009), (Peh *et al.* 2013), (Crossman *et al.* 2013), (Villa *et al.* 2009), (Sherrouse *et al.* 2011), (Bagstad *et al.* 2013b), (Guisan *et al.* 2013)
Uncertainties	Limitations of the ecosystem services framework	(Potschin & Haines-Young 2011), (Hein *et al.* 2016), (Schmidt *et al.* 2016), (Hamel & Bryant 2015)
	Limitations for policies and decision making	(Hauck *et al.* 2013), (Bull *et al.* 2016), (Grêt-Regamey *et al.* 2013a)
Books	ES mapping and valuation	(Burkhard & Maes 2017)
	Environmental economics	(Tietenberg & Lewis 2016), (Perman *et al.* 2003)
Reports	International	(United Nations 2014), (Pascual *et al.* 2010), (de Groot *et al.* 2010b), (Brondízio *et al.* 2010)
	European	(Maes *et al.* 2016b), (Maes *et al.* 2015), (Balmford *et al.* 2012), (Banko *et al.* 2013), (Egoh *et al.* 2012)
	United States	(Binder *et al.* 2017)
	Swiss	(Staub *et al.* 2011)

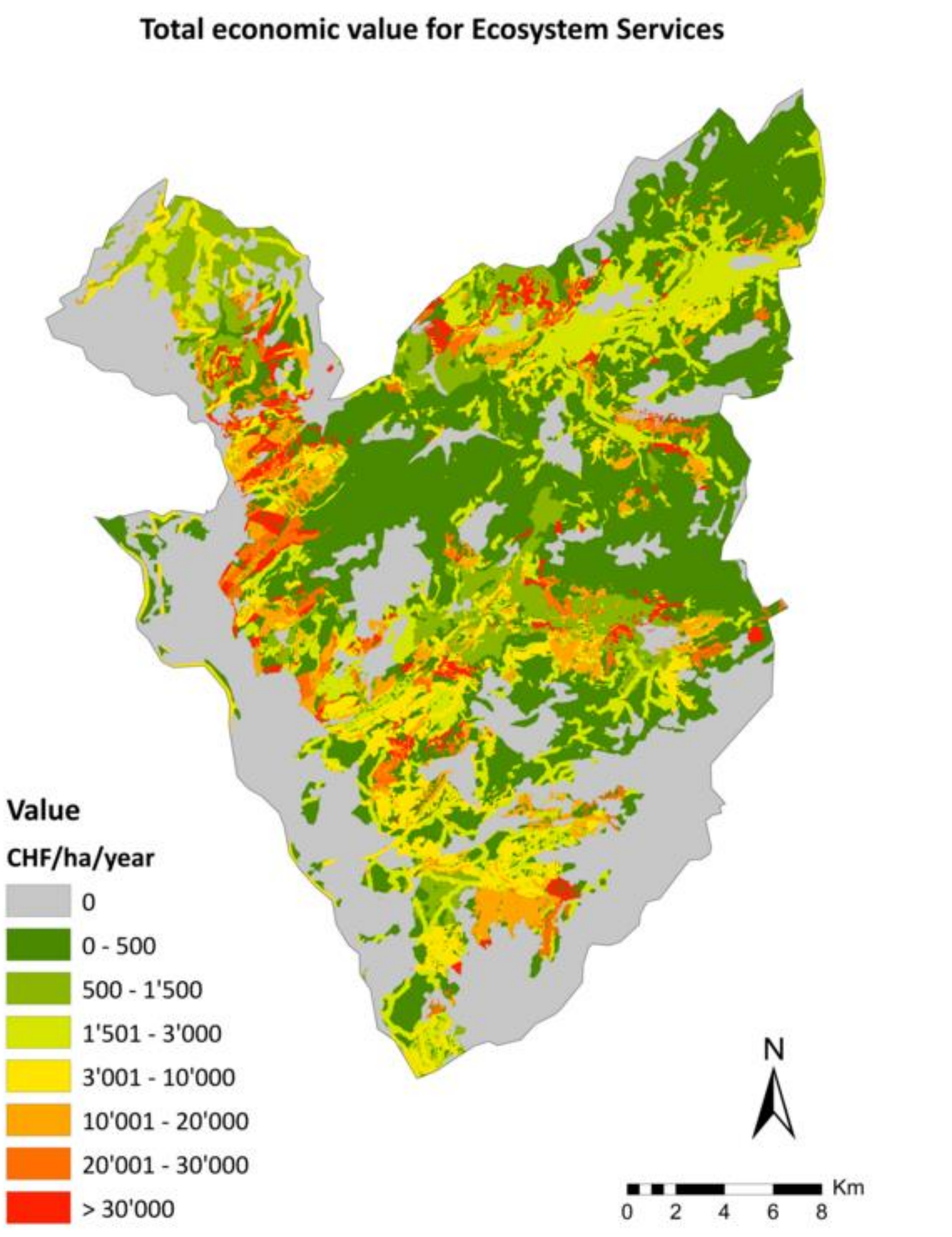

Figure 3. Distribution of the total economic values in CHF/hectare per year calculated for a subset of ecosystem services within the study area of the *Alpes Vaudoises.*

288

Zonation solutions

When ecosystem services are included in the analysis, priority areas for conservation are not the same as the ones selected by Zonation focusing on biodiversity only (Figure 4 and 5.). Numerical results of Zonation solutions comparisons are available in Table 3. A relatively low weight for services in the analysis (i.e. up to 9% weight) implies a high spatial overlap (i.e. more than 75%) with Zonation solution prioritizing biodiversity only (Figure 5A). In this case, the performance of both conservation networks is comparable since solution focusing on biodiversity covers on average 44% of all species ranges and Zonation solution prioritizing biodiversity and services representing 9% of total weights in the analysis covers 42% of all species ranges. For the same scenarios, the average cover of areas supplying services comprised in the new conservation network is 25% for the solution including services and 17% for the solution focusing on biodiversity only, indicating that even a low weight for services in the analysis induces a non-negligible increase in ecosystem services protection.

The cover of species range protected becomes lower when the weight for services increases in the analysis, relative to biodiversity, but remains higher than the average species range protected by existing protected areas (25%) for all Zonation solutions with services representing up to 83% of weight in the analysis. All SCP scenarios with a weight for services higher than 83% result in an outcome solution with a lower efficiency for biodiversity protection than existing protected areas (i.e. average species range protected lower than 25%). The extreme scenario with services representing 99% of weight in the analysis (i.e. each service has a weight of 10’000), implies that two species (*Luzula sudetica (LC)* & *Gnaphalium norvegicum (LC)*) have none of their predicted range protected by the new conservation network. The average species range protected by this Zonation solution falls to 18.7%.

With the increase in weight for services, the spatial overlap between Zonation solutions and existing reserves decreases (Table 3). These changes in areas to prioritize are represented in Figure 4 (B-H)**.** Figure 4A shows the location of existing protected areas (i.e. IUCN categories Ia & IV) and Figure 4B shows the biodiversity network previously obtained. Spatial overlap between these two conservation networks was measured as 34%. Figures 4C-G represent Zonation solutions with different weighting scenarios for services. We can see in Figure 4H the priority areas selected by Zonation focusing only on ecosystem services, which are predominantly located on the North West side of the study area. Conversely, areas selected by Zonation focusing only on biodiversity (Figure 4B) are more represented in the South East part of the study area. As the weight for services increases in the analysis, the priority areas selected tend to overlap with the prioritization solution based on ecosystem services only (Figure 4H). This trend is well represented in Figure 5, which represents the spatial overlap between four different prioritization scenarios including services and the scenario focusing on biodiversity only.

Table 3. Results of Zonation solutions for different ecosystem services weights. Average proportion of distribution ranges remaining in the new conservation networks for biodiversity (species) and ecosystem services. Number of biological features (species and services) that have none of their range included in the new conservation network. Spatial overlap of different Zonation scenarios with existing protected areas (i.e. IUCN categories Ia and IV representing 18.12% of the study area) and the biodiversity network obtained without ecosystem services in the Zonation analysis.

Zonation solutions	**Average proportion remaining in % for**		***Features not included in the network***	**Spatial overlap in % with**		**% of weight for services in the analysis**
	Biodiversity	**Services**		**Existing reserves**	**Zonation solution without services**	
Existing reserves	25	10	1	100	34	0
Biodiversity only	44	17	0	34	100	0
Services weight						
1	43	19	0	33	82	*1*
10	42	25	0	33	76	*9*
25	40.3	31	0	30	70	*20*
50	38	35	0	28	66	*34*
75	36	39	0	26	61	*43*
100	35	41	0	23	52	*50*
200	30.8	45	0	19	44	*67*
500	25	48	0	13	32	*83*
1000	21.7	49	0	11	28	*91*
10’000	18.7	50	2	9	23	*99*

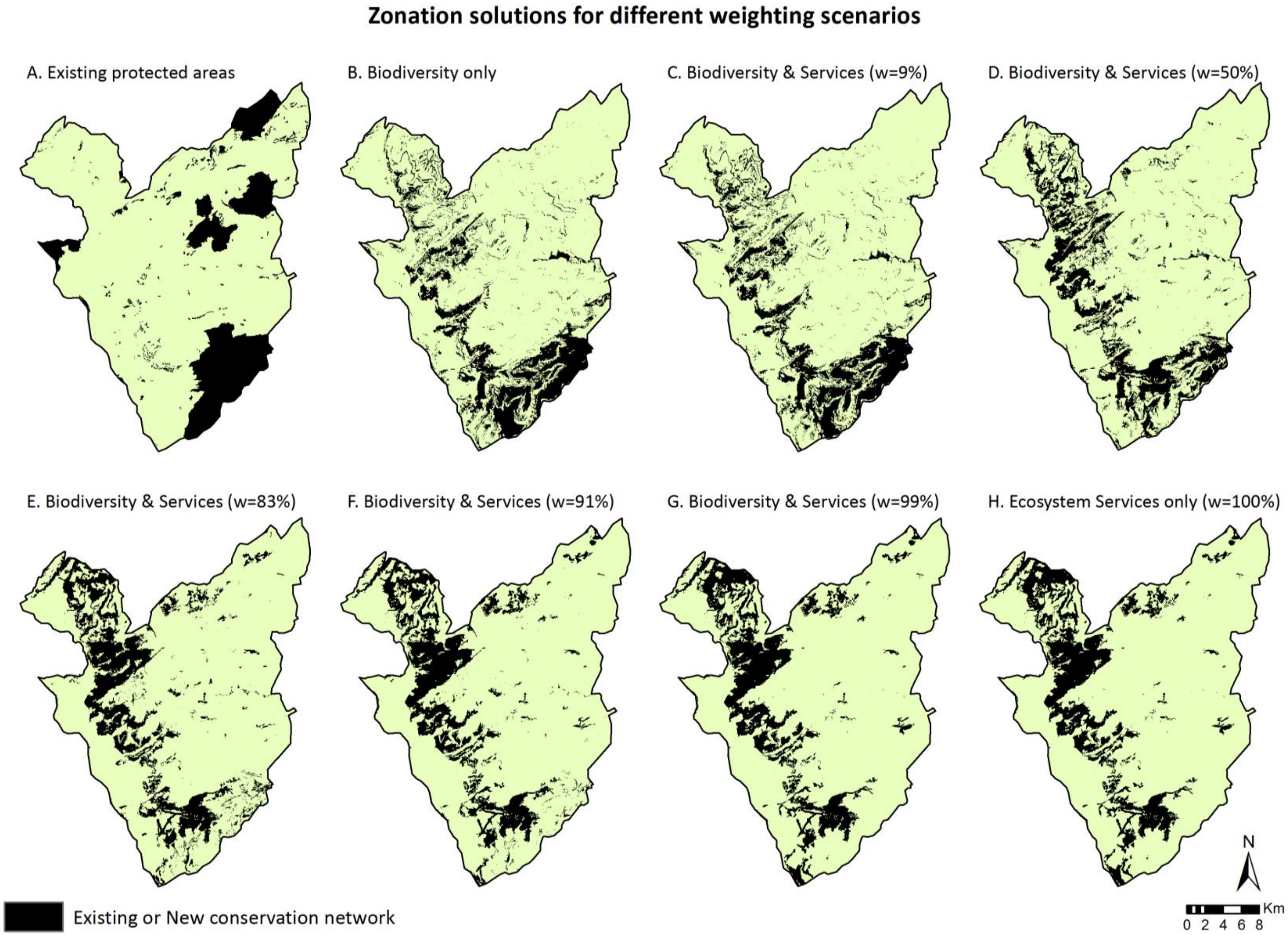

Figure 4. Proposed protected areas under different scenarios. Existing protected areas (A), Zonation solution prioritizing biodiversity only (B), Zonation solutions for scenarios including biodiversity and ecosystem services with different weights(C-G) and Zonation solution focusing on ecosystem services only (H). The importance allocated to services compared to biodiversity in each scenario is given by the percentage of weight for services (w). The top 18.12% of priority areas selected by Zonation was extracted for each scenario, in order to keep the same proportion of the landscape in new conservation networks than existing protected areas.

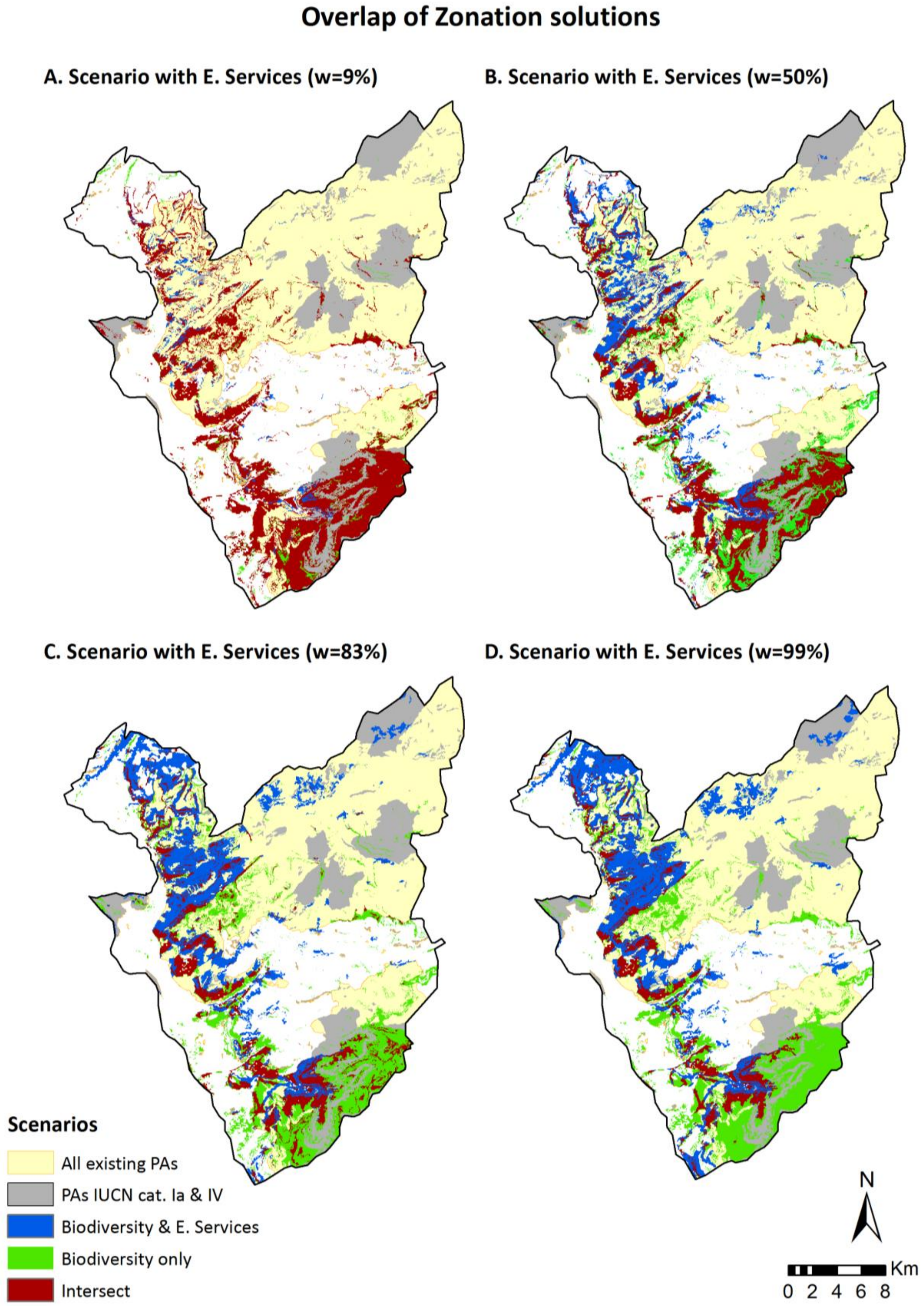

Figure 5. Zonation solutions comparison created by overlaying the biodiversity network with different scenarios including services, with services representing: 9% (A), 50% (B), 83% (C) and 99% (D) of total weights in SCP analysis. The overlapping regions (i.e. prioritized in both solutions) are shown in red. Areas prioritized by analysis including biodiversity and services are shown in blue and areas prioritized by analysis focusing only on biodiversity are shown in green. Existing protected areas (IUCN categories Ia and IV) are shaded in grey and other protected areas with lower levels of protection are represented in yellow.

Discussion

This study shows an applied example of a framework to integrate nature's benefits to people into spatial conservation planning at regional scale. Results obtained with SCP analyses targeting both biodiversity and ecosystem services showed that existing protected areas are not optimally located to protect biodiversity and ecosystem services supply in the study area of the *Alpes Vaudoises*. This result emphasizes the need to use decision support tools, such as SCP analysis, to improve conservation planning at regional scale. However, whether biodiversity and ecosystem services should be treated separately or together in SCP analyses is still debated (Chan *et al.* 2011, Cimon-Morin *et al.* 2013). A recent study stated that both analyses should be conducted and compared. In the case of existing trade-offs between biodiversity and services, the decision will depend on stakeholders' preference for specific conservation goals (Kukkala & Moilanen 2017).

In each step followed by the proposed framework (Table1), choices have been made regarding methods and parameters. Limitations and uncertainties are associated with these methodological steps and can influence the outcome of spatial prioritization analyses.

First, the choice of which services to include in the analysis, performed in the second step of the framework, is determinant. In this case study, the selection of services was mainly based on the availability of data for the study area. If the same framework was applied to implement real conservation planning options, this selection should be done by decision makers and based on stakeholders' preferences and political decisions, depending on specific conservation goals and targets to be protected. Among the services included in this case study, the ones related to hunting (i.e. recreation and meat provision) require being interpreted in a broader context. No added value for these services in existing protected areas, where hunting is forbidden or highly regulated, does not mean that these areas do not have the ability to supply hunting services. Also, including hunting services into SCP to select new protected areas makes sense only if hunting is still allowed in new reserves. Thus, before selecting target features for SCP analysis, it is important to define the level of protection desired for new protected areas and, more generally, the aims of the SCP analysis needs to be clearly defined. Well-defined aims allow developing an appropriate model, built from ecological information describing the best specific conservation goals (Moilanen *et al.* 2014). The subset of ecosystem services included in this study represents a good proxy to value forests since eight out of the ten selected services are provided by this ecosystem. This probably induces a bias toward forests in the spatial prioritization analysis performed in this study. The inclusion of additional services provided by other ecosystems can allow a better balance in the evaluation of ecosystem services provided within the study area. Biodiversity data available for this study comprise species distribution models for insects, amphibians, reptiles, and plants. The addition of other taxonomic groups when available (e.g. mammals, birds or fishes) could provide a complete analysis for conservation planning and has the potential to help reach different conservation goals. Also, taking into account invasive species in SCP could help to reduce competition pressure on native species in protected areas, and thus improve biodiversity protection. Prediction maps for alien species known in the study area could be included as conservation costs in the framework. This way, areas predicted to be suitable for invasive species would be avoided in protected areas, and specific conservation actions could be implemented to prevent invasions.

The choice and availability of indicators used to quantify and value services (i.e. Steps 3 & 4) can also be a source of uncertainties or limitations (Cimon-Morin *et al.* 2013). The use of different indicators and valuation methods can result in different results for the same services. For this reason, the working group MAES proposed a framework for ecosystems assessment in the EU, with a list of potential indicators listed with corresponding quality labels, based on the ability to convey information to decision makers (Maes *et al.* 2016). The overemphasis on economic valuation was identified as one of the main gaps in ecosystem services literature. One reason for this is the lack of well-defined methodologies to estimate non-instrumental (i.e. intrinsic) value of nature (Gómez-Baggethun *et al.* 2014, Small *et al.* 2017). This also explains the bias in the literature toward services for which a market exists. Furthermore, for any valuation method applied, results will be highly dependent on social, cultural and economic contexts in which the ecosystem service framework is applied. In this study, services related to hunting are valued based on the price of meat or licenses. These estimations reflect only part of the real value of hunting. The greatest benefits probably come from the avoided negative consequences of non-regulated prey populations, rather than meat provision or the pleasure linked to the hunting experience. However, these consequences have not been estimated in monetary units until now and forces to use incomplete data (available) for the valuation of hunting services. Hydrogeological protection services were valued using the avoided damages costs method. However, other methods could be applied and tested, like the replacement cost method that estimates the costs of replacing forests by a technological substitute.

For a complete estimation of the value of ecosystems for human well-being, one should include two additional types of values, ecological and socio-cultural (Brondizio *et al.* 2010). The ecological value is represented by the integrity, health or resilience of ecosystems. Socio-cultural value comes from the non-material well-being provided by nature to people, involving ethical, religious or spiritual values. These values cannot be fully estimated by economic valuation and require alternative metrics to be developed (De Groot *et al.* 2010a, 2010b).

This study also highlights the importance of weights assigned to the different biological features accounted for in SCP analysis, and more generally in any decision-making process. Increasing the importance of ecosystem services relative to biodiversity in the analysis implies a decrease in biodiversity protection by the new conservation network. These results emphasize the existing trade-off between ecosystem services and biodiversity, and more generally between the different features susceptible to be prioritized. Decision making for conservation planning implies different steps, comprising the identification of the problem, the definition of objectives and possible actions, the evaluation of consequences and identification of trade-offs between costs and benefits of actions (Gregory *et al.* 2012, Guisan *et al.* 2013). This study illustrates the application of SCP analysis to assess the potential consequences of alternative actions for biodiversity protection. Different weighting scenarios for ecosystem services simulate decisions (i.e. conservation targets) and the varying ranges of species protected by new conservation networks represent the consequences of simulated actions for biodiversity. Results of this study showed that including ecosystem services in conservation planning, even with a small weight in the analysis, allows improving the benefits supplied by ecosystems.

This framework can be used by decision-makers to increase the economic value extracted from ecosystems as well as non-monetary benefits provided by nature while preserving biodiversity at the same time. A sustainable management of ecosystems within protected areas has to be assumed to fulfill this goal (Smith *et al.* 2016). This decision support tool can be especially useful to improve the regional economy of Alpine regions, which is highly sensitive to changes in ecosystem services supply (Grêt-Regamey *et al.* 2008b). For example, stakeholders may want to prioritize valuable areas for tourism development (Gios *et al.* 2006). Giving too much weight to services in the analysis will increase the economic benefits supplied, to the detriment of biodiversity protection. Decision makers have to define a threshold for the importance (i.e. weight) of services that still improve conservation.

Trade-offs also happen among services when they are provided by the same ecosystem (Turkelboom *et al.* 2016). For example, services of timber provision, carbon sequestration, and hydro-geological protection are provided by forests, but harvesting timber implies a loss of carbon sequestration and protection services (Pang 2017). This trade-off is especially present in the study area of the *Alpes Vaudoises,* because most of the forests are considered as protective against natural hazards and are thus not intensively exploited for timber production, but rather managed to maximize their protective role. For this reason, timber harvesting is low in this area and is non-profitable due to high harvesting costs (Grêt-Regamey *et al.* 2008b). The ecosystem services framework proposed in this study gives insights for ecosystem services trade-offs in conservation planning. The importance (i.e. weight) given to each service in SCP can also be variable, and new conservation networks can be designed to favour a given service more than others. Such weighting scenarios for SCP would require a complete analysis of consequences for biodiversity and competing services.

Conclusion & Perspectives

As a first challenge, further studies could investigate uncertainties associated with the ecosystem services framework applied in this study.

- Different quantification and valuation methods could be tested simultaneously, to assess the variability of values obtained with the different approaches for the same service. Uncertainties in the assessment and mapping of ecosystem services in the Alps have already been considered in previous studies (Grêt-Regamey *et al.* 2013).
- Different techniques can be used to create species prediction maps that will be integrated as biodiversity features in Zonation. A threshold has to be set to change continuous suitability predictions into presence-absence data for each pixel of the raster map. The thresholding method applied can change the binary presence-absence distribution maps (Liu *et al.* 2013), influencing the results of SCP analysis.

Also, additional analyses could be performed to assess the robustness of the conclusions drawn from the results to the addition or suppression of services. The same SCP analysis could be done with a subsample of services, to see how many prioritized areas are in common with analysis including all services. For example, by selecting five out of the ten services included in this study and repeating the SCP analysis to obtain an average percentage of common area prioritized. This could be repeated for different subsamples of services using a bootstrap-like approach, to inform on the representativeness of the subset of services included in this study as a proxy for the whole array of existing ecosystem services.

Additional efforts could be done to gather missing information and data necessary for the quantification and valuation of ecosystem services in the study area. This way, a complete evaluation of nature's value, for the different ecosystem types present in the study area, could be used to improve conservation planning.

Another major challenge in the field of conservation planning including ecosystem services is the inclusion of dynamic processes, allowing to create scenarios for future services supply and value (Kubiszewski *et al.* 2017, Song 2018). As reported by the Millennium Ecosystem Assessment and the COPI project, land use and management changes influence a lot the provision of ecosystem services and their values for societies (Costanza *et al.* 2014). Forecasting future services supply requires representing the changing bundles of services in space and time (Mina *et al.* 2017), as well as feedbacks between social and ecological systems (Nicholson *et al.* 2009). Land use change scenarios give insights in the future location of different types of ecosystems, but more information is needed regarding the state (i.e. functionality) and biophysical structure that are at the basis of the ecosystem service cascade model (Haines-Young & Potschin 2010, De Groot *et al.* 2010a). Dynamic interdependencies between services or between biodiversity and services make predictions regarding future ecosystem services supply challenging to assess. When it comes to estimate future economic values for ecosystem services, another source of uncertainty arise from the fact that economic values depend highly on the demand side of the market. A given service can gain or lose value in time due to changing preferences or needs of consumers. Mapping future services supply would help to create adapted new conservation networks prioritizing areas supplying services in space and time.

To conclude, including economic values for ecosystem services with biodiversity into spatial conservation planning is an interdisciplinary approach linking ecology with economics (Polasky & Segerson 2009). This approach has the potential to raise awareness about the importance of nature's services compared to other goods provided by human capital (Kubiszewski *et al.* 2013, Costanza *et al.* 2014). It can also improve communication and collaboration between researchers and decision makers. For this framework to be useful for conservation planning, a good communication between researchers and conservation actors is needed. This way, efforts of scientists would be convergent with needs from the field concerning existing conservation problems.

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Vincent C, Fernandes R, (2018), Climate and land-use changes can reshuffle priority conservation areas in mountain landscapes (Submitted).

Von Grünigen S, Montanari D, Ott W, (2014). Wert der Erholung im Schweizer Wald. Schätzung auf Basis des Waldmonitorings soziokulturell (WaMos 2). Bundesamt für Umwelt, Bern.

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Wijen F (2012) Globalisation and Natural Resources Law. *Environmental sciences*, **8168**, 15,67.

Appendix A – Supplementary Tables for methods

Table A1. Correspondence between Corine-Land-Cover classes and Ecosystem types applied by the MAES initiative. Source: Maes, J., Teller, A., Erhard, M., Liquete, C., Braat, L., Berry, P., *et.al.* & Paracchini, M. L. (2013). Mapping and Assessment of Ecosystems and their Services. An analytical framework for ecosystem assessments under action, 5, 1-58.

CLC Level 1	CLC Level 2	CLC Level 3	Ecosystem types level 2
1. Artificial surfaces	1.1. Urban fabric	1.1.1. Continuous urban fabric	Urban
		1.1.2. Discontinuous urban fabric	
	1.2. Industrial, commercial and transport units	1.2.1. Industrial and commercial units	
		1.2.2. Road and rail networks and associated land	
		1.2.3. Port areas	
		1.2.4. Airports	
	1.3. Mine, dump and construction sites	1.3.1. Mineral extraction sites	
		1.3.2. Dump sites	
		1.3.3. Construction sites	
	1.4. Artificial non-agricultural vegetated areas	1.4.1. Green urban areas	
		1.4.2. Sport and leisure facilities	
2. Agricultural areas	2.1. Arable land	2.1.1. Non-irrigated arable land	Cropland
		2.1.2. Permanently irrigated land	
		2.1.3. Rice fields	
	2.2. Permanent crops	2.2.1. Vineyards	
		2.2.2. Fruit trees and berry plantations	
		2.2.3. Olive groves	
	2.3. Pastures	2.3.1. Pastures	Grassland
	2.4. Heterogeneous agricultural areas	2.4.1. Annual crops associated with permanent crops	Cropland
		2.4.2. Complex cultivation patterns	
		2.4.3. Land principally occupied by agriculture, with significant areas of natural vegetation	
		2.4.4. Agro-forestry areas	
3. Forests and semi-natural areas	3.1. Forests	3.1.1. Broad-leaved forest	Woodland and forest
		3.1.2. Coniferous forest	
		3.1.3. Mixed forest	
	3.2. Shrub and/or herbaceous vegetation association	3.2.1. Natural grassland	Grassland
		3.2.2. Moors and heathland	Heathland and shrub
		3.2.3. Sclerophyllous vegetation	
		3.2.4. Transitional woodland shrub	Woodland and forest
	3.3. Open spaces with little or no vegetation	3.3.1. Beaches, dunes, and sand plains	Sparsely vegetated areas
		3.3.2. Bare rock	
		3.3.3. Sparsely vegetated areas	
		3.3.4. Burnt areas	
		3.3.5. Glaciers and perpetual snow	
4. Wetlands	4.1. Inland wetlands	4.1.1. Inland marshes	Wetlands
		4.1.2. Peatbogs	
	4.2. Coastal wetlands	4.2.1. Salt marshes	Marine inlets and transitional waters
		4.2.2. Salines	
		4.2.3. Intertidal flats	
5. Water bodies	5.1. Inland waters	5.1.1. Water courses	Rivers and lakes
		5.1.2. Water bodies	
	5.2. Marine waters	5.2.1. Coastal lagoons	Marine inlets and transitional waters
		5.2.2. Estuaries	
		5.2.3. Sea and ocean	Marine

Table A2. Valuation methods used to value ecosystem services. Three primary economic valuation approaches, comprising 13 different valuation methods, and three methods of economic value transfer are classified. Non-economic valuation comprises two main approaches, which are sub-divided in ten different methods. For each valuation method, a brief description and range of application is given, as well as the reference for more detailed information.

	Approach	Method	Description	Application	References*
Primary economic valuation	Stated preferences	**Contigent valuation**	Surveys used to estimate people's WTP or WTA for a change in ES supply.	All ES	*1*
		Contingent Ranking	Ask people to rank-order hypothetical situations that differ in terms of environmental amenity available.	ALL ES	*2*
		Participatory valuation	Group discussion to assess the WTP of stakeholders for an ES	All ES	*1*
		Choice experiment	Ask people to discriminate between ES and other goods to estimate their WTP for the ES.	All ES	*1, 2*
	Revealed preferences	**Travel cost**	Valuation based on travel costs and entrance fees people agree to pay for cultural services.	Recreational benefits of environmental resources	*1, 2*
		Hedonic pricing	Change in price of marketed goods according to change in environmental characteristics.	Environmental characteristics that vary with marketed goods (i.e. houses).	*1, 2*
	Market cost	**Damage cost avoided**	Estimated value of avoided damages thanks to ES	ES providing a protection against hydrogeological events.	*1*
		Defensive expenditure	Value estimated from expenditure on protection of ecosystems.	ES delivered by protected ecosystems	*1*
		Public pricing	Value estimated from Governmental expenditures, taxes or subsidies.	ES involving public expenditures	*1*
		Replacement cost	Cost of replacing the ES by human-made technology or service.	ES replaceable by human-made technology or service	*1*
		Restoration cost	Cost of ensuring ES provision by restoration of degraded ecosystems.	ES provided by restored ecosystems	*1*
		Market price	Observed market prices for ecosystems goods and services	Marketed ES	*1*
		Production function	Estimation of production function with an ES input.	ES providing inputs into marketed goods production	*1*
Value transfer	Benefit transfer	**Unit value transfer**	Use of adjusted value for ES from an existing primary valuation study	All ES	*1*
		Value function transfer	Use of a value function from an existing primary valuation study	All ES	*1*
		Meta-analytic function transfer	Use of a value function from multiple primary valuation studies	All ES	*1*

Non-economic valuation	Consultative methods	**Questionnaires**	Surveys on people's perceptions on particular topics or issues.	All ES	*3*
		In-depth interviews	Qualitative information about people's interpretation of how they value or understand something.	All ES	*3*
	Deliberative and participatory approaches	**in-depth groups**	Aim to discover the positions of participants regarding pre-defined issues and their interactions.	All ES	*3*
		Citizen juries	Building of informed preferences through dialogue between the public, experts and politicians.	All ES	*3*
		Health-based valuation	Measure the combined outcomes of health related factors on human well-being.	All ES	*3*
		Q-methodology	Classification of beliefs and preferences of a group of people.	All ES	*3*
		Delphi surveys	Structured group interaction process directed in "round" of opinion collection and feedback.	All ES	*3*
		Rapid rural appraisal	Systematic but semi-structured activity out in the field by a multidisciplinary team designed to investigate rural life.	All ES	*3*
		Participatory rural appraisal	Incorporate the knowledge and opinions of rural people in the planning and management of projects.	All ES	*3*
		Participatory action research	Action research in which professional social researchers collaborate with organizations in studying and transforming those organizations.	All ES	*3*

***References for Table A2:**

[1] Brander LM, Crossman ND (2017). Economic quantification. In B. Burkhard & J. Maes (ed.), Mapping ecosystem services (pp. 115-125). Sofia: Pensoft Publishers.

[2] Tietenberg TH, Lewis L (2016). Environmental and natural resource economics. Routledge.

[3] Christie M, Fazey I, Cooper R, Hyde T, Deri A, Hughes L, *et.al.* (2008). An Evaluation of Economic and Non-economic Techniques for Assessing the Importance of Biodiversity to People in Developing Countries. Defra, London.

Table A3. Subset of ecosystem services for which additional data is needed to be quantified, mapped and valued for the study area of the Alpes Vaudoises. * WTP = Willingness to pay.

Section, Division \ Group		Class	Class Type	Biophysical indicator	Economic indicator
Provisioning	Nutrition\ Biomass	Reared animals and their output	**Meat from reared animals**	*Livestock*	*Price of meat*
		Wild plants, algae and their outputs	**Mushrooms**	*Mushrooms harvested*	*Price of mushrooms*
			Wild berries	*Berries harvested*	*Price of berries*
		Wild animals and their output	**Freshwater fish**	*Fishes*	*Price of fish*
			Honey	*Honey harvested*	*Price of honey*
	Nutrition\ Water	Surface water for drinking	**Drinking water**	*Water supply*	*Price of water*
	Materials\ Biomass	Fibres and other materials from plants	**Natural remedies and medicines**	*Plants harvested*	*Price of substitute medicine*
Regulating	Mediation \ Liquid flows	Flood protection	**Protection by water retention areas**	*Capacity of retention*	*Value of protected infrastructures*
	Maintenance\ Pest and disease control	Pest control	**Pest and disease control by living organisms**	*Presence of mutualist species*	*Price of chemical treatment*
	Maintenance\ Soil formation & composition	Decomposition and fixing processes	**N-fixing in soil by plants**	*Nitrogen-fixing plants*	*Price of fertilizer*
Cultural	Physical & experimental interactions	Physical use of landscape	**Fishing recreational activity**	*Number of fishers*	*Price of licence*
	Intellectual and representational interactions	Cultural	**Cultural heritage**	*Cultural sites*	*People's WTP**
		Aesthetic	**Scenic beauty**	*People's preferences*	*People's WTP**
		Entertainment	**Observation of birds or other attributes of nature**	*People's preferences*	*People's WTP**

Appendix B – Supplementary methods

Quantification and valuation of ecosystem services

Part 1. Provisioning services

- **Cheese Etivaz AOP provision**

Biophysical quantification

L'Etivaz AOP is a type of cheese produced only between 1000 and 2000 m of elevation. This alpine product is exclusively produced within a specific region defined by 10 communes out of the 28 present in the study area (Châteaux-d'Oex, Rougemont, Rossinière, Ollon, Villeneuve, Ormont-Dessus, Ormont-Dessous, Corbeyrier, Leysin, and Bex). The average annual production of cheese per commune was calculated based on the annual production per chalet and the location of the chalets provided on the website of the Cooperative Etivaz AOP.

Economic valuation

The market price method was applied to value the provision of cheese EtivazAOP within the study area. A market price of 13.50 CHF/kg was used, according to the annual benefit of the Cooperative Etivaz AOP divided by the total amount of cheese produced in kg per year.

References

Etivaz, 2010, website of *Cooperative L'Etivaz AOC*. [ONLINE], http://www.etivaz-aoc.ch. [Accessed 19 July 2017].

- **Milk provision**

Biophysical quantification

The amount of milk produced per year per commune in the study area was calculated from the number of exploitation per commune (OFS 2016) multiplied by the average amount of milk produced per agricultural exploitation, estimated at 196'992 kg per year at low elevations and 105'503 kg per year in mountainous areas (OFAG, 2016). Since the part of cow's diet made of grasses is only 46% of their total diet (OFS 2013), a correction factor of 0.46 was used to estimate the milk produced from grassland materials only.

Milk produced per commune [kg/year] = Exploitations per commune * Average milk produced * 0.46

Economic valuation

The market price method was applied to value milk production. A price of 64 cts/kg was used for lowland agricultural exploitations and 67 cts/kg for mountain agricultural exploitations (OFAG 2016).

Value of milk provision = milk produced per commune [kg/year] * market price of milk [CHF/kg]

The total value was divided by the surface area of grasslands for each commune, to obtain the value per hectare for milk provision.

References

OFS 2016, Recensement des exploitations agricoles, Statistique Vaud

OFS, 2013, De l'herbe au lait – La production de lait en Suisse. Actualités OFS 7 Agriculture et sylviculture. Neuchâtel.

OFAG, 2016, Evaluation des données sur la production de lait

- **Meat provision from hunting activity**

Biophysical quantification

To quantify wild meat provision, the most frequently hunted animals in the study area were identified according to the annual fauna report of the "Direction Générale de l'Environnement" (DGE) Vaud (DGE/BIODIV 2017). Three species were selected, the deer, the roe, and the chamois. Statistical data about the average number of animals killed per wildlife area between the years 2012 and 2016 provided by the Vaud canton were used to quantify meat provision.

Table B1. Average weight and meat yield per species hunter used to calculate the average value per animal hunted. An average market price of meat of 20.44 CHF/kg was used.

	Weight kg	Yield in kg	Price CHF/kg	Value per animal
Roe	25	10	20.44	204.4
Chamois	40	16	20.44	327.04
Deer	180	72	20.44	1471.68

Economic valuation

The market price method was applied to value meat provision, using an average market price for the meat of 20.44 CHF/kg (Proviande CH 2015). The average value per animal hunted was calculated for the three species selected above, by multiplying the market price of meat by the average weight per animal, taking into account the mean yield of meat (Bang *et al.* 2009, Schmidt *et al.* 2000) (Table S5).

References

Bang, P., Dahlström, P., *2009, Guide des traces d'animaux, les indices de présence de la faune sauvage,* les guides naturaliste, DELACHAUX ET NIESTLE.

Dan Schmidt, 2000, How much meat will your deer yield, Deer & Deer Hunting, Butcher & Packer DGE/BIODIV, 2017, Rapport annuel de faune 2016, Saint-Sulpice

Proviande CH, 2015, Le marché de la viande 2015

- **Timber provision**

Biophysical quantification

To quantify the service of Timber provision by forests, harvesting rates in m^3/ha/year for coniferous and resinous tree species available from the National Forest Inventory (NFI2-NFI3, 1993/95-2004/06) were used. These data were available for the different forest districts present in the study area.

Economic valuation

The market price method was applied to value Timber provision. Wood harvested from both coniferous and broad-leaved trees was separated into 3 categories of use: i) construction wood ii) industrial wood iii) energy wood. The average market price for timber was calculated, taking into account the percentages of wood harvested per category of use for coniferous and deciduous tree species (OFEV 2016). Timber was valued 73.18 CHF/m^3 for coniferous and 81.44 CHF/m^3 for deciduous tree species (Table S6). Timber harvested in forest areas comprising both types of tree species was valued using a weighted mean of 76.23 CHF/m^3, using the percentage of coniferous trees in Swiss forests of 63% (OFEV 2016) and timber values calculated for coniferous and deciduous tree species.

	Category of use	Coniferous	Deciduous
% of timber	**Construction**	0.707	0.722
	Industry	0.092	0.139
	Energy	0.201	0.139
Value CHF/m^3	**Construction**	87	92
	Industry	46	51
	Energy	37	57
Value CHF/m^3		**73.18**	**81.44**
% in Swiss forests		0.63	0.37

Table B2. Summary of percentages of timber exploited in the three categories of use for coniferous and deciduous tree species and corresponding market prices used to calculate the average value of coniferous and deciduous timber. The last line in the table gives the percentage of coniferous and deciduous tree species in Swiss forests, used to compute the weighted mean for timber harvested in mixt forests (76.23 CHF/m^3).

References

Brändli, U.-B. (Réd.) 2010: Inventaire forestier national suisse. Résultats du troisième inventaire 2004–2006. Birmensdorf, Institut fédéral de recherches sur la forêt, la neige et le paysage WSL. Berne, Office fédéral de l'environnement, OFEV. 312 p.

Brassel, P., Brändli, U.-B. (Réd.) 1999 : Inventaire forestier national suisse. Résultats du deuxième inventaire 1993–1995. Birmensdorf, Institut fédéral de recherches sur la forêt, la neige et le paysage WSL. Berne, Office fédéral de l'environnement, des forêts et du paysage, OFEFP. 435p.

OFEV (Ed.) 2016: Annuaire La forêt et le bois 2016, Office fédéral de l'environnement, Berne. Etat de l'environnement n°1540:172p.

Part 2. Regulating services

- **Carbon sequestration**

Biophysical quantification

Carbon sequestration was quantified based on the annual wood increment recorded by the National Forest Inventory (NFI3 04/06 – NFI4 09/13). The following equation was used to translate the annual wood increment into kg of CO_2 sequestrated by trees per ha in one year (adapted from Häyhä *et al.* 2015):

$$\text{Annual wood increment } (m^3/ha/yr) * \text{wood density } (kg/m^3) * \% \text{ dry mass } * \% \text{ carbon } * 3.67 * 120\%$$

Where a wood density of 450 kg/m^3 was used for coniferous species and 700 kg/m^3 for deciduous species (www.lignum.ch). A % of dry mass of 0.45 was used to estimate the weight of biomass without taking into account the water present inside plant tissues (Krajnc 2015). The % carbon value is the coefficient of carbon proportion in woody biomass and was fixed to 0.5 in this study (Paladinić *et al*. 2009). A conversion factor from C to CO_2 of 3.67 was used as well as a correction factor of 1.2 to account for carbon sequestrated by roots, which represent 20% of total biomass.

Economic valuation

To assign a monetary value to the service of carbon sequestration, the Social Cost of carbon (SCC) of 40.8 CHF/ton of CO2 was used. The SCC is an estimation of future economic loss caused by the emission of one additional metric ton of carbon dioxide (National Academies of Sciences, Engineering and Medicine 2017). According to the Federal Interagency Working Group on the Social Cost of Greenhouse Gases (IWG), the current estimate of the SCC is $42 per metric ton of CO2, corresponding to 40.8 CHF.

References

Abegg, M., Brändli, U.-B., Cioldi, F., Fischer, C., Herold-Bonardi, A., Huber M., Keller, M., Meile, R., Rösler, E., Speich, S., Traub, B., Vidondo, B., 2014: Quatrième inventaire forestier national suisse - tableaux et cartes des résultats de l'IFN 2009-2013 disponibles sur internet (IFN4b). [Published online 06.11.2014] http://www.lfi.ch/resultate/, Birmensdorf, Institut fédéral de recherches WSL.

Häyhä, T., Franzese, P. P., Paletto, A., & Fath, B. D. (2015). Assessing, valuing, and mapping ecosystem services in Alpine forests. *Ecosystem Services*, *14*, 12-23.

Krajnc N., 2015, Wood Fuels Handbook, Food and agricultural organization of the United Nations, Pristina, 40p.

National Academies of Sciences, Engineering, and Medicine, 2017, valuing climate damages: Updating estimation of the social cost of carbon dioxide. National Academies Press.

Paladinić, E., Vuletić, D., Martinić, I., Marjanović, H., Indir, K., Benko, M., & Novotny, V. (2009). Forest biomass and sequestered carbon estimation according to main tree components on the forest stand scale. Periodicum biologorum, 111(4), 459-466.

- **Hydrogeological protection services (avalanches, landslides, and rock falls)**

<u>Biophysical quantification</u>

Zones protected by forests for the different natural hazards considered were identified using indicative maps of risk zones available from the Vaud canton. A GIS allowed to intersect roads and buildings maps with protected zones, in order to identify infrastructures protected by forests. The total length of protected roads in km and the total surface of the protected building in square meters allowed to quantify the service of protection supplied by forests against natural hazards (i.e. avalanches, landslides and rock falls).

<u>Economic valuation</u>

The economic valuation of hydrogeological protection services was realized through the avoided damages cost method. This method consists in valuing the protective forest according to the total value for infrastructures protected. Roads were valued depending on categories (national, cantonal or communal) with values ranging from 2.2 to 44 billion of CHF per km (Lukic & Forster 2017). Buildings were valued using the price per square meter of 9140 CHF for the district of Riviera – Pays-d'Enhaut and 6270 CHF for the district of Aigle, calculated by comparis.ch from the price of apartment and houses between the year 2005 and 2015. A reduction factor of 0.5 was used to account for the probability of damage to buildings and roads (Fuchs 2007).

References

Lukic D., Forster M., 2017, Etude – Analysede l'état et de la conservation de la valeur des routes cantonales en Suisse, Infra Suisse, Zurich, 20p.

Fuchs, S., Thöni, M., McAlpin, M. C., Gruber, U., & Bründl, M. (2007). Avalanche hazard mitigation strategies assessed by cost effectiveness analyses and cost benefit analyses—evidence from Davos, Switzerland. Natural Hazards, 41(1), 113-129.

Comparis.ch SA, 1996-2017, Le marché immobilier Suisse en un clic, Zurich, https://fr.comparis.ch/, [Accessed 21 July 2017]

Part 3. Cultural services

- **Recreation from hunting activity**

<u>Biophysical quantification</u>

The quantification of recreational benefits provided by hunting activity was done using data about the number of animals killed per wildlife area within the study area for three species (i.e. the deer, the roe and the chamois) provided by the DGE and already used to quantify the service of wild meat provision.

<u>Economic valuation</u>

To value this service, the price of hunting licenses for the different species hunted (i.e. deer, roe, and chamois) was used to estimate the minimum willingness to pay (WTP) of people for hunting. The price of hunting licenses was: 1000 CHF for the deer and the chamois and 800 CHF for the roe (Décisions du 3 Juillet 2017). For each species, the number of animals hunted was multiplied by the corresponding hunting license. The value was divided by the total forest area in hectare for each wildlife area to obtain the recreational value of hunting activity in CHF/ha for the study area.

References

DGE, 2017, *Décisions du 3 juillet 2017 sur la chasse en 2017-2018*, Département du territoire et de l'environnement, Canton de Vaud

- **Forest recreation service**

<u>Quantification</u>

To quantify the recreation in forests within the study area, the results of two "Socio-Cultural Forest Monitoring" surveys were used. A first version of the survey (WaMos1) was completed in 1997 (OFEFP (ed.) 2000) and a second version (WaMos2) was carried out in 2010 by the

Swiss Federal Institute for Forest, Snow and Landscape Research WSL on behalf of the FOEN (OFEV et WSL (ed.) 2013). This study investigates how the Swiss population perceive the forest and behave in relation to this ecosystem. People's relationship with forests is determined with the help of telephone and email surveys, questioning people about their preferences for a selection of forest-related services. More than 3000 interviews were given to randomly selected informants in the whole country.

According to the results of this study, a majority of people go into the forest to walk, enjoy nature (63.7%) or practice different sports (39%). On average, they have a preference for mixt forests, composed by coniferous and deciduous tree species, having also a preference for places located near watersheds. Based on these preferences, a quantification of recreational services supply by forests was realized by combining preference factors in a GIS (mixt/simple forest and watersheds presence) with the presence of hiking trails in the forest. Different levels of appreciation were assigned to the categories obtained.

Mapping

The WaMos2 survey revealed that about two thirds (63.7 %) of interviewed people go into the forest to walk and enjoy the nature without any specific activity. Additionally, 39% of them go into the forest to practice different sports, including jogging, Nordic walking and mountain bike. These recreational activities are mainly practiced on or near forests hiking trails. To represent people's preferences for recreation in the forest within the study area, a map of forests was overlaid to a map of hiking trails present in the study area. A 100m buffer was applied to hiking trails in forests to select forests area considered for recreation purpose. This GIS layer was again overlaid to another 100m buffer map of watersheds in the study site. This allowed to obtain 4 categories of recreation sites in the forest: I) Hiking trails within simple forests without watersheds. II) Hiking trails within mixt forests without watersheds. III) Hiking trails within simple forests with watersheds. IV) Hiking trails within mixt forests with watersheds (see Table S7).

Economic valuation

The valuation of the recreation in forests was done based on the results of a study published by the Federal Office for the Environment (Von Grünigen *et al.* 2014), which takes advantage of the results of the WaMos2 study (OFEV et WSL (Ed.) 2013). In this study, the monetary value of recreation in Swiss forests is calculated based on the expenditure method. The total expenditure incurred for recreation in forests, comprising travel costs, entrance fees, and opportunity costs are calculated and added. A mean value of 9 CHF/day per visitor was calculated. From this value, the mean annual expenditure per visitor was calculated with the help of the frequencies of visits obtained from the WaMos2 survey. A recreational value between 290 and 589 CHF/visitor/year was obtained. The variation comes from the margin of interpretation of the visit frequency categories used in the WaMos2 survey. A recreational value between 1.9 and 3.9 billion of CHF, with an average of 2.8 billion of CHF was calculated for the whole Switzerland. Based on these values and the total forest surface in Switzerland of 1.26 million of ha (OFEV 2016), a range of value from 1505 CHF to 3059 CHF/ha was calculated, with an average of 2172 CHF/ha. These values were attributed to the 4 levels of recreation in forests (Table S7).

Table B3. Categories of recreation sites in forests and the corresponding level of recreation, based on people's preferences for the type of forest (i.e. mixt, coniferous or deciduous) and the presence of watersheds. The economic values in CHF/ha per year calculated from previous studies (Von Grünigen *et al.* 2014, and OFEV & WSL (Ed.) 2013) were assigned to the different levels of recreation.

Level of recreation	Type of forest	Watershed presence	Economic value (CHF/ha/year)
1	Mixt	Yes	3059
2	Mixt	No	2171
2	Simple	Yes	2172
3	Simple	No	1505

References

OFEV (Ed.) 2016: Annuaire La forêt et le bois 2016, Office fédéral de l'environnement, Berne. Etat de l'environnement n°1540:172p.

Office fédéral de l'environnement, des forêts et du paysage (OFEFP) (éds), 2000, Les attentes de la société envers la forêt suisse. Enquête d'opinion. Berne. Cahier de l'Environnement, n°309: 151p.

OFEV et WSL (Ed.) 2013: La population suisse et sa forêt. Rapport sur l'enquête sur le monitoring socioculturel des forêts (WaMos 2). Office fédéral de l'environnement, Berne, et Institut fédéral de recherches sur la forêt, la neige et le paysage WSL, Birmensdorf. Connaissance de l'environnement n° 1307: 92 p.

Von Grünigen S., Montanari D., Ott W. 2014: Wert der Erholung im Schweizer Wald. Schätzung auf Basis des Waldmonitorings soziokulturell (WaMos 2). Bundesamt für Umwelt, Bern.

Part 4. Species prediction maps

Species prediction maps used as input features in Zonation to identify priority areas were obtained from Vincent *et al.* (submitted).

Species distribution maps were created for plants, amphibians, reptiles, and insects. For a complete list of species, see Vincent *et al.* (submitted). Observational data from field surveys in the study area of the *Alpes Vaudoises* and environmental variables (i.e. temperature and precipitation) were used to model the current distribution of species.

Three different modelling techniques were used for each species: Generalized Linear Models (GLM), Generalized Additive Models (GAM) and Maximum Entropy (MaxEnt). A weighted mean of these three models was computed to create an ensemble of small models (ESMs), using the predictive performance of each model estimated with a maximisation of the True Skill Statistic (maxTSS; Liu et al. 2005) to weight individual models. Species data were separated in two groups for the evaluation of models (i.e. 75% for calibration and 25% for validation). Each model was evaluated using the maxTSS method. The same method was applied to change probability distribution into binary presence-absence distribution maps for each species considered. For more details on the modelling techniques applied and the evaluation of models, refer to Vincent *et al.* (submitted).

Appendix C – Supplementary results

Table C1. Overview of number of studies valuing different ecosystem service types from peer reviews and additional studies valuing ecosystem services in Alpine regions. *Types of services selected to be mapped and valued in this study.

Type of ecosystem Services		Number of studies from				
		Schmidt *et al.* 2016	Grêt-Regamey *et al.* 2008	Martinez-Harms & Balvanera 2012	Additional studies in Alpine regions	**Total**
Cultural	*Scenic beauty*	/	5	4	[3], [7], [4], [13]	13
	Recreation	96	4	9	[8], [10]	**111***
Regulating	*Extreme flood events regulation*	46	3	3	[3], [5], [6], [7] [10], [11], [12], [15]	**60***
	Climate regulation (i.e. C. sequestration)	36	2	11	[3], [5], [6], [10]	**53***
	Waste treatment	31	/	/	/	31
	Soil fertility	14	/	4	/	18
Provisioning	*Water*	26	/	4	[10]	31
	Food	82	/	11	[10]	**93***
	Material	68	/	8	[5], [6], [7], [10]	**80***
	Medicinal resources	28	/	/	/	28

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Table C2. Studies considered in the literature review, classified by topics and sub-topics, followed by complete references.

Topic	Sub-topic	References
Definition & classification		(de Groot *et al.* 2002), (Wallace 2007), (Boyd & Banzhaf 2007)(Fisher *et al.* 2008),(Fisher *et al.* 2009), (Roy Haines-Young & Potschin 2013) (La Notte *et al.* 2017), (Schröter *et al.* 2014)
Socio-ecology	Ecosystem services and human well-being \ Why to protect ecosystems?	(Nicholson *et al.* 2009), (Pascual *et al.* 2017), (Chan *et al.* 2016), (Bennett *et al.* 2016), (Costanza *et al.* 2017)
Mapping & valuation	Quantification of services and mapping	(Boerema *et al.* 2017), (Bagstad *et al.* 2013a), (Crossman *et al.* 2013), (Martínez-Harms & Balvanera 2012), (Schägner *et al.* 2013), (Brown & Fagerholm 2014)
	Natural capital accounting and valuation methods	(Goio *et al.* 2008), (Onofri *et al.* 2017), (Hackbart *et al.* 2017)
	Economic valuation	(Gios *et al.* 2006), (Grêt-Regamey *et al.* 2007), (Grêt-Regamey & Kytzia 2007), (Troy & Wilson 2006), (Häyhä *et al.* 2015), (Sumarga *et al.* 2015), (Costanza *et al.* 2014), (Grilli *et al.* 2014), (de Groot *et al.* 2012), (Gómez-Baggethun & Ruiz-Pérez 2011), (Rewitzer *et al.* 2017)
	Non-economic valuation & cultural value	(Walz *et al.* 2016), (Zoderer *et al.* 2016), (Oteros-Rozas *et al.* 2014), (Kelemen *et al.* 2014), (Chan *et al.* 2012)
	Conceptual framework	(Gunton *et al.* 2017), (Maes *et al.* 2016a), (Díaz *et al.* 2015)
	Mountain regions	(Haida *et al.* 2016), (Fuchs *et al.* 2007), (Teich & Bebi 2009), (Walz *et al.* 2016), (Notaro & Paletto 2012)
	Future scenarios	(Gago-Silva *et al.* 2017), (Schägner *et al.* 2013), (Civantos *et al.* 2012)
Conservation planning	Cost benefit analysis	(Chan *et al.* 2011), (Naidoo & Ricketts 2006), (Naidoo *et al.* 2006), (Sarkki *et al.* 2016), (Ingram *et al.* 2012)
	Ecosystem services and biodiversity	(Dee *et al.* 2017), (Crouzat 2015), (Schneiders *et al.* 2012), (Harrison *et al.* 2014), (Cimon-Morin *et al.* 2013)
	Land use planning, Land use change, Management	(Sumarga & Hein 2014), (Ditt *et al.* 2010), (Grêt-Regamey *et al.* 2008), (Ma *et al.* 2016), (Egoh *et al.* 2008), (Chen *et al.* 2009), (Grêt-Regamey *et al.* 2013b), (Burkhard *et al.* 2012), (Sumarga & Hein 2014), (Turner *et al.* 2015),
	Spatial conservation prioritization, Policy support and Decision making	(Maes *et al.* 2012), (Hauck *et al.* 2013), (de Groot *et al.* 2010a), (Chan *et al.* 2006), (Grêt-Regamey *et al.* 2017), (García Márquez *et al.* 2017), (Di Minin *et al.* 2017), (Di Marco *et al.* 2017), (Verhagen *et al.* 2017), (Moilanen *et al.* 2011), (Geneletti 2011)
	Multiple modelling and tools	(Nelson *et al.* 2009), (Peh *et al.* 2013), (Crossman *et al.* 2013), (Villa *et al.* 2009), (Sherrouse *et al.* 2011), (Bagstad *et al.* 2013b), (Guisan *et al.* 2013)
Uncertainties	Limitations of the ecosystem services framework	(Potschin & Haines-Young 2011), (Hein *et al.* 2016), (Schmidt *et al.* 2016), (Hamel & Bryant 2015)
	Limitations for policies and decision making	(Hauck *et al.* 2013), (Bull *et al.* 2016), (Grêt-Regamey *et al.* 2013a)
Books	ES mapping and valuation	(Burkhard & Maes 2017)
	Environmental economics	(Tietenberg & Lewis 2016), (Perman *et al.* 2003)
Reports	International	(United Nations 2014), (Pascual *et al.* 2010), (de Groot *et al.* 2010b), (Brondízio *et al.* 2010)
	European	(Maes *et al.* 2016b), (Maes *et al.* 2015), (Balmford *et al.* 2012), (Banko *et al.* 2013), (Egoh *et al.* 2012)
	United States	(Binder *et al.* 2017)
	Swiss	(Staub *et al.* 2011)

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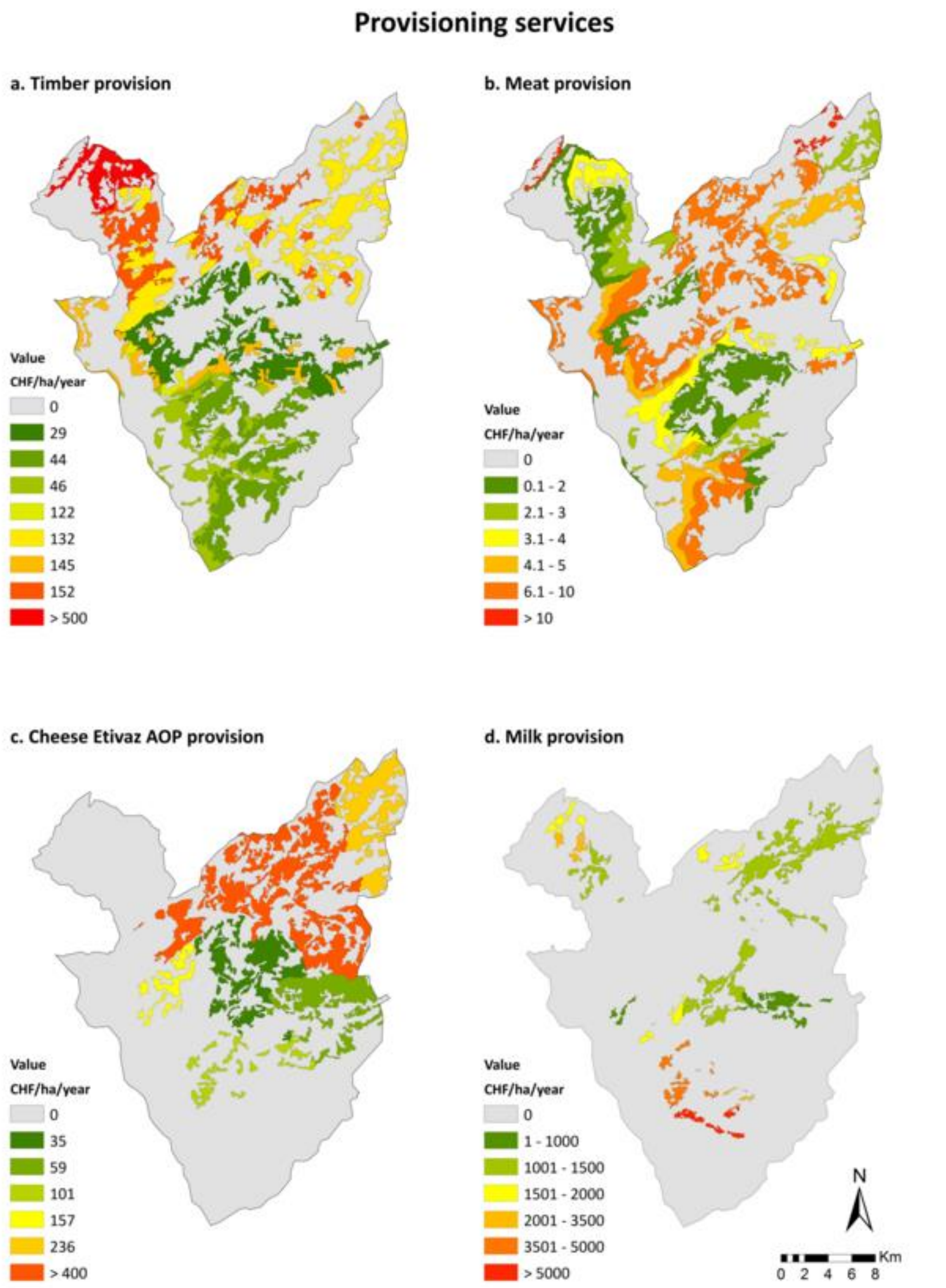

Figure S1. Individuals maps of economic values for provisioning services. a) Timber harvested for construction, industry and energy production, b) Wild meat from hunting, c) Cheese Etivaz AOP produced in alpine environments, d) Milk provided by agricultural exploitations at low elevation.

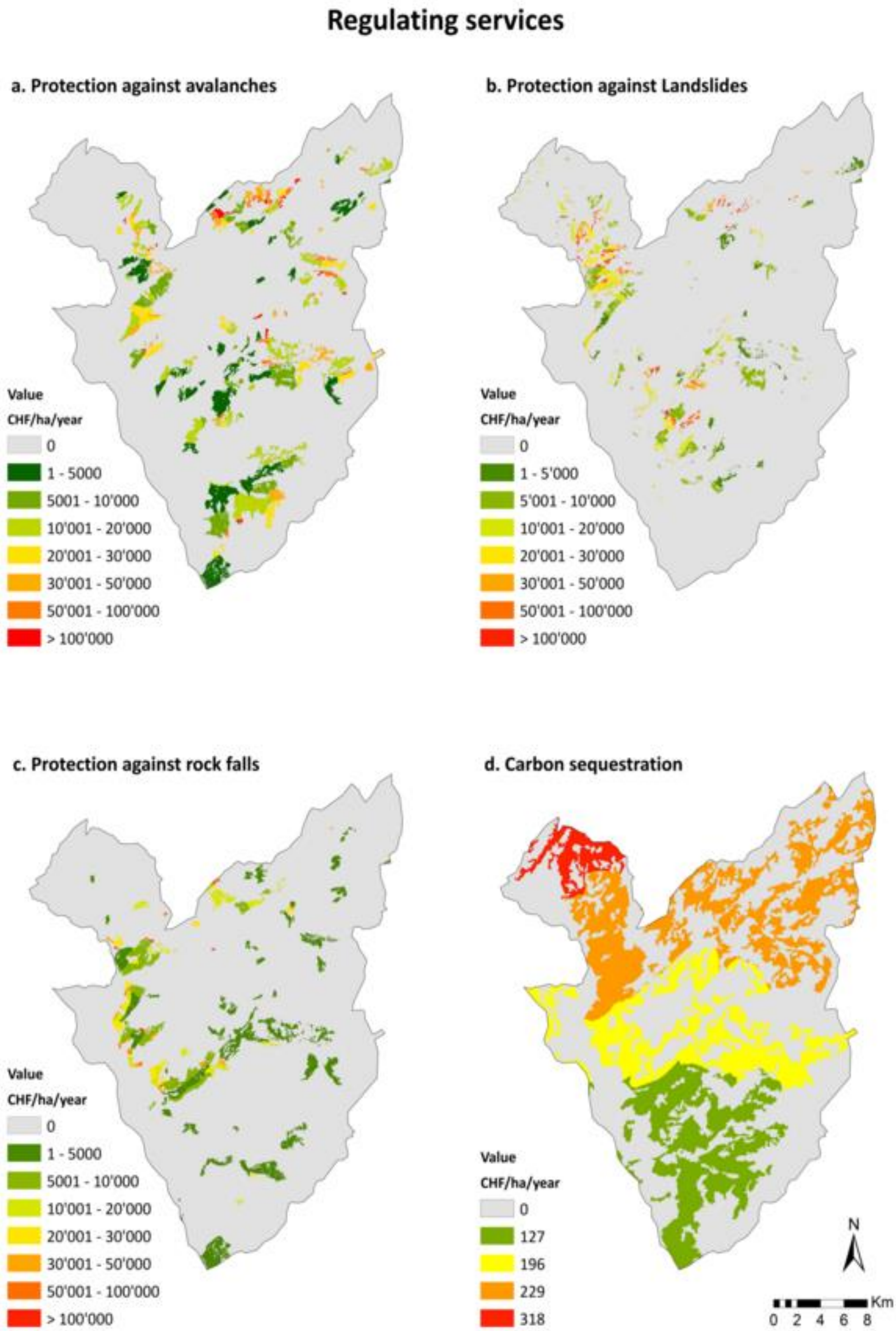

Figure S2. Individual maps of economic values for regulating services. Protection by forests against a) Avalanches, b) Landslides c) Rock falls, and d) Climate regulation from carbon sequestrated by forests.

Cultural services

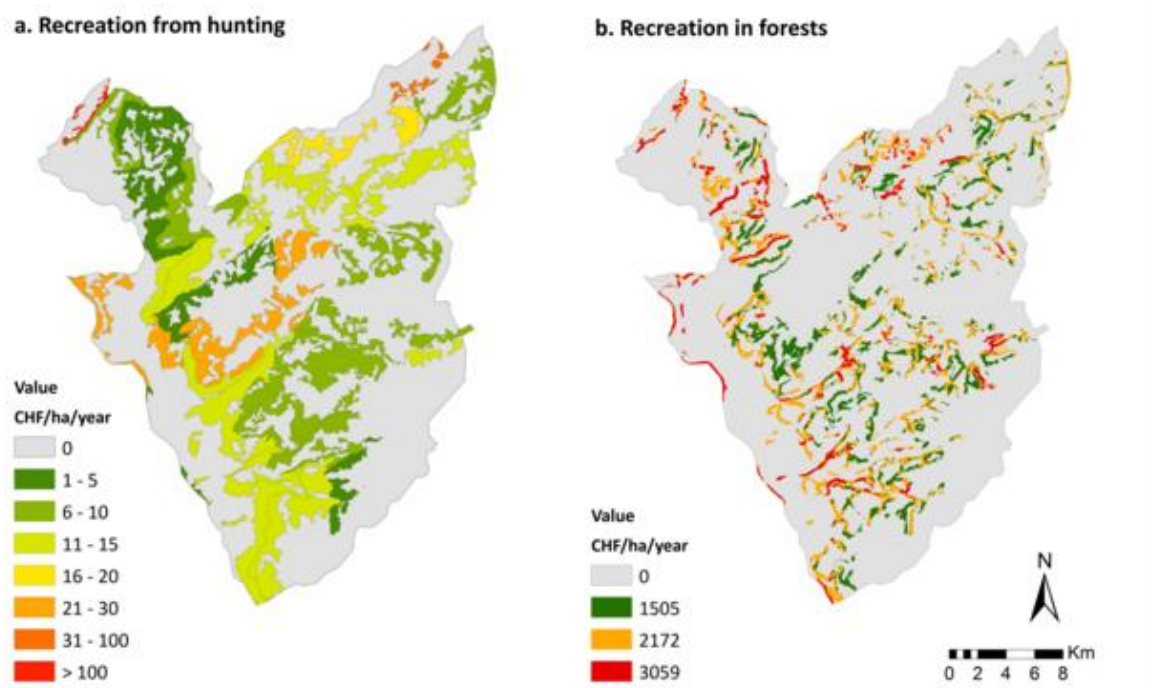

Figure S3. Individuals maps of economic values for cultural services. a) Recreational benefits from hunting estimated from the minimum willingness to pay of people, b) Value of recreation in Swiss forests, based on the results of Von Grünigen *et al.* (2014).