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New perspectives for spatial planning in Switzerland: the role of ecosystem services

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Summary

Spatial planning deals with the spatial expression of human activities in an integrated way to minimize their negative impacts on the natural and land systems. Rapid land use and land cover changes are important drivers of change of socio-ecological systems, and the benefits that people derive from biodiversity and ecosystem functions, known as ecosystem services (ES). The concept of ES has the potential to frame the systematic integration of a comprehensive ecological understanding in spatial planning. Despite early legislation in Switzerland to promote the sustainable use of natural resources, urbanisation and economic development led to deep changes in the landscape with an increase in urban and wooded surface areas, mostly at the expense of agricultural land. However, intensification and cropping also had negative impacts on biodiversity and soil multifunctionality. ES may have been affected to different degrees by past and current land management strategies and some could have been maximised at the expense of others. Better integration of ES into spatial planning requires an understanding of: (i) the relationships between land management strategies and the supply of ES, (ii) the degree of uptake of the ES concept in current planning documents, (iii) the spatio-temporal patterns of ES supply and their drivers of change, and (iv) place-based knowledge to develop planning policies with multiple objectives.

The aim of this thesis is to understand the role of ES for spatial planning in Switzerland. With the use of a holistic approach, which considers multiple timeframes, scales, methods and stakeholders, four hypotheses are tested in individual articles published in international peer-reviewed journals. The first article seeks to understand the historical dynamics of ES and analyses regional diversity of ES changes in Swiss cantons. It is exploratory in nature and sets out regional clustering in the supply of ES. It shows the limited impact of current land management policies to preserve ES supply, and their application at the cantonal level develops long lasting "regionalities" in the supply of ES. The second article includes qualitative aspects to understand the uptake of ES in cantonal structural plans (*Plan directeur*). It shows the strong discrepancies in the level of representation of ES across cantons, the little emphasis put on some ES across all plans, notably in binding parts, and the lack of coordination between cantons. The third paper explores the spatial patterns and drivers of temporal variations of ES supply at the municipal level in the canton of Vaud. It demonstrates that ES trade-offs and synergies vary across space and time and respond to different drivers of change. The last article puts emphasis on stakeholder's preferences and perceptions of ES to better consider ES in planning. It demonstrates the importance of considering different viewpoints of key stakeholders to develop integrated planning measures for ES.

Overall, the findings of this thesis highlight empirically clear territorial clustering of ES at the cantonal and municipal scale. It suggests the need for improvement in five areas at the federal level:

1) Coordination between key institutions at the federal level, but also at the cantonal level between different sectors (environment, agriculture and planning);

2) Stricter implementation of the Federal Act on Spatial Planning with a need to move from a multidisciplinary approach to an interdisciplinary approach;
3) Incentives to assist farmers in changing their ways and regulate the sector in addition to current direct payments;
4) Revision of the Sectorial Plan on land crop rotation areas with higher protection of such areas, providing two paradigm changes (from a productive-only approach to multifunctional approach, and from the concept of self-sufficiency to self-production);
5) Strengthening the legal framework around the integration and protection of protected areas and biodiversity in planning.

Finally, we discuss two planning alternatives with the use of land sparing (i.e. concentrating intensive agriculture or urban development in a small area, leaving maximum space for conservation) and land sharing (i.e. conserving and improving the level of multiple ES supply and biodiversity on the same land) strategies in Switzerland. We conclude that such dichotomy is not suitable and that both principles could be used to guide spatial planning in hilly and mountainous regions and in the Plateau area, respectively.

Altogether, this work contributes to closing the gap between research on ES and the integration of this knowledge in spatial planning. It makes use of a spatially and temporally informed methodology to call for a paradigm change in spatial planning based on an in-depth understanding of making human benefits from ecosystems explicit, and dealing with trade-offs.

Résumé

L'aménagement du territoire traite de l'expression spatiale des activités humaines de manière intégrée afin de minimiser leurs impacts négatifs sur les systèmes naturels et terrestres. Des changements accélérés de l'utilisation et de la couverture du sol sont des moteurs importants du changement des systèmes socio-écologiques, ainsi que des bénéfices que la population humaine obtient de la biodiversité et des fonctions des écosystèmes, connus sous le nom de services écosystémiques (SE). Le concept des SE a le potentiel d'encadrer l'intégration systématique d'une compréhension écologique globale dans l'aménagement du territoire. Malgré l'adoption précoce d'une législation en Suisse visant à promouvoir l'utilisation durable des ressources naturelles, l'urbanisation et le développement économique ont entraîné de profonds changements dans le paysage avec une augmentation de la surface des zones urbaines et boisées au détriment, surtout, des terres agricoles. Cependant, l'intensification des cultures et des rotations ont aussi eu des impacts négatifs sur la biodiversité et la multifonctionnalité des sols. Les SE peuvent avoir été affectés à différents degrés par les stratégies passées et actuelles de gestion du sol, entrainant la maximisation de certains SE au détriment d'autres. Une meilleure intégration des SE dans l'aménagement du territoire exige une meilleure compréhension (i) des relations entre les stratégies de gestion du sol et la fourniture de ces services, (ii) du degré d'adoption du concept des SE dans les documents de planification actuels, (iii) des modèles spatio-temporels de fourniture de SE et leurs facteurs de changement, et (iv) des connaissances locales pour élaborer des politiques de planification répondant aux multiples objectifs.

L'objectif principal de cette thèse est de comprendre le rôle des SE dans l'aménagement du territoire en Suisse. Dans le cadre d'une approche holistique, qui tient compte de multiples périodes de temps, échelles, méthodes et parties prenantes, quatre hypothèses sont testées dans des articles individuels, publiés dans des revues internationales à comité de lecture. Le premier article cherche à comprendre la dynamique historique des SE et analyse la diversité régionale des changements des SE dans les cantons suisses. De nature exploratoire, il en ressort un regroupement régional de l'offre des SE. Il montre l'impact limité des politiques actuelles de gestion du sol pour préserver la fourniture des SE. De fait, leur application au niveau cantonal développe des « régionalités » durables dans la fourniture des SE. Le deuxième article se focalise sur des aspects qualitatifs pour comprendre l'intégration des SE dans les plans directeurs cantonaux. Il montre de fortes disparités dans le niveau de représentation des SE d'un canton à l'autre, le peu d'importance accordée à certains SE, notamment dans les parties contraignantes des plans, et le manque de coordination entre les cantons. Le troisième article explore les tendances spatiales et les facteurs des variations temporelles des SE au niveau communal dans le canton de Vaud. Il démontre que les compromis et les synergies entre SE varient dans l'espace et dans le temps, et répondent ainsi à différents facteurs de changement. Le dernier article met l'accent sur les préférences et les perceptions des parties prenantes de l'aménagement à l'égard des SE afin de mieux tenir compte de ces derniers dans la planification. Il démontre l'importance de tenir compte des différents points de vue pour élaborer des mesures de planification intégrée pour les SE.

Dans l'ensemble, les résultats de cette thèse mettent en évidence de manière empirique une concentration territoriale claire des SE à l'échelle cantonale et communale. Cela suggère qu'il y a lieu d'apporter des améliorations dans cinq domaines au niveau fédéral :

1) Coordination entre les institutions clés au niveau fédéral, mais aussi au niveau cantonal entre les différents secteurs (environnement, agriculture et planification);
2) Une mise en œuvre plus stricte de la Loi fédérale sur l'aménagement du territoire avec la nécessité de passer d'une approche multidisciplinaire à une approche interdisciplinaire;
3) Incitations pour aider les agriculteurs à changer leurs habitudes et réglementer le secteur en plus des paiements directs actuels;
4) Révision du plan sectoriel sur les surfaces d'assolement avec une meilleure protection de ces surfaces, en prévoyant deux changements de paradigme (d'une approche exclusivement productive à une approche multifonctionnelle, et du concept d'autosuffisance à celui d'autoproduction);
5) Renforcer le cadre juridique autour de l'intégration et de la protection des aires protégées et de la biodiversité dans la planification.

Pour finir, nous traitons de deux alternatives de planification à travers l'utilisation des concepts d'économie des terres (c'est-à-dire concentrer l'agriculture intensive ou le développement urbain sur une petite zone, en laissant un maximum d'espace pour la conservation) et de partage des terres (c'est-à-dire conserver et améliorer le niveau de fourniture de multiples SE et de la biodiversité sur une même terre) en Suisse. Nous concluons qu'une telle dichotomie n'est pas appropriée et que les deux principes pourraient être utilisés pour guider l'aménagement du territoire dans les régions vallonnées et montagneuses, et dans la région du Plateau, respectivement.

Dans l'ensemble, ce travail contribue à réduire l'écart entre la recherche sur les SE et l'intégration de ces connaissances dans l'aménagement du territoire. Il utilise une méthodologie spatialement et temporellement explicite pour fournir des indications sur un changement de paradigme en matière d'aménagement du territoire fondé sur une compréhension approfondie de l'explicitation des bénéfices qu'offrent les écosystèmes à l'être humain, et des compromis à faire entre ceux-ci.

Mots-clés aménagement du territoire; services écosystémiques; surfaces d'assolement; interdisciplinarité; cantons; communes; Suisse

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List of abbreviations

ANOVA: Analysis of variance

ARE: Federal Office for Spatial Development

BZ: Building zones

CAP: Common Agricultural Policy

CES: Cultural ecosystem services

CICES: Common International Classification of Ecosystem Services

CORAT: Association of Western Planning and Urbanism Offices

DEM: Digital elevation model

ES: Ecosystem services

FA-EP: Federal Act on the Protection of the Environment

FA-SP: Federal Act on Spatial Planning

FDFA: Federal Department of Foreign Affairs

FOA: Federal Office for Agriculture

FOEN: Federal Office for Environment

GIS: Geographic Information System

LAT: Loi fédérale sur l'aménagement du territoire

LCRA: Land crop rotation areas

LULC: Land use land cover

MEA: Millennium Assessment

NCP: Nature's contribution to people

NUTS: Nomenclature of Territorial Units for Statistics

PCA: Principal component analysis

PCNM: Principal coordinates of neighbour matrices

PES: Provisioning ecosystem services

PS SDA: Sectorial Plan of land crop rotation areas

RDA: Redundancy analysis

RES: Regulating ecosystem services

SES: Socio-ecological system

SFSO: Swiss Federal Statistical Office

SFU: Swiss Farmers Union

STI: Space-time interaction

STREAM: Spatial tools for river basins and environment and analysis of management options

TEEB: The Economics of Ecosystem Services and Biodiversity

UAA: Utilized agricultural areas

VIF: Variation inflation factor

Chapter 1

Introduction

1.1 Motivation

1.1.1 Spatial planning and socio-ecological systems

Spatial planning is a key instrument for decision-making to coordinate human activities and minimize their negative impacts on the natural and land systems (Geneletti, 2011; Rozas-Vásquez et al., 2018). In Switzerland, spatial planning is a particularly important subject due to diverse political, geographical, economic and cultural settings. A large share of the economy depends on the services provided by the environment and the landscape, as shown by the importance of tourism or agriculture (Brand et al., 2013). While rural areas and mountainous regions make up 77% of the Swiss territory, and integrate more than two thirds of Swiss municipalities, urbanization is very advanced despite the lack of large metropolises (Conseil fédéral, 2015). Competition between different land uses is reaching its highest level since the start of the 20th century and ecological systems are under pressure. The federal government introduced a variety of counter measures since the middle of the 20th century, starting with the 1969 revision of the Constitution which grants spatial planning with two distinct objectives, still valid today: achieve an appropriate occupation of the territory, and ensure a sound use of the land. However, the reality of spatial planning in Switzerland is more complex. Cantons and municipalities (communes)[1] are jointly responsible for planning. They should harmonize activities with a spatial impact towards achieving integrated management of different land uses in order to reduce conflicts, and achieve ecological, economic and social objectives.

The concept of social-ecological system (SES) has been proposed to represent the intimate connections between humans and ecosystems which appears at various scales (Ostrom, 2009). At the frontier between the social and ecological systems, the concept of ecosystem services (ES) has been proposed to make explicit "the benefits people obtain from ecosystems" (MEA, 2005). It is an elegant and communicative umbrella term that supports making services from nature explicit, and has the potential to redefine perspectives on human-nature relations. Various methods can be used to quantify or value such services to foster discussions about trade-offs in planning decisions. Indeed, the concept of ES can play a key role at the science-policy interface. It has the potential to frame the systematic incorporation of a more comprehensive ecological understanding into spatial planning (Wilkinson et al., 2013).

Both social and ecological systems were long recognized as a priority in Switzerland and attempts to integrate them indirectly into planning were formulated before the creation of the term (Berkes and Folke, 1998; Gallopín, 1991). As the provision of ES depends largely on land

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[1] In this thesis, the term "municipality" is used as a synonym for "communes" in the context of spatial planning in Switzerland

use and management, sustainable use of natural resources has been an element of the legislation in Switzerland before it was integrated into spatial planning per se. Early examples are the Federal Act on Forest coming into force at the end of the 19th century, followed by the Wahlen Plan at the end of the Second World War, which aimed to preserve the best arable land from an agricultural production perspective called land crop rotation areas (LCRA [2] or *surfaces d'assolement*).
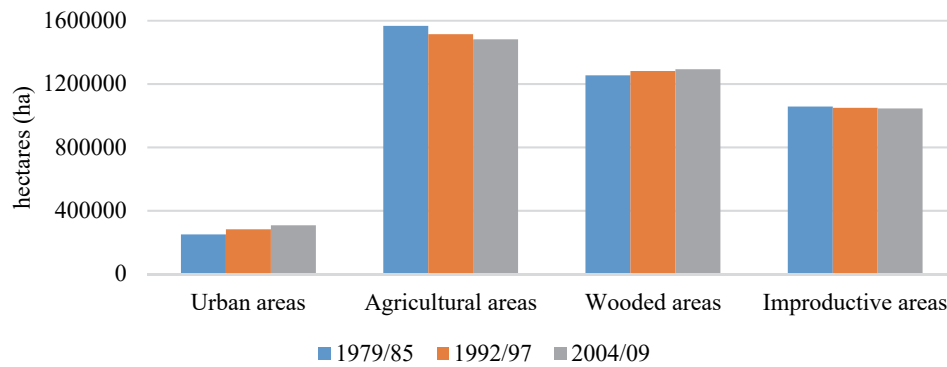
Figure 1.1 Evolution of land use in Switzerland from 1979 to 2009

Despite early legislations to promote sustainable use and management of natural resources and indirectly ensuring the provision of ES, urbanization and economic development led to drastic changes in the landscape. Between 1979/85 and 2004/2009, 85,000 hectares (ha) of agricultural land were lost (Figure 1.1), with an increasing loss rate of arable land from -2.2% over the period 1985/1997 to -4.7% over the period 1997/2009. Today, 1.1 m^2 of agricultural land is still lost every second, much of which to urbanization (FOA, 2016a). Along with this loss, intensification and cropping have decreased biodiversity and soil fertility, resulting in a loss of food production potential but an increase in actual production. A similar loss trend is observed in mountain regions where agricultural land, especially pastures, have decreased due to land abandonment, which led to the expansion of forests, a change in cultural landscapes and related ES including aesthetics and recreation (Loran et al., 2018). Jaeger and Schwick (2014) identified that urban sprawl was much lower in large city centres due to a trend of densification than in suburban regions including inner suburbs of large cities, suburbs of large cities, medium-size towns and suburbs of medium size towns between 1935 and 2002. Overall, the loss of agricultural areas, the increase of forest cover due to land abandonment in alpine areas, higher forest fragmentation in the lowlands, and the loss of traditional landscapes show that spatial development is not as conservative towards SESs and ES as called for by the Federal Constitution.

In Switzerland, most research on the relationship between spatial planning and ES focused either on the assessment of few ES at the local scale and their integration into prospective work; or decision making support tools, which did not necessarily consider spatial relations between ES as well as their spatial patterns (Grêt-Regamey et al., 2017; Schwaab et al., 2018).

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[2] For language consistency, the term *land crop rotation areas (LCRA)* will be used in this document.

Science that supports decision-making and addresses planning issues requires an understanding of the interactions among components of SESs such as associations, drivers of change, and their dynamics over space and time. This suggests a need for an approach that is able to capture the temporal and spatial dynamics of ES, and to inform and support policy making.

1.1.2 Research gaps and needs

Switzerland considers most rural areas as an economic resource, which should be used in a controlled manner. However, rural areas are the dominant pool of ES, where most external flows occur towards urban areas, and they also suffer from a high level of human impact. Spatial planning is a key element to manage territories, particularly in the specific context of federal governance. Despite various land management strategies, there is not a homogenous strategy at the federal level with a global vision to serve as a basis for future development of rural areas and mountainous regions, and to demonstrate their benefits (Conseil fédéral, 2015). In addition, measuring the impact of current land management policies is tedious. It is challenging to determine if the balance between the protection of the environment and development is achieved effectively, or if temporal and institutional complexities create a virtual balance.

As land become more urbanized and fragmented in Switzerland, the concept of ES could be regarded as an increasingly important framework and tool to support spatial planning. Various land management policies had an impact on spatial planning. However, they may have impacted ES to various degrees, as some could have been maximised at the expense of others leading to trade-offs (Lüscher, 2003). The terms synergy and trade-off are often used to refer to ES associations (Mouchet et al., 2014). Following the general rule in the literature, an ES synergy is a positive ES association (i.e. one in which both services increase or decrease), and an ES trade-off is a negative ES association (i.e. one in which on service decreases while another one increases) (Howe et al., 2014; Spake et al., 2017). The federal system creates some regional discrepancies in the implementation of national land use or other policies (e.g. agricultural) that may affect the supply of ES. For example, a strict policy for the preservation of the best arable land (i.e. LCRA or *surfaces d'assolement*) strongly affects the provision of some ES (Guerra et al., 2016). In this context, the problem is typically a trade-off between agriculture and other ES such as water purification or the control of erosion due to agrochemical contamination, sedimentation of waterways, etc. (Power, 2010). Numerous challenges exist to manage landscapes and optimize specific ES simultaneously (Turkelboom et al., 2018). It includes changes in land use in space and time, changes in management objectives, the intensity of use of natural resources or the mix between technical and nature-based solutions (for flood regulation, for example). There is a need to understand when, where and the extent to which such trade-offs may have occurred, as well as the governance context, to formulate planning recommendations.

1.1.2.1 Historical evolution of planning-ES relations

Understanding the historical dynamics of ES and their relationship with land management policies and potential drivers of change is the first step towards the use of ES into spatial planning. The effect of using different spatial scales in the assessment of dynamics and the need

for spatially explicit approaches have been highlighted in various work (Dong et al., 2015; Martín-López et al., 2017; Qiu et al., 2018). In Switzerland, spatial planning decision-making takes place at three levels: federal (i.e. the Confederation), cantonal and municipal. Policies with a spatial incidence are within the jurisdiction of the Confederation, the cantons or the communes. Therefore, it is relevant to conduct ES studies at multiple spatial levels (Roces-Díaz et al., 2018).

While a broad scale is appropriate in descriptive assessments such as identifying regional discrepancies, finer levels are also directly relevant for policy making and should be considered further. To improve our understanding of the relationship between planning and ES, there is a need for research approaches that consider historical dynamics of ES through space and time, at different planning levels. A high spatial level can be used as preliminary assessment to capture the broader challenges related to regional differences in the extent of land management strategies implementation, as it could be the case in Switzerland (Messer et al., 2016). Reproducing a similar, although more detailed work, at a lower planning level could complement the results to strengthen the credibility, legitimacy and salience of the approach to inform spatial planning (van Oudenhoven et al., 2018).

1.1.2.2 Integration in planning documents

A second step towards in the future integration of ES in spatial planning is to understand the uptake of ES in current planning practices. Indeed, the limited understanding of how ES knowledge is used into spatial plans constrains our ability to learn from, replicate, and convey an ES approach (McKenzie et al., 2014). For example, decision support tools were built to integrate ES into planning (Ahern et al., 2017; Grêt-Regamey et al., 2017) but we argue that prior to the development of tools to integrate ES into future development zones, and more generally into spatial planning, it is appropriate to understand how ES are currently embedded into the main planning instruments. Yet, current research is mainly geared towards integrating place-based knowledge on ES into decision-making. Despite their necessity, such work does not offer insights on the current ways ES are managed into current planning instruments which is a fundamental step to identify limits and potential lines of work for integration of ES into planning. To make ES research more meaningful for supporting management and planning decision-making, it is necessary to understand the current uptake of ES in planning (Cortinovis and Geneletti, 2018; Piwowarczyk et al., 2013). Therefore, an approach that assess the integration of ES into planning documents is required (Wilkinson et al., 2013).

1.1.2.3 Place-based knowledge

The interdisciniplary nature of spatial planning requires the use of tools to integrate multiple perspectives and actors in the decision-making process. Although the two previous steps are required in an integrated ES assessment, they have limited value for planning as they are not directly actionable by planners and decision-makers. The operationalization of the ES concept in planning could be partially constrained by the existing legal framework, and the multiplicity of stakeholders. While spatial planning has the potential to mainstream ES across governance levels, the integration of ES into spatial planning is a multi-stakeholder challenge. The planning scale as well as the multiple levels of decision-making may be additional constraints to the

operationalization of the concept. Developing planning policies with multi-objectives, informing decision making to secure the supply of ES and considering demand may be addressed by involving local knowledge (Castro et al., 2013).

1.1.3 Research hypotheses

The ES concept opens a new perspective for spatial planning. We argue that the concept is intrinsically transdisciplinary which helps foster a co-constructed, legitimate understanding of complex issues. We also postulate that building a temporally informed framework is crucial to understand the spatio-temporal dynamics of individual services and their associations. The aim of this research is to **understand the role of ecosystem services for spatial planning in Switzerland**.

The research gaps highlighted in section 1.1.2 are addressed by four research hypotheses and were tested in four corresponding research articles. The issue of scale is critical in ES research and for spatial planning. Therefore, we decide to address the following research hypotheses in an order based on scale. Hypotheses 1 and 2 are tested at a broader, cantonal scale. Hypotheses 3 and 4 are tested are the finer, municipal scale. The first research gap on the historical evolution of planning-ES relations frames hypotheses 1 and 3, while the second gap (integration in planning documents) and third gap (place-based knowledge) frame hypotheses 2 and 4, respectively.

(1) The current enforcement of federal land management strategies had limited influence in the preservation of ecosystem services.

(2) The concept of ecosystem services has been used by cantons and integrated into basic spatial planning documents.

(3) Ecosystem services trade-offs and synergies vary across space and time and respond to different drivers of change.

(4) Ecosystem services could be better considered in the development of planning measures by integrating place-based stakeholder knowledge.

The overarching objective of the first two hypotheses is to provide the reader with an overview of the evolution of ES in Switzerland. It sets the scene for a more detailed assessment at a finer spatial level. The two last hypotheses testing will be conducted at a finer scale, building on the outcome of the first two hypotheses (section 1.1.5).

1.1.4 Structure of the thesis

The remainder of the thesis is organised into three main parts. In the first part, section 1.2 and 1.3 offer a theoretical and contextual background on land management, spatial planning and ecosystem services. Section 1.2 provides an introduction to the decision-making process in Switzerland, the history of spatial planning and the concept of ES. Section 1.3 discusses methodological pluralism and itemizes the methods used in this work.

The second part of the thesis is divided in four chapters (chapters 2 to 5), each consisting of an individual article, which addresses one of the hypotheses formulated in section 1.1.3.

Chapters 2, 3, 4, and 5 address the hypotheses in order. In chapter 2 and 3, the cantonal scale is of interest. Chapter 2 tests the first hypothesis. It presents an approach to understand the historical dynamics of ES and to analyze the regional diversity in ES changes in Switzerland. A spatio-temporal approach was used to examine changes of nine ES and their relationships from 1986 to 2015 across the twenty-six Swiss cantons. "Regionalities" in the supply of ES and the relationship between the federal land management strategies and ES are discussed. In chapter 3, the second hypothesis is tested. The integration of ES into spatial planning at the cantonal scale in Western Switzerland is reviewed. A directed content analysis of seven cantonal structural plans (*Plan directeur cantonal*) was used to assess how ES were covered in various sections of the plans and to explore the differences in the level of ES integration across cantons.

In the two following chapters, the municipal scale is considered. The canton of Vaud is used as study site (section 1.1.5). Chapter 4 tests the third hypothesis. It focuses on understanding the spatial patterns and drivers of temporal variations of ES supply. It assesses associations of ES temporal variations, delineates ES clusters from changes in ES supply between 1979 and 2014, and identifies potential drivers of changes in ES supply. Finally, we discuss the potential implications for spatial planning. Chapter 5 tests the fourth hypothesis. It presents an assessment of stakeholder perspectives on ES to facilitate their integration in spatial planning. It uses an innovative methodology to characterize stakeholders' perceptions of the importance of ES for spatial planning and set priorities.

The last part of the thesis (Chapter 6) provides a general discussion on the key findings of the articles, and concludes by an overarching reflection on the policy implication and the need for future research.

1.1.5 Study area

This research tests the relevance of land management strategies for considering ES, assesses ES supply, and advocates for the inclusion of multiple stakeholders. A national assessment is needed to guide landscape planning and management, as well as to meet the needs of a wide range of users (Bryce et al., 2016). Complex spatial interactions between various ecosystems makes ES assessment difficult at the national scale, and a finer assessment may be needed to analyze the diversity in ES and corresponding changes to inform policy making. It is sensible to approach the hypotheses at different spatial levels as to understand the complexity of these cross-cutting issues.

The researcher should be able to identify real world issues, or case-specific issues, in order to find the suitable unit of analysis. This work is taking place at two distinct spatial planning levels. The overarching objective of the first two hypotheses (chapter 2 and 3) is to provide the reader with an overview of the evolution of ES in Switzerland. For example, we will test whether the enforcement of federal land management strategies had limited influence in the preservation of ES, and that the concept of ES has been used and integrated into planning documents. It focuses on understanding the historical dynamics of ES, analyzing the regional diversity in ES changes, and identifying the current level of integration of the concept in existing planning documents. Therefore, it is necessary to focus on sub-levels of the

Confederation to analyse similarities and differences. To get a better understanding of these issues it is suitable to conduct a cross-regional analysis, especially in countries like Switzerland where regional differences in the extent of policy implementation may be expected (Messer et al., 2016). The two first hypotheses will be tested at the cantonal scale. It will act a "support structure" for the two remaining hypothesis and set the scene for a more detailed assessment at a finer spatial level.

The two last hypotheses testing (chapter 4 and 5) will be conducted at the municipal scale, building on the outcome of the first two hypotheses. The study area is the canton of Vaud (Figure 1.2)
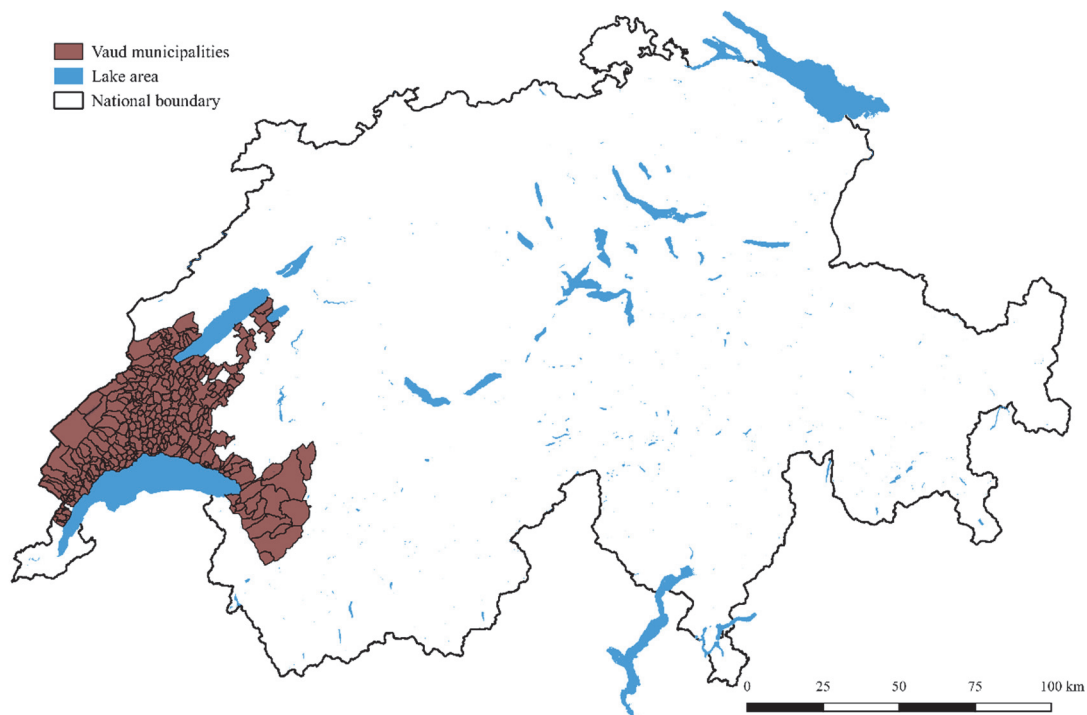
Figure 1.2 Administrative boundaries of municipalities in the canton of Vaud

It is located in the Western, French-speaking part of the country, with a population of 767,497 inhabitants in 2015 (Statistique Vaud, 2017). It has a total surface area of 321,224 ha and a large topo-climatic gradient (altitude: 372 - 3,210 m a.s.l). Due to municipal grouping, the number of municipalities went from 390 in 2003 to 309 in 2017. The area of municipalities ranges from 31 ha to 11,370 ha. The canton of Vaud was selected for geographical and practical reasons. First, it has a large variety of landscapes from lowlands to two principal mountain regions being the pre-Alps in the south-east and the Jura in the north-west. Both regions are linked by a plateau. The climate is considered temperate, largely influenced by the Léman lake at the southern border and the Neuchâtel lake at the northern border. It has the second largest quota of arable land in Switzerland. Second, the canton is undergoing a large urbanization trend. Between 1979 and 2014, the extent of urban areas went from 24,000 ha to 32,143 ha, while the

extent of agricultural areas decreased by 9,858 ha (Figure 1.3). The extent of wooded areas increased by 2,656 ha mainly in mountainous regions (SFSO, 2015). With the protection of forests, agricultural areas are dominated by cropping, and account for 40% of the area, while urban land accounts for about 10% of it. Therefore, land use conflicts between agricultural and urban areas are frequent. If observed land use change continue, they will significantly affect the long-term provision of ES in the canton.
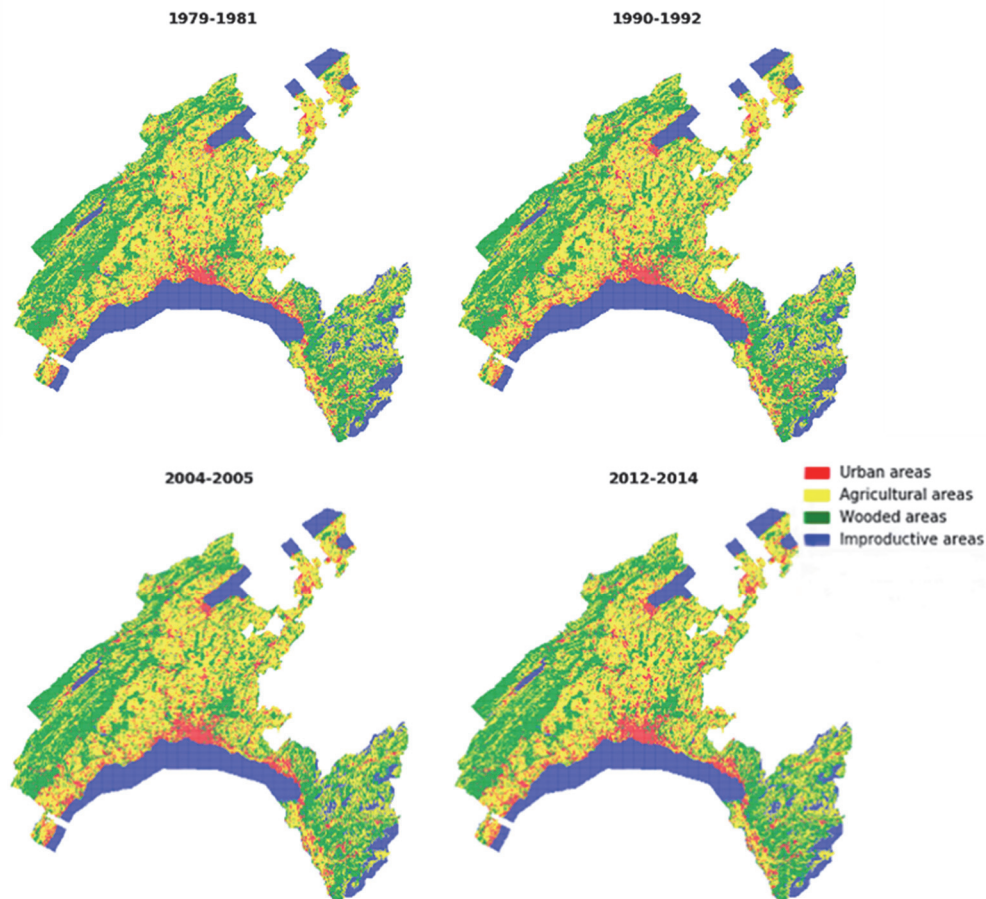
Figure 1.3 Land use / land cover in the canton of Vaud from 1979 to 2014

1.2 Theoretical background

1.2.1 Context: Swiss governance, policy framework and spatial planning

1.2.1.1 Decision making structure

In Switzerland, spatial planning decision-making takes place at three levels: federal, cantonal and municipal. Public policies with a spatial incidence are within the jurisdiction of the Confederation, the cantons or the municipalities. The federal government enforces Federal Acts and coordinates cantonal planning activities. Sectorial plans are the main instruments for planning at the federal level to coordinate national activities with a spatial incidence and those of the cantons and the municipalities. The cantons implement Federal Acts and enforce related cantonal laws, as well as regulations on buildings and roads. In spatial planning, they are responsible to draft a structural plan (*Plan directeur cantonal*) that addresses the configuration of land use in the canton, and the perspectives of spatial development. All cantons, except

Geneva, delegate the responsibility of specifying how the land should be used to municipalities, which develop land use plans (*Plans d'affectation*) and specify for landowners how land should be used and built on at the plot level. The vertical division of competences depends on the policy and on the cantons. Public policies affect the location of buildings and private activities, and constrain the implementation of private projects. Therefore, the spatial incidence of public policies directly affect land use (Matthey and Schuler, 2017).

Adequate control of territorial development creates and maintains favourable spatial settings for economic and social prosperity at all decision-making levels, and preserves natural resources. It implies suitable, coherent solutions to land use challenges such as land scarcity. It includes suitable location of housing, economic activities and services at the regional scale, valorisation and densification of the built environment, preservation of arable land, and preservation of rural landscapes (Matthey and Schuler, 2017).

However, adequate control of territorial development is problematic in the current governance framework. The main political challenge is to establish common objectives between the three levels of decision-making. Institutional challenges refer to the independence of each authority at a particular level of decision-making, and to the guarantee of land ownership. Furthermore, territorial challenges refer to the interdependence of public policies yielding potential indirect, long-term effects on the environment for instance.

Federal principles seek to address these challenges and provide some consistency at the federal level for policies and activities with a spatial incidence. However, these did not exist before the 1970s. Only specific agreements between authorities at different levels promoted the coordination of projects with a large spatial incidence. Such responses were crucial and played a major role in territorial development. An example is the capacity development of urban centers associated with the improvement of public transport facilities to connect urban areas during the phase of peri-urbanization between 1975 and 1995 (Matthey and Schuler, 2017).

1.2.1.2 Land management policies

- Spatial planning policy

In the past, spatial planning was neither the responsibility of the Confederation or the cantons, but the result of endeavours to control urban development at the municipal level starting from the second half of the 19th century (Matthey and Schuler, 2017). The Constitutional Article 22[quater] Cst of 1969 (now art. 75) grants spatial planning with two distinct objectives, still valid today:

- Achieve an appropriate occupation of the territory
- Ensure a sound and moderate use of the land

In 1971, the Federal Act on Water Protection against Pollution came into force. It was the first official document to make a clear distinction between building zones and non-building zones. A construction permit could only be granted when the zone could be linked to the water sewage system. A permit could be granted to construct outside building zones, or outside the water and sewer system, only for farm facilities or related constructions. The Federal Council noted that the Act did not mention explicitly the link between water networks, and spatial

planning (Mahaim, 2014). This led to insufficient legal protection against undesirable constructions. It is interesting to note that the management of natural resources (i.e. water) was the former argument to legislate on spatial planning.

Federal authorities took provisional measures on spatial planning. A Federal decree, detailing urgent measures for spatial planning was adopted in 1972 (Matthey and Schuler, 2017). It compelled the cantons to define provisional building zones and non-building zones. Building would only be possible if deemed compatible with the objectives set by the decree. Exemptions were granted on rare occasions. The first draft of the *Loi fédérale sur l'aménagement du territoire* (LAT) or *Federal Act on Spatial planning* (FA-SP)[3] of 1974 was rejected because it strongly codified the two distinct objectives of spatial planning. The FA-SP of 1979 defined the principles for spatial planning in the country. It addressed both objectives, with a stronger emphasis on land use (Mahaim, 2014). Subsequently, the cantons were required to provide a *Plan directeur cantonal* or cantonal structural plan within five years of the entry into force of the FA-SP. Municipalities shall execute it through a municipal structural plan and land use plans. In 1984, only three cantonal structural plans were submitted, and in 1989, ten were still missing (Mahaim, 2014). One of the main article in the FA-SP encourages the cantons to diffentiate the areas allocated to building zones and non-building zones, as the former were often too large. One objective was to limit the trend of urban sprawl observed in the 1950s and the 1960s (Hänni et al., 2008).

The partial revision of the FA-SP of 1995 came into force in 1997. An important amendment targeted the right of landowners to build on their land, if the local authorities did not yet do so on the corresponding building zones. A flexible measure for the construction of farms and facilities was also adopted. A federal ordonnance revising the FA-SP was adopted in 1998 and came into force in 2000. Two main amendments were included. The first amendment waived the distinction between agricultural processes dependent or independent on soil processes to create a single category of agricultural area. The second amendment included additional potential exemptions for building outside existing building-zones. In 2005, the Federal Council established a new series of amendments regarding admissible activities, involving construction in agricultural areas. It included tourism, biomass energy production or animal keeping. The amendments were adopted in 2007.

The first stage of the major revision of the FA-SP was voted in 2013 and came into force in 2014. The FA-SP revision 1, or FA-SP 1, created the legal basis for the development of denser urban areas. The revision includes measures to promote compact urban development through infill (re)development and densification, a nationwide taxes scheme on property value gains from planning measures, and the reduction in size of undeveloped building zones based on future demand in the next 15 years. The objectives were two folds. The first objective was to preserve LCRA specifically by strengthening the requirements to use LCRA as building-zones (Messer et al., 2016). The second objective was to improve the attractiveness of Switzerland as a living and working environment, and to preserve the landscape. The current article 24c allows the reconversion of farming facilities constructed before their inclusion into non-building

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[3] For language consistency, the term *Federal Act on Spatial planning* (FA-SP) will be used.

zones. The second stage of the revision currently undergoes a public consultation process. The objective is to adapt all measures related to building outside building zones by integrated all important factors and adhering to the two main objectives of spatial planning.

The success of spatial planning policies is hardly measurable. According to McConnell (2010), a policy is successful when 'it achieves the goals that proponents set out to achieve and attracts no criticism of any significance and/or support is virtually universal'. In Switzerland, three elements are essential to the success of land use policies: (i) the cooperation between sectorial policies, (ii) the vertical coordination (Confederation, cantons and municipalities), (iii) the horizontal coordination (cantons and municipalities inside a functional territory). Messer (2017) argues that the distribution of competencies between the three institutional levels was not revised directly by structural reforms. The power of cantons and municipalities at the institutional level creates a gap between institutional territories and functional territories such as ecosystems, which may impede the success of land use policies.

- Agricultural policy

Between 1870 and 1970, the development of rural areas was based on economic policies. Nowadays, the Federal Office for Spatial Development (ARE) wants to limit urban sprawl and territorial fragmentation. 64% of Swiss citizens voted for the revision of the FA-SP in 2013. However, the FA-SP is not the only policy with an impact on territorial development. Indeed, agriculture and the concept of LCRA are arguably having a strong influence as well (Matthey and Merle, 2016). It originates from the Wahlen Plan, established in 1940, that tried to double the surface of cultivated land to ensure food self-sufficiency, should imports stop (Matthey and Schuler, 2017).

To ensure food self-sufficiency and profitable agriculture, the Federal Act on Agriculture of 1951 aimed to increase the revenues of farmers and maintain agricultural activities on the territory. The objectives were to ensure food self-sufficiency and financial support to rural areas. The tools were border protection and guaranteed prices for farmers. It was the starting point of intensive agriculture (Mahaim, 2014). In the late 1960s, some measures aimed to improve economic mobility in rural areas through the construction and upgrade of the road network.

The Federal Act on Investment Aid in Mountainous Regions of 1974 aimed to develop the local economy and limit rural exodus, using subsidies and incentives for private and public stakeholders to create development centres. In general, there has not been a specific rural development policy but various sectorial policies to incentivise the development of a particular industry. The Bonny Decree of 1978 targeted regions with a poor economic performance. It was mainly a fiscal policy set to attract businesses by providing direct fiscal abatements. In 2008, a new ordinance came into force in continuity of the Bonny Decree, but limiting the number of areas benefiting from fiscal abatements from 28% of the population to 10.1%. The Confederation defined thirty zones benefiting from fiscal abatements for job-creating, innovating businesses. A transitory regime was set for isolated areas, which also benefited from 50% of fiscal abatements, affecting 20% of the population in total. Finally, rural-specific policies successfully achieved to hinder the economic downturn of rural areas (Serrano, 2014).

Two main reforms of the Swiss agricultural policy framework were conducted in 1992 and 1999 (El Benni and Finger, 2013). The "pre-revision" political framework included public market support, maintaining high output production prices. In addition, the farms operating in adverse conditions in hilly and mountainous regions received farm-level support. Household payments were part of those measures. With the first reform of 1992 coming into force in 1993, market price support was reduced and direct payments were introduced (Lehmann and Stucki, 1997). General direct payments (complementary payments, integrated production payments, and adverse geographical conditions payments) and voluntary "ecological" direct payments (sustainable production in the use of natural resources, pollution reduction, and favour non-market benefits such as biodiversity, landscape protection or animal welfare) formed the basis of the reform. The second reform came with the revision of the Federal act on Agriculture in 1999 abolishing market support and linking the direct payments system to a cross-compliance approach including compulsory integrated (ecological) production requirements. For example, farmers have to set aside 7% of their land as ecological compensatory area to receive financial support from the government (Mann, 2003). Farmers can also have a more environmentally friendly production and apply for an additional payment. A vineyard hillside payment and animal unit-based payment were also introduced in 1999. It was added to the direct payments in adverse conditions. We note that the concepts of supply security, resource preservation and decentralised land use were introduced in the Constitution Art. 104 in 1999. In September 2017, the people voted to include the concept of food security in the Constitution, within Art. 104*a*. Following, the intention to "green" agricultural practices, the Federal Office for Environment (FOEN) and the Federal Office for Agriculture (FOA) published a state report 2016, following a first report setting 13 environmental objectives for agriculture in 2008. The report concluded that some progress were made for the preservation of plant variety, ecological compensatory areas for biodiversity or water course renaturation, but none of the 13 objectives were met. It stated the urgency to take measures for biodiversity, greenhouse gas emissions, nitrogen and soil fertility (FOEN/FOA, 2016).

In comparison, the Common Agricultural Policy (CAP) of the European Union follows similar historic trends. However, the objectives and the implementation of policy instruments diverge in time. Switzerland promoted a multifunctional agriculture from the 1980s, displacing food security goals to the environment, ecology and welfare of the rural community. The principle of multi-functionality was introduced in the Federal Constitution in 1999 (Article 104). Switzerland effectively introduced direct payments for income support and environmental objectives before the European Union, through reforms in 1992 and 1999 (Curry and Stucki, 1997; El Benni and Finger, 2013). Today, the CAP is framed around two "pillars". The first pillar relates to market support and agricultural revenues. Direct payments to farmers are the main instrument of the CAP (70% of the total budget). It was introduced in 1992 as a guaranteed income stream for farmers. The beneficiaries have to adhere to a number of environmental and animal welfare criteria. The second pillar relates to the development of rural areas, set in 2003. The objective is to promote the socio-economic dynamism of rural areas, through retrofitting old exploitations, promoting tourism or training for farmers. It makes up 25% of the budget with a large set of measures co-financed by member states. The European Commission advances similar objectives as Switzerland, such as food security, environment and territorial

balance, but the PAC remains less focused on the second pillar promoting multifunctionality (Kroll and Barjolle, 2010).

Despite the reforms and amendments of policies targeting agriculture, the initial objective of self-sufficiency set by LCRA remained. However, the legislation did not prevent the continuous loss of arable land, so the Confederation acted by amending the FA-SP in 1989 and by drafting the Sectorial Plan on LCRA in 1992.

Utilized agricultural areas (UAA) or *surfaces agricoles utiles (SAU)* [4] is a statistical concept to evaluate the areas used for agricultural production. There are 1.05 million ha of UAA in Switzerland (FOA, 2016a). About 40% of UAA are land crop rotation areas. The Sectorial Plan on LCRA ensures that each resident would have a daily intake of 2,300 calories in the event of border closure. 355,000 ha of open arable land were selected based on this condition. The quantity was taken up to 438,460 ha to allow for sufficient crop rotation (ARE, 1992). It is important to note that this is only valid if the best arable land are preserved. Therefore, the Sectorial Plan is based only on the quality of arable land and does not consider other indicators such as population, or ecosystems. Each canton has a quota of LCRA. For example, LCRA account for 1.4% of the total area of the canton of Valais and 19.5% of UAA respectively. This is 24.3% and 69.7% respectively in the canton of Vaud (Ruegg, 2016).

Claude Lüscher published a report in 2003 evaluating the basis, the evolution and the relevance of LCRA. He concluded that 'all interviews and position statement underpin that it is crucial to maintain the sectorial plan on LCRA but that it is necessary to expand and update the rationale. Self-sufficiency in case food shortage belongs to the past'. A revision of the Sectorial Plan is under consultation since the beginning of 2019 (ARE, 2018). The rationale remains food self-sufficiency in case on shortages. It primarily calls for the need for accurate soil data before any measures are taken to review the inventories.

Although it is not its former objective, the concept of LCRA, after the need to respect the quotas set by the Sectorial Plan was included in the FA-SP, now belongs to a set of tools to limit urban expansion and prevent territorial fragmentation along with the Federal Act on Forest, the Federal Act on the Protection of Nature and Cultural Heritage, the Federal Act on the Protection of Waters against Pollution and the ordonnances on natural hazards.

- Forest policy

The enactment of the Federal Act on Forest in 1876 was one of the earliest environmental policy law in Switzerland and a major step forward for the sustainable use of natural resources. The law holds a similar position as the Sectorial Plan on LCRA as it seeks to protect a type of land use both in terms of spread and spatial distribution. Forests may only be cleared in the State's public interests for projects that contribute to the wide public and that are not motivated by financial interests. If a permit is issued for such project, trees must be replanted in the same region covering the same extent. Cantonal planning regulates forest management and should account for their multifunctionality. In the Plateau region, infrastructure caused a decrease in the total core area and an increase in the number of patches, but the strong persistence of net

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[4] For language consistency, the term *Utilized agricultural areas* (UAA) will be used.

forest cover was mainly a consequence of the Forest Act. Mountainous areas have experienced a strong expansion in forest cover between 1850 and 2000, and the imperative of forest conservation substantially constrains land use in mountain regions (Loran et al., 2016; Loran et al., 2018).

In 2011, the Federal Council adopted the Forest Policy 2020. It aimed to harmonize forest policies at the cantonal level, optimize timber exploitation, ensure forest multifunctionality and protect them against climate change. While the wooded areas increase and cover 32% of the total surface area, biodiversity and the global forest health are threatened by urbanization, and climate change, especially in the Alps (Fisher et al., 2015). One of the measures was to increase the surface area of forest reserves to 10% of the forest cover in 2030 (Borzykowski et al., 2017).

1.2.1.3 Spatial planning challenges and prospects

Dessemontet (2011) argued that urban sprawl is linked to a spatial shift related to job creation, outside city centres. New urban centralities emerge in peripheral areas and rural areas. This reflects major changes in the scale of production of cities. Residential areas spread in a more diffuse way, further away from city centres due to the combined effect of greater road networks and the spatial shift of employment opportunities (Chenal and Kaufmann, 2007). Building on agricultural areas and urban sprawl, notably in the 1990s led to the revision of the FA-SP (Fahrländer Partner, 2008; Jaeger et al., 2008). The discussions initially included amendments such as the freezing of building zones at the national scale for twenty years, denser urbanization or taxes for properties in rural areas. The project was rejected in 2009, and a lighter version was accepted in 2012. The principle of distinction between building and non-building zones also has a limited impact on preserving agricultural areas (Dessemontet, 2011). Various mechanisms already exist to favour the coordination and weighing of different interests, but it does not have the power to solve conflicts of objectives. The deficiency of horizontal and vertical coordination mechanisms as well as the inadequate inclusion of the territorial dimension within sectorial policies are the main causes. Other plausible causes are the divergence within sectorial policies in the characterisation of rural areas, for example in the definition of decentralised occupancy and subsidiarity. We detail below these issues by focusing on the example of LCRA.

The inflexibility of the FA-SP reveals that the Confederation sets strict criteria for LCRA such as prohibiting their use for another purpose than food production and the need to compensate for their loss if the quotas are not met (Messer et al., 2016). According to Beat Röösli (in Messer et al., 2016), the best arable land are located next to urban areas and suitable for building with low slope conditions and good sun exposure. In contrast, there are less productive land, also adapted for construction, which may be used either as building zones or as LCRA if their criteria are relaxed. However, such prospects yield severe potential consequences including greater territorial fragmentation. This strongly suggests that the concept of LCRA is not only a tool to manage agricultural production, but also spatial planning and building zones. Food production, and agriculture in the broader sense, now come second with respect to spatial planning (Ruegg, 2015). Despite, the increasing use of LCRA as a spatial planning tool and the various revisions of the FA-SP, urban sprawl was not prevented.

The conflict of objectives arise from divergent interests such as the protection and exploitation of resources, and the different forms of exploitation. ARE showed that the implementation of projects of cantonal or national interest usually have a negative impact on LCRA (ARE, 2006). In other words, it is acceptable to lose some LCRA to build an infrastructure of national importance. At the same time, Lüscher (2003) also argued that LCRA do not protect the most valuable land from an environmental and biodiversity perspective. On the contrary, they are exploited intensively and contain high pollutant loads, yielding potential irreversible consequences for ecosystems (Turner et al., 2016). Conflicts between LCRA and environmental interests such as ecological compensation, water course restoration or flood protection may also affect the benefits humans gain from ecosystems. The priority given to LCRA over other ecosystems is questioned considering the existing demographic pressure and increasing environmental strain caused by climate change. In their report, Messer et al. (2016) identified theoretical, political and institutional gaps related to LCRA, three of which are most relevant to this research to question the use of this concept as a spatial planning tool.

(i)   The criteria applied to define LCRA are heterogeneous between the cantons and remain unchecked. Slope, altitude, land quality, pollution are diverse criteria used by the cantons to build their inventory of LCRA. However, the absence of clear values for each of them allowed cantonal authorities to use different sets of criteria. For example, flood risk areas can still be included in the inventory of LCRA. The Rhone Area in the canton of Valais contained 570 ha of LCRA. The cantonal authorities requested an adjustment of LCRA quotas. A similar case took place in the canton of Geneva (Thomi et al., 2008). The cantonal authorities had to purchase private land, and controversially used public money. The allocation of LCRA may not have considered other benefits and features from ecosystems such as the protection against floods.

(ii)   Inter-cantonal diversity in the inclusion of special cases (e.g. intensive orchards, golf courses, etc…) reflects the decoupling between the inventories of LCRA and their initial objective. Unclear guidelines give a greater leeway to deal with special cases, potentially leading to an over-estimation of available land to meet the objective of self-sufficiency. It remains impossible to compare LCRA between cantons. It may also lead to the selection of poor quality land.

(iii) LCRA are considered on a sectorial basis by cantonal authorities. The main risk is that a revised inventory of LCRA is not included in the planning process, which may jeopardize their protection.

The 2019 revision of the Sectorial Plan under consultation maintains the same quotas for each canton and the possibility to request some LCRA for construction projects if compensated in land or money. It could be a powerful tool for the densification of centers but one should remain cautious as it does not plan to include other criteria such as environmental indicators.

Through the lens of LCRA, we therefore question that the current land management strategies determined at the cantonal level are appropriate to consider the sustainable use of

environmental benefits. We argue that other tools may be more appropriate to consider the interaction between the benefits from ecosystems, other than food production.

1.2.2 Conceptual background: needs and methods for ecosystem services in spatial planning

1.2.2.1 Social-ecological systems through ecosystem services

Arthur Tansley introduced the concept of "ecosystem" in 1935 (Tansley, 1935), to define nature as ecosystem functions, and classify ecological processes such as water infiltration, seed dispersal or nutrient cycling, etc. within an ecosystem. This progessively led to the commodification, valuation and monetization of ecosystems. The term ecosystem services (ES) emerged in the literature in the 1980s to relate ecosystems and their benefits to humans, as well as to facilitate collaborative approaches to address potential issues related to the preservation of nature. Costanza et al. (1997) defined an ecosystem service as the 'flow of materials, energy, and information from natural capital stocks with manufactured and human capital services to produce human welfare'. Another, more simple, definition from Wu (2014) stated that ES are "the benefits that people derive from biodiversity and ecosystem functions". Direct benefits include water filtration, pollination, soil formation, etc. The global ES have been valued at 125 trillion dollars per year, with an annual rate loss of 4 to 20 trillion per year due to land use changes (Costanza et al., 2014). However, this is difficult to assess due to the scale and complexity of ecosystems, and SESs.

A system, such as a SES, evolving in a stable manner, may still progressively loose resilience. Motesharrei et al. (2014) suggested that the world is living at or just above subsidence level. The resilience of a system is its ability to maintain ES and maintain the option for future users to absorb shocks. Promoting resilience requires flexibility and adaptability in decision-making on the use of resources. A system should be designed to decrease failure rates and handle arriving cascade of failures from elsewhere in the system (Fisk and Kerhervé, 2006). Short-term measures implemented without considering long-term impact leads to a loss of redundancy in the system and reduces the resistance to shocks. Optimizing the system by relying heavily on fertilizers or satisfying short-term energy demand are examples of such reduction. Here, technology is relied upon to optimize the system. In addition, the variability and frequency of poor performance will increase if the actual (expanded) system boundaries are not considered, resulting in unpredictable systems dynamics and feedbacks. A conflict arises between the optimization to satisfy short-term efficiency and political interests, and long-term resilience, creating a fragile system.

The management of SESs through the ES lens integrates an anthropocentric metaphor (Crouzat et al., 2018). While decision making at local level is often preferred for spatial planning, it may lack information on the social-ecological linkages that sustain flows of ES (Langemeyer et al., 2016). For example, the concept of self-sufficiency at the backbone of LCRA preservation becomes relative when the broader aspects of food production are considered. According to ARE (2006), the risk of a crisis occurring changed but did not drop. Major risks are demographic and ecological. The population grew by almost 22% between 1992 and 2016 but LCRA quotas have not increased accordingly. Switzerland relies entirely on imports for fertilizers and fossil fuels, and more than 40% for food (FOA, 2016b). Interestingly,

almost 80% of imports came from the European market in 2016 (FDFA, 2017). Therefore, the concept of self-sufficiency and the arbitrage to protect land based on their productivity is called into question. There is a clear need to review the allocation of productive land based on other principles to have a more integrated management of ES. The use of ES into spatial planning is an opportunity to make land management choices that increase the delivery of one or more ES at the expense of the delivery of others (Turkelboom et al., 2018).

1.2.2.2 Ecosystem services conceptual framework

A clear distinction between ecosystem processes and the results of these processes is necessary to classify ES and to avoid redundancy. The widely-used classification provided by the Millennium Ecosystem Assessment (MEA, 2005), which classifies ES in four categories: provisioning, regulation, cultural and supporting, has been criticized for the risk of double counting between supporting services and others (Grunewald and Bastian, 2014: 46; Haines-Young and Potschin, 2010). A breakdown into productive (economic), regulating (ecological) and societal services (cultural) allows relating to the three pillars of sustainability (Bastian et al., 2012; Haines-young and Potschin, 2011). Hermann et al. (2011) presented a dual classification, namely passive services divided into "regulating and life sustaining" functions and "potential" functions, and active services including services provided by anthropogenic activities. The general lack of consensus on the classification of ES shows that the researcher would be able to adapt it to meet specific needs. The Common International Classification of Ecosystem services (CICES) attempted to overcome this by classifying ES into three main categories: provisioning (e.g. food and timber production), regulation and maintenance services, (e.g. protection from natural hazards or biodiversity), and cultural services (e.g. cultural heritage and landscape beauty) (Haines-Young and Potschin, 2011). This research fits into the CICES version v4.3 that uses these categories: regulating, provisioning and cultural (Haines-Young and Potschin, 2013).

Recently, Diaz et al. (2018) argued for a paradigm shift from the concept of ES to the notion of nature's contribution to people (NCP) to 'recognize the central and pervasive role that culture plays in defining all links between people and nature'. However, some authors argued that the ES approach was not failing to engage perspectives from social sciences, and that recent work on cultural ES attempted to address the complexity of SES (Braat, 2018; Maes et al., 2018a).
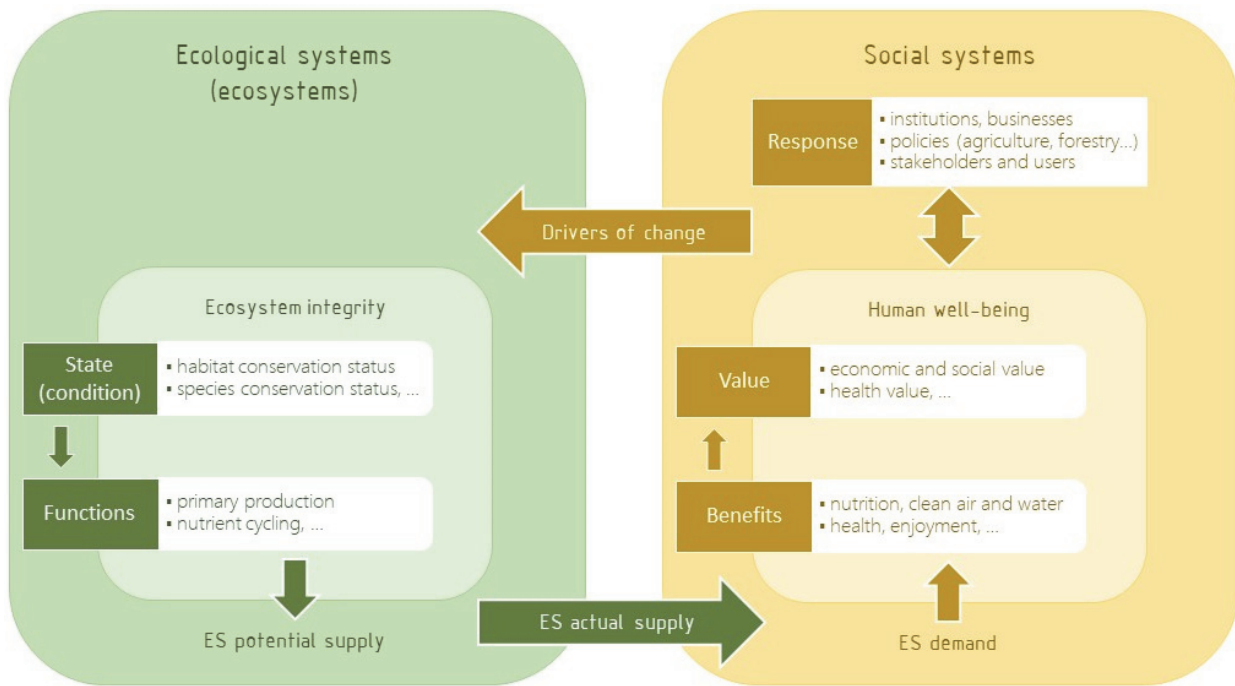
Figure 1.4 Conceptual framework used for testing the hypotheses in this thesis. A simple conceptual framework linking the social systems with the ecological systems (or ecosystems) via the actual supply of ES, and through the drivers of change that affect ecosystems either as a consequence of using the services or as indirect impacts due to human activities. The governance of the coupled socio-ecological system is an integral part of the framework. It includes institutions, stakeholders and users of ES who affect ecosystems through direct or indirect drivers of change (modified from Maes et al., 2013)

Studies on ES should clearly distinguish between ecosystem functions and ecosystem services but ambiguity resides in the definition of ecosystem functions. Two meanings stand out in the literature. Jax (2016) reviewed that it can either be denoted as an ecosystem process giving rise to a specific service, or to the 'potential' that an ecosystem has to deliver a service to humans. Here, the term 'function' is avoided and only ecosystem 'potential' is used. LCRA, and UAA in general, are already used for food production, resulting in different requirements for the selection of indicators to assess ecosystem potential (Heink et al., 2016). ES potential supply differs from ES actual supply as the amount of services provided or used in natural conditions given the current land use. It excludes human input. For example, the provision of ES such as food production relies partly on manufactured and human capital. In their report, Maes et al. (2013) argued that it is challenging to discount human input, explaining why agricultural production is still used as an indicator for the provisioning service of agroecosystems, despite the inclusion of human input. On the demand side, Villamagna et al. (2013) argued that ES demand is desired/required level of the ES by the society. Bearing in mind the different ES classifications and terms, figure 1.4 shows the conceptual framework adopted in this work.

1.2.2.3 From assessment to spatial planning

- Ecosystem services value

The anthropocentric nature of ES led the concept to be used as an argument for valuing nature, and such valuation was often translated as the monetization of nature. It is motivated by the idea that ecosystems will benefit if the advantages arising from them, and the external costs of damaging them, are made explicit in a single measure (Silvertown, 2015). In other words, monetization is presented as a mean to reach decision-makers and get conservation ideas across. A fundamental problem is that there is no market for many ES. Three main solutions exist to fill this gap: (i) create a market such as carbon trading, (ii) stated preference methods which imply conducting surveys of how people would value a service in a hypothetical market (i.e. contingent valuation), and (iii) revealed preferred method which imply using surrogate values such as the travel cost to a protected area (Silvertown, 2015). Trading is at the centre of this approach to ES, which lays great stress on commensurability. However, we postulate that this conceptual approach displaces and devalues ecosystem preservation. Economies exist inside ecosystems. Some ecosystems cannot be valued and sometimes can be endangered by monetization, for example with the collapsing price of carbon in the EU trading system or the increased price on the market of valuable species (Burgess et al., 2014). The contingent valuation method depends on environmental awareness, and disposable income. It does not consider the moral feeling of people towards biodiversity conservation and provides a biased estimate of the value of an ecosystem. Zander et al. (2014) showed that 80% of surveyed people did not want endangered birds to go extinct in Australia, but none was willing to pay for their conservation. The main argument for monetizing ES is that it allows connecting with policy-making, but the evidence that it results in benefits that would not otherwise occur are rarely observed. Many case studies compiled between 2010 and 2014 by The Economics of Ecosystems and Biodiversity (TEEB) lack evidence that monetization improved biodiversity or ES (Sukhdev et al., 2010; Sukhdev et al., 2014). Alternatives to monetization to value ES exist (Bagstad et al., 2013; Duarte et al., 2016; Rossi et al., 2008; Schröter et al., 2014). In ES research, the term "value" is broader than simple monetary value; it endorses a definition of importance and usefulness that are translated through ecological or sociocultural values. We advance that using biophysical and social values for all ES can help to support decoupling of spatial planning from economic development and refocus the debate on the preservation of fundamental environmental features to human well-being. This should be made more explicit when the temporal dimension is considered (Kain et al., 2016; Rodriguez et al., 2006).

- Ecosystem services assessment

The study of land use and land cover is the primary tool to describe ES supply and the imbalance of a territory at a certain time. Maps can present successive states of land use and land management, giving a clear insight of changes over a defined period. It can illustrate the results of a hypothesis to inform decision-makers. ES mapping at different spatial scales is increasingly used for ES assessment (Burkhard et al., 2012; Gos, 2013; Maes et al., 2013), despite the complexity to represent the location of ES supply. However, studies at different time steps remain scarce (Tomscha and Gerbel, 2016).

Andrew et al. (2015) identified five categories of ES mapping:

- Direct mapping with surveys and census approach. A complete spatial distribution of ES is possible.
- Points based measurements of ES to develop empirical models.
- Rule-based models when no data about ES exists.
- Extrapolation, where a set of land cover is assigned to a level of ES supplies based on their values.
- Data integration, where a synthesis of existing spatial products are used to map ES based on rule-based models.

These methods are valid to map two broad conceptual approaches: benefit transfer of aspatial estimates of ES supply, and models to quantify the mechanisms of ES supply and use (Andrew et al., 2015).

Mapping of benefit transfer focuses on ES supply using aspatial estimates of ES value, which are not always generated within the area of interest. It uses two mapping methods previously described. Extrapolation is preferred when ES values are continuous. A rule-based method is preferred when the data is categorical. Benefit transfer is a suitable method as a primary approach to ES mapping to deal with poor data availability (Burkhard et al., 2012). However, one limitation is that the value of an ES is assumed constant and is often assigned to a land cover class. The non-linearity between land cover and ES value, as well as the context-dependence are not considered.

Models integrate ecological production functions and provide a more complete picture than benefit transfer. It considers the structure and functioning of ecosystems to express the provision of ES and has been used to value non-market ES (Lester et al., 2013). Ecological production functions are effective in assessing multifunctionality and interactions between services (synergies, tradeoffs or neutralism). However, the model selection depends primarily on the scale of output. Pandeya et al. (2016) suggested that an integrated approach is needed to capture all linkages and trade-offs, as well as ES values. Potschin and Haines-Young (2016) defined three broad operational approaches to ecosystem assessment: habitat or land cover approach, which is equivalent to benefit transfer, a systems approach, which is equivalent to modelling, and a place-based approach. The habitat approach is widely used because it presents the status and trends of services in specific habitats or land use practices. The systems approach is more complex and generally provides a more complete picture as it involves modelling of a service through production functions. Three spatially explicit models are gaining attraction in the field of ES assessment: InVEST, ARIES and LUCI (Bagstad et al., 2013; Duarte et al., 2016, Pandeya et al., 2016). Table 1.1 provides a review of the three modelling tools, among several others reviewed. Finally, place-based approaches tend to consider the social context in greater extent and focus on interdisciplinary work. Typical place-based approaches are participatory in nature, including participatory mapping.

Table 1.1 Comparative analysis of three spatially explicit ES modelling tools for regional scale (adapted from Sharps et al., 2017; Vigerstol and Aukema, 2011).

Model Description	Strengths	Weaknesses
InVEST		
Land use and land cover are combined with data on ES supply and demand.	Large library of manuals and examples of input data per model	Results provided by sub-watershed scale which may be insufficient
Output in biophysical and economic terms	Estimates of valuation	Limited capacity to incorporate variation in demand within land classes
Written in Python	Requires intermediate GIS skills	Strong ES expertise required
	Models are run independently	
	Combination of various input scale possible	
LUCI		
Models ES condition and identifies locations where interventions can improve ES with built-in user defined trade off tool	Easy interpretation of color-coded maps	Requires higher spatial data
Input as biophysical processes, topography and lookup tables	Inclusion of trade-off module so can provide different outputs for impact of land use change on several ES	Unable to consider demand
Output in the form of color-coded maps	Uses fine scale element that reflect landscape elements	
Written in Python	Requires basic GIS skills	
	Results at every point in the landscape	
ARIES		
Context-driven association of modular components.	Less data and expertise required than InVEST for using basic models	Strong technical skills required for customized models
Inputs are beneficiaries, probabilistic estimation based on Bayesian Networks when equation of biophysical processes are lacking, and dynamic flow	Implementable in data scarce areas due to probabilistic approach	Machine learning and code complexity may reduce chances to reach a consensus and acceptance by decision-makers
Output differentiates between potential and actual benefits	'Flow and Use' model map flow components and model demand spatially (but require local information)	
	Results at every point in the landscape	

The tools to value ES need to be tailored to the type of ES, the scale of the assessment and the complexity of interactions at such scale. Research showed that not all ES can be maximised simultaneously other than by trade-offs (Allan et al., 2015; Bradford et al., 2014). Therefore, the assessment of ES is often restricted to one or few ecosystems rather than multiple ecosystems, which may create gaps in the analysis. Some ES are not independent when they rely on the same ecosystem process or when they are affected by common external factors (Gos, 2013). The concept of *bundle* ES refers to the association of ES that are 'consistent in space and time due to shared mechanisms' (Gos, 2013). The identification of ES bundles allows interacting ES to be managed coherently together instead of individually. For example, agriculture and ES are interrelated in at least three ways, which may create ES bundles (Dale and Polasky, 2007). Agro-ecosystems are generators of positive ES such as soil retention and food production, agro-ecosystems are receivers of positive ES such as pollination, and agro-ecosystems directly affect other services. Indicators for ES should be adequate to reflect the complexity of ecological linkages and should account for the scale of resolution as well as the dynamic nature of ES. Biophysical measurements can be used as indicators of provisioning and

regulating services. Although, the use of a single tool such as InVEST is attractive to model these ES in a consistent manner, recent work calls for use of multiple tools and approaches (Langemeyer et al., 2016). For example, an interpretative value based on participatory mapping approaches can be used for idiosyncratic elements of cultural services.

Finally, most ES studies clearly lack an understanding of the uncertainty associated with ES assessment. It arguably corroborates the complexity to grasp uncertainty in a technical, spatially explicit research but also limits the validity of findings (Brunner et al., 2017). Credibility, salience, legitimacy and feasibility are four key elements to have an impact on decision-making (van Oudenhoven et al., 2018). Tools to address uncertainty are qualitative (e.g. uncertainty matrix) and quantitative (e.g. Monte Carlo analysis, sensitivity analysis, etc.). (Hamel and Bryant, 2017; Refsgaard et al., 2007).

Therefore, a system-based approach can be used to value provisioning and regulating ES, while a place-based approach with participatory mapping can be used to quantify cultural ES values using web-GIS tools such as Maptionnaire (https://maptionnaire.com/), or the aspects of demand. Although one should be cautious with offering advanced GIS-functionality online to people with no GIS experience (Ingensand and Golay, 2011), the general use of multiple methods, including place-based, purpose-orientated and participatory approaches are more transparent and help deal with uncertainty (Barton and Harrison, 2017).

- Ecosystem services integration into policy

ES monitoring standards are still evolving and monitoring multiple ES and their interactions is challenging but crucial for spatial planning. Most work integrating a temporal element took a prospective approach. They also assume that temporal and spatial variability are constant through time. This approach may miss significant trade-offs and synergies among ES by ignoring the impact of landscape history (Tomscha and Gergel, 2016). However, assumptions are made about the future without a complete understanding of the past conditions of ES and their interactions. Therefore, historical assessments of ES are also crucial for an integrated approach, capturing the impact of policy implementation and the evolution of ES associations. Understanding the history of ES associations is important to inform current decision-making as it provides the unique opportunity to make the link between past policy measures and their effects on ES. For example, policies for agriculture may restrain investments in the concept of ES and lead to a decrease in such services (Turner et al., 2016).

In addition, we postulate that identifying the relationship between social demand and ES supply is crucial for spatial planning because ES provide fundamental elements to human well-being. Although ES demand assessments should be considered into planning, it presents a major challenge and is often overlooked in ES research. ES supply provides an incomplete picture because it does not consider the demand side reflecting the social system. Demand should be assessed independently of supply (Andrew et al., 2015). However, diverging perspectives on ES demand exist. Villamagna et al. (2013) argues that ES demand is the desired/required level of ES by the society, whilst Burkard et al. (2012) suggest that demand should equate to the actual use and benefits received, because of the complexity to distinguish between ES and actual human needs. ES demand is embedded in a complex SES and can be spatially

disconnected from ES providing areas. The assessment of demand is complex. Therefore, the inclusion of a wider stakeholder audience is crucial to build on ES assessment including demand that is actionable by planners and decision-makers.

1.2.3 Switzerland and ecosystem services

1.2.3.1 Sustainable development

The concept of sustainable management of natural resources has long been an element of the legislation in Switzerland. The Federal Act on Forest 1876, and the subsequent revision in 1991, set the principles of forest conservation by forcing the logging industry, or other forest clearing activities, to compensate the losses (Mahaim, 2014). The Federal Act on the Protection of the Environment (FA-EP) wanted to introduce of a concept of sustainability equivalent to Article 73 of the revised Constitution in 1999, stating: 'The Confederation and the cantons shall work towards establishing a sustainable balance between the environment, especially its regeneration capacity, and human exploitation.' (Conseil fédéral, 2016). However, the final version of FA-EP adopted in 1983 made a single mention of sustainability regarding soil protection and did not include the prospect of long-term stewardship of natural resources. We note that the current version mentions in Art. 1 the long-term stewardship of natural resources.

The concept of sustainable development was established in 1987 by the Brundtland Commission, and was accepted by the international community at the Rio Earth Summit in 1992. Broadbent (2012) argued that the term sustainability implies three elements: complexity due to the lack of a single optimal solution, value-based decision-making and interdisciplinary work through the concept of three capitals.

From this point, nations started to include the concept in their legislation. Switzerland first included it indirectly into the Federal Act on the Protection of Waters, in 1991. The cantons must ensure that the quantity of water withdrawn from aquifers does not exceed the actual quantity of recharge. The Constitution was revised in 1999 to include the concept of sustainable development. It is important to note that the recommendations from Kölz and Müller (1990) to include several articles on natural resources preservation and a new legal mechanism to enforce environmental policies were rejected by the Federal Council.

Nowadays, all major federal acts (FA-SP, FA-EP, Federal Act on Forest or Federal Act on Agriculture) have references to sustainability and/or sustainable development.

1.2.3.2 Implementation of the ecosystem services concept

In Switzerland, ecosystem services are a recent field of research. The Federal Office for Environment published the first inventory of relevant final ecosystem goods and services, and related indicators in 2011 (FOEN, 2011). The inventory was drawn based on the Millennium Ecosystem Assessment (MEA), the Common International Classification of Ecosystem Services (CICES), and through expert elicitation. In 2014, the FOEN published a guideline report for the assessment of ES at the national scale. The document focused on the practical application of the ES concept with strong emphasis on data availability (Grêt-Regamey et al., 2014a).

Although the current version of the FA-EP does not refer explicitly to ecosystem services, it aimed, through Article 1, to 'protect humans, animals and vegetation, their biocenosis and biotopes, against harmful or inconvenient infringements, and to preserve natural resources in a sustainable manner, especially biological diversity and soil fertility.'. Research from the Swiss Federal Institute of Aquatic Science and Technology focus on aquatic ecosystems, and related services with ongoing projects on energy and hydropower production, river management, biodiversity and conservation (Langhans and Lienert, 2016; Reichert et al., 2015). The Swiss Tropical and Public Health Institute also conducts research to investigate the relationship between ES and human health with a strong emphasis on water and sanitation in developing countries. Several studies conducted in Switzerland focus on a single ES or a category of ecosystems, of which agroecosystems are an important field of research. Agroecosystems were studied through their aesthetic quality (Junge et al., 2015), the local and global agricultural production chains (Schmitt et al., 2016), or adaptation capacities to respond to climate change (Kopainsky et al., 2015; Tendall and Gaillard., 2015). The National Research Project 68 (NRP 68) put a strong focus the sustainable use of soil as a resource. Following this trend, the contribution of soils to ES has been a very active research field (Greiner et al., 2018).

Mountainous regions are also one of the most studied areas in Switzerland (Brunner et al., 2017; Grêt-Regamey, 2008; Rewitzer et al., 2017). For example, Briner et al. (2013) and Huber et al. (2014) used normative mathematical programming models to understand synergies and trade-offs of ES in mountainous regions, taking the Visp region in the canton of Valais as case study. Lindemann-Matthies et al. (2014) provided a comparative study of attitudes towards forest ES between China and Switzerland.

The relationship between spatial planning and ES in Switzerland has been limited to the assessment of few ES at local scale and their integration into prospective work. For example, Schwaab et al. (2018) used multiple-objective optimization to analyse the impact of zoning decisions on the protection of agricultural productivity between municipal and supra-municipal zoning, while Stritih et al. (2019) used Bayesian networks to quantify uncertainties in avalanche protection models in the region of Davos. One notable exception was the new spatial decision support tool, PALM (Potential Allocation of urban development areas for sustainable Land Management), which aimed at supporting the allocation of urban development zones based on the integration of ES (Grêt-Regamey et al., 2017). However, a simple set of quantification methods was used to assess ES synergies and trade-offs, and spatial relations between ES as well as their spatial patterns were not well considered. To date, no work has brought together an assessment of historical ES supply and their spatio-temporal relationships, the link with land management policies and drivers, as well as stakeholder perspectives to facilitate their integration into spatial planning.

1.3 Methodology

1.3.1 Quantitative or qualitative methods?

The thesis could help decision-makers to approach spatial planning from a different perspective. It will use knowledge from several disciplines to generate recommendations to support current planning practices in Switzerland. It combines ecology, geography, spatial

planning and governance to formulate a holistic response to issues of environmental degradation, urbanization and land scarcity in Switzerland. Figure 1.5 shows how the research hypotheses are embedded within this thesis' conceptual framework. Each hypothesis integrates some facets of the framework, and has some degree of overlap.
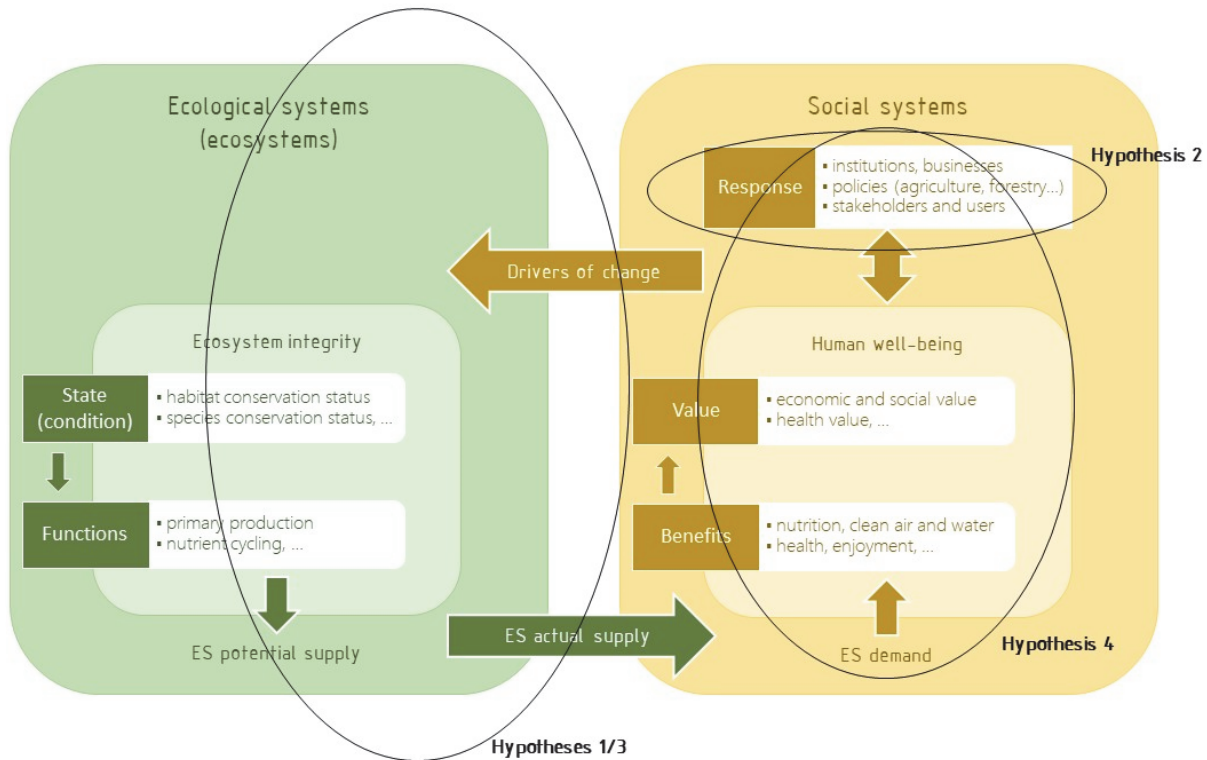
Figure 1.5 Operationalisation of the conceptual framework and hypotheses testing

In sciences, a 'paradigm war' rages over the use of quantitative and qualitative methods (Bryman, 2003), where both types of research are deemed incompatible. It opposes the 'positivist' worldview of quantitative research, with the 'interpretivist' view of qualitative research. From an ontological perspective, quantitative research sees the existence of independent reality, which can be partial, but can be studied in a systematic way. Some qualitative researchers argue that reality does not have an independent existence, and is shaped by people's mind (Murphy et al., 1998). From an epistemological perspective, a 'value-free' element is inherent to quantitative research (Lincoln and Denzin, 1994). The researcher is able to maintain an objective attitude toward the research topic. The element is not present in qualitative research because of pre-existing assumptions or beliefs (Glogowska, 2010). Quantitative and qualitative research have been further defined as deductive and inductive, respectively (Wisdom, 2012). A deductive approach refers to testing prior hypotheses through a process of evidence gathering, and often statistical testing. An inductive approach refers to evidence gathering through interviews, observations or document analysis to generate a theory or a hypothesis. However, prominent researchers believe that the paradigm war is over (Barbour, 1999; Patton, 1990).

From the transdisciplinary nature of the work, it is necessary to contend that a dichotomy exists between qualitative and quantitative approaches (Newman and Benz, 1998;

Onwuegbuzie and Leech, 2005), and that inherent strengths and weaknesses of both approaches can complement each other to understand SESs in a greater extent. For example, the concept of cultural ES has a large social component, which cannot be systematically and coherently grasped with quantitative methods (Pandeya et al., 2016). It would be wrong, if not irrelevant, to believe that there are hard and generalizable survey data that can lead to a complete understanding of a concept which exists only through the eye of human beings. However, regulating and provisioning ES are more easily quantified with biophysical and/or economic models. Studies that use only one method are more vulnerable to errors than studies that use multiple ones (Haines-Young and Potschin, 2008). The initial approach of this research is a hypothetico-deductive approach in the sense that it tests predetermined hypotheses. In practice, it involves a mix of characteristics from inductive and deductive paradigms to address open-ended questions such as the selection of suitable ES. It provides a means to perform cross-data validity checks. A pragmatic view is necessary in the context of this study, and the use of mixed methods is appropriate. Greene et al. (1989) outlined five broad purposes of mixed methods:

- Triangulation (i.e. seeking convergence in the study of the same phenomena);
- Complementarity (i.e. seeking illustration or clarification of the results from one method with results from the other);
- Development (i.e. using the result of one method to inform the other);
- Initiation (i.e. pointing out difference to re-frame the research question);
- Expansion (i.e. expand the breadth and range of research).

In accordance with this classification, mixed methods will be used for complementarity and development. The main constraint of combining methods lies into the conversion of purely quantitative measures into detailed, qualitative descriptions, although it enhances legitimation (Onwuegbuzie and Teddlie, 2003). This will not be part of the study so combining methods remains appropriate.

1.3.2 Combining methods

Increasing our understanding of a complex SES requires a shift from studying different elements separately, towards a more holistic focus, considering multiple times, scales, stakeholders and their interactions (Seppelt et al., 2011). The ES concept can play a key role at the science-policy interface. Therefore, there is a need to include some conceptual and methodological diversity to facilitate inter- and transdisciplinary dialogue and communication, as well as capturing value pluralism (Ainscough et al., 2019). In ES research, value pluralism assumes that different ES have a diversity of values, value expressions and valuation languages, which may be comparable to some degree but cannot be elicited in an integrated way on a single measurement scale (Jacobs et al., 2016a). Methodological pluralism seeks to capture value pluralism through the use of multiply methods, which may be qualitative or quantitative (Popa et al., 2015). Accounting for value pluralism is crucial in ES research and may be achieved by using qualitative methods to assess more intangible values associated to ES (Scholte et al., 2015), integrating participatory framework for the elicitation of social demand and stakeholders' perspectives (Castro et al., 2014; Stosch et al., 2019), and including different ES values (biophysical, social, etc.) (Haines-Young and Potschin, 2008). Although, no method is capable of capturing all types of values (Jacobs et al., 2018), it becomes clear that

methodologies that seek purely to understand human needs will not capture ecological dynamics underpinning ES. Similarly, approaches focusing only on biophysical values will miss the important aspect of intangible values and the breadth of social demand (Dendoncker et al., 2018).

This work combines a large variety of qualitative and quantitative methods, some initially applied is other fields, and tailor them to fit the scope of work. The methods used to test the hypotheses are summarized in table 1.2. We note that all but one hypotheses combine qualitative and quantitative methods. Methodological limitations are addressed in individual chapters.

Table 1.2 Main methods used to test the research hypotheses

	Category	Type	Objective
Chapter 2 (Hypothesis 1)	Qualitative	Semi-structured interviews	Selection of ES
			Identify major planning policies
		Web-based participatory mapping	Assess and map cultural ES in Switzerland
	Quantitative	Stochastic modelling (i.e. Markov chain)	Model land use / land cover change
		Linear interpolation	Determine yearly land use / land cover
		Proxy-based models	Reconstruct yearly values of ES
		Space-time interaction (STI)	Examine changes in the provision of ES over time and space
		Spearman correlation	Assess ES associations
		Mantel statistics	Spatial autocorrelation between cantonal level of ES supply
		K-means cluster analysis	Identify ES bundles
		Redundancy analysis	Examine relationships between the provision of ES and policy shifts
Chapter 3 (Hypothesis 2)	Qualitative	Directed content analysis	Identify key concepts and variables throughout cantonal structural plans
			Account for a lack of consistency in the terminology
	Quantitative	/	/
Chapter 4 (Hypothesis 3)	Qualitative	Semi-structured interviews	Selection of ES
		Web-based participatory mapping	Assess and map cultural ES in Switzerland
	Quantitative	Process-based models (e.g. STREAM, InVEST)	Assess and map provisioning and regulating ES
		Proxy-based models (e.g. InVEST)	Assess and map provisioning and regulating ES
		Spearman correlation	Assess ES associations
		K-means cluster analysis	Identify ES bundles

		Redundancy analysis	Examine relationships between the provision of ES and socio-economic attributes
Chapter 5 (Hypothesis 4)	Qualitative	Stakeholder analysis	Identify the main stakeholder groups that are relevant to ES management and spatial planning
		Q-methodology (semi-structured interviews)	Reveal patterns between stakeholders across a sample of variables (ES)
	Quantitative	Q-methodology (factor analysis)	Reveal patterns between stakeholders across a sample of variables (ES)

Chapter 2

Historical dynamics of ecosystem services and land management policies in Switzerland

Abstract

Ecosystem services (ES) are dynamic over space and time. Understanding and quantifying spatio-temporal trade-offs and synergies among multiples ES, as well identifying the drivers of change provides an opportunity to make the link between ecosystems, policy and land management. We present an approach to understand the historical dynamics of ES and to analyze the regional diversity in ES changes in Switzerland. A spatio-temporal approach was used to examine changes of nine ES and their relationships from 1986 to 2015 across the twenty-six Swiss cantons. We found that ES supply was dependent on the spatial and temporal distribution of interacting factors. The relationships between ES shifted through time, and the correlation between the supply of ES and the distance between cantons was significant but remained almost constant through time. Each canton is providing a specific bundle (a set of positively correlated ES), dominated by just a few services. Trajectories in ES supply were related to changes in population density and the surface area of organic farming, reflecting trajectories in national strategies of land use planning and agriculture, respectively. Cantons with the lowest supply of ES had the highest population density, while the cantons with the greatest abundance of cultural ES had the lowest population density, which suggests that the densification trend in Switzerland could yield negative externalities. The promotion of organic farming and moderate population density was suitable to ensure sustainable supply of provisioning and regulating ES, but not cultural ES. We provide clear evidence of the dynamic nature of ES through time. Analyses of the relationships between the drivers and ES supply allows identifying the potential limits of national policies and new forms of land use planning based the ecosystem multifunctionality of territories.

2.1 Introduction

Ecosystem services (hereafter ES) can be defined as "the benefits that people derive from biodiversity and ecosystem functions" (Wu, 2014). The Millennium Ecosystem Assessment defined ES using a typology of "supporting", "regulating", "provisioning", and "cultural" (MEA, 2005), but studies suggested the risk of double counting between supporting services and other ES (Grunewald and Bastian, 2014; Haines-Young and Potschin, 2010). The common international classification of ES (CICES) attempted to overcome this by classifying ES into three main categories: provisioning, regulation and maintenance, and cultural (Haines-Young and Potschin, 2011).

The use of ES into spatial planning is an opportunity to make land use and management choices that increase the delivery of one or more ES at the expense of the delivery of others (Turkelboom et al., 2018). However, research showed that not all ES can be maximised simultaneously other than by trade-offs (Allan et al., 2015; Bradford et al., 2014). The concept of ES bundles refers to the association of ES that are 'consistent in space and time due to shared mechanisms' (Gos, 2013). The identification of ES bundles allows interacting ES to be managed coherently together instead of individually.

However, ES do not only evolve over space but also over time, and history is important in their current provision (Dallimer et al., 2015; Pinto et al., 2013; Tomscha et al., 2016). It also provides the unique opportunity to understand the trends in ES supply, the rates and underlying causes of change (Renard et al., 2015; Vallet et al., 2016). Historical data helps determining ES bundles among multiple ES as a basis for spatial planning (Dittrich et al., 2017). The study of land use and land cover is the primary tool to describe the potential and the imbalance of a territory at a certain time. Maps can present successive states of land use and land management, giving a clear insight of changes over a defined period. It can illustrate the results of a hypothesis to inform decision-makers (Burkhard et al., 2012; Gos, 2013; Maes et al., 2013). However, studies at different time steps remain scarce (Tomscha and Gergel, 2016).

The importance of assessing spatio-temporal dynamics of ecosystems, as well as their complexities, has been highlighted in a range of studies (Carpenter et al., 2011; Miyasaka et al., 2017; Pilosof et al., 2017). Most ES research has focused on mapping the supply of only few services at a single point in time and/or space (Baró et al., 2017; Lopes and Videira, 2017; Palomo et al., 2013). Despite that this approach is insufficient to conclude that observed associations between ES are generalizable over the entire area under study (Mouchet et al., 2014), the total number of studies on the historical dynamics remains small (Plieninger et al., 2016). In addition, the published articles either show the evolution of ES at relatively large time-steps (Jiang et al., 2013; Renard et al., 2015) or focus on a few ES (Lautenbach et al., 2011; Stürck et al., 2015). In addition, cultural ES are often excluded because their embedded social complexity is difficult to reconstruct over time (Dittrich et al., 2017; Jiang et al., 2013). It often requires the use of multiple data sources, and makes assumptions of constant ecosystem management practices or prices (Grêt-Regamey et al., 2013).

Understanding and quantifying spatio-temporal changes in ES supply, as well identifying drivers of change, is not straightforward (Hein et al., 2016; Jaligot et al., 2018a). Land use

change has increased in recent decades and policy shifts, e.g. from market support to direct
payments, are some of the major drivers of change in land management practices (El Benni and
Finger, 2013). It may therefore lead to some important changes in ES provision. Despite the
theoretical link between policy and ES, it is rarely made explicit (Feng et al., 2005; van Meijl
et al., 2006). This is mainly due to the lack of empirical information about spatial and temporal
flows of ES as well as historical monitoring system (Guerra et al., 2016; Haines-Young et al.,
2012).

Understanding historical dynamics is especially important in countries where regional
differences in the extent of policy implementation may be expected, e.g. in a federal system
(Messer et al., 2016). In Switzerland, the federal system creates some regional (hereafter
cantonal) discrepancies in the implementation of national land use or other policies (e.g.
agricultural) that may affect the provision of ES. For example, a strict policy for the preservation
of the best arable land (i.e. *surfaces d'assolement* or land crop rotation areas) or forested areas,
strongly affect the provision of some ES (Guerra et al., 2016).

While field-scale studies are important tools, national and regional ES assessment are also
needed (Lautenbach et al., 2011). Howe et al. (2014) argued that a focus on provisioning
services hinders the understanding of socio-environmental relationships, and stressed the
importance of looking at tradeoffs in detail at different scales and by ES type. In Switzerland,
research on the current and future state of ES has been conducted at the field scale (Schneider
et al., 2013) and regional scale (Brunner et al., 2016; Rewitzer et al., 2017). However, no study
has yet focused on the past spatio-temporal dynamics of ES at the national level including an
analysis of tradeoffs and synergies among multiple ES.

The aim of the study is to understand the historical dynamics of ES in Switzerland and to
analyze the regional diversity in ES changes. To establish an indicator framework to support-
decision making, it is necessary to derive the information from the availability of data at the
appropriate scale (Hauck et al., 2016; Maes et al., 2012). Based on literature review, expert
elicitation and data availability, we selected nine ES and assessed their annual supply from 1986
to 2015 in each canton. Then, the presence of space-time interactions, synergies, trade-offs and
ES bundles was tested. Finally, we evaluated the relationships between the spatial distribution
of ES and socio-economic drivers reflecting the implementation of two major policies that may
affect the provision of ES. The limits of both policies are also discussed.

2.2. Data and methods

2.2.1 Study area

Switzerland is a landlocked country of 4.1 million hectares (ha) with a large topo-climatic
gradient (altitude: 196–4634 m a.s.l) (SFSO, 2018a). Switzerland can be divided into five
distinct biogeographical regions: the Plateau, with low elevation and oceanic climate, the
Norther Alps and Jura with medium to high elevation and oceanic climate, the Central Alps
with intra-alpine and continental climate and the Southern Alps with an insubrian climate
(Gonseth et al., 2001). Human habitation has defined landscapes and land use patterns (Price et
al., 2015). In 2009, agriculture was covering 35.9% of the land surface area, while wooded
areas and urban areas accounted for 31.3% and 7.5% respectively. Urban areas grew by 23.4%

at an annual growth of 0.9% mostly at the expense of agriculture between 1985 and 2009 (SFSO, 2015).

Switzerland is a federation of twenty-six sovereign states called cantons. Cantons are the third level of the Nomenclature of Territorial Units for Statistics (NUTS), which sets out the division of European countries (Figure 2.1). Cantons are further divided into districts and municipalities, which results in decentralized political power, and potential discrepancies with regards to the implementation of land management strategies (SFSO, 2018b).

Figure 2.1 Map of the Switzerland. Note that NUTS 2 is not an administrative level for national policies.

2.2.2 Approach

2.2.2.1 Quantification of ES

Based on literature review followed by the elicitation of five academic experts on spatial planning and ecosystem services in Switzerland, we selected fifteen ES. The selection fell into the CICES framework version V4.3 that classifies final ES into three categories: regulating, provisioning and cultural (Haines-Young and Potschin, 2013). Five indicators for each category were selected based on their relevance to the study area, and the availability of current spatial data. Experts were asked to rank the indicators in order of importance based on their relevance to spatial planning and assessment feasibility. The list was shortened to meet specific criteria of historical data availability across the study period (1986–2015), and the 26 cantons. For example, erosion control was considered an important indicator but could not be assessed within

the study's spatio-temporal scope. Table 2.1 shows the nine ES valued, as well as their respective indicators and units: two regulating ES, two provisioning ES and five cultural ES. Using primary data from various sources, we quantified the annual supply of all ES for each canton. The detailed methodology is set out in Appendix A.1.

2.2.2.2 Major policy shifts and explanatory variables

During the expert elicitation, two policies have been identified as major potential drivers of ES changes. First, the Federal Act on Spatial Planning of 1979 (*Loi fédérale sur l'aménagement du Territoire*) sets out the principles for land use planning in the country (Mahaim, 2014). One of the main outcome was to compel the cantons and the communes to divide their territory into building and non-building zones. The recent revision of the Act in 2012 supported the densification of urban areas, with the objective of limiting the trend of urban sprawl observed in the 1950s and the 1960s (Hänni et al., 2008). Second, a major shift in the agricultural policy marked the end of public market support, maintaining high output prices, and the introduction of area-based payments (based on different geographical production settings) and financial support for environmental friendly production (Lehmann and Stucki, 1997; Mann, 2003). The operationalization of both policies was translated into three relevant indicators: the extent of settlement outside building zones, and population density for the Federal Act on Spatial Planning, and the percentage of land attributed to organic farming for the agricultural policy (Table 2.1). Although direct payments would have been a relevant indicator of the main agricultural policy for the last 30 years, the data gap prior to 1992 limited its suitability. The detailed methodology to quantify the three indicators is set out in Appendix A.2.

Table 2.1 Ecosystem services quantified from 1986 to 2015 across Switzerland, and covariables to explain the drivers of change in the distribution of ecosystem services

Ecosystem service category	Ecosystem service	Unit
Regulating	Carbon stock	t Carbon / ha
	Flood regulation	δ(max-mean)
Provisioning	Food production	t/ha
	Timber production	m^3/ha
Cultural	Heritage	ha
	Landscape aesthetics and landmark	ha
	Outdoor activities	ha
	Inspiration, spiritual and religious	ha
	Simple nature value	ha
Covariables	Level of settlement outside building zones	δ(density BZ- density canton)
	Organic farming	% land for organic farming
	Population density	habitant/km^2

2.2.2.3 Spatio-temporal dynamics in the supply of ES

The final dataset comprised 26 cantons, 30 years, and nine ES with diverse units and range of variation. Before analysis, the dataset was transformed using the transformation $x' = \log 10(x + 1)$ to meet assumptions of normality, and standardized to unit variance and zero-mean (Renard et al., 2015).

The data was collected across cantons to unravel the processes that drive variation in the supply of ES. The initial step was to examine whether the spatial patterns displayed by the ES supply had varied through time, as it suggests that the underlying processes varied as well (Laliberté et al., 2009). To statistically examine changes in the provision of ES over time and space, the *space–time interaction* (STI) analysis was used following Legendre et al. (2010). The time and space variables were coded using principal coordinates of neighbor matrices (PCNM). The centroid of each canton was used to code the space variable. The matrices were treated in a two-way analysis of variance (ANOVA) Model 5 with 999 permutations (Legendre et al., 2010). A significant interaction indicated that the spatial structure of an ES has changed through time, which indicates that some process caused the change. When STI was significant, separate tests were performed to assess temporal variations from site to site, and the spatial distribution from time to time using a one-factor ANOVA nested model (Models 6a and 6b) (Legendre et al., 2010; Renard et al., 2015). When STI is not significant, one should test the significance of the time and space effects without replications using an ANOVA Model 2. This was not the case in this study. Based on Legendre et al. (2010), we conducted a multivariate analysis first before applying the STI analysis to each individual ES for each year because the power of the test improves with this variable. The test were performed using the *adespatial()* package in R (Dray et al., 2017). Significant space–time interactions require deeper analysis to understand the underlying processes of change. The next steps were to understand the temporal relationships among ES, their spatial distribution and the drivers of change (Renard et al., 2015).

2.2.2.4 Temporal relationships among multiple ecosystem services

The period of study (1986–2015) was divided into six 5-year intervals to assess the relationship among ecosystem services through time ($n = 36$ pairs). Spearman correlations were performed for each time step to test the monotonic relationships between pairs of ES (Egoh et al., 2008; Legendre and Legendre, 2012; Mina et al., 2017; Vollmer and Grêt-Regamey, 2013). Pairwise correlations are often used to identify synergies and trade-offs between ES (Jia et al., 2014; Lauf et al., 2014; Raudsepp-Hearne et al., 2010).

2.2.2.5 Spatial distribution of ecosystem services value through time

Spatial autocorrelation examines the level of synchrony between ES observed across cantons (Legendre, 1993). A standard statistical test for multivariate data is the Mantel statistics, which computes the overall relationship between distance and the correlation coefficient between pairs of sites (Borcard and Legendre, 2012; Klain and Chan, 2012; Oden and Sokal, 1986; Ord and Getis, 1995). When plotted against distance classes, it produces a multivariate correlogram. Borcard and Legendre (2012) confirmed that the power of the test in Mantel correlograms was high for multivariate data. The test was performed for the six 5-year periods separately using Spearman's correlation in the *vegan()* package in R (Oksanen et al., 2007). Each value was tested for significance using 999 permutations.

We further identified ES bundles (i.e. mix of positively correlated ES that are provided together in the same place and time) using a k-means clustering analysis on the entire time series (Derkzen et al., 2015; Raudsepp-Hearne et al., 2010; Renard et al., 2015). The best partition was selected based on the "simple structure index" method (Dolnicar et al., 1999). In

total, seven bundles were identified and ES abundances were normalized by the maximum ES value obtained for each service to facilitate comparison among bundles.

2.2.2.6 Drivers of ecosystem services dynamics through time and space

Canonical analysis allow a quantitative test for causal relationships between a multivariate dependent variables (i.e. ES) and explanatory variables (Mouchet et al., 2014). The relationships between the provision of ES and socioeconomic attributes of the cantons were examined using a redundancy analysis (RDA). The test was performed on the entire time series by relating ecosystem services to three explanatory variables or indicators of land management policy: the extent of settlement outside building zones, the extent of organic and population density. The objective was to determine the potential limits of the implementation of national policies at the cantonal scale. The relationships were tested using a permutation test (999 permutations) (Legendre and Legendre, 2012; Martín-López et al., 2012). The RDA was combined with a (forward) stepwise procedure to select the model with the combination of explanatory variables with the highest R^2 and smallest *p*-value (Mouchet et al., 2014; Legendre and Legendre, 2012; Urban et al., 2006). Multicollinearity among predictor variables was checked using the Variation Inflation Factors (VIF). All values were close to 1 indicating that multicollinearity was not a problem in our model (Groß, 2003; Zuur et al., 2009). The test was conducted using the *vegan()* package in R (Oksanen et al., 2007).

2.3 Results

2.3.1 Spatio-temporal changes of ES provision

The multivariate analysis of space–time interaction showed that the supply of ES changed significantly over both time and space (Table 2.2). The test was also significant when performed for each individual ES. Results showed that the provision of each service changed significantly through time when the effect of time was tested separately (df = 390, P < 0.05). The STI analysis also showed that only the supply of food production and timber production were significantly different between cantons at each time step when the effect of space was tested separately (df = 480, P < 0.05). Finally, the highly significant space–time interactions (P < 0.05) showed that the temporal change in the provision of each ES was not the same in all cantons.

Table 2.2 Results of the space-time interaction analysis (STI)
Independent tests were performed for spatial and temporal structures. A significant STI indicates that the temporal change was not the same in all cantons.

Ecosystem services	STI		Space effect		Time effect	
	R^2	*p*-value	R^2	*p*-value	R^2	*p*-value
Multivariate	0.025	<0.001	0.429	<0.001	0.070	<0.001
Food production	0.011	0.003	0.748	<0.001	0.079	<0.001
Timber	0.058	<0.001	0.802	<0.001	0.133	<0.001
Flood regulation	0.15	<0.001	0.304	0.391	0.414	<0.001
C stock	0.0012	<0.001	0.293	0.997	0.003	<0.001
Heritage	1E-04	<0.001	0.353	0.585	2E-04	<0.001
Landscape beauty	1E-04	<0.001	0.349	0.667	1E-04	<0.001
Outdoor activities	1E-04	<0.001	0.658	1	1E-04	<0.001
Inspiration	1E-04	<0.001	0.366	0.384	2E-04	<0.001
Simple nature value	1E-04	<0.001	0.375	0.266	2E-04	<0.001

2.3.2 Changes in the temporal relationship among ES

The relationship among ES changed through time at the cantonal scale (Table 2.3). All cultural ES were synergetic through time, with very strong correlations ($r > 0.8$) for all periods. The relationship between food production and timber production became increasingly negative over time. A similar trend was also observed with flood regulation but weaker relationships were detected in the two last periods. Food production showed consistent and mainly significant tradeoffs with cultural ES, except the simple value of nature. While the tradeoff between food production and cultural ES seem to follow an inverted U-shape with a peak in the period 1996–2000, the tradeoff between timber production and two cultural ES seems to follow a U-shape with peaks in the first and last time period. On the contrary, flood regulation showed consistent significant synergies with cultural ES. Finally, carbon stock showed non-significant relationship with all ES, except for timber production where synergies were significant through time although decreasing.

Table 2.3 Pairwise correlation between ecosystem services through time

The star subscript indicate a significant relationship ($p<0.05$). Red reflects a negative correlations that are defined as trade-offs ($r \leq -0.14$). Green reflects a positive correlation that is defined as a synergy ($r \geq 0.14$). In this study, $-0.50 \geq r$ or $r \geq 0.50$ was considered as strong, $-0.17 \geq r \geq -0.50$ or $0.50 \geq r \geq 0.17$ was considered as moderate, and $-0.14 \geq r \geq -0.17$ or $0.17 \geq r \geq 0.14$ was considered as weak.

Ecosystem services		1986-1990	1991-1995	1996-2000	2001-2005	2006-2010	2011-2015
Provisioning							
Food production	Timber	-0.1	-0.13	-0.11	-0.15	-0.21*	-0.27*
Food production	Flood regulation	-0.1	-0.1	-0.19*	-0.20*	-0.1	0
Food production	C stock	-0.1	-0.1	-0.1	-0.1	-0.1	-0.14
Food production	Heritage	-0.1	-0.1	-0.17*	-0.14	-0.1	-0.1
Food production	Landscape beauty	-0.19*	-0.19*	-0.23*	-0.19*	-0.18*	-0.12
Food production	Outdoor activities	-0.17*	-0.17*	-0.21*	-0.17*	-0.18*	-0.12
Food production	Inspiration	-0.16	-0.15	-0.21*	-0.15	-0.14	-0.1
Food production	Simple nature value	0	0	-0.11	-0.1	0	0
Timber	Flood regulation	0.1	0.24*	0	0.38*	0.1	0.1
Timber	C stock	0.25*	0.23*	0.30*	0.15	0.23*	0.18*
Timber	Heritage	-0.1	0.1	0.1	0.1	0	0
Timber	Landscape beauty	-0.16	0	0	0	-0.1	-0.13
Timber	Outdoor activities	-0.1	0.1	0.13	0.1	0	-0.1
Timber	Inspiration	-0.23*	0	0	0	-0.12	-0.21*
Timber	Simple nature value	-0.26*	0	0	0	-0.15	-0.26*
Regulating							
Flood regulation	C stock	0	0.12	0.13	0.1	0.1	0.1
Flood regulation	Heritage	0.65*	0.62*	0.39*	0.57*	0.64*	0.60*
Flood regulation	Landscape beauty	0.53*	0.47*	0.45*	0.55*	0.64*	0.60*
Flood regulation	Outdoor activities	0.51*	0.49*	0.44*	0.58*	0.60*	0.58*
Flood regulation	Inspiration	0.53*	0.47*	0.48*	0.54*	0.60*	0.57*
Flood regulation	Simple nature value	0.47*	0.39*	0.42*	0.51*	0.56*	0.51*
C stock	Heritage	-0.1	-0.1	-0.1	0	0	0
C stock	Landscape beauty	0	0	0	0	0	0
C stock	Outdoor activities	0	0	0	0	0	0.1
C stock	Inspiration	0	0	0	0.1	0.1	0.1
C stock	Simple nature value	0	0	0	0	0	0
Cultural							
Heritage	Landscape beauty	0.87*	0.87*	0.87*	0.87*	0.87*	0.87*
Heritage	Outdoor activities	0.82*	0.82*	0.82*	0.82*	0.83*	0.83*
Heritage	Inspiration	0.84*	0.83*	0.83*	0.83*	0.83*	0.83*
Heritage	Simple nature value	0.80*	0.79*	0.79*	0.79*	0.78*	0.78*

Landscape beauty	Outdoor activities	0.97*	0.97*	0.97*	0.98*	0.98*	0.98*
Landscape beauty	Inspiration	0.95*	0.95*	0.95*	0.95*	0.95*	0.96*
Landscape beauty	Simple nature value	0.92*	0.92*	0.92*	0.92*	0.92*	0.92*
Outdoor activities	Inspiration	0.93*	0.93*	0.93*	0.94*	0.94*	0.95*
Outdoor activities	Simple nature value	0.91*	0.91*	0.91*	0.92*	0.93*	0.93*
Inspiration	Simple nature value	0.97*	0.97*	0.97*	0.98*	0.98*	0.98*

2.3.3 Changes in the spatial relationship among cantons

Mantel correlograms consistently showed significant, strong positive spatial autocorrelations between the supply of ES across short distances of 50 km ($r>0.20$, $p<0.05$, Figure 2.2). Spatial autocorrelation was also negative and significant for four time periods between 1991 and 2010 at an intermediate distance of 120-km ($r=0.15$, $p<0.05$, Figure 2.2) showing that the provision of ES tend to be dissimilar as distance increases. Other relationships across distances were non-significant. We retained only half of the spatial data as autocorrelation from lag distances over half the spatial span of the data are often spurious due to the small number of lag-pairs (Legendre and Legendre, 2012). The Mantel tests showed that the cantons shared positive correlative structure, indicating linkages between the provision of ecosystem services and the geographical distance between cantons (Table 2.4). Overall, there is clear evidence ($p<0.05$) that cantons with similar structure in ES supply are spatially close together, so in other words, the dissimilarity in the provision of ES is a function of geographical distance between sites.
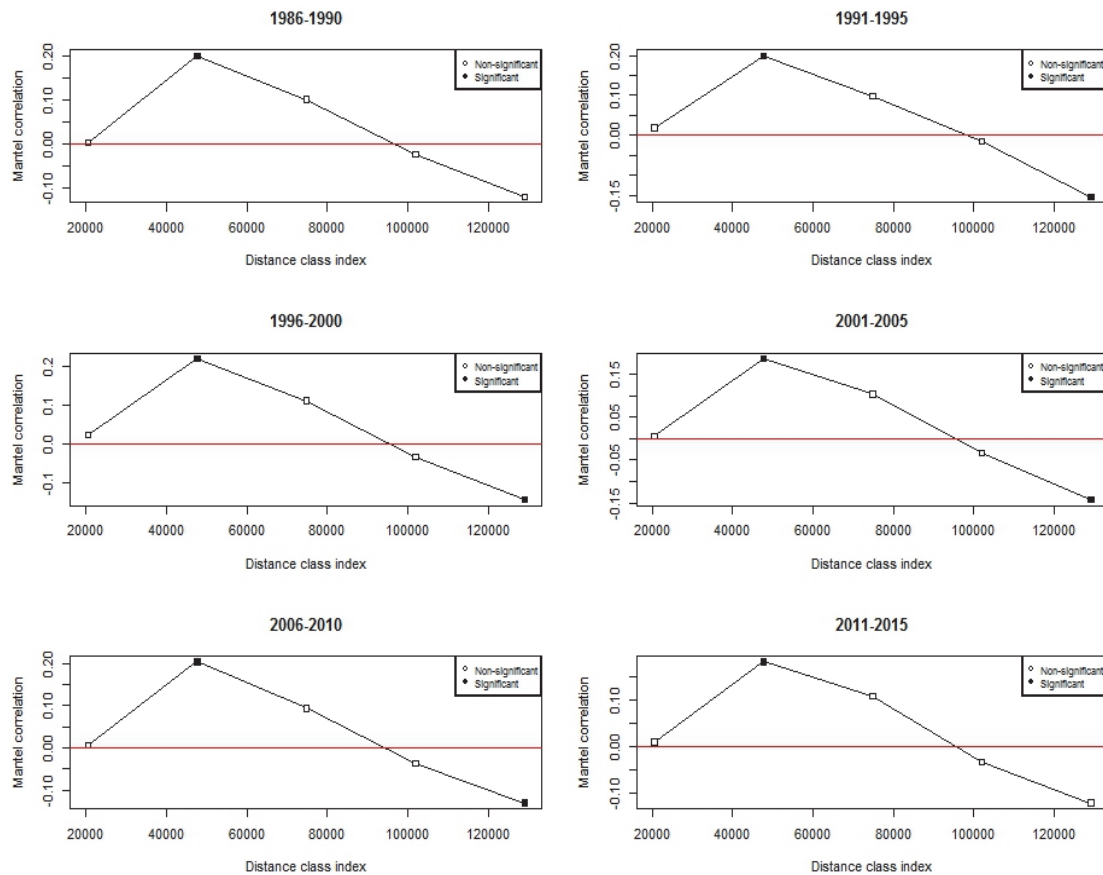
Figure 2.2 Mantel correlograms for the six time periods
Distance index is equal to distance in meters

Table 2.4 Mantel statistics for the six time periods

Time period	Mantel statistic	p-values
1986-1990	0.268	0.014
1991-1995	0.269	0.006
1996-2000	0.29	0.004
2001-2005	0.244	0.011
2006-2010	0.258	0.012
2011-2015	0.25	0.009

The k-means clustering analysis partitioned the cantons into seven groups (hereafter bundles) based on the type and abundance of ES provided through time (Figure 2.3, Figure 2.4). The results from the Mantel test showed that Mantel statistics remained fairly constant over time so that the spatial distribution of ES bundles remained unchanged (Table 2.4). This confirms the previous result of the STI analysis showing that the space effect was mostly non-significant (Table 2.2). Therefore, the temporal evolution of bundle distribution was not evaluated. Figure 2.3 shows that bundle 6 was characterized by the highest abundance in cultural ES and flood regulation. The bundle with the lowest abundance of ES was bundle 2. Bundle 3 provided the highest abundance of food production, timber production and carbon stock, and low abundances of cultural ES. Finally, bundle 1 and bundle 5 provided high and intermediate abundance of all ES, except food production respectively. On the contrary, bundle 4 showed low abundance of all ES expect food production for which the supply was high.
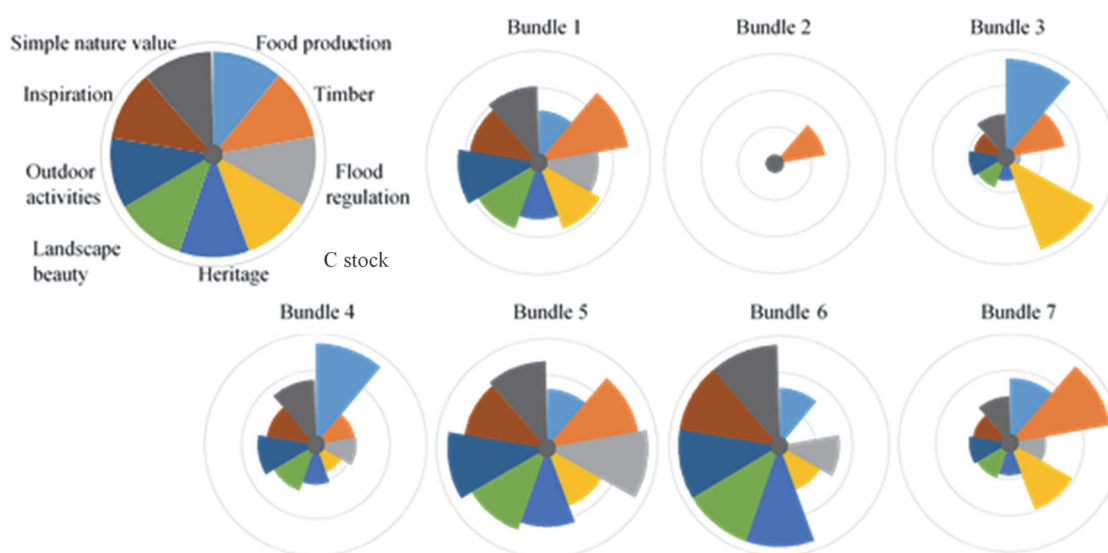
Figure 2.3 Ecosystem services bundles and relative abundances

Figure 2.4 Map of ES bundles

2.3.4 Drivers of ES dynamics

The RDA indicates a statistically significant association between the provision of ES and explanatory variables (adjusted $R^2 = 0.289$, $p \leq 0.001$, 999 permutations). Population density and organic farming were the two most relevant drivers for the provision of ecosystem services according to the variable selection procedure ($p \leq 0.001$) (Figure 2.5). The first axis explained 90% of the total variance. Cantons with the lowest abundance of ES (bundle 2) had the highest population density. Cantons providing provisioning ES and carbon stock (bundle 3 and bundle 7) were positively related to high levels of organic farming and moderate population density. By contrast, the cantons that are specialized in the provision of cultural ES (bundle 6) were related to low level of organic farming and had low population density. Cantons in bundle 5 showed a high abundance of all ES except for food production in a low population density environment and intermediate amount of organic farming. Bundle 1 and bundle 4 showed less clear relationships with explanatory variables, and average abundances of ES.

Figure 2.5 Redundancy analysis and partitioning of cantons into seven bundles.
Each ecosystem services bundle is identified by a polygon. The arrow identifies the explanatory variables where Dens is population density, BZ is the extent of settlement outside building zones and OF is organic farming.

2.4 Discussion

2.4.1 Discussion of results

This study provides empirical evidence that the spatio-temporal supply of individual ES and their relationships were dynamic through space and time. It confirms previous results, which stated that the spatial relation and configuration of environmental, social and economic characteristics are related to the provision of ES through time (Guerra et al., 2014; Guerra et al., 2016; Renard et al., 2015). In other words, ES provision is dependent on the spatial and temporal distribution of interacting factors. The analyses showed that the relationships between ES shifted through time. The correlation between the supply of ES and the distance between cantons was also significant but remained almost constant through time.

Pairwise associations among ES showed that relationships are not fixed through time. In Switzerland, a trade-off between food production and other ES has been present through time. This trade-off may be explained by the intensification of agriculture at the expense of social benefits and regulating ES (van Berkel and Verburg, 2014; Zimmermann, 2006). It showed the limits of the current Swiss policy that preserves the best arable land (i.e. land crop rotation areas or *surfaces d'assolement*) to ensure the multifunctionality of the territory in the supply of ES. The consistent synergies between timber production and carbon stock, as well as flood regulation may be explained by the strong protection of forested areas in the country (Frehner et al., 2005), whereby the exploitation of wood resources does not impede the multifunctionality of those areas. These results showed the importance of understanding the local policy framework because other studies found a trade-off between carbon storage and timber (Schwenk et al., 2012).

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Relationships involving cultural ES also changed through time. The strength of the synergistic relationship between cultural ES and flood regulation increased over time, while the trade-off increased with food production and timber production. The analysis of temporal associations among ES allows understanding the national trajectories in ES trade-offs and synergies. These are reflected in the spatial distribution of ES bundles, where bundle 6 showed high abundance of synergetic cultural ES and flood regulation, while bundle 1 and 5 had an average abundance for all ES except food production. The spatial distribution of ES has been structured in space because the geographical distance between cantons had an impact on their supplies. The results suggests that ES supply tended to have a similar structure at a distance of 50-km. Therefore contiguous cantons are likely to have a similar distribution in ES supply. The spatial autocorrelation tests performed over six time periods showed little variation in the spatial relationship among ES. It contradict previous results that showed an increase in spatial autocorrelation through time (Renard et al., 2015). We suggest that two underlying processes are responsible for the formation of trade-offs, synergies and bundles, and the lack of change in their spatial distribution: (i) the inertia of the federal system creates 'regionality' in the supply of ES. Neighbouring cantons tend to follow a similar path in the supply of ES and on the type of ES bundles and (ii) the geographical setting affects the supply of ES (Haines-Young and Potschin, 2010; Cord et al., 2017). For example, some Alpine cantons (i.e. Valais, Ticino and Graubünden) belong to the same bundle, i.e. bundle 6, which has a high abundance of cultural ES.

The relationships between the indicators of two main land management policies (Federal Act on Spatial Planning and direct payments for eco-friendly agricultural practices) and the supply of ES helped determine the limits of policy implementation at the cantonal scale. Population density and the extent of organic farming were the two most important drivers of change in the provision of ES. The extent of settlement outside building zones had a minor impact. It was clear that cantons with the lowest supply of ES (Basel Stadt and Geneva in bundle 2) had the highest population density, despite that both cantons are more distant than the significant distance for autocorrelation of 50-km. It suggests that the supply of ES would decrease drastically if other cantons would reach the same density level with a similar planning strategy, such as individual housing. In addition, cantons with the highest supply of cultural ES had low population density. Therefore, the densification process set out by the Federal Act on Spatial Planning should consider that there might be a density threshold to ensure sustainable supply of ES.

The percentage of land attributed to organic farming also had a strong impact on the supply of ES. The supply of regulating and provisioning ES was related to high and moderate levels of organic farming, and moderate density. This confirms this capacity of the new agricultural policy to maintain high supply of food production, carbon stock, food production and flood regulation. It is in accordance with previous studies showing that organic farming maintains ES and can contribute to food supply (Barral et al., 2015; Sandhu et al., 2010). On the contrary, the supply of cultural ES was highest with low organic farming and low population density. This is explained by the trade-off between agriculture (i.e. food production) and cultural ES. In that respect, we suggest that the promotion of organic farming and moderate population density may be suitable to ensure sustainable supply of provisioning and regulating ES, but not cultural ES.

2.4.2 Discussion of methods

The methodological approach resulted in significant preliminary treatment to establish the spatial–temporal dynamics of ES provision at the cantonal scale, and relations between policy measures/drivers. It is important to stress that the availability and quality of primary data is a challenge for all historical work. Long-term primary data are often not available for many ES (for example, flood regulation, pollination and most cultural ES), which are usually not represented in historical studies. This limits the identification of key trade-offs, in particular with provisioning ES (Dallimer et al., 2015; Renard et al., 2015; Selim et al., 2016). This study overcome this limitation by using a combination of participatory mapping, stochastic modelling (i.e. Markov chain), interpolation and proxy-based models to reconstruct the historical values of ES (Costanza et al., 2017; Rabe et al., 2018). There are some caveats related to the assumption that land use/land cover and interpolated time series indirectly used to assess some ES, evolved linearly (Grêt-Regamey et al., 2014b). This was mainly due to the lack of update of national land use/land cover database, and consistent monitoring of policy implementation across cantons (Messer et al., 2016). Some uncertainty relies in the use of stochastic models to predict land use change but the accuracy measurement showed the robustness of this approach (Appendix A). Overall, we acknowledge the limitation of the interpolation and proxy-based approach, but do not consider that these differences influence the overall trends and outcomes. The results, including for CES, are bringing valuable information to the broader debate on spatial planning in Switzerland. In addition, land use change and ES are often assessed using such approaches, especially in the absence of historical data (Kastner et al., 2011; Ramankutty and Foley, 1999; Verburg and Bouma, 1999). The use of centroids to code space variables in the spatial analyses yields a potential underestimation of spatial autocorrelation between larger contiguous cantons. However, the use of polygon centroids of various sizes and shapes is common (Gardiner et al., 2009; Klain and Chan, 2012; Nelson and Boots, 2008; Ord and Getis, 1995). Overall, the results captured the relationship between larger cantons, which is satisfactory for this study. Further work could be conducted at the municipal scale to capture the intensity of relationships between border municipalities and to test the scale-dependence of ecosystem services (Syrbe and Walz, 2012).

Regarding the selection of socio-economic drivers, we are aware that other interactions are not accounted for. Data availability for the period of study was a key limiting factor to integrate other potential drivers of change. However, we are confident that the indicators of land use planning and agricultural policy mechanism are the main drivers considering the land use planning context in Switzerland, as shown by other work (El Benni and Finger, 2013; Grêt-Regamey et al., 2017; Vuilleumier and Prélaz-Droux, 2002). The importance of introducing the ecosystem framework to decision-making has already been highlighted (Daily et al., 2009). The use of several ES rather than only a limited set proved to be more effective to describe the historical systems dynamics.

2.5 Conclusion

This study quantifies the historical dynamics of ES in Switzerland and assesses the drivers of change. Nine ES and three indicators of major policy shifts were quantified yearly from 1986

to 2015. A combination of participatory mapping, stochastic modelling, interpolation and proxy-based models was used to reconstruct historical values.

Results showed that the spatio-temporal provision of individual ES and their relationships were dynamic through space and time. The supply of ES tended to have a similar structure at a distance of 50-km, which showed little variation trough time. The analysis of temporal associations among ES allowed understanding the national trajectories in pairwise ES trade-offs and synergies. These results are reflected in the spatial distribution of ES bundles. Population density and organic farming were the two most important drivers of change in the supply of ES. Analyses of the relationships between the drivers and ES supply allowed identifying the potential limits of national policies. For example, cantons with the lowest supply of ES had the highest population density, while cantons with the greatest abundance of cultural ES had the lowest population density. It suggests that densification trend in Switzerland could yield negative externalities, should other cantons reach the same population density following a similar planning strategy such as individual housing. In addition, the promotion of organic farming and moderate population density may be suitable to ensure sustainable supply of provisioning and regulating ES, but not cultural ES. Overall, this study sets out "regionalities" in the supply of ES that could be used to inform land use planning based on ecosystem multifunctionality of territories. The implication of these results is that spatial planning at a supra-cantonal level may be necessary to integrate ES into decision-making. It requires some level of coordination between cantons, which is not often achieved within the federal governance framework. Considering ES into spatial planning could provide an alternative to current planning tools, which are applied individually at the cantonal level.

This research is among the first studies to quantify the spatio-temporal historical dynamics of multiple ecosystem services at the national scale. It has demonstrated an approach to assess past ES supply, and understand the main drivers of change related to the national political context. Despite the intrinsic limitations of historical assessments, we show the potential of historical ES assessment to help rethink land use and territorial planning, especially in countries like Switzerland where land availability is limited and the preservation of ES multifunctionality is primordial.

Chapter 3

Integration of ecosystem services in regional spatial plans in Western Switzerland

Abstract

The concept of ecosystem services (ES) is regarded as an increasingly important framework and tool to support spatial planning. A limited understanding of how ES knowledge is used in spatial plans constrains our ability to learn from, replicate, and convey an ES approach. This study examined how ES were integrated into spatial planning at the regional scale in Western Switzerland. A directed content analysis of cantonal structural plans was used to assess how ES were covered in various sections of the plans and to explore the differences in the level of ES integration across cantons. First, the results showed that ES were found in each section of the plans but were not equally distributed. Provisioning ES were always the most mentioned while regulating ES were the least considered. Second, strong discrepancies existed between cantons may demonstrate the lack of cantonal coordination to integrate ES. Finally, the concept of ES was more embedded in nonbinding than in binding parts. Promoting the concept at the national level may facilitate the integration of ES at lower planning scales. Further work could focus on other cantons to ensure that the results are fully representative of the current situation in Switzerland.

3.1 Introduction

Spatial planning is a key instrument for decision-making to coordinate human activities, and minimize their negative impacts on natural and land systems (Geneletti, 2011; Rozas-Vásquez et al., 2018). It offers promising opportunities for more integrated management of different land uses in order to reduce conflicts, and achieve ecological, economic, and social objectives (Lester et al., 2013). The main challenge in spatial planning is finding ways to organize landscapes, land use, urbanization, the use of natural resources to meet requirements of society in terms of well-being, environmental quality, and economic prosperity, as well as safeguarding biodiversity (Opdam et al., 2006; Selman, 2009). In the last two decades, the ecosystem services (ES) concept has been considered a valuable alternative to address this challenge, as it is a broad and inclusive concept that allows for the quantification and qualification of multiple social benefits from ecosystems, and thus the consideration of landscape multifunctionality (Almenar et al., 2018; De Vreese et al., 2016; Grêt-Regamey et al., 2008). ES conceptual framework, mapping, and indicators have been developed as part of evidence bases for spatial plans (Gómez-Baggethun and Barton, 2013; Scott et al., 2018). At the conceptual level, Scolozzi et al. (2012) used a Delphi procedure with decision-makers to assess changes in ecosystem services to explore how ES could be integrated into spatial planning. At the instrumental level, ES knowledge can be used to guide specific decisions (McKenzie et al., 2014; Turkelboom et al., 2018). At the strategic level, ES knowledge provides support for plans and policies (Almenar et al., 2018; Cortinovis and Geneletti, 2018). For example, a focus could be on building a tool or decision support systems (DSSs) (Kazak and van Hoof, 2018), to support the allocation of urban development zones (Grêt-Regamey et al., 2017) or on a working method for realizing specific ES integrated with urban development (Ahern et al., 2014). At this level, ES knowledge is expected to help planners make sustainable land use decisions by providing a more comprehensive understanding of trade-offs that may arise from them (De Groot et al., 2010; Mouchet et al., 2017a; Mouchet et al., 2017b). However, there is limited research on how policy-makers use ES knowledge in decision-making (Laurans et al., 2013; Scolozzi et al., 2012).

The limited understanding of how ES knowledge is used into spatial plans constrains our ability to learn from, replicate, and convey an ES approach (McKenzie et al., 2014). To fill this gap, scientists have used participatory approaches to elicit the opportunities and limitations of using the ES concept into planning practices from key stakeholders (Langemeyer et al., 2016). Different methods have been used to include key informants. Fürst et al. (2014) applied a score card tool to assess the performance of the ES concept in landscape planning and reveal the potential imbalances regarding the consideration of different ES groups in the Netherlands and Germany. Focus groups and interviews were also used to understand the limitations of ES use in planning in Stockholm at the municipal level (Kaczorowska et al., 2016). Other work showed that participation approaches can be used to prioritize ES (Mascarenhas et al., 2016; Uhde et al., 2015), but it did not discuss the integration of the ES concept in existing measures. Although elicitation approaches are useful to integrate place-based knowledge in decision-making and to gain a better understanding of how ES can be used for land use adaptation, they do not measure the actual implementation of ES into current planning practices.

Some studies reported the uptake of ES in planning practices by reviewing the content of documents, including strategic plans (Piwowarczyk et al., 2013; Wilkinson et al., 2013), strategic environmental assessments (Geneletti and Zardo, 2016; Rozas-Vásquez et al., 2017; Rozas-Vásquez et al., 2018), and urban plans (Cortinovis and Geneletti, 2018; Hansen et al., 2015; Rall et al., 2015). However, very limited research has yet focused on the integration of ES in spatial plans at the regional scale. Regional planning can be defined as the "spatial (re)allocation of land use activities, infrastructure, and settlement growth across a larger area of land for which a public regional planning authority is responsible" (Frank et al., 2014). It is a multilevel and multi-sectorial activity that aims to minimize land use conflicts and favor synergies (Frank et al., 2014). The main challenge is accommodating various public demands regarding areas which have the potential to provide different ES. Therefore, one may gain further understanding of the potential impact of planning decisions by comparing the level of reference to ES across regions, especially in countries where regional differences in the extent of policy implementation may be expected (e.g. in a federal system) (Messer et al., 2016).

In Switzerland, regional planning represents the center piece of spatial planning (Hersperger et al., 2017). The federal system creates some regional (hereafter cantonal) discrepancies in the implementation of national land use or other policies (e.g. agricultural) that may affect the provision of ES. The regions (hereafter cantons) also have some leeway in the interpretation of national policies, which may lead to different levels of integration of ES. Research on the current and future state of ES has been conducted at the field scale (Schneider et al., 2013) and regional scale (Brunner et al., 2016; Rewitzer et al., 2017). Grêt-Regamey et al. (2017) developed a DSS (Kazak and van Hoof, 2018), to integrate ES in future urban development zones, which can be used over the entire country but did not include an analysis of cantonal spatial plans (hereafter structural plans). Cantonal structural plans are the centerpiece of spatial planning in Switzerland (ARE, 2018). Cantonal structural plans are made of three main sections: context, strategy, and operation. It is important to note that only a limited amount of contents is binding and set the actual actions that will be implemented in the canton. They have a broader scope covering aspects such as transportation, urban development, energy supply, or landscape preservation. Hersperger et al. (2017) analyzed the integration of landscape goals at the cantonal level but this did not focus on the entire document and fell out the ES framework. Switzerland is a relevant study area to attempt to address the underrepresentation on ES integration in spatial plans at the regional scale in the literature.

The aim of this research is to assess how ecosystem services are integrated into spatial planning at the regional scale in Switzerland. The first objective is to evaluate how ES are covered in various components of the structural plan. The second objective is to explore the differences in the level of ES integration into structural plans across cantons. The final objective is to evaluate the potential differences in the integration of ES in binding and nonbinding parts of the document.

3.2 Methods

3.2.1 Study area

Switzerland is a landlocked country of approximately 4.1 million hectares (ha) with a large topoclimatic gradient (altitude: 196-4634 m a.s.l.) (SFSO, 2018a). Switzerland is a federation

of twenty-six sovereign states called cantons. Each canton has its own government and parliament. Canton are further divided into districts and municipalities, which results in decentralized political power, and potential discrepancies with regards to the implementation of land management strategies. We note that the districts are not political entities but only administrative units. In 2009, agriculture covered 35.9% of the land surface area, while wooded areas and urban areas accounted for 31.3% and 7.5%, respectively. Urban areas grew by 23.4% at an annual growth rate of 0.9%, mostly at the expense of agricultural areas between 1985 and 2009, which decreased by 5.4% over the same period (SFSO, 2015); unproductive areas such as glaciers also decreased by 1.1% (SFSO, 2015). We note that wooded areas grew between 8 and 28% in the Alps and Southern Alps, respectively, since 1985, for a total increase of 3.1% (Brändli, 2015). Switzerland has a relatively high population density and demographic growth compared to other European countries, so that urbanization has defined landscapes and land use patterns in recent decades (Price et al., 2015).

3.2.2 Framework for analysing the integration of ES into structural plans

In Switzerland, spatial planning is guided by the Federal Act on Spatial Planning of 1979. The Act stipulates that all cantons must draft a comprehensive plan as the main tool for territorial management. The main objective of the structural plan is to coordinate all activities with an impact of the spatial organization of a territory (ARE, 2018). Activities tackled at the cantonal scale are, for instance, water management, resource management, energy provision, transport or tourism. In this research, we analyzed seven structural plans from the seven full or partial French-speaking cantons in Western Switzerland (Figure 3.1). The cantons were chosen because they are members of the Association of Western Planning and Urbanism Offices (CORAT), and their structural plans were translated available in French. The plans can be accessed through the Federal Office for Spatial Development (ARE, 2018).
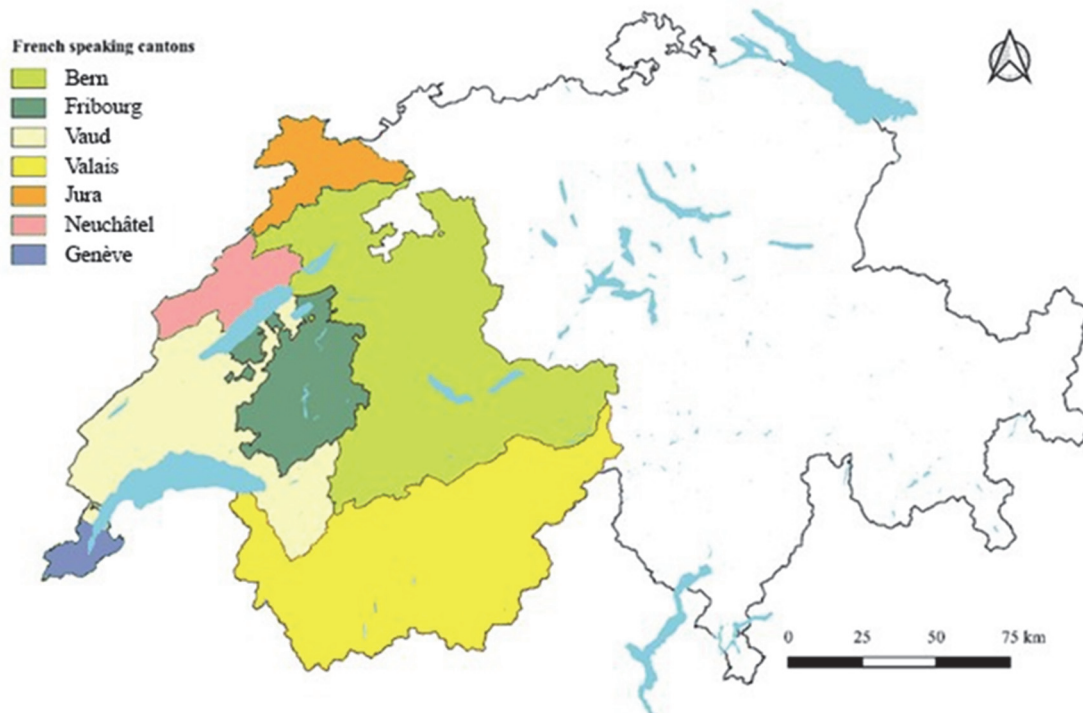
Figure 3.1 Full or partial French-speaking cantons in Switzerland.

We drew on directed content analysis to explore the integration of ES into cantonal structural plans. We considered that an assessment at the cantonal level was appropriate because it is the main planning scale in Switzerland. In addition, it is particularly adequate for ES integration since regions have administrative boundaries that more closely follow natural features (mountain ranges, watersheds, etc.) than municipal boundaries (Fürst et al., 2014; Mascarenhas et al., 2015).

A directed content analysis was performed by dividing the documents in two different stages, reading all the content and identifying ES related measures using the three ES categories: regulating, provisioning, and cultural, according to the CICES classification v4.3 (Haines-Young and Potschin, 2013). It is important to note that directed content analysis focuses on plans themselves and not on the outcomes they produce (Rega et al., 2018; Woodruff and BenDor, 2016).

Planning often has established practices which may limit the explicit mention to "ecosystem services" (Rozas-Vásquez et al., 2018). In addition, the different wording used in the field of ES makes the use of a keyword-based analysis inappropriate (Braat and De Groot, 2012; Geneletti and Zardo, 2016; Rozas-Vásquez et al., 2018). Hsieh and Shannon (2005) recommended using directed content analysis to support and extend an existing theory as well as identifying key concepts and variables throughout the documents. We chose to perform a deeper content analysis that accounts for the implicit use of the ES concept (Cortinovis and Geneletti, 2018; Schubert et al., 2018).

Following the guideline of the Federal Office for Spatial Development and the report from Messer et al. (2013), the cantonal structural plans were divided into two different stages: (1) the strategic section and (2) the operational section (Figure 3.2). We note that most plans included a short (e.g. few pages long) context section, as an introduction to the role and the history of the plan in the broader planning process. Since the context was not available for all plans (e.g. Geneva and Jura), and the main action lines referred to the operational subsections, we excluded it from the analysis.
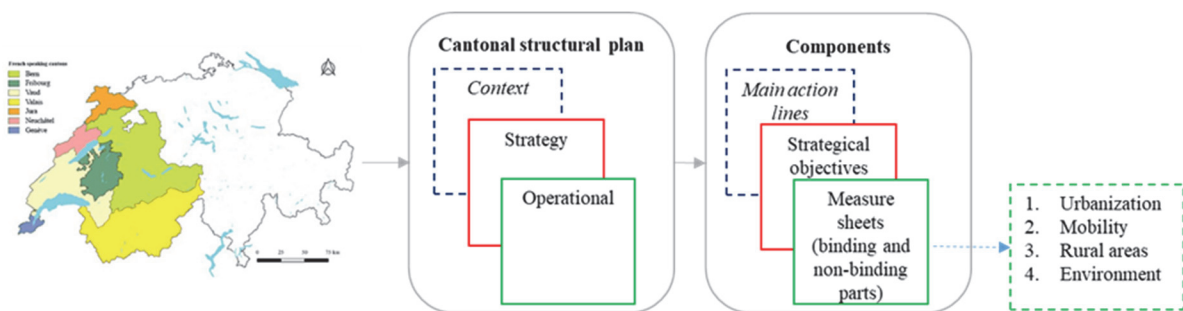
Figure 3.2 Conceptual framework for the subdivision of cantonal structural plans.

The strategic section is a few tens of pages long and focuses on the main strategic themes and corresponding objectives. We note that these may be named differently in the various plans. For example, in the canton of Vaud and Neuchatel, the strategic themes are named strategies and policy priorities, respectively, while the objectives are named action lines in both plans. For consistency, the term strategic objectives will be used. The operational section relates the operationalization of strategies using thematic sheets, divided in measure sheets and project

sheets. For the purpose of this study and consistency across plans, only measure sheets were analyzed. The measures are tools to implement the strategies.

Measure sheets have binding and nonbinding parts. Binding parts typically include the measure statement, the implementation principle and the division of competencies, while nonbinding parts detail the problem statement and an explanatory report. Cantons split the operational section in several subsections where measure sheets are classified. However, there is no consistency in the number and in the denomination of subsections (Messer et al., 2013). As a preliminary step, we reviewed each operational section and identified the four most recurring subsections. We reclassified the measure sheets in four subsections: urbanization, mobility, rural areas, and environment to ensure consistency between operational sections (Table 3.1).

Table 3.1 General themes from the four operational subsections in cantonal structural plans.

Urbanization	Mobility	Rural areas	Environment
Urban areas	Public transport	Agricultural areas	Surface water management
Densification	Freight	Building outside building zones	Groundwater management
Building and non-building zones	Mixed mobility	Ecological networks	Water supply
Commercial areas	Civil aviation	Landscapes	Air quality
Tourism	Individual transport	Natural hazards	Energy production
Public infrastructures	Soft mobility	National parks	Remediation sites
Industrial areas		Biotopes	Mineral extraction

We note that cantons are not obliged to implement a monitoring system for all measures. For example, the canton of Neuchâtel set a monitoring and controlling office as well as a set of indicators to assess change and its effectiveness, while others are still developing it.

3.2.3 Directed content analysis

In general, planning has a long history of recognizing the benefits of natural resources and natural areas, as well as its contribution to well-being without using the specific term "ecosystem services" (McHarg and Mumford, 1969; Wilkinson et al., 2013). Directed content analysis can be used to identify key concepts and variables throughout the documents (Hsieh and Shannon, 2005; Raparthi, 2018), and to account for this lack of consistency in the terminology, we captured every time the plan discusses explicitly or implicitly about the

benefits ecosystems provide. However, we excluded general statements about environmental protection, landscape preservation, or building green areas, as there is no benefit associated with it, in accordance with previous work (Hansen et al., 2015; Schubert et al., 2018).

3.2.3.1 Integration of ES in structural plan components

For each stage, we calculated the recurrence of explicit and implicit mentions to each ES category. To cope with different linguistic preferences between cantons, we used a binary coding system of 0 and 1 and limited the number of mentions to one per strategical objective or measure sheets. A strategic objective or measure sheet that mentioned an ES explicitly would receive a score of 1. We summed the binary scores to give a total number of ES mentions in the plan sections (e.g. strategic sections and four operation subsections). This is in accordance with a previous work using content analysis that counted and added textual elements (Mascarenhas et al., 2015; Schubert et al., 2018). The number of strategical objectives and measure sheets varied across cantons. For example, Vaud had 58 measure sheets while Geneva had 43. Therefore, we relativized the total number of mentions by the number of strategical objectives or measure sheets in each section to measure the relative frequency of ES mentions for each plan section, and multiplied it by 100. The maximum result of 100 meant that an ES category was mentioned in all strategical objectives or measure sheets, while the minimum result of 0 meant that an ES category was not considered in the section. Finally, we averaged the results between cantons to get a general measure of ES integration in plan components.

3.2.3.2 Difference in ES integration across cantons

The index and references sections of structural plans were not considered in this study, in accordance with a previous work (Mascarenhas et al., 2015). However, the location of key terms or mentions of ES is crucial to evaluate differences in the integration of ES into structural plans across cantons. Whether ES are acknowledged lower or higher up into the document section, can be interpreted as the degree of importance given to the concept. In addition, Krippendorff (1980) mentioned the need to develop a set of criteria for a quantitative measurement of plan quality. The rationale behind this process is to capture how well ES knowledge is embedded within planning, and ease comparison between plans (Woodruff and BenDor, 2016). For example, acknowledging one ES in the operational section has less impact on planning than recognizing synergies and trade-offs, or the need for spatial-explicit information. Therefore, we developed a five-level coefficient system that accounted both whether the mention to ES was lower or higher in the plan and the level of ES knowledge included. We used the coefficient system to evaluate how ES were addressed across plan components (i.e. strategic section and four subsections of the operational section) (Table 3.2). The coefficient system was modified after previous work (Baker et al., 2012; Cortinovis and Geneletti, 2018; Geneletti and Zardo, 2016). The assigned coefficients were cross-checked by the two authors of this research (Geneletti and Zardo, 2016; Piwowarczyk et al., 2013).

Table 3.2 Coefficient system to evaluate ES integration across plan components.

Coefficient	Strategic section	Operational section
0	No evidence of objectives related to ES	No mention of ES
1	Some objectives relate the preservation of ES	Mentions ES in the problem statement only
2	Acknowledges ES interactions	Direct mention of a single ES in the implementation principle and/or of ES interactions in the problem statement
3	Acknowledges the link between ecosystems and well-being	Acknowledges ES interactions such synergies and trade-offs in the implementation principle
4	Acknowledges that ES should be a priority for planning	Measures provide information on ES assessment and / or spatially explicit information

In the strategic section, the concept of ES may not be explicitly mentioned, so acknowledging the relation between ecosystems and well-being was considered more important than acknowledging for ES interaction. In the operation section, a measure stating that "cantons and communes should protect land crop rotation areas in a sustainable manner to prevent constructions and preserve its fertility" would be assigned a coefficient of 2, while a measure acknowledging ES synergies and trade-offs such as "agriculture is multifunctional, ensuring food production […], and preserving landscape beauty at the same time," would be assigned a 3. Finally, spatially explicit mapping of ES was recognized as critical for their integration in planning (Grêt-Regamey et al., 2017). Therefore, it is assigned the highest score in accordance with previous work (Cortinovis and Geneletti, 2018).

Finally, we conducted a comparative analysis at the cantonal scale. For each canton, we multiplied the relative frequencies of ES mentions with the coefficient obtained for each section and subsection of the structural plans. We note that canton-specific frequencies were used and not the aggregated result aforementioned. The output was aggregated to show the final score by canton and ES categories. This allowed for the identification of variable levels of integration of ES between cantons for each ES category.

3.2.3.3 Binding and nonbinding operational parts

The measure sheets in the operational section are split into nonbinding and binding parts, which set the actual actions that will be implemented in the canton. Therefore, this may also be interpreted as a degree of importance given to ES. It is important to understand how ES mentions are distributed between binding and nonbinding parts of measure sheets. First, we calculated the recurrence of mentions to ES in binding and nonbinding parts, separately. Again, we limited the number of mentions to one per measure sheet and relativized the number of mentions by the number of measure sheets for each canton to get the relative frequency of ES mentions. Then, we developed a five-level coefficient system and used it to assess how well the

ES concept was embedded in the two parts of measure sheets (Table 3.3). The coefficient system was different than the previous one (Table 3.2) because the coefficients had to be independent of the location in the measure sheets (e.g. problem statement, implementation principle, etc.) The objective was to capture the differences between binding and nonbinding parts. Again, spatially explicit mapping of ES was recognized as critical for their integration in planning (Grêt-Regamey et al., 2017). Therefore, it is assigned the highest score in accordance with previous work (Cortinovis and Geneletti, 2018).

Table 3.3 Coefficient system for the analysis of binding and nonbinding operational parts.

Coefficient	0	1	2	3	4
	No mention of ES	One ES mentioned	Multiple ES mentioned	Acknowledges trade-offs and synergies	Acknowledges need for spatially explicit data

Then, the relative frequency of ES mentions was multiplied by the coefficient for each binding and nonbinding part of the measure sheets. The results were aggregated by ES category to give a total score of ES integration in binding and nonbinding parts independently in each canton. To show whether ES were more embedded in one part or the other, we calculated the difference between the total scores of the binding parts and the nonbinding parts. A positive result was interpreted as ES being better integrated in the binding part while a negative result meant that ES were considered mostly in the nonbinding part.

3.3 Results

3.3.1 Frequency of ES mention in structural plan components

There is a great variability in the representation of ES across plan components. Most ES were present in less than 50% of all structural plan components (Figure 3.3). The environment subsection was the second most representative component for all ES after rural areas, while mobility failed to address ES in more than 80% of all measures. While regulating ES (RES) were present in less than 20% of the strategies and measure sheets, more variability was observed for the provisioning and cultural categories. Provisioning ES (the acronym PES is not used to avoid confusion with payment for ecosystem services) were represented in 33% of strategical objectives. In the operational section, the representation of provisioning ES varied from 16% to 83%, in the mobility and rural areas subsections, respectively. A similar trend can be observed for cultural ES (CES), where the lowest representation was observed in the mobility subsection and the greatest in the rural areas subsection. In proportion, the representation of provisioning ES and CES followed a similar trend across components. For example, when provisioning ES representation was at the highest in the rural areas subsection, CES embedding also reached its highest level. On the contrary, both reached their lowest level in the mobility subsection. This was less clear for RES which were almost equally represented in the rural areas and environment subsections.
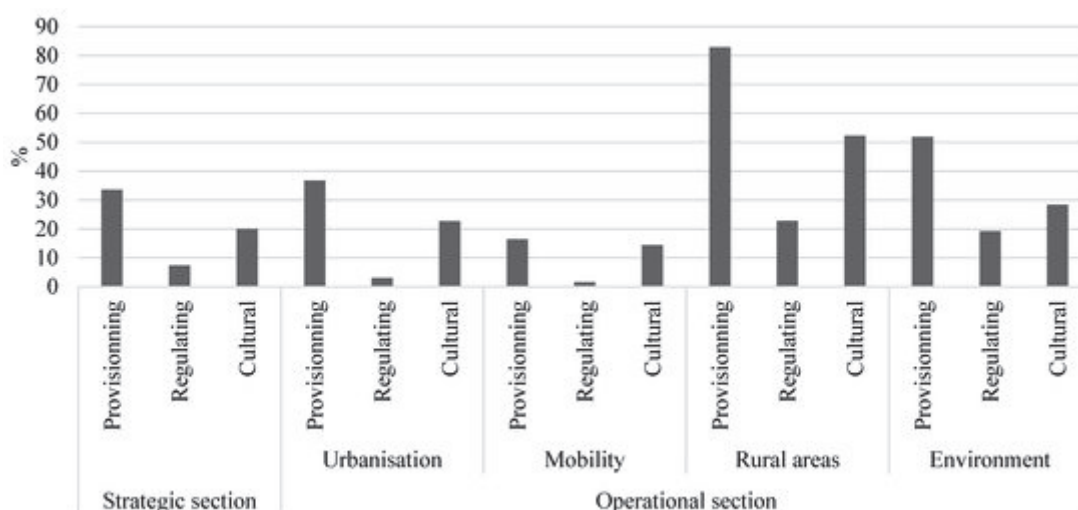
Figure 3.3 Frequency of ES mention in the different plan components.

We note that provisioning ES were always the most represented followed by CES and RES, which were always represented to a very low level (e.g. 3% in urbanization and 1.5% in mobility measure sheets).

3.3.2 ES integration across cantons

The final scores displayed in Figure 3.4 show the relative frequency of ES integration in structural plan components, multiplied by the coefficients obtained for the strategic section and each of the operational subsections (Table 3.2). RES showed the lowest representation across all cantons, while CES showed medium representation and provisioning ES scored the highest in all cantons. The final scores were 3.5 to 5 lower for RES than for provisioning ES. However, the results showed there were some differences within each ES category between cantons. The cantons of Valais, Vaud, and Geneva tend to stand out for all ES categories, with Valais scoring the highest for all categories. Vaud showed a higher score for the integration of RES than Geneva, while the opposite was true for provisioning ES and CES. The cantons of Neuchâtel and Jura almost displayed the same level of ES integration on aggregate with the former scoring better for CES and the latter for provisioning ES and RES. Finally, Bern was the canton with lowest scores across ES categories: 2 to 8 times lower than other cantons. For example, Valais had a score of 8.45 for CES while Bern had a score of 1.1.
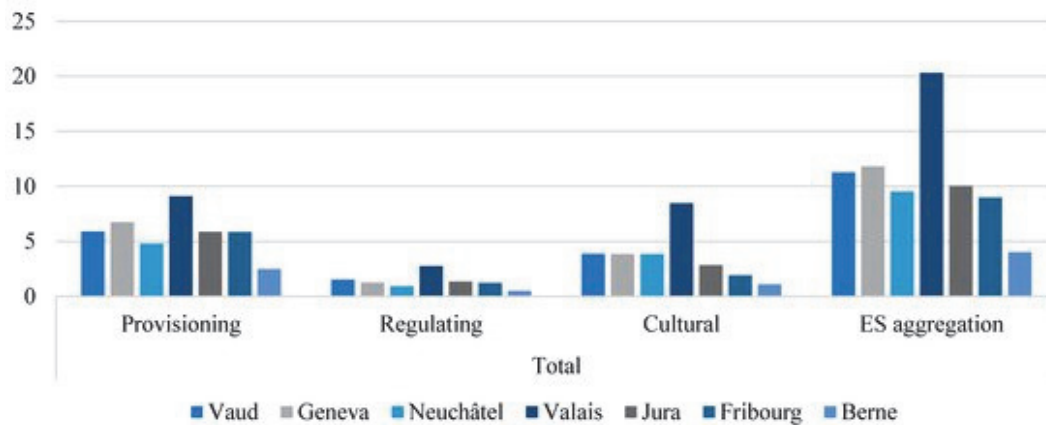
Figure 3.4 Ecosystem services integration across cantons.
 "ES aggregation" is the sum of all final scores obtained for each ES category.

3.3.3 Binding vs. nonbinding operational parts

Measure sheets in the operational section are divided into binding and nonbinding parts. Binding parts include the measure statement, the implementation principle and the division of competencies, and are binding for the authorities. The nonbinding parts are included into the measure sheets and are found under the terms problem statement and explanatory report. Figure 3.5 shows the cantonal differences in ES representation between binding and nonbinding parts for each ES categories. We note that the entire measure sheet was binding in the canton of Bern so the analysis could not be performed. First, some cantons performed better at integrating ES in the binding parts. Valais was the best performing one followed by Vaud and Neuchâtel. Although, provisioning ES and CES tend to be more present in binding parts in all three cantons, RES scored poorly. RES scores were even zero and negative for Neuchâtel and Vaud, respectively. The last three cantons—Geneva, Fribourg, and Jura—show a lower integration of ES in binging parts. While scores were always negative for provisioning ES and RES in the three cantons, it was positive for CES in Fribourg and Jura.
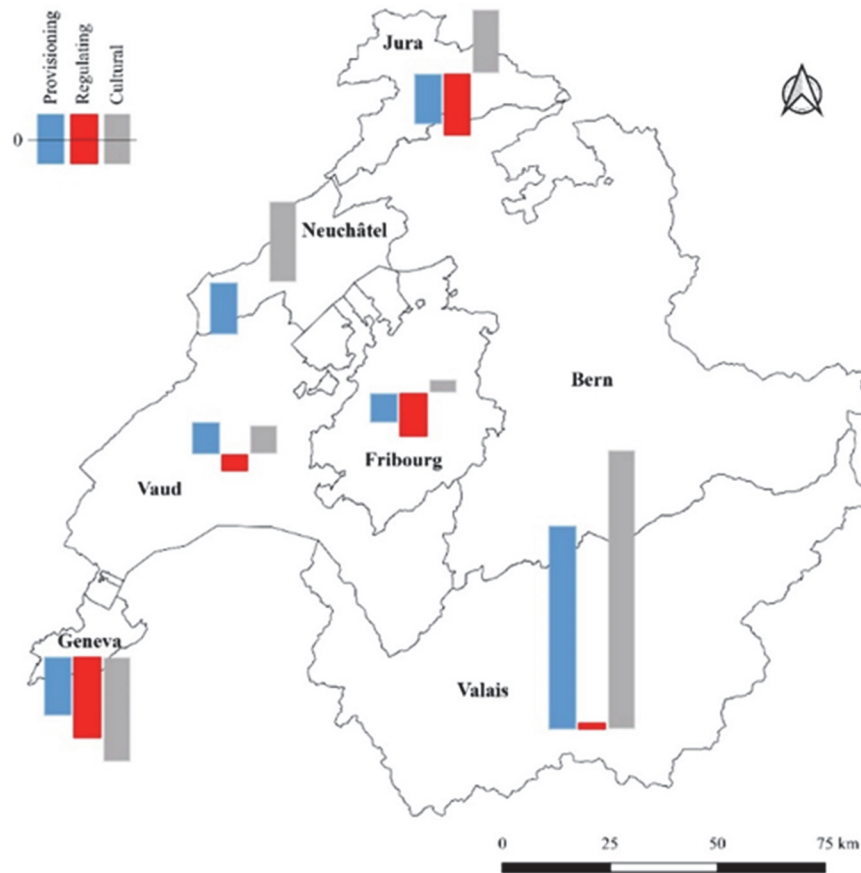
Figure 3.5 Difference in integration between binding and nonbinding operational components. The bar height tells how the extent of the difference in ES embedding.

It is important to note that RES were the least represented ES category in binding parts, across cantons except in Valais where the score was slightly positive. On the contrary, CES tend to be better integrated in binding parts except in Geneva where the score was strongly negative. The results were more mixed for provisioning ES, where positives scores were observed in Vaud and Valais, and negative scores were observed for the four others.

3.4 Discussion

3.4.1 Discussion of results

The integration of the ES concept as base for evidence in spatial planning has been increasingly promoted in the literature (Hansen et al., 2015; Grêt-Regamey et al., 2017), as well as in policy guidelines (Burkhard et al., 2018). Regional planning is particularly relevant for the integration of the ES concept because it aims to reconcile different land uses and weight the various public demand areas which have the potential to provide different ES (Frank et al., 2014). Despite some advances in the analysis of its implementation in decision-making, particularly in strategic environmental assessments (Mascarenhas et al., 2015; Geneletti and Zardo, 2016; Rozas-Vásquez et al., 2018), little evidence is available in terms of ES integration within spatial planning across regions and within different sections of spatial plans. The results are discussed in four subsections: three addressed the research objectives and the last one addressed the requirements for coordination across cantons. We also provide a discussion of the methods.

3.4.1.1 Harmonizing ES representation in plan components

In this study, a directed content analysis was conducted to explore the various levels of ES integration across full or partial French-speaking cantons in Switzerland. Cross-cantonal comparison is considered fundamental in the operationalization of ES-related research (Cortinovis and Geneletti, 2018). First, we showed that all categories of ES were found in each section of the structural plans (i.e. strategical section and four operational subsections). However, their presence was not equally distributed across sections and cantons, in accordance with other studies (Kumar and Geneletti, 2015; Rall et al., 2015). Provisioning ES were always the most mentioned services across all plan components, with the highest frequency found in the rural areas operational subsection. It shows the importance given to provisioning services in Switzerland, particularly food production, which has been part of planning in the country for decades (ARE, 1992). This is translated through the federal requirement to preserve the best arable land in the country, also called land crop rotation areas (LCRA). The focus on LCRA preservation has progressively shifted from managing agricultural production to supporting spatial planning and the allocation of building zones (Ruegg, 2015). We postulate that the strong focus on provisioning ES failed to recognize the importance of other services, particularly RES. It also tends to confirm the previous hypothesis that the focus of LCRA could have a negative impact on other ecosystems, and potentially on their benefits (Lüscher, 2003).

Studies conducted at the urban scale also found that ES integration was generally greater in the operational section than in the strategic section. However, they also showed that CES, such as recreation, were the most recognized ES followed by RES (Cortinovis and Geneletti, 2018; Wilkinson et al., 2013). Food supply was one of the least represented ES, which could be expected in the urban context. It shows that the scale of analysis has a strong impact on the results and care should be taken in the interpretation of results concerning ES priorities in spatial planning (Spake et al., 2017).

Interestingly, the integration of CES tend to follow the one of provisioning ES, proportionally. A possible explanation is the relationship between agricultural landscapes and CES such as leisure, landscape aesthetics, or heritage. In other words, cantons stipulated multiple times that there was a strong relationship between the forms of food production and CES. This is in accordance with reports from the Federal Office for Environment (Steiger, 2016) and research in other contexts (Bennett et al., 2009; Quintas-Soriano et al., 2016), but it is in contradiction with other work which showed that the synergy between agriculture and CES was weaker than previously thought in Switzerland (Jaligot et al., 2018b).

3.4.1.2 Discrepancies in ES integration across cantons

A lower integration of RES was detected consistently across cantons. We note that references to flood regulation services were the most common in all plans. Others such as carbon sequestration were rarely mentioned. A possible explanation is the high importance given to water correction in the country to mitigate flood regulation and ensure water supply. Provisioning ES were most represented followed by CES, as shown by other research (Turkelboom et al., 2018). However, there were strong discrepancies in the level of representation of ES across cantons, where Valais tend to integrate ES better than other cantons and Berne was the least performing. It demonstrates the lack of coordination between cantons

to integrate ES. In addition, missing directives on the integration of ES at the national level may lead to different interpretation of how ES should be included in land management policies, if at all. We also note that cantons may score poorly due to recurrent general statements about environmental protection, landscape preservation, or building green areas. However, these "keywords" do not stipulate any benefit that human may get from ecosystems. We postulate that lack of details in the cantonal structural plans may lead decision makers to miss the focus of ES preservation and address other topics which received more detailed explanation such as transport.

3.4.1.3 Binding and nonbinding integration of ES across cantons

The results from the analysis on binding and nonbinding operational parts confirmed that less attention was given to RES compared to provisioning ES and CES. Most cantons mentioned RES mainly in the nonbinding parts while the opposite was observed for CES, except for Valais, which discussed all ES predominantly in the binding parts. We previously mentioned that provisioning ES were the most represented category across structural plan components, followed by CES. However, the opposite was true when it came to making ES binding, except in Vaud. This shows that cantons tend to mention more evenly provisioning ES in both binding and nonbinding parts, but also give more importance to CES as an element of spatial planning.

Finally, we note that Geneva showed the lowest level of ES embedding in binding parts. It is also the most urbanized canton, with urban areas making up a third of the total surface area, where it makes up only 2.5% in Valais, which is also the least urbanized canton (SFSO, 2015). One may postulate that the integration of ES in structural plans is related to the level of urbanization, as cantons with the largest shares of agricultural, wooded, or unproductive surfaces integrated ES better as a binding element. It is acknowledged that the ability of urban ecosystems to provide services is often jeopardized by fast land use change (Arnold et al., 2018; Ortiz and Geneletti, 2018), and that including them in spatial plans is crucial (Schubert et al., 2018). However, this can be limited by the current instruments and tools for mapping and assessing urban ES (Zhao et al., 2018).

3.4.1.4 Requirements for coordination across cantons

Albert et al. (2014) pointed out that integrating ES in planning is highly dependent of the flexibility of governmental planning instruments, as integrating new elements may require active support from higher authorities. In Switzerland, spatial planning is guided by the Federal Act on Spatial Planning of 1979. The Act stipulates that all cantons must establish a list of priorities within their structural plan. They are also entitled to scale the areas that will be affected by urbanization, coordinate urbanization, and transport, as well as favor inner development (e.g. densification). In the Act, very little reference is made to environmental protection and no implicit or explicit mention is made to the concept of ES. There is no evidence that the concept of ES has been considered for supporting spatial planning decisions at the national level. In the same way, no cantonal structural plan included explicitly the term "ecosystem services" despite some reference to the Swiss Biodiversity Strategy which take up the ES concept. While Tzoulas et al. (2007) showed that interdisciplinarity was crucial for

addressing the complexity of the spatial planning process, Salet and Faludi (2000) argued to move to interdisciplinary from multidisciplinary because planning requires knowledge within and across disciplines. A multidisciplinary team with deep theoretical understanding and empirical expertise from diverse fields, as well as some transdisciplinary practitioners, is needed to integrate ES (Chan et al., 2006). However, the results showed little evidence of multidisciplinary between spatial planning and environmental planning. The two themes are divided between two different offices and little overlap seems to exist.

Integrating ES into spatial planning may be a promising approach towards sustainable development because it makes the benefits of ecosystems to humans explicit, as well as corresponding trade-offs with socioeconomic aspects such as urbanization (Grêt-Regamey et al., 2017). However, it requires a shift of focus from urban development, also known as the urbanistic paradigm (Rozas-Vásquez et al., 2018) of spatial planning, to a more holistic approach (Rozas-Vásquez et al., 2018). We argue that the cantonal structural plan is a strong tool to consider ES in territorial development. The different level of ES integration across cantons shows that beyond some requirements from the Federal Act on Spatial Planning, cantons have sufficient room to take up the concept of ES into the binding parts of their structural plans. However, promoting the concept at the national level may be key to facilitate the integration of ES at lower scales.

3.4.2 Discussion of methods

In this study, a directed content analysis was conducted to assess how ES were integrated into spatial planning at the regional scale in Switzerland. Regional planning usually concerns spatial areas that are sufficiently large to study and address ecosystem processes (Albert et al., 2014). In addition, cantonal structural plans are the centerpiece of spatial planning in Switzerland. Therefore, the scope of the analysis was particularly relevant for this study. We analyzed seven cantonal structural plans of full or partial French-speaking cantons. The number of reports was reduced given the scope of our study which was to focus only on members of the Association of Western Planning and Urbanism Offices (CORAT). We acknowledge that considering about 25% of total structural plans (7 out of 26 cantons) may not be fully representative of the current situation in Switzerland. However, the results were significant and could illustrate an overall picture of the current state of the relationship between ES and spatial planning in the country. Other studies only focused on a limited sample but drew significant conclusions on the integration of ES into planning (García-Llorente et al., 2018; Hansen et al., 2015; Mascarenhas et al., 2016).

Directed content analysis is more time-consuming than keyword-based analysis but allows for the inclusion of implicit mentions to ES. We acknowledge that directed content analysis is more prone to subjective interpretation than a keyword-based approach that would use a predetermined list of codes. However, the lack of consistency in ES terminology and linguistic preferences in cantonal structural plans made directed content appropriate in the research context. According to Hsieh and Shannon (2005), two main challenges inherent to the use of a theory-based approach apply to this study and may lead to (i) finding evidence supportive of that theory and (ii) overemphasizing the theory by ignoring contextual information. We attempted to address these challenges by determining conditions to the identification of ES

mentions. For example, we excluded general statements about environmental protection, landscape preservation or building green areas. In addition, the scores were cross checked by all the authors of this research (Piwowarczyk et al., 2013; Wilkinson et al., 2013; Geneletti and Zardo, 2016).

Kolbe and Burnett (1991) recognized the potential methodological problems associated with directed content analysis and stressed the need to assess the nature of past applications. Based on previous work (Jacobs et al., 2016b; Maczka et al., 2016; Rosa and Sánchez, 2015), we argue that it is a valuable and appropriate approach to conduct this type of study. It is powerful tool to perform in more in-depth analysis as it facilitates understanding between the relations between implicit and/or explicit mention of a concept (Rozas-Vásquez et al., 2018).

3.5 Conclusions

The concept of ES is regarded as an increasingly important framework and tool to support spatial planning. While quantifying ES trade-offs and synergies is key for policy-makers, it is also necessary to understand the implementation of the concept at an operational level, through spatial plans. The focus on the regional scale has been considered important to including ES knowledge into planning but most work focused on the urban scale. This study aimed to assess how ES were integrated into spatial planning at the regional scale in Switzerland.

The first objective was to evaluate how ES were covered in various section of the structural plan. All categories of ES were found in each section of the structural plans (i.e. strategical section and four operational subsections). However, their presence was not equally distributed across sections, with a strong focus on provisioning ES that may omit the importance of other services. However, the integration of CES tends to follow the one of provisioning ES, proportionally. An explanation may be the relationship between agricultural landscapes and CES. This is in accordance with federal guidelines and research in other contexts, but recent work in Switzerland questioned the strength of the relationship between both elements. Further research is needed to adjust the prominence given to this relationship in spatial planning.

The second objective was to explore the differences in the level of ES integration into structural plans across cantons. A lower integration of RES was also detected, while provisioning ES were most represented followed by CES. However, strong discrepancies also existed, which may demonstrate the lack of coordination between cantons to integrate ES. The integration of ES in structural plans appeared to be related to the level of urbanization, as cantons with the largest shares of agricultural, wooded, or unproductive surfaces integrated ES better as a binding element.

The final objective was to evaluate the potential differences in the integration of ES in binding and nonbinding parts of the operational section. The concept of ES was more embedded in nonbinding operational sections than in binding section. We believe that the limited number of federal requirements to be included in cantonal structural plans provides the opportunity for cantons to take up the concept into the binding parts of their structural plans. However, promoting the concept at the national level could be the key to facilitate the integration of ES at lower scales. To further emphasize this, conducting a similar type of analysis on German-speaking cantons, and comparing the results would be a valuable addition.

Overall, directed content analysis was a valuable tool to understand how ES were integrated into spatial planning across regions. It provided the flexibility to cope with the lack of consistency in ES terminology and linguistic preferences in cantonal structural plans. The main inherent challenges of a theory-based approach are overemphasizing the theory and ignoring contextual information, as well as finding more supportive evidence of that theory. Future research may focus on further addressing these potential biases by combining content analysis with a keyword-based approach and comparing the results.

Chapter 4

Assessing spatial temporal patterns of ecosystem services in Switzerland

Abstract

Despite the importance of understanding the historical dynamics of ecosystem services (ES), little research has focused on a historical, spatially explicit, assessment of ES supply. This research is aimed at understanding the spatial patterns and potential drivers of temporal variations of ES supply. It has assessed associations of ES temporal variations, delineated ES bundles from changes in ES supply over time, and identified potential drivers of ES bundles. Finally, we discuss the potential implications for spatial planning. We reconstructed the spatio-temporal patterns of 11 ES supply in the canton of Vaud, Switzerland, between 1979 and 2014. We used Spearman's rank coefficient, k-means clustering and redundancy analysis to understand the spatial patterns and potential drivers of temporal variations of ES supply. Municipalities were grouped into four clusters based on ES supply changes over four decades. Food production showed the most negative associations with other ES. Regulating ES were not always synergetic and were less related to increases in population density than cultural ES, which were found in low population density municipalities. In general, synergetic ES may not respond to the same potential drivers. Municipalities were able to supply ES at different levels but none showed an increase in all ES. ES can be synergetic in one bundle, but antagonistic in another. Different processes can cause a change in the same ES depending on their supply location. It seems unrealistic to require each municipality to have a multifunctional territory in the current political context.

4.1 Introduction

Ecosystem services (hereafter ES) can be defined as "the benefits that people derive from biodiversity and ecosystem functions" (Wu, 2014). Human societies have always relied on ES to enhance their well-being (Liu et al., 2019). As spatial planning is a key instrument for decision-makers to coordinate human activities and meet the requirements of society in terms of well-being, environmental quality, and economic prosperity, and as the concept of ES accesses the same thematic areas, both could complement each other to organize landscapes, land use, urbanization and the use of natural resources (Baró et al., 2016; Opdam et al., 2006; Scott et al., 2018). It is the opportunity to make planning decisions that will increase the supply of one or more ES (Turkelboom et al., 2018).

Nevertheless, not all ES can be maximized simultaneously other than by trade-offs (Vallet et al., 2018). ES can be associated together when they respond to the same driver of change or ecological process, or when their interactions cause a change in one of them that alters the provision of another (Bennett et al., 2009). The terms synergy and trade-off are often used to refer to ES association (Mouchet et al., 2014). Following the general rule in the literature, an ES synergy is a positive ES association (i.e. one in which both services increase or decrease), and an ES trade-off is a negative ES association (i.e. one in which on service decreases while another one increases) (Howe et al., 2014; Spake et al., 2017). The concept of ES bundles is an efficient way to compile and convey information on consistent associations in time and/or space to decision-makers based on the importance and co-occurrence of different ES (Christ et al., 2015; District et al., 2017; Raudsepp-Hearne et al., 2010). In this study, the concept of ES bundles refers to the associations of ES that are 'consistent in space and time due to shared mechanisms' (Gos, 2013). ES bundling allows the capturing of key patterns in the provision of ES driven by past ecological and social dynamics (Raudsepp-Hearne et al., 2010). The identification of bundles can guide spatial planning and priority setting (Mastrangelo et al., 2014).

The assessment and mapping of ES and ES bundles in their current state at various scales has gained traction over the past decade, particularly in Europe (Jopke et al., 2015; Maes et al., 2018b; Rabe et al., 2018). However, ES do not only change over space but also over time, and history is critical in their current provision (Dallimer et al., 2015; Luo et al., 2019; Tomscha et al., 2016). Numerous studies have reported ES associations such as possible trade-offs between provisioning and regulating ES. Although these studies may contribute to the defining of spatial priorities (e.g. ES hotspot protection or landscape multifunctionality promotion), there is a risk of drawing incorrect conclusions due to inferences based on spatial relationships regarding interactions over time (Vallet et al., 2018; Xu et al., 2017). In addition, static assessments do not reflect whether an ES has been degraded through time or whether it has recovered from a prior unfavorable state (Stürck et al., 2015). Research focusing on the historical dynamics of ES remains limited (Plieninger et al., 2016; Tomscha and Gergel, 2016).

Indeed, several authors have argued that there is a need for spatio-temporal assessments of ES, as caused by land use and policy change, to understand the trends in ES supply, the rates and underlying causes of change (Liu et al., 2019; Renard et al., 2015; Vallet et al., 2016). Recent studies that assessed historical dynamics have used official statistical data at the

municipal (Renard et al., 2015) and national scales (Jaligot et al., 2019a). These studies identified the potential limits of land management strategies by capturing changes in ES associations and their relationships with potential drivers. While this "space-for-time" approach may contribute to defining spatial priorities, it captures only snapshots of ES interactions at different phases of land use transitions. It may characterize ES associations in such a way that important dynamics are missed (Vallet et al., 2018). They have also lacked a spatially explicit quantification of ES that would account for changes in land use and landscape configuration (Verhagen et al., 2016).

ES maps created over a single time frame may suggest a trade-off, but may show a synergy when viewed over time due to the importance of shared attributes such as forest cover. Using a "change-over-time approach" (i.e. ES associations determined from a map difference) may moderate these issues (Tomscha and Gergel, 2016). While some studies have focused on a spatially explicit assessment of historical ES supply using a "change-over-time approach", they either integrated only a few ES (Guerra et al., 2016; Huang et al., 2018; Vigl et al., 2016), or missed integrating drivers of change, which are necessary to inform policy and management (Vallet et al., 2016; Vigl et al., 2017). In Switzerland, most ES research has focused on assessing the current and future state of ES at the field scale (Schneider et al., 2013), regional scale (Brand et al., 2013; Rewitzer et al., 2017), watershed scale (Zarrineh et al., 2018), and national scale (Braun et al., 2018; Jaligot et al., 2018b). Although the dynamic nature of ES over space and time has been shown (Jaligot et al., 2019a), no work has yet focused on a historical, spatially explicit, quantification of multiple ES supply considering changes between different time steps, and the identification of potential drivers of change.

To bridge this gap, this research aims to understand the spatial patterns and drivers of temporal variations of ES supply. We do so by quantifying 11 ES at four points in time. The specific objectives are: (1) to assess changes in associations of ES temporal variations, (2) to delineate ES bundles from the spatial pattern of changes in ES supply over time, (3) to identify potential drivers of ES bundles, and (4) to discuss the potential implications for spatial planning.

4.2 Material and methods

4.2.1 Study site

Switzerland is a landlocked country of 4.1 million ha (SFSO, 2018a). It is a federation of 26 sovereign states called cantons, which results in decentralized political power split between the cantons and the municipalities. The canton of Vaud is used as the study site in this research.
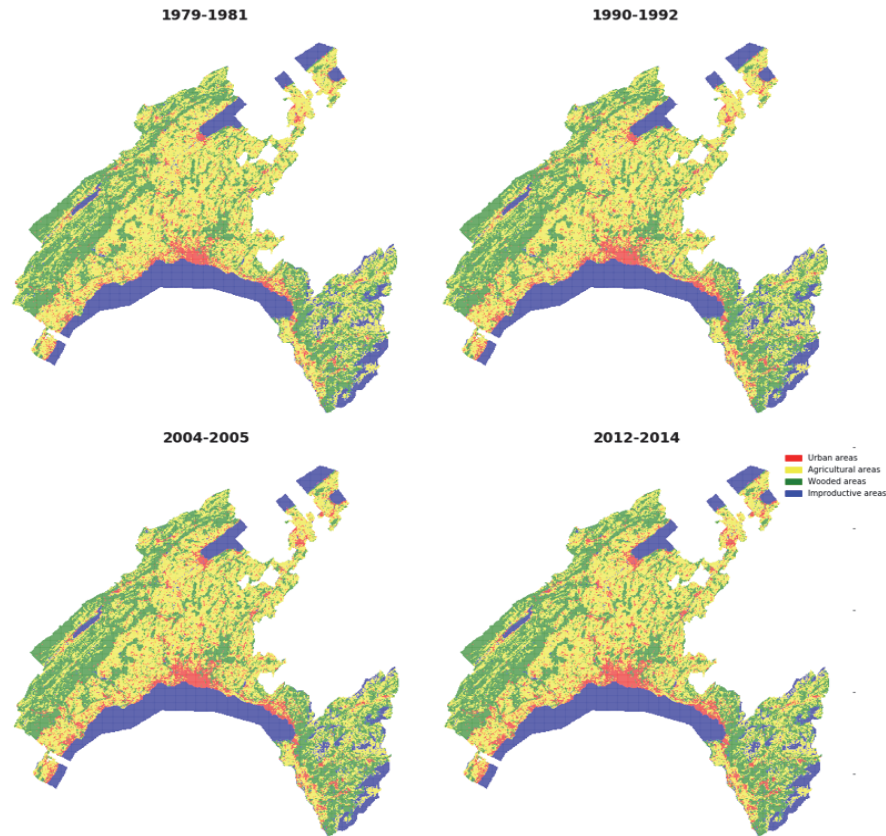
Figure 4.1 Evolution of main land uses in the canton of Vaud

Vaud is located in the western, French-speaking, part of the country, with a population of 767,497 inhabitants in 2015 (Statistique Vaud, 2017). It has a total surface area of 321,224 ha and a large topo-climatic gradient (altitude: 372–3210 m a.s.l). The canton comprises 309 municipalities, ranging from 31 to 11,370 ha.

We chose the canton of Vaud because it has a large variety of landscapes from lowlands to alpine regions. It also has the second largest quota of arable land in Switzerland, which has undergone urbanization. Between 1979 and 2014, the extent of urban areas grew from 24,000 ha to 32,143 ha, while the extent of agricultural areas decreased by 9,858 ha. The trend mainly affected arable land with their total surface area decreasing from 77,718 ha in 1979–1981 to 70,039 ha in 2012–2014. As such, urbanization is ongoing mainly on productive agricultural areas. In addition, the extent of wooded areas increased by 2,656 ha, mainly in mountainous regions in the eastern and western parts of the canton, at the expense of alpine pastures, with a loss of 1,623 ha (SFSO, 2015) (Figure 4.1).

4.2.2 Data analysis

4.2.2.1 Mapping of historical ES supply

Based on literature review followed by the elicitation of five academic experts on spatial planning and ecosystem services in Switzerland, 15 ES were initially selected (Jaligot et al., 2019a). The selection fell into the Common International Classification of Ecosystem Services framework version V4.3 that classifies final ES into three categories: regulating, provisioning

and cultural (Haines-Young and Potschin, 2013). For the purpose of this study, the list was shortened to 11 ES to meet the criteria of data availability across our study period (1979–2014). For example, timber production could not be assessed in this study as data were not available at the appropriate scale, but other ES were added, such as erosion control, flood regulation and water purification, compared to earlier work (Jaligot et al., 2019a). In total, one provisioning, five regulating, and five cultural ES were assessed (Table 4.1). We used mixed indicators ranging from potential capacity to actual supply, as in most work focusing on ES bundles (Christ et al., 2015; Queiroz et al., 2015; Spake et al., 2017; Vigl et al., 2017). Using primary data from various sources, we quantified the annual supply of all ES for each canton at four time steps: 1979–1981 (period 1), 1990–1992 (period 2), 2004–2005 (period 3), and 2012–2014 (period 4), corresponding to the four available land use/land cover (LULC) datasets available in the canton (SFSO 2015). We used a combination of participatory mapping for cultural ES (e.g. public participatory GIS), process-based (e.g. STREAM model for flood regulation) and proxy-based models (e.g. InVEST tool for pollination) to reconstruct the spatio-temporal patterns of ES supply. The mapping resolution was 100 m, like the LULC dataset. The detailed methodology and data sources are set out in Appendix B.1.

Table 4.1. Ecosystem services supply quantified for four different time steps in the canton of Vaud. Type refers to the type of ES supply, which can be potential supply or actual supply.

ES category	Ecosystem service	Type	Code	Unit
Regulating	Carbon stock	Potential/Actual	Carb	t ha−1 yr−
	Flood regulation	Actual	Flood	Index (dimensionless)
	Erosion control	Actual	Eros	t ha−1 yr−
	Water purification	Actual	Puri	Index (dimensionless)
	Pollination	Potential	Poll	Index (dimensionless)
Provisioning	Food production	Actual	Food	t ha−1 yr−
Cultural	Heritage	Potential	Herit	Index (dimensionless)
	Landscape aesthetics and landmark	Potential	Aest	Index (dimensionless)
	Outdoor activities	Potential	Out	Index (dimensionless)
	Inspiration, spiritual and religious	Potential	Insp	Index (dimensionless)
	Simple nature value	Potential	Simp	Index (dimensionless)

Our analysis was conducted at the municipal scale, as it is one of the most important for spatial planning in Switzerland. The mean of ES was calculated for each municipality (Liu et al., 2019; Queiroz et al., 2015; Spake et al., 2017). Higher indicator values correspond to greater ES supply. Maps of ES supply variations are available in Appendix B.2.

4.2.2.2 ES associations over time

To assess changes in pairwise ES associations, we calculated the variations of each ES between two consecutive time steps (period 1–period 2, period 2–period 3, period 3–period 4), and between the start and the end of the entire study period (period 1–period 4). We computed Spearman's rank coefficients between variations of ES on different time periods, including the entire study period. We note that the values were not transformed in order to preserve directionality in the data. We used Spearman correlation as it is suitable for non-normal data

and widely used in the literature (Qiu et al., 2018; Roces-Díaz et al., 2018; Schripke et al., 2019). Pairwise correlations are often used to identify synergies and trade-offs between ES (Raudsepp-Hearne et al., 2010; Spake et al., 2017). All significant correlations (*p* value < 0.05) were considered high ($|r| \geq 0.5$), moderate ($0.3 \leq |r| < 0.5$), and weak ($0.1 \leq |r| < 0.3$) (Cohen, 1992). The analysis was conducted using the *hmisc()* package in R (Harrell, 2019).

4.2.2.3 Cluster analysis of ES temporal variations

To identify co-occurrence of ES changes in bundles in a spatially explicit manner, a k-means cluster analysis was used over the entire study period (period 1–period 4). Following the widely adopted approach from Raudsepp-Hearne et al. (2010), a principal component analysis was first computed to quantify the main multivariate interrelationships between ES (Lin et al., 2018; Turner et al., 2014). For the purpose of this analysis, each ES was standardized by maximum value to a scale ranging from 0 to 1, in order to render them unitless and comparable, by subtracting from each value the minimum value observed for the dataset and then dividing by the difference between the observed maximum and minimum values (Paracchini et al., 2011). A key advantage of using PCA scores for bundling is that PCA axes represent uncorrelated components of ecosystem service data (Legendre and Legendre, 2012). K-means clustering was then applied to the relevant PCA axes representing 95% of the total variance to delineate ES bundles using 1,000 random starts and 10,000 iterations. The optimal number of clusters was qualitatively determined by examining the silhouette measure (Schripke et al., 2019). As ES could be used to inform spatial planning, we wanted to compare the performances of municipalities at supplying multiple ES. In total, four bundles were identified and ES changes were standardized to present ES z-scores averaged across all municipalities belonging to a specific bundle. A positive z-score refers to an above-average change in ES values and a negative z-score refers to a below-average change in ES in the study region (Spake et al., 2017). We refer to Appendix B.2 for the directionality of changes between 1979 and 2014 in each municipality. The analysis was conducted in Python v.3.6.

4.2.2.4 Drivers of ES bundles

The last step was to investigate the potential drivers of ES bundles, or the potential variables that may be linked to changes in ES supply in a specific bundle. Drivers are the factors that cause ES relationships to develop or change (Bennett et al., 2015). It is important to include human drivers such as environmental management or socio-political drivers (Dade et al., 2018). Potential drivers of ES change were selected based on a compromise between relevance and data availability at the municipal scale. It included social and ecological components that were used in the quantification of ES, to account for their influence on the clustering of the municipalities (e.g. LULC, topography) (Mouchet et al., 2017a; Spake et al., 2017), and other variables identified based on the literature (Table 4.2). Changes in LULC and population density variables have been widely used as drivers (Kienast et al., 2015; Fei et al., 2016; Jaligot et al., 2019a). Changes in the extent of protected areas relate to environmental governance, which tends to be highly correlated with high ES supply (Palomo et al., 2013; Santos-Martín et al., 2019). Finally, changes in municipal taxes per capita was used as an indicator of economic density (Mouchet et al., 2017a). To be consistent with the dependent variables (i.e. ES), potential drivers were calculated for the first and last periods, and the variation between the two

was used in the analysis. Each driver was standardized by maximum value to a scale ranging from 0 to 1.

Table 4.2. Overview of potential drivers of ES bundles

Potential driver	Code	Description	Unit	References
Agricultural areas	Agr	Municipality land area occupied by agricultural areas	%	SFSO (2015)
Arable land areas	Ara	Municipality land area occupied by arable land	%	SFSO (2015)
Urban areas	Urba	Municipality land area occupied by urban areas	%	SFSO (2015)
Wooded areas	For	Municipality land area occupied by wooded areas	%	SFSO (2015)
Population density	Den	Population density as the number of inhabitants divided municipal surface area	Inhab / km^2	Statistique Vaud (2017)
Protected areas	Prot	Municipality land area occupied by protected areas	%	DGE (2019), FOEN (2019 a, b)
Economic density	Tax	Total municipal tax revenues divided by the number of inhabitants	CHF / per capita	Statistique Vaud (2017, 2018)
Elevation	Alt	Mean derived from DHM25 global digital elevation model	Meters	Swisstopo (2001)
Slope	Slop	Mean derived from DHM25 global digital elevation model	Degrees	Swisstopo (2001)

Canonical analysis allows the quantitative testing of the relationships between a multivariate dependent variable (i.e. ES) and explanatory variables (i.e. potential drivers) (Mouchet et al., 2014). For each bundle, a redundancy analysis (RDA) was combined with a (forward) stepwise procedure to select the model with the combination of explanatory variables with the highest R^2 and smallest *p*-value (Legendre and Legendre, 2012; Mouchet et al., 2017a; Urban et al., 2006). Multicollinearity among predictor variables was checked using the Variation Inflation Factors (VIF), and collinear variables were removed from the model. All VIF values were smaller than 5, indicating that multicollinearity was not a problem in the models (Groß, 2003; Zuur et al., 2009). The test was conducted using the *vegan()* package in R (Oksanen et al., 2007).

4.3 Results

4.3.1 Temporal patterns of ES change associations

The many negative and positive associations between ES changes highlighted their complex relationships over time. A positive temporal correlation indicated that the pair of ES changed in the same direction, while a negative correlation indicated that they changed in opposite directions (Figure 4.2). All cultural ES changed in the same direction through time indicating a synergetic relationship over the entire study period. In contrast, food production showed the largest number of negative associations with most other ES. Changes in food production were negatively correlated with erosion control, carbon stock, and two cultural ES (i.e. heritage and inspiration) through time. Nevertheless, changes in food production tended to have positive and significant relationships with changes in flood regulation.

Regulating ES showed various levels of associations, not always consistent through time. Changes in carbon stock always had a very significant, positive relationship with flood regulation. Relationships with pollination and erosion control were mostly insignificant, either positive or negative. Interestingly, the correlation between carbon stock and water purification was never consistent through time, but was negative and significant over the entire study period. This was also the case for pollination. Although there was no clear trend of significant correlation between erosion control and two regulating ES, it had a significant positive correlation with pollination and water purification. Finally, pollination was never significantly related to carbon stock or flood regulation, except over the entire study period where a negative relationship was observed. Changes in pollination tended to have a positive association with erosion control and water purification for each period and over time.

Associations between changes in cultural and regulating ES tended be positive and significant. Erosion control and flood regulation, as well as water purification, had the strongest positive associations with cultural ES across each period and over the entire study period, respectively. Carbon stock was positively related to landscape aesthetics but the relationships were less clear and/or insignificant with other cultural ES. A similar observation could be made for the relationship between pollination and simple nature value.
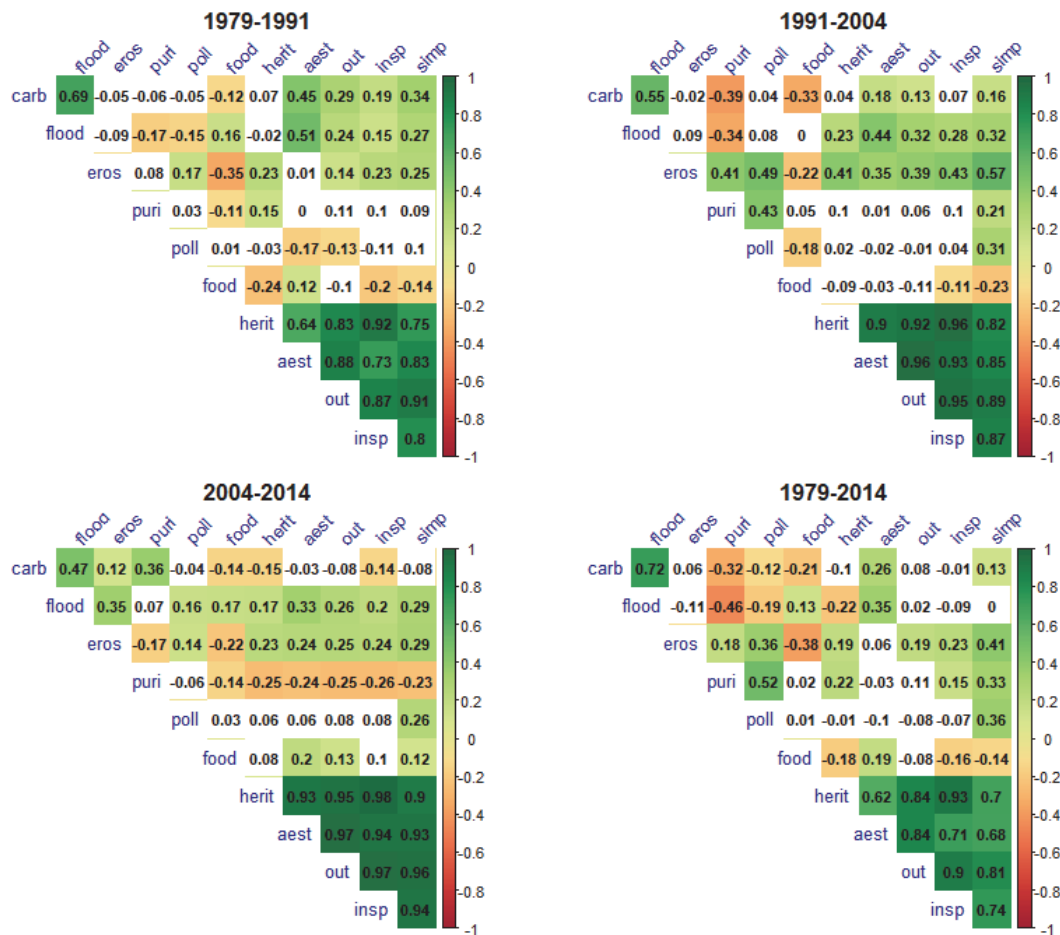

Figure 4.2 Historical association of ES temporal variations.
Highlighted cells indicate a significant relationship ($p < 0.05$). Orange and red colours reflect significant, negative correlations that are defined as trade-offs, while green colours reflect significant, positive correlations that are defined as synergies.

4.3.2 Spatial patterns of ES variations

The k-means clustering analysis partitioned the canton into four bundles based on changes over the entire study period (Figure 4.3). Bundle 2 comprised 142 municipalities, and was characterized by a highly above-average change in food production, but also slightly above-average changes in pollination, flood regulation and water purification. The municipalities were clustered in the central part of the canton, belonging to the lowlands (i.e. the Plateau region). They are characterized by agricultural land coverage at low elevation and low-to-intermediate cover of other land uses. Most urban municipalities located in the south of the canton bordering Lake Geneva belonged mostly to the third bundle. It comprised 63 municipalities characterized by the largest, above-average, change in pollination and water purification. Moderate, above-average changes were also observed for erosion control and the cultural service heritage. We note that bundle 3 was also characterized by the lowest change in food production. The eastern and western regions were dominated by bundle 1 and bundle 4, respectively. Forty-eight municipalities belonged to bundle 1, which was dominated by cultural ES, carbon stock, erosion control and flood regulation in wooded areas. Finally, 56 municipalities made up bundle 4, which was defined by the lowest, below-average, change in all cultural ES, erosion control, pollination and water purification. An average change in food production occurred in the bundle, and slightly above-average changes were recorded for carbon stock and flood regulation.

4.3.3 Drivers of ES variations

RDA revealed that the combination of changes of the following variables were significant ($p < 0.05$) and explained the co-variation of ES indicators in bundle 1: protected areas, population density, agricultural areas and altitude (Figure 4.4). Changes in cultural ES were strongly related to population density, while regulating ES were related to different factors. Carbon stock was strongly related to altitude and changes in protected areas, as were, to a moderate extent, erosion control and flood regulation. Water purification and pollination, as well as food production, were strongly related to changes in agricultural areas. Seven variables were significantly driving bundle 2: urban areas, arable land, population density, forest areas, protected areas, slope and altitude. Food production was related to forest cover and protected areas, as well as slope. Changes in pollination were related to population density, forest cover and protected areas. Other regulating ES such as flood regulation and carbon sequestration were mostly related to slope and altitude, and to a minor extent forest cover and protected areas, but were negatively related to urban areas. The relationships were less clear for culture ES and erosion control. Bundles 3 and 4 were associated with a more restricted set of factors (Figure 4.4). In the case of bundle 3, altitude, slope, forested cover and urban areas were the significant potential drivers. Regulating ES were associated with slope and forest cover, except pollination which was related to changes in arable land and urban areas. Changes in heritage and inspiration were driven by changes in urban areas. The last bundle was potentially driven by the fewest number of variables: altitude, protected areas and slope. Carbon stock were strongly related to altitude, protected areas and slope, while food production and water purification were negatively associated with altitude. Relationships between other ES and potential drivers were less clear.
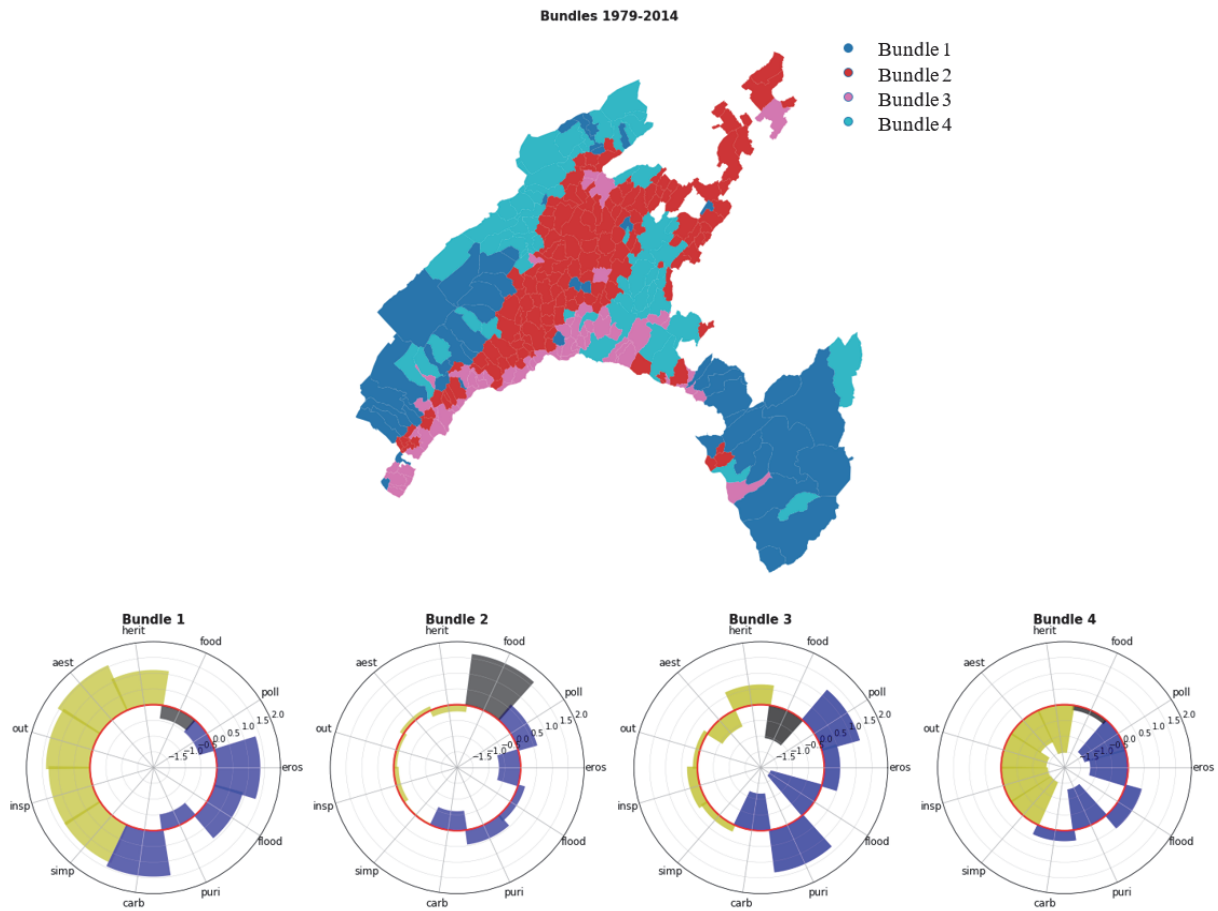
Figure 4.3 Distribution of ecosystem services bundles in the canton of Vaud for the period 1979-2014. The red line indicates an average ES change. The blue segments indicate regulating ES, the green segments indicate cultural ES, and the black segment indicates provisioning ES. Values are ES z-scores averaged across all municipalities belonging to a specific bundle. A positive z-score refers to an above average change in ES values and a negative z-score refers to a below average change in ES. We refer to Appendix B.2 for the directionality of changes between 1979 and 2014 in each municipality.
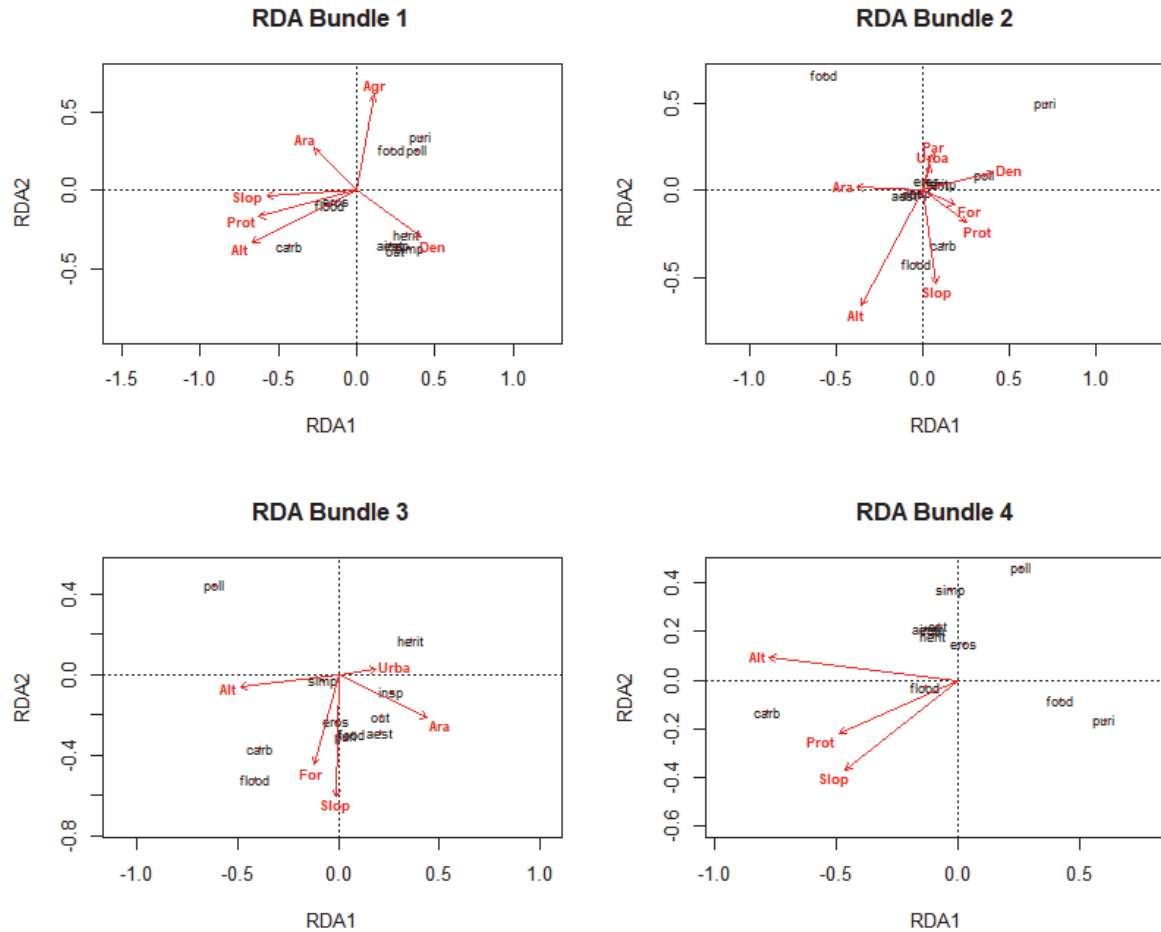
Figure 4.4 Redundancy analysis biplots
Bundle 1 parameters explained 29% of the variance (*p*<0.001), 23% in bundle 2 (*p*<0.001), 15% in bundle 3 (*p*<0.001), and 26% in bundle 4 (*p*<0.001). Codes are in table 4.1 and 4.2.

4.4. Discussion

4.4.1 Spatio-temporal patterns of ES

In general, our findings confirm previous results, which stated that the variations of ES through time are related to spatial configuration, and to the configuration of social-economic and environmental characteristics within a region (Spake et al., 2017). Our framework of analysis was used to make sense of relationships between ES patterns in a complex social–ecological system. The bundling exercise captured key patterns in the provision of ES driven by past ecological and social dynamics (Raudsepp-Hearne et al., 2010). While the general pattern of bundle formation, with a forest-dominated bundle (bundle 1) or an urban dominated bundle (bundle 3), was consistent with other work (Lorilla et al., 2018; Quieroz et al., 2015), the trade-offs and synergies within a specific bundle could vary, showing that bundle analysis remains context-specific. Our results also highlighted the contrast between the most productive and highly populated lowland region (the Plateau) in the central part of the canton, and the less productive ones in the west and east. In line with other work (Mouchet et al., 2017a; Quieroz et al., 2015), we noted a dichotomy in bundle types with those where ES trade-offs tended to arise from the ability of a specific land use to provide a service (e.g. forests for multiple services

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in bundle 1), and those tending to arise from conflicting land uses (e.g. food production vs. erosion control in bundle 2).

Persisting negative relationships between food production and regulating or cultural ES confirmed the results of previous work (Power, 2010). This trade-off may be explained by lasting intensive agriculture since the 1980s at the expense of social benefits and regulating ES (van Berkel and Verburg, 2014; Zimmermann 2006). Services provided in the Plateau region, clustered in bundle 2, were mostly limited to food production. The highly above-average change showed that food production was maximized at the expense of most other ES, suggesting that trade-offs could appear whenever a particular service is maximized (Quieroz et al., 2015). Nevertheless, we noted that food production showed little correlation with some ES, such as flood regulation and pollination, as well as outdoor activities and landscape aesthetics. One explanation could be that changes in these services and their associated land uses were less mutually exclusive, thus more easily combined (DeFries et al., 2004). In other words, ES that are often shown as antagonistic in the literature may demonstrate a synergy if changes over two consecutive time steps are considered, in accordance with Tomscha and Gergel (2016).

Landscape multifunctionality was the highest in bundle 1, where urbanization and crop production were the lowest. It was characterized by a below-average change in food production and a strong increase in most regulating and cultural services (especially erosion control and carbon stock) due to ongoing land use shifts from agricultural land into wooded areas caused by land abandonment in mountainous regions, natural reforestation and the increase in protected areas (Schripke et al., 2013; Vigl et al., 2016). This was consistent with other studies that suggested that afforestation, natural forest growth and an increase in riparian-zone vegetation have the potential to simultaneously increase carbon sequestration, forest recreation and food regulation (Qiu and Turner, 2013; Weller et al., 2011). However, urban municipalities in bundle 3 could also provide multiple services. Swiss urban areas are relatively green, with patches of wooded areas acting as protection against erosion, or parks that are adequate for the activity of pollinators. Similar results were found in Swedish (Quieroz et al., 2015) and Danish municipalities (Turner et al., 2014). However, these findings also contrasted with other studies, in which urban bundles provided a negligible amount of ES (Baró et al., 2017; Lorilla et al., 2018).

Interestingly, regulating ES were not always synergetic, which tends to contradict previous results (Braun et al., 2018; District et al., 2017). The negative associations between water purification and carbon stock, as well flood regulation, typically occurred in bundle 3 that was dominated by a well-below-average change in food production, carbon stock and flood regulation, and above-average change in water purification. One explanation could be the coupled effects of a large urbanization trend and the decrease in fertilizer use, which led to negative changes in the supply of food, carbon stock and flood regulation, but an increase in water purification supply, respectively.

Although, cultural and regulating ES were most often synergetic, analyzing the potential drivers of change of different bundles showed that neither category responded to the same drivers. While bundle 1 showed an increase in all cultural ES, as well as carbon stock, flood regulation and erosion control, the potential drivers were different. In accordance with previous

work, changes in cultural ES tended to be related to population density (Liu et al., 2019), while regulating ES were mostly related to the presence of protected areas and high altitude (Spake et al., 2017). In the same bundle, changes in food production, pollination and water purification were more related to the percentage of agricultural areas. Bundle 4 was a mix of agricultural and non-agricultural municipalities. The above-average change in carbon stock and flood regulation responded to the same drivers of protected areas and altitude. The relationships in bundle 4 showed a steep decrease in most ES supplies. Despite the large increase in protected areas, which had a positive impact on carbon sequestration and flood regulation, and the presence of cropping areas, which led to an average change in food production, the supply of CES and other regulating ES decreased drastically. Therefore, regulating services of carbon stock and flood regulation tend to occur in municipalities that are more remote, and are less impacted by an increase in population density than cultural ES, which tend to co-occur in municipalities that are poorly densely populated (bundle 1).

4.4.2 Implications for spatial planning

A critical question for planning is how to integrate multiple services and ensure their sustainable use while minimizing trade-offs. The decision of landscape specialization (i.e. land sparing) for a specific ES, such as food production, was observed for bundle 2 and led to the concentration of agricultural production and the limited supply of all other services. In other words, municipalities that favored a land sparing management policy did not succeed in ensuring landscape multifunctionality, and confirmed that the current Swiss policy that preserves the best arable land (i.e. land crop rotation areas or *surfaces d'assolement*) has limited power in ensuring the supply of multiple ES (Jaligot et al., 2019a; Lüscher, 2003). Regions prone to supply cultural ES were located mostly in areas distant from urban municipalities, as those services typically suffer from urban sprawl, a high increase in population density and agricultural intensification, as was the case for bundle 1 (Vigl et al., 2017). The results also highlighted that ES can be synergetic in one bundle but antagonistic in another, and that different processes can cause changes in the same ES depending on their supply location.

As shown in bundle 4, protected areas may be a good option to safeguard biodiversity but may not be the sole answer to preserve ES supply (potential or actual) (Castro et al., 2015). It also shows that some municipalities may not have the right geographical and socio-economic situation to minimize trade-offs. It is clear that municipalities were able to supply ES at different levels, and none showed an increase in all ES. It seems unrealistic to require each municipality to have a multifunctional territory in this context. The current political context offering high levels of protection to arable land and forests may not be suitable to minimize trade-offs between all service categories. We suggest two different perspectives for spatial planning. The first perspective would entail agreements on different planning practices at a supra-municipal level in Switzerland to better protect ES and ensure landscape multifunctionality if current policies remain (Schwaab et al., 2018). In other words, some municipalities would supply part of the services, while others would supply the remaining ones. This would facilitate the planning process and alleviate the challenge for municipalities to provide a multifunctional landscape, which is persistent across space and time (Zarrineh et al., 2018). The second perspective could be that municipalities adopt land sharing practices (i.e. integrating the

provision of multiple ES on the same land). This could be translated by merging sectorial policies leading to moderate density changes, and the promotion of extensive agriculture and forest multifunctionality in the same landscape. However, it would require a drastic revision of current planning policies. Future research on testing the applicability of these perspectives as viable planning options by focusing on governance, policy and ES demand aspects is required.

4.4.3 Methodological considerations

This study used a combination of participatory mapping, process-based and proxy-based models to reconstruct the spatio-temporal patterns of ES supply (Costanza et al., 2017; Rabe et al., 2018). Despite the use of different methods to reflect, whenever possible, the underlying ecological processes, and the integration of ES indicators that are believed to be relevant in the study area, this research has some potential limitations which should be highlighted.

First, some of these methods have limitations. For example, using participatory mapping to obtain a value of cultural ES for each LULC category was equivalent to the benefit transfer approach (Burkhard et al., 2012). However, mapping a spatial attribute with a point does not provide information related to the extent of the supply area outward from that point. In addition, fewer places were mapped in terms of inspiration and simple nature value possibly due to their rather vague and spatially inexplicit character (Rall et al., 2017). Therefore, a hardcopy and polygon-orientated approach could be an appropriate complement to this approach.

Second, an important consideration is the interpretation of our results on the influence of ES selection and indicators. The selection of ES indicators comprised both potential supply values, based on the capacity of ecosystems, and actual values, considering the actual benefits, as in most previous ES bundle analyses (Christ et al., 2015; Queiroz et al., 2015; Spake et al., 2017; Vigl et al., 2017). Therefore, the observed associations between ES do not necessarily imply that they are supplied jointly but that the ecosystem has the potential for supplying both or that human practices support ES coexistence (Christ et al., 2015). For example, the potential for outdoor activities could be high in forested areas, even if they are very remote and probably less used. Therefore, ES bundles delineated by cluster analysis in this study are not entirely generalizable to other regions, as the results depend on the variables used (Rodríguez-Loinaz et al., 2015). However, Christ et al. (2015) argued that mixing indicators is interesting as it highlights that the ES actually supplied in a bundle depends on land management choices. For example, consistent associations between crop production and pollination capacity emphasizes that actual pollination depends on the intensity of agricultural practices. In addition, some of the variables used as potential drivers of change were directly used in the modeling of ES supply (e.g. land cover, topography). We did so to account for their influence on the clustering of municipalities, and to be consistent with similar work on ES bundles (Mouchet et al., 2017a; Spake et al., 2017).

Finally, scale is an important consideration in the interpretation of our results. Assessing ES across the smallest administrative units allowed us to identify shared ES supply and trade-offs between different areas in the canton. However, municipal boundaries could be relevant for some services, such as cultural ones, but arbitrary for managing water-related services, as they bisect ecologically meaningful units such as watersheds (Spake et al., 2017). At the municipal

level, the identification of ES bundles relies on spatial coincidence (Christ et al., 2015), where it is assumed that ES relationships likely emerge from common drivers. However, some ES often do not respond to drivers represented at this scale. Also, coarse spatial units are highly heterogeneous in terms of LULC types, leading ES relationships to be largely driven by fractional land cover. In other words, ES relationships will mainly reflect LULC distribution, where two ES may show a trade-off because they simply compete for space. Although this might be the case for static approaches, we believe that a temporally informed framework such as the "change-over-time" approach (Tomsha and Gerbel, 2016), that considered ES associations determined from a map difference, may mitigate this issue (Tomsha and Gerbel, 2016; Vallet et al., 2018). Although administrative boundaries rarely coincide with ecological ones (Vigl et al., 2016), municipality level was considered as a convenient scale for ES analysis to inform policy making while providing accurate spatio-temporal patterns for managers and policy makers (Roces-Díaz et al., 2018).

4.5 Conclusion

This paper presents a spatially explicit approach to assess ES supply, and identifies potential drivers of change in the last 40 years. We show that the patterns of ES changes are not static through time. In this study, maps of ES bundles were used as valuable tool for prioritization and problem identification, showing ES associations that are consistent through space and time. We analyzed the spatial distribution of ES bundles, delineated by cluster analysis. The maps provided valuable insights for targeted management decisions. Some ES categories such as cultural and regulating ES were most often synergetic in all bundles. However, analyzing the potential drivers of change of different bundles showed that neither ES category responded to the same potential drivers, as cultural ES responded to changes in population density, while regulating ES responded mostly to the presence of protected areas and high altitude.

The results provide strong evidence that ES can be synergetic in one bundle, but antagonistic in another, and that different processes can cause change in the same ES depending on their supply location. It was clear that municipalities supplied ES at different levels, and none showed an increase in all ES over time. It seems unrealistic to require each municipality to have a multifunctional territory in the current policy context. We suggest two potential planning perspectives based on the results. The first perspective could be the implementation of supra-municipal planning, if current planning policies remain, to better protect ES and ensure landscape multifunctionality. This would facilitate the planning process and alleviate the challenge faced by each municipality to provide a multifunctional landscape. The second perspective could be that municipalities could adopt land sharing practices (i.e. integrating the provision of multiple ES on the same land). However, this would require a drastic revision of current planning policies by merging sectorial policies, and further research is required on aspects of both policy and ES demand. Overall, our findings and approach could be applied to develop ecosystem-based management and planning policy.

Chapter 5

Stakeholders' perspectives to support the integration of ecosystem services in spatial planning in Switzerland

Abstract

Integrating the concept of ecosystem services (ES) into spatial planning is an opportunity to make land use and management choices that maximize the delivery of multiple ES. The assessment of social demand can be useful for the identification of priority areas or potential conflicts among stakeholders. We used Q-methodology to understand stakeholder perspectives on ES to facilitate their integration into spatial planning in the canton of Vaud, Switzerland. Three perspectives, utilitarian, cultural and protective, were analyzed and used to discuss potential implications for spatial planning. First, ecosystem multifunctionality and synergies among ES should be emphasized. Second, the food production system should move away from a productive-only approach, to a system that protects soils and their functions. Providing a paradigm change, arable land could be protected to the same level as forests and farmers could be incentivized further to change their practices. Finally, our findings show a potential over-interpretation of the importance of cultural ES in current planning policies, as most participants would be ready to change their behaviors to preserve biological functions. It would be useful to conduct a similar study in other cantons to ensure that the results are fully representative of the current situation in Switzerland.

5.1 Introduction

Ecosystem services (hereafter ES) can be defined as "the benefits that people derive from biodiversity and ecosystem functions" (Wu, 2014). ES are directly influenced by spatial planning, which is a key instrument for decision-making to coordinate human activities and their influences on land systems. Including ES in spatial planning is considered a suitable approach for informing, communicating, and consensus-building between multiple actors as it allows multi-sectoral and interdisciplinary collaboration (Albert et al., 2014; Rozas-Vásquez et al., 2018). While the concept of ES is considered complementary to current spatial planning practices, there is increasing awareness that benefits provided by natural and land systems were often overlooked or underestimated in planning decisions (Cortinovis and Geneletti, 2018; Hein et al., 2016; Jaligot and Chenal, 2019). To overcome this issue, work has been conducted to develop integrated assessment of ES requiring different values, interdisciplinarity, use of multiple methodologies (qualitative and quantitative) at various temporal and spatial scales (Gómez-Baggethun et al., 2014; Pandeya et al., 2016). The use of ES into spatial planning is an opportunity to make land use and management choices that maximize the delivery of multiple ES (Turkelboom et al., 2018). Therefore, the assessment and mapping of ES have gained traction, particularly in Europe, under the requirement from the EU Biodiversity Strategy to Member States to evaluate and map ES (Target 2-Action 5) (Jopke et al., 2015; Maes et al., 2013; Rabe et al., 2018). However, research showed that not all ES can be maximized simultaneously other than by trade-offs (Allan et al., 2015; Bradford et al., 2014). ES tradeoffs could be addressed by the assessment of ES supply at various planning levels, to assist stakeholders in making rational decisions, particularly within a temporal informed framework (Jaligot et al., 2019b). However, tradeoffs not only arise due to relationships between ES but also due to diverging stakeholders' perception of ES supply with deep-rooted conflicts over rights and resources (Spash, 2013; Stosch et al., 2019). The growth of conflicting human demands on ES poses a serious threat to ecosystem health and the sustainable development of human society as ES depend on the interactions between supply side (ecosystem) and the demand side (socio-economic) (Maes et al., 2013). While much work has focused on the quantification and mapping of ES supply, relatively little effort was put on assessing stakeholder's preferences and perceptions of ES, which can be defined as social demand (Castro et al., 2013). However, this is essential to improve the provision of ES for all stakeholders and decrease conflicts to help their integration in planning (Castro et al., 2016).

ES management decisions often involve complex, uncertain, scientific, social or cultural elements with conflicting perceived values by stakeholders, as well as the increasing public concern for environmental management (Armatas et al., 2014; Winkler and Nicholas, 2016). Recent work called for a deeper understanding of value plurality underlying the different positions held by various stakeholders to improve public support, avoid conflicts and convey legitimate information to integrate ES into spatial planning (Crouzat et al., 2018; Martín-López et al., 2015; Turner and Daily, 2008). Stakeholders perceive value, demand and prioritize ES in different ways, which can be quantified as the social demand for ES (Martín-López et al., 2014). However, assessing social demand can be useful for the identification of priority areas for integration into planning or potential conflicts among stakeholders (Castro et al., 2014).

It is essential for planners and policy makers to consider the perception of stakeholders to integrate ES into spatial planning to address not only ecological priorities but also social demand (Buchel and Frantzeskaki, 2015). Policy makers should promote rural areas as not only working landscapes for agriculture but also as ecosystems with a broad range of services that contribute to human well-being in an equal manner (Gutman, 2007; Lüscher, 2003). In Switzerland, sustainable management of ES in rural areas is challenged because of complex administrative processes characterized by a decision-making process that is "layered" (Messer et al., 2016), and "fragmented" (Hersperger et al., 2017). Currently, the concept of ES is poorly integrated into planning instruments (Jaligot and Chenal, 2019). Recent work attempted to integrate the economic concept of ES demand as the preferences people express for different ES under a budget constraint in an integrated modeling framework (Brunner et al., 2016). Agent-based modeling was used to model future demand and the resilience of social-ecological systems (Grêt-Regamey et al., 2019). Despite previous research highlighting the importance of integrating ES demand in economic terms, to our knowledge, limited work attempted to understand the plurality of stakeholders' perceptions of ES under a spatial planning perspective in Switzerland.

This study aims at assessing stakeholder perspectives on ES to facilitate their integration into spatial planning. The specific objectives are: (i) to identify relevant stakeholders through stakeholder analysis, (ii) to characterize stakeholders' perceptions of the importance of ES for spatial planning, and (iii) to discuss the implications for spatial planning. We used stakeholder analysis followed by Q methodology to identify key stakeholder's values, or social demand, associated with ES to improve their management. Q-methodology is a tool for discourse analysis that combines both quantitative and qualitative data through statistical analysis to explore different opinions that exist about a topic (Brown, 1996).

5.2 Methodology

5.2.1 Study site

The canton of Vaud is located in the western, French-speaking part of Switzerland, with a population of 767,497 inhabitants in 2015 (Figure 5.1) (Statistique Vaud, 2017). It has a total surface area of 321,224 ha. In past decades, the canton has undergone a large urbanization trend with the extent of urban areas increasing from 24,000 ha to 32,143 ha, while the extent of agricultural areas decreased by 9858 ha. Although the canton has the second-largest quota of arable land in Switzerland, according to its urbanization trend, its total surface area decreased from 77,718 ha in 1979/1981 to 70,039 ha in 2012/2014. As such, urbanization is ongoing mainly on productive agricultural areas. The opposite is observed for wooded areas as their extent increased by 2656 ha, mainly in mountainous regions in the eastern and western parts of the canton, at the expense of alpine pastures (SFSO, 2015). Changes in land use triggered different variations in ES supply and led to trade-offs over time, which should be mitigated. The concept of ES accesses the same thematic areas as spatial planning, so both could complement each other to organize landscapes, land use, urbanization and the use of natural resources (Turkelboom et al., 2018).
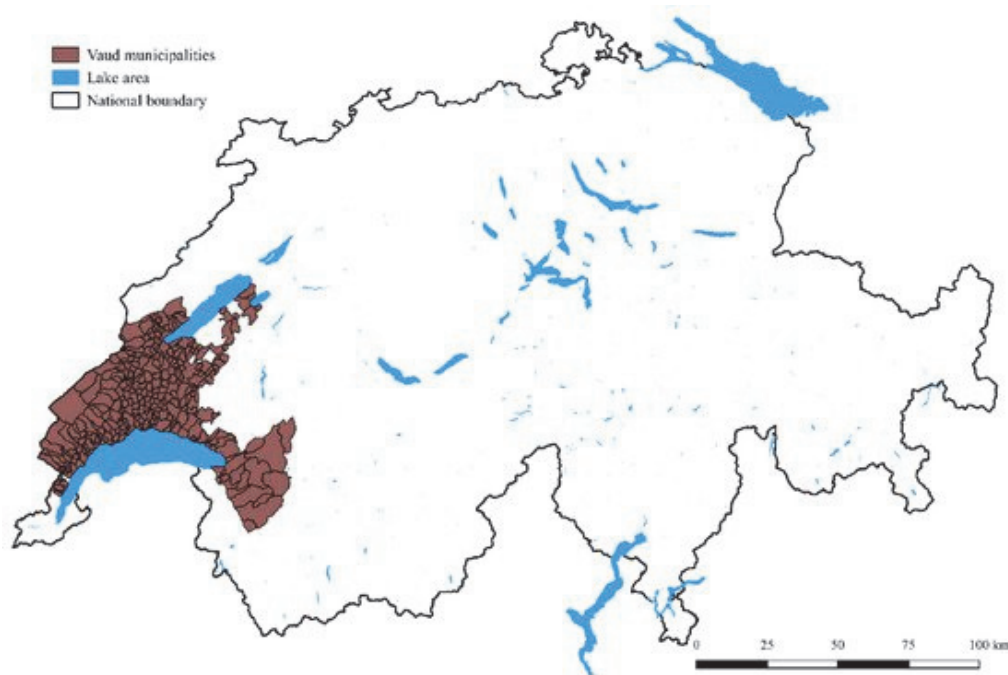
Figure 5.1 Administrative boundaries of municipalities in the canton of Vaud.

5.2.2 Q-methodology

Gathering stakeholders' perspectives on ES required a participatory approach. Participatory methodologies of monetary or non-monetary valuation of ES usually ask participants to choose from a variety of answers, which are associated with subjective beliefs, before ranking them or scoring them. The researcher will often loose individual and personal position by using basic statistical analysis such as averaging. Measuring subjectivity in a structured away, while preserving individual data can be done with the Q methodology (Brown, 1996; Stephenson, 1953). The methodology is useful to reveal patterns between stakeholders across a sample of variables, in contrast to a standard survey approaches or semi-structured interviews that see patterns among variables across a sample of participants (Barry and Proops, 1999). The objective is to use variance analysis in Q-methodology combined with correlation analysis among statements (Q-set) to prioritize ES for spatial planning by the person-sample or stakeholders (P-set) with varying perspectives. The method involves the following steps: Developing diverse statements on a subject (Q-statements), asking participants from the P-set to sort these statements following a quasi-normal distribution during individual interviews (Q-sorts), and examining the relationships among Q-sorts using inverted factor analysis and extracting the dominant factors (Brown, 1996). We note that the limitations of the methods are discussed in section 5.4.3.

5.2.2.1 Q-Set

The statements were pre-prepared by the authors to cover eleven ES mapped in previous work (Jaligot et al., 2019b). The selection fell into the CICES framework version v4.3 (Haines-Young and Potschin, 2013). Each ES was translated into three statements that could capture individual perception in the specific local context. The statements can be derived from a broad range of sources, including peer-reviewed literature, grey literature, direct interviews, and

personal opinions (Pike et al., 2015). All these sources were investigated during the generation
of the Q-set. We derived 33 initial Q-statements (three for each service to avoid over-
representation of one service over another) based on previous Q-studies on people's perception
of ecosystem services (Bredin et al., 2015; Buchel and Frantzeskaki, 2015; Winkler and
Nicholas, 2016). In addition, interviews used in the selection of ES (Jaligot et al., 2019b), and
cultural values were elicited in Switzerland using a participatory approach (Jaligot et al.,
2018b). We pilot-tested the Q-set with 10 researchers in the field to make sure that they were
sufficiently clear and relevant. The result of this process was a set of 33 statements, which were
presented to individual stakeholders from the P-set (Table 5.1).

Table 5.1 Thirty-three Q-statements of ecosystem services.

CICES Category	Ecosystem Service	N°	Statement
Regulating	Carbon stock	20	Ecosystems help regulate climate by sequestering carbon dioxide
		4	Ecosystems are green lungs for urban areas
		33	The role of soils is as important to store carbon as one of forests
	Flood regulation	12	Ecosystems moderate weather events and maintain river channel stability
		26	The influence of ecosystems on flood reduction plays a role before its occurrence and after its formation
		6	Ecosystems regulate river discharge and help achieve flood damage reduction at the lowest costs
	Erosion control	19	Ecosystems support the vegetation that protects soils from washing out
		23	Ecosystems prevent soils from washing out and ensures their fertility and productivity
		5	Ecosystems protect soils from erosion, which facilitates crop management and sustains homogenous crops
	Water purification	27	Water filtration by ecosystems can help maintain healthy aquatic habitat
		11	Water filtration by ecosystems is essential to get good drinking water quality
		32	Water filtration is linked to microbial diversity and natural land cover continuity
	Pollination	22	The state of biodiversity is essential to support the life of pollinators
		8	The activity of pollinators cannot be compensated by technology and plant-protection products
		18	Pollination supports many benefits such as the production of food, recreational opportunities, etc.
Provisioning	Food production	17	Ecosystems provide adequate grounds for intensive farming
		28	Croplands are the most essential component of food self-sufficiency in the region
		7	Crops may be dependent on other ecosystems but technology and plant-protection products could be substitutes
Cultural	Heritage	9	Ecosystems are strongly tied to local traditions and identity
		31	Ecosystems encourage a sense of community and transmission between people
		13	Ecosystems are crucial to pass down traditions to future generations
	Landscape aesthetics and landmark	10	Ecosystems reflect the beauty of nature
		24	Ecosystems allow to unwind in beautiful landscapes
		16	The structure of the underlying landscape appears in a beautiful way in the canton
	Outdoor activities	30	Ecosystems are a good place to exercise (e.g. running, cycling, skiing)

	2	Ecosystems are a good place to sit or walk (e.g. lunch, reading, dog walking)
	21	Tourists attracted by ecosystems in the canton benefit the region
Inspiration, spiritual and religious	3	Ecosystems help to have a creative activity (painting, writing, playing music)
	14	Ecosystems help to get new professional or creative ideas
	25	Ecosystems are important constituents of religious beliefs
Simple nature value	1	It is joy to know that ecosystems are being protected
	29	There is no substitute for being physically connected to ecosystems
	15	Ecosystems' functioning can be used as an example for human societies (e.g. biomimetic)

5.2.2.2 P-Set

The objective was to identify the main stakeholder groups that are relevant to ES management and spatial planning in the study area. Stakeholder analysis is characterized by two main stages (Reed et al., 2009): (i) identification of stakeholders, and (ii) analytical categorization of stakeholders. The steps can vary based on the purposes of the analysis, and the variables used in the classification systems such as power, proximity or interests (Gass et al., 1997; Paletto et al., 2015). Considering the dependence on ES and the relevance in the decision-making process, the main categories of stakeholders are primary stakeholders and secondary stakeholders. Shepherd (2004) describes primary stakeholders as those who are most dependent upon ES, and most likely to take an active part in managing them. Secondary stakeholders are over-powerful voices that may include local government officials who live near ES but do not greatly depend on it or those who depend on it but have a low degree of influence such as farmers, tourists and international conservation organizations.

- Identification of stakeholders

We split the stage of stakeholder identification in two steps to build an iterative process (Paletto et al., 2015; Turkelboom et al., 2018). First, the first list of 14 stakeholders is set based on three information sources: Our research group, name request to key informants, as well as the grey literature. The criteria used to make the first list of stakeholders are (i) the dependence on the ES (or stake in ES trade-offs), and (ii) the proximity with the services in order to consider mainly local stakeholders. Second, previously unknown stakeholders were identified with a snowball sampling approach, in which initial stakeholders provide additional people to take part in the study (Harrison and Qureshi, 2000). The initial group of primary stakeholders was administered a short questionnaire during the interview where they identified unknown stakeholders who were relevant to the study from their involvement in ES trade-offs and the decision-making process. Overall, 29 secondary stakeholders were identified, and 18 accepted to take part in the study. To avoid bias, no pre-defined list of stakeholder categories was proposed, and the number of stakeholders was not limited.

- Categorization of stakeholders

Stakeholders identified in the previous stage are divided into seven groups: "Nature conservation", "agriculture", "forestry", "planning", "academia", "tourism" and "residents".

The secondary screening was required to make sure that all the stakeholders were allocated to the proper stakeholder groups.

There are varying views on the number of participants in Q methodology. While some studies sampled more than 60 participants (Armatas et al., 2014; Calvet-Mir et al., 2012; Pike et al., 2015), others argued that fewer participants than the number of statements in the Q-set are adequate (Bredin et al., 2015; Hermelingmeier and Nicholas, 2017; Webler et al., 2009). For the purpose of this study, a medium number of participants was considered sufficient to be confident that the breadth of viewpoint within each stakeholder group was captured. Thirty-two stakeholders were selected based on the stakeholder analysis (14 primary and 18 secondary stakeholders), in line with previous work (Buchel and Frantzeskaki, 2015; Hermelingmeier and Nicholas, 2017; Lee et al., 2017). We note that two stakeholders could not due to the exercise at the time, bringing the total number of participants to 30. We conducted 45 min to 60 min long, individual face-to-face interviews.

5.2.2.3 Interview and Q-Sorts

Before the interviews, the participants were given an explanation about the purpose of the study and the categories of ES (Table 5.1). The second and main part of the interview was the Q-sorting phase where the quantitative data was generated. The participants were asked to sort the 33 statements, based on their priorities for spatial planning. Each statement was printed on a separate card and numbered randomly for further analysis. To reduce the cognitive burden, they were asked to classify the statements in three main categories: Those that they disagreed with, those that they agreed with, and neutral. Then the participants placed statements from each pile on a board representing a quasi-normal distribution on a nine-points scale from −4 to +4 (i.e. disagree to agree). The board contained the exact number of statements in the Q-set (Figure 5.2). The participants first placed the cards from the pile "disagree", and consecutively until they ran out of cards to create a Q-sort. The last part of the interview focused on gathering qualitative data to help interpret the Q-sorts, in which the participants were asked to discuss the reasoning for ranking the statements in the way they did. They were also asked if they would have sorted the statements differently in consideration of another context than the canton of Vaud. Follow-up questions aimed to establish whether they thought anything was missing or whether they wanted to comment on the statements.
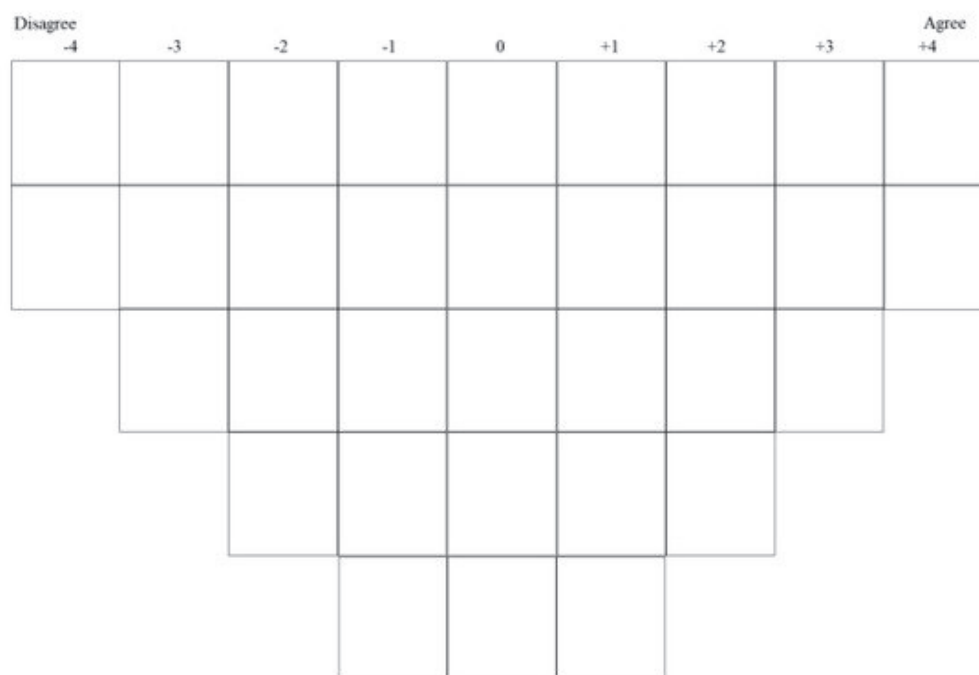
Figure 5.2 Q-methodology grid.

The data were analyzed using the software PQMETHOD (version 2.35) (Schmolck, 2014) by conducting by-person factor analysis, incorporating Varimax rotation to help eliminate noise (Brown, 1980). It enables the identification of natural groupings of Q-sorts, or rankings, according to similarities and dissimilarities between respondents. The Q-sorts that load significantly onto a particular factor suggest that they exhibit a similar pattern of sorting and represent similar viewpoints. Therefore, a factor represents shared values and understanding among respondents (Dziopa and Ahern, 2011). We note that the grouping could be different than the stakeholder categorization conducted initially. The rankings can also be non-significant (i.e. not loaded significantly onto any factors) or confounded (i.e. loaded significantly onto more than one factor). Principal component analysis (PCA) was used to categorize all Q sorts by the factors identified (Webler et al., 2009). Based on Watts and Stenner (2005), we decided which factors should be selected for interpretation based on two criteria. The factor had to have an eigenvalue > 1 and at least two Q sorts that loaded significantly upon it alone. In that respect, three factors were selected for analysis. An "ideal" ranking for each factor was generated from a weighted average. The ranking included all the statements that loaded significantly on that factor, and the score of these statements (from −4 to +4) (Table 5.2), allowing comparison and interpretation of each factor.

Table 5.2 Statements comprising the Q-set, their respective rank, and z-scores for each perspective. The most important statements within the perspectives are indicated by higher or lower rank and z-scores. Statements with red z-scores received lower scores and are considered less important. Statements with green z-scores received higher scores and can be considered more important. Distinguishing statements are indicated next to the particular z-scores for each of the perspectives (* for p-value < 0.05, ** for p-value < 0.01). Bold rank and z-scores indicate statement were high levels of agreement among the perspectives.

CICES Category	ES	Statement	Utilitarian		Cultural		Protective	
			Rank	z-Score	Rank	z-Score	Rank	z-Score
Regulating	Carbon stock	Ecosystems help regulate climate by sequestering carbon dioxide	**2**	**1.01**	**2**	**0.90**	**1**	**0.65**
		Ecosystems are green lungs for urban areas	0	0.3 *	2	0.88	2	1.16
		The role of soils is as important to store carbon as one of the forests	2	1.0 *	1	0.46 *	–2	–0.61 **
	Flood regulation	Ecosystems moderate weather events and maintain river channel stability	1	0.75 *	4	1.43	3	1.33
		The influence of ecosystems on flood reduction plays a role before its occurrence and after its formation	**0**	**0.17**	**0**	**–0.04**	**0**	**–0.12**
		Ecosystems regulate river discharge and help achieve flood damage reduction at the lowest costs	**1**	**0.82**	**1**	**0.26**	**1**	**0.40**
		Ecosystems support the vegetation that protects soils from washing out	**2**	**1.03**	**3**	**1.31**	**3**	**1.31**
	Erosion control	Ecosystems prevent soils from washing out and ensures their fertility and productivity	1	0.82 **	4	1.80 **	1	0.15 **
		Ecosystems protect soils from erosion, which facilitates crop management and sustains homogenous crops	1	0.38	–1	–0.33	0	0.12
	Water purification	Water filtration by ecosystems can help maintain healthy aquatic habitat	3	1.31 *	0	0.2 *	2	0.76 *
		Water filtration by ecosystems is essential to get good drinking water quality	4	1.38 **	–2	–1.05 **	2	0.75 **
		Water filtration is linked to microbial diversity and natural land cover continuity	3	1.19 **	0	0.01	–1	–0.22
	Pollination	The state of biodiversity is essential to support the life of pollinators	4	1.595	2	0.76 **	4	1.75
		The activity of pollinators cannot be compensated by technology and plant-protection products	1	0.92 **	–1	–0.37 **	4	1.98 **
		Pollination supports many benefits such as the production of food, recreational opportunities, etc.	**3**	**1.14**	**3**	**1.14**	**2**	**0.89**
Provisioning	Food production	Ecosystems provide adequate grounds for intensive farming	–1	–0.66 *	–4	–1.86 *	–3	–1.18 *
		Croplands are the most essential component of food self-sufficiency in the region	2	1.08 **	–3	–1.18	–3	–1.59
		Crops may be dependent on other ecosystems, but technology and plant-protection products could be substitutes	–3	–1.19	–3	–1.45	–4	–1.93

5. STAKEHOLDERS' PERSPECTIVES TO SUPPORT THE INTEGRATION OF ECOSYSTEM SERVICES IN SPATIAL PLANNING IN SWITZERLAND

Category	Statement						
Heritage	Ecosystems are strongly tied to local traditions and identity	-3	-1.10 **	-1	-0.44	-1	-0.45
	Ecosystems encourage a sense of community and transmission between people	-2	-1.01 **	0	-0.09	0	-0.10
	Ecosystems are crucial to pass down traditions to future generations	-1	-0.86	-3	-1.17	0	-0.1 **
Landscape aesthetics	Ecosystems reflect the beauty of nature	0	-0.5	1	0.43 **	-1	-0.52
	Ecosystems allow to unwind in beautiful landscapes	0	-0.23	1	0.53 *	-1	-0.16
	The structure of the underlying landscape appears in a beautiful way in the canton	-1	-0.62	-1	-0.33	-3	-1.51 **
Outdoor activities	Ecosystems are a good place to exercise (e.g. running, cycling, skiing)	-2	-0.91 **	2	1.13 **	-4	-1.61 **
	Ecosystems are a good place to sit or walk (e.g. lunch, reading, dog walking)	-1	-0.80	3	1.35 **	-2	-0.65
	Tourists attracted by ecosystems in the canton benefit the region	-1	-0.78	-2	-0.45	1	0.17 *
Inspiration, spiritual, religious	Ecosystems help to have a creative activity (painting, writing, playing music)	-2	-1.02 *	1	0.43 **	-1	-0.53 *
	Ecosystems help to get new professional or creative ideas	-2	-0.87	-2	-0.7	0	-0.15
	Ecosystems are important constituents of religious beliefs	-4	-1.92 **	-4	-2.40 *	-2	-0.67 **
Simple nature value	It is a joy to know that ecosystems are being protected	0	-0.11	-1	-0.21	-2	-0.96 **
	There is no substitute for being physically connected to ecosystems	-3	-1.04 **	0	0.04 **	3	1.4 **
	Ecosystems' functioning can be used as an example for human societies (e.g. biomimetic)	-4	-1.29	-2	-1.01	1	0.26 **

Cultural

To facilitate cross-factor comparisons the total weighted scores were standardized into z-scores. It allows to detangle which statements are "consensus statements" (not statistically distinguishable between the two factors at p-value > 0.05) and "distinguishing statements" (statistically distinguishable between the two factors at p-value < 0.05). For statements that are neither consensus nor distinguishing, no comparison is possible. The factors were interpreted with the aid of information during the interviews. Each factor is presented as a perspective, representing different viewpoints (Barry and Proops, 1999).

5.3 Results

Three factors explained 55% of the study variance and 29 of the 30 Q-sorts or rankings loaded significantly (p-value < 0.01) onto one of the three factors, suggesting three distinct viewpoints. Based on the factor analysis, we were able to identify three perspectives to represent the different viewpoints of the participants: Utilitarian, cultural, and protective. One Q-sort was not significant for any factor and was not included in any perspective. Ideal rankings were produced for each factor and presented in Table 5.2.

5.3.1 Consensus between participants

The results did not demonstrate a high level of agreement between the participants with 5 of 33 statements classified as consensus statements, reflecting a poor level of agreement (Table 5.2). All consensus statements belonged to regulating ES showing that people tended to understand the role of ecosystems to regulate climate and weather perturbation. The positive scores associated with carbon sequestration showed that a consensus exists on the capacity of natural systems to mitigate anthropogenic emissions. In addition, the participants strongly agreed with the crucial role of pollination as a support of other environmental benefits. The agreement was also very strong on the positive role of vegetation to prevent soil erosion. Although two of the three statements related to the flood regulation service received general agreement, the average scores (0 or +1) demonstrate that the relative importance of the service was less clear for most participants. Finally, we note that there was no general agreement on the relative importance of provisioning and cultural ES.

5.3.2 Factor interpretation

5.3.2.1 Factor A: utilitarian perspective

Factor A focused on utilitarian values of ecosystems in the canton of Vaud. Seventeen participants were significantly associated with the utilitarian perspective. They tended to highly agree with the link between ecosystems and their biological functions but less with ecosystems and their social functions. They emphasized the importance of regulating ES (Q-statements with a significant rank of +2 to +4), especially water purification and carbon stock (Table 5.2). They also considered that croplands were "the most essential component of food self-sufficiency in the region" but believed in that intensive farming and the use of agricultural land for animal husbandry was not a sustainable solution and should not be a priority in spatial planning. Despite that most participants did not feel that cultural ES should be prioritized compared to other services (Q-statements with a significant rank of −4 to −2), most also agreed that the focus should not be put on economic or recreation values of ecosystems. Although,

some participants mentioned that ES supply cultural benefits to "avoid the society from being depressed", as well as the high potential in the canton to attract tourists due to its right geographical settings, they considered that these services should not be a priority in planning, as these were not essential to human survival. The average, non-significant rank of the landscape aesthetic service confirmed that respondents might not consider it essential in spatial planning. Respondents tended to agree that ecosystems should be protected fully instead of being used for outdoor activities, especially if they are strongly tied to the local economic system with heavy infrastructures like skiing.

Participants believed it is important to polarize the debate and making a clear distinction between what is urgent or not on a higher level. For example, they felt that the public should understand why agriculture and water filtration are more important than subjective cultural values.

5.3.2.2. Factor B: cultural perspective

Factor B focused on cultural values of ecosystems in the canton. Six participants were significantly associated with the cultural perspective. Participants were sensible to the issue of integration of cultural aspects in spatial planning, which bring strong benefits to the population, especially in urban areas. The perspective showed the importance of cultural ES, with a strong emphasis on outdoor activities (positive and significant rank). The slightly above average score of landscape aesthetics showed that landscape beauty could be a component of spatial planning but is less important than outdoor activities or some regulating ES. As participants associated with other perspectives, they strongly disagreed with the association between ecosystems and religious beliefs in the canton.

In addition, the perspective strongly emphasized the importance of some regulating ES such as erosion control (+4), the role of soils to store carbon (+2) and the link between biodiversity and pollination (+2) (Table 5.2). However, it tended to agree less on the relationship between water filtration and good water quality, suggesting that the respondents may think that grey infrastructures are more efficient than natural processes. Finally, the perspective demonstrated negative and significant scores for food production. Participant justified this choice as current agricultural practices are focused on productivity even though Switzerland will never be able to compete with neighboring countries (e.g. France or Italy) in terms of production potential.

5.3.2.3. Factor C: protective perspective

The protective perspective shared elements with the utilitarian perspective, but tended to diverge from the cultural perspective. Six participants were significantly associated with a protective perspective. The perspective recognized the need for ecosystems to exist and function properly as a priority. Then, if and only if, the two first conditions were met, should we consider gaining benefit from them. Therefore, the emphasis was put on simple nature value and regulating functions such as pollination, erosion control and water purification with significant positive scores (Table 5.2). Although it was acknowledged that ecosystems help to regulate climate, respondents believed in the importance of controlling greenhouse gas emissions in priority, which explains the non-significant and negative scores for the service of carbon storage.

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In line with the cultural perspective, a strong negative score was recorded for food production. Participants considered current agricultural practices as mostly intensive with patches of cropland that failed to consider the need for extensive areas to allow for soil regeneration and maintain its quality. In addition, respondents also mentioned that the canton would not be self-sufficient alone. They suggested that food self-sufficiency should not be an objective for preserving arable land, but the soil quality should.

Cultural ES were considered less vital than others, but essential for well-being from a psychological perspective. A participant mentioned that "it would be unbearable to live in a place with no access (physical or not) to natural or semi-natural areas", explaining the mostly positive scores of the service of simple nature value (Table 5.2). However, we note the overall negative and significant ranks of landscape aesthetics and outdoor activities, which demonstrates their relatively low importance for the preservation of intrinsic nature values.

5.4 Discussion

5.4.1 Unraveling stakeholder's perspectives

Historical trajectories of ES in the canton of Vaud could be attributed to undervaluing the full range of ES provided by rural areas, and institutional practices that serve to limit broader stakeholder engagement in planning decisions (Jaligot et al., 2019b, Lüscher, 2003). Unraveling the areas of agreement and disagreement as well as the main viewpoints of different stakeholders on the value of ES is important to develop planning policies and ensure a successful implementation (Raymond et al., 2013). We used Q methodology to identify key stakeholder's values, or social demand, associated with ES to improve their management. The stakeholders' perspectives were grouped into three main groups or perspectives: Utilitarian, cultural, and protective that showed some level of agreement but favored different management regimes.

The utilitarian perspective grouped almost 60% of the participants and highlighted two key messages. First, preserving services that are critical to human survival, such as regulating ES that mitigate climate change and protect against weather events, was dominating the responses. Although the cultural and protective perspectives provided a different rationale to prioritizing regulating ES as it highlighted the importance to protect biological functions without necessarily benefiting from them, the importance given to regulating ES, especially pollination, water purification, and erosion control, showed the need to consider and integrate synergies between ES. Pollination was deemed crucial for its role in food production and other services. However, other work has shown that while the contribution of wild bees to crop production is significant, service supply is restricted to a limited subset of bee species. Conserving the biological diversity of bees, therefore, requires more than just ES-based arguments (Kleijn et al., 2015). One alternative could be a stronger legal framework to consider biodiversity in planning. For example, the number of legally binding protected areas for biodiversity is low, except important biotopes, and the state of protected wetlands is decreasing due to drying or nitrogen input (Birdlife, 2017). Further research is required to address the better integration of biodiversity in planning.

However, there are clear diverging views on the priority given to food production. While the utilitarian perspective stressed that croplands were essential for food self-sufficiency in line with the Swiss policy that preserves the best arable land (i.e. *surfaces d'assolement* or land crop rotation areas), and the need for a progressive change in agricultural practices, the cultural and protective perspectives shared a different view. In both groups, the stakeholders mentioned the fallacy of considering that agricultural practices shift from intensive to sustainable when the use of inputs fertilizers decrease. They also stressed that farming remains intensive from the pressure it puts on soil natural functions due to crop rotations, fragmentation or field boundary management (Tscharntke et al., 2005). Current agriculture is focused on productivity, so the current legislation on crop rotation areas could be protecting land for intensive agriculture.

The second message from the utilitarian perspective was that cultural aspects should not be prioritized in planning, in opposing view with the cultural perspective, where cultural aspects were vital elements for well-being. Two reasons may explain the utilitarian responses. On the one hand, most cultural values are not related to ecosystems. Cultural heritage, traditions, and landscape aesthetics may be linked to human interventions in the landscape rather than undisturbed ecosystems. This view was shared by the three perspectives. Therefore, the place given to heritage and landscape aesthetics in planning may be overestimated (Jaligot et al., 2018b). On the other hand, cultural benefits such as outdoor activities are not essential for our survival, according to some stakeholders (Small et al., 2017). It is also believed that people would perform outdoor activities regardless of human interventions. Natural systems require full protection instead of being used, sometimes in an intensive manner (e.g. skiing), suggesting a land sparing approach (Zarrineh et al., 2018). A similar view on the need for protection was shared by the protective perspective. However, the perspective highlighted that humans need to live in harmony with nature instead of differencing uses, suggesting a land sharing approach (Zarrineh et al., 2018).

5.4.2 Implications for spatial planning

In general, stakeholders tended to agree that regulating services should not be provided by other means than by natural or semi-natural ecosystems. A service that cannot be provided naturally is a direct consequence of inadequate land use. Therefore, ecosystem multifunctionality and synergies should be integrated into planning. However, this requires that current trade-offs are addressed and mitigated (Jaligot et al., 2019b).

Based on the findings and stakeholder's perspectives, a paradigm change in the food production system would be needed, moving away from a productive-only approach, to a system that protects soils and preserves their functions. Demand is changing to promote local and organic products (Haller et al., 2013; Porcher, 2011). Switzerland may have a leading role to play either in the ban of pesticides and/or experiencing new modes of agriculture (agro-ecology). It could also reduce the use of arable land for fodder production as half of the arable land is currently used for fodder production (Ferjani et al., 2018). For example, a change in the current paradigm could be the integration of the term "self-production" instead of self-sufficiency, as Switzerland is unlikely to become fully self-sufficient if current imports of food, fodder, petrol, and fertilizers are considered (Ferjani et al., 2018).

The current political framework with the Sectorial Plan on crop rotation areas should not impeding this transition. Some stakeholders may advocate that the Forest law has also been a determinant of agricultural land losses in the canton in the past decade. However, the forest grows mainly on abandoned pastures, and remains stable as well as becomes more fragmented in the Plateau region (Loran et al., 2018). As a stakeholder suggested, one way to avoid conflict between the forestry and agricultural sectors would be to integrate forestry-related infrastructures into wooded areas instead of using agricultural land. Although, the current political context offering protection to arable land and forests may not be suitable to minimize trade-offs between all service categories (Jaligot et al., 2019b), the authors suggest that crop rotation areas could receive the same protection level as forests, providing a paradigm change, based on the importance given by the stakeholders to crop rotation areas and limiting intensive farming. More emphasis should be put on soil quality, as well as maintaining production knowledge (farming techniques and a large variety of crops). Higher authorities at the federal level could be in charge of helping farmers change their ways and regulate the sector. For example, incentives and guarantees coming from the federal government for farmers that are willing to change their practices may be a good option in addition to current ecological payments (Ferjani et al., 2010).

Finally, most participants considered cultural aspects as important, but with negative impacts on the environment. It demonstrates the possible overestimation of the importance of cultural ES in current planning policies, especially for outdoor activities and landscape aesthetics. The stakeholders could be ready to give away their privileges in terms of outdoor activities and aesthetics values to safeguard biological functions. For example, a swift change from winter-based tourism based on heavy infrastructures and sprawl, to soft/eco-friendly tourism that is more evenly split between the seasons could be an option. However, further research is required on the type of tourism the public would prefer to limit negative impacts on the environment

5.4.3 Methodological considerations

The authors used Q-methodology, alongside stakeholder analysis, to reveal people's perspectives on the integration of ES into spatial planning in the canton of Vaud. This approach is useful to understand the different viewpoints in a specific context, but it also has shortcomings. First, it does not allow for generalizations, and the results would not be applicable to other cantons in Switzerland. In addition, the selection of Q-statements is inherently subjective, as there are no standards for their selection (Webler et al., 2009). Despite that the participant sample is of moderate size ($n = 30$), the authors believe that the inclusion of various stakeholders, and testing the Q-statements, has helped to provide a good overview of the range of perspectives within the planning debate.

Second, the given Q-statements and the forced normal distribution can give participants the feeling that they cannot express freely their view (Winkler and Nicholas, 2016). The authors tried to address this during the interview by assisting the participants with the statement meaning and stressing that there were no wrong or right answers in this prioritization exercise.

5.5 Conclusions

The concept of ES is considered complementary to current spatial planning practices, but the benefits provided by natural and land systems were often underestimated in planning decisions. Although the assessment of ES supply is key towards the integration of ES in spatial planning, recent work called for a deeper understanding of social demand and value plurality underlying the different positions held by various stakeholders. This study explores the different stakeholder perspectives on ES to facilitate their integration into spatial planning in the canton of Vaud in Switzerland. Q-methodology was applied to reveal three dominant perspectives: utilitarian, cultural, and protective.

Although the low level of agreement between the perspectives demonstrated that different management regimes were favored by the participants, three key elements integrate aspects discussed by the three perspectives and could have implications for spatial planning in the canton.

First, stakeholders tended to agree that ES should primarily be provided by natural or semi-natural ecosystems. Therefore, ecosystem multifunctionality and synergies should be integrated into planning.

Second, Switzerland could have a leading role to play in the change of the food production system, moving away from a productive-only approach, to a system that protects soils and preserves their functions. The current political framework with the Sectorial Plan on crop rotation areas would not impede this transition. Providing a paradigm change, arable land could be protected to the same level as forests and farmers could be incentivized further to change their practices, in addition to current ecological payments.

Finally, cultural aspects were important, but with few negative impacts on the environment. The importance placed on regulating ES rather than cultural ES revealed that an emphasis on cultural ES, such as outdoor activities and landscape aesthetics, could be counterproductive in the protection of other ES. According to the participants, cultural ES should be a priority only if ecological functions are protected.

To explore further the gap between various stakeholder's perspectives, it would be useful to conduct a similar study in another canton in Switzerland and compare the results to understand if similar suggestions for spatial planning could be drawn at a higher planning level.

Chapter 6

Synthesis

6.1 Summary of key findings

The concept of ES is increasingly regarded as an important tool to support spatial planning (Almenar et al., 2018; Grêt-Regamey et al., 2008). Integrating the concept into spatial planning is a promising approach towards sustainable development because it makes human benefits from ecosystems explicit, and deals with trade-offs. In Switzerland, spatial planning is key to manage territories in the specific context of federal governance. Historically, cantons and municipalities have been jointly responsible for spatial planning, which calls for a better coordination and harmonization of activities with a spatial impact towards achieving an integrated management of land uses. Nevertheless, research showed that Swiss land management policies had been taken up to different degrees in cantons and municipalities, which in turn may have impacted ES to different levels (Lüsher, 2003; Messer et al., 2016). Therefore, this thesis considered both cantonal (chapter 2 and 3) and municipal (chapter 4 and 5) levels to understand the role of ecosystem services for spatial planning in Switzerland.

The methodological approach developed in the first article of this thesis was used to understand the historical dynamics of ES and analyse regional diversity in ES changes in Swiss cantons. It allowed to detangle regional clustering of changes in ES supply and to test whether the current enforcement of federal land management strategies had limited influence in the preservation of ES (*hypothesis 1* in chapter 2). The results of the analysis explained that the distribution of ES tend to be structured in space within Swiss territories, whereby contiguous cantons are likely to have a similar distribution in ES supply with very little variation through time. A trade-off between food production and other ES existed in all cantons, indicating that the current policy on LCRA (*surfaces d'assolement*) fails to ensure the multifunctionality of territories. It shows the limit of the Sectorial Plan on LCRA. On the contrary, the exploitation of wood resources did not impede multifunctionality, demonstrating the positive impact of the Forest Act (Frehner et al., 2005). The analysis of drivers showed that the densification trend in Switzerland could yield negative externalities if a territory would reach the same population densities as the cantons of Geneva or Basel-Stadt. In addition, the promotion of organic farming and moderate population density may be suitable to ensure sustainable supply of most ES but cultural ES only to a limited extent. Overall, this study is exploratory in nature and sets out regional clustering in the supply of ES. It suggests that the impact of current land management policies is limited to safeguard ES supply, and their application at the cantonal level develops long lasting regionalities in the supply of ES. Therefore, we accept the first hypothesis. The implications for planning policies are discussed in section 6.2.

In the line of exploring regional differences in the relationship between ES and spatial planning, the second article took a qualitative perspective to understand the uptake of ES in current planning documents. By focusing on cantonal structural plans, it tested whether cantons

used the concept of ES and integrated it into their main planning document (*hypothesis 2* in chapter 3). Strong discrepancies in the level of representation of ES across cantons was detected, with a poor emphasis put on regulating ES across all plans. Neighbouring cantons showed varying degrees of ES integration in structural plans and demonstrated the lack of coordination between cantons to include ES to support planning. Despite that very little reference was made to environmental protection or an explicit mention to the concept of ES in the Federal Act on Spatial Planning, cantons showed flexibility in the integration of the ES concept, although none referred explicitly to the term "ecosystem services". Generic "keywords" such as environmental protection or landscape preservation do not stipulate benefits that humans get from ecosystems. Analyses showed that provisioning ES were the most represented in all sections of plans, which demonstrated the general importance given to services such as food production compared to other services. The strong emphasis on LCRA preservation showed that the concept is used as a support tool for spatial planning and the allocation of building zones. Interestingly, the integration of cultural ES tend to follow the one of provisioning ES, proportionally. The attention given to provisioning ES and cultural ES was confirmed by their relative integration in binding parts of the documents, compared to regulating ES, which were mostly detected in nonbinding sections. It shows that cantons put a strong emphasis on the link between agriculture and cultural services, which contradicts quantitative results from the previous article and others which showed that synergies between agriculture and cultural ES could be weaker than previously thought in Switzerland (Jaligot et al., 2018b). Overall, we reject the second hypothesis stating that the concept of ES has been used by cantons and integrated into basic spatial planning documents. The implications for planning policies are discussed in the next section.

It is important to remind that planning takes place at different spatial levels. While the previous broad scale studies are useful descriptive assessments, it was necessary to take this work to a lower level to ensure the credibility, salience and legitimacy to inform spatial planning (van Oudenhoven et al., 2018). We focused on the canton of Vaud for the rest of the research. The objective was to test whether ES trade-offs and synergies varied across space and time and responded to different drivers of change at the municipal level (*hypothesis 3* in chapter 4). The findings revealed that changes of ES supply through time are related to spatial configuration, as well as socio-economic and environmental characteristics of a region, which is consistent with our previous results. There was a large contrast between the Plateau region and the mountainous regions in the canton. A clear dichotomy arose in the supply of ES if a land use within an area had the ability to provide multiple services (e.g. forests), or those that were supplied from conflicting land uses (e.g. agricultural areas). We note that persisting trade-offs between food production and other ES were observed throughout the canton, particularly in the lowlands (Plateau region). This is empirical evidence to show that lasting intensive agriculture since the 1980s was done at the expense of social and regulating environmental benefits. It also shows that trade-offs could appear whenever a service supply is maximized. In addition, we pointed to the mutual exclusiveness of changes in some services and their associated land use. This is the case for outdoor activities and food production for example. In that respect, the potential drivers of change were different between ES. Changes in cultural ES tend to be clearly related to population density (Liu et al., 2019), while changes in regulating ES related to the

extent of protected areas (Spake et al., 2017). Overall, we accept the hypothesis that changes in ecosystem services trade-offs and synergies vary across space and time and respond to different drivers of change. The implications for planning policies are discussed in section 6.2.

Similar to this work, a lot of research focused on the quantification and mapping of ES supply and less emphasis was put on assessing stakeholder's preferences and perceptions of ES (Castro et al., 2013; Spash, 2013; Stosch et al., 2019). However, this is essential to reduce trade-offs arising from diverging stakeholders' perceptions with conflicts over rights and resources. The last part of this thesis focused on integrating place-based stakeholder knowledge to better consider ES in planning (*hypothesis 4* in chapter 5). It tested that ES could be better considered in the development of planning measures by integrating place-based stakeholder knowledge. Our findings showed that the stakeholders favoured three perspectives: utilitarian, cultural and protective. Although the three regimes used different rationale, all stressed the importance of regulating ES to mitigate climate change and mitigate extreme weather events. It should not be provided by other means than natural or semi-natural ecosystems. The contrary would be synonym of inadequate land use. This shows a clear contradiction with the results from the content analysis of cantonal structural plans, which put less emphasis on regulating ES compared to provisioning or cultural ones. However, a major disagreement arose on the priority given to food production. While the utilitarian regime believed that arable land were essential to ensure food-self-sufficiency in accordance with the Sectorial Plan on LCRA, the two other groups shared a different view. Both stressed the fallacy of considering that there is an ongoing change from intensive to sustainable agriculture simply from a slight decrease in the use of fertilizers. In their view, farming remains intensive from the pressure on soils, land fragmentation and boundary management. Lastly, cultural ES were considered less vital than others, but still important from a psychological perspective. Nevertheless, our results showed that the relationship between natural ecosystems and cultural heritage, landscape aesthetics or outdoor activities could be overestimated in planning, as the three perspectives contend that human interventions in the landscape better link to cultural ES supply than undisturbed ecosystems. Overall, the identification of different perspectives to represent viewpoints of key stakeholders confirmed the hypothesis that ES could be better considered in the development of planning measures by integrating place-based stakeholder knowledge. The implications for planning policies are discussed in the next section.

6.2 Planning policy implications

The concept of ES could help rethink land use and territorial planning in the Swiss context of limited land availability and the need to preserve ecosystem multifunctionality. This work highlights empirically clear territorial clustering both at the cantonal and at the municipal scale. We highlight implications at the federal level and discuss planning alternatives to be implemented in Swiss territories.

6.2.1 Key reforms at the federal level

In general, a greater involvement of federal authorities may be required for a better integration of multifunctional ecosystems and ES in spatial planning. We identify five main point of action at the federal level: coordination, stricter implementation of the Federal Act on

Spatial Planning and interdisciplinarity, agricultural practices and direct payments, revision of the Sectorial Plan on LCRA, and protected areas.

6.2.1.1 Coordination

According to chapter 2 and 3 (*hypotheses 1* and *2*), there is a lack of coordination between cantons to integrate ES in planning and manage their supplies. The flexibility offered by the Federal Act on Spatial Planning leaves the cantons with sufficient room to take up the concept of ES in their strategic planning. However, we postulate that federal directives on the integration of ES may lead to: (i) a uniform interpretation of how ES should be included in land management policies, (ii) a shift of focus the urbanistic paradigm of spatial planning, and (iii) the prevention of "keyword" planning. Urban cantons like Geneva or Basel-Stadt are the most impacted by the low supply of ES and their ability to supply ES is often restrained by fast land use change. Including ES becomes even more pressing for these cantons, along with tools for mapping and monitoring ES.

The stakeholder perspectives unravelled in chapter 5 (*hypothesis 4*) display quite an ambiguity with stated desires to cooperate on some aspects, while defending contradictory interests. Historically, a first example would be the clear dichotomy between the discourse and the action during the negotiations on direct payments for ecological performance in the 1990s. At the time, greening agriculture became a legal matter, which was seized as an opportunity for the political groups to appropriate agro-environmental issues and impose their definition along with regulating policies. The greening of agriculture took place along with a commodification of environmental measures, in a context of great difficulties for the agricultural sector with the end of market support. This reform was timely and greening measures were politicized. It demonstrates conflicts linked to the harmonization of positions according to specific agendas. In addition, differences in terms of both budget and political legitimacy, as well as the influence of lobbies and the food industry, weighs on the orientation of current agro-environmental policies. We also note the need for a deep institutional reform to alleviate the imbalance of power between these key institutions. A second example is that the instruments to protect land outside building zones (e.g. LCRA or forests) against excessive building activities fall within the competencies of planning agencies. Therefore, it is crucial to create overlap between key institutions such as the Federal Office for Spatial Development, the Federal Office for Environment, and the Federal Office for Agriculture, but also at the cantonal level between different cantonal services (environment, agriculture and planning).

6.2.1.2 Spatial planning regulation: stricter implementation and interdisciplinarity

Planners should follow a strict implementation of the Federal Act on Spatial Planning and restrict building zones in priority. Our findings in chapter 2 and 4 suggested a clear relationship between changes in ES supply and population density Densification measures in existing infrastructure should be pursued, rather than settlement expansion. We note that some very densely populated cantons failed to maintain ES supply so a strict monitoring network should be implemented at the federal level.

We need to raise awareness about the positive sides of densification and the good externalities it could bring on the quality of life. However, it is very dependent on the urban

forms that municipalities favour. A development project planned by urban planners or estate developer will not integrate ES the same way. We should change our ways of planning by integrating other competencies. We argue for the need to move spatial planning from a multidisciplinary approach to an interdisciplinary approach.

6.2.1.3 Agricultural practices and direct payments

Switzerland is not able to compete with neighbouring countries for cheap agricultural goods. It is also unlikely to achieve food self-sufficiency. In addition, demand is changing to promote local products. In the light of the findings in chapter 3, 4 and 5, we suggest two paradigm changes: (i) from a productive-only approach to a multifunctional approach on soils, and (ii) from self-sufficiency to self-production. However, such changes are likely to encounter strong opposition from both farmers and other powerful actors such as farmers associations, political parties or lobbies. Therefore, the federal level should implement incentives to assist farmers in changing their ways and regulate the sector in addition to current direct payments for ecological performance, which have limited positive effects on biodiversity and ES. In addition, a large share of agricultural land is taken for livestock and half of the arable land is used for fodder production (Ferjani et al., 2018). We believe that directives at the federal level for the extensification of croplands should be coupled with incentives to decrease the share of land allocated for the meat sector to compensate for the loss of land and productivity. An additional positive impact would be a reduction in CO_2 and methane emissions. Current funds for direct payments are used specifically for benefits of public interests that do not fall within the market economy (e.g. animal welfare, diverse landscape architecture, production in unfavourable geographical areas, etc.). A concrete application could be to add a type of contribution for direct payment to push for a reduction of livestock agriculture and an increase in extensive crops for direct human consumption. In general, the instruments for direct payments should be targeted further on the delivery of multiple ecosystem functions.

6.2.1.4 Revision of the Sectorial Plan on LCRA

In the light of possible changes in agricultural practices through two paradigm changes (from a productive-only approach to a multifunctional approach, and from self-sufficiency to self-production), we suggest a reform of the Sectorial Plan on LCRA and it should go further than the revision proposal under public consultation since the beginning of 2019. We note that the latter also maintains the same quotas for each canton and the possibility to request some LCRA for construction projects providing compensation in land or in money when compensation with a surface of similar quality and quantity is impossible.

First, the Sectorial Plan should not be impeding these paradigm changes. More emphasis should be put on soil quality, maintaining production knowledge, and favouring other modes of agriculture (e.g. organic, semi-covered, flower band within crops, etc.). This goes along the need of extensive areas to allow for soil regeneration and maintain its quality.

Second, we believe that advocating a conflict between forests and agricultural land is a logical fallacy, as forests grow mainly on abandoned pastures, and remain stable and fragmented in the lowlands region where intensive farming is common. On the contrary, the Forest Act is a perfect example of the limit of environmental protection in the country, as it did

not prevent cities to grow and forests to become fragmented, though net forest cover remains stable in the lowlands (Loran et al., 2018). It demonstrates the paradox of our ability to come together for an environmental cause but still work around it for our development. In addition, forest clearings are allowed following a very specific procedure whereas the decision is more subjective when LCRA are considered. We suggest that LCRA should receive the same level of protection as forests to prevent further loses, providing the two paradigm changes aforementioned.

Finally, it is important to maintain a certain level of food self-production for two main reasons: production standards, especially in terms of ecology and environmental protection; and the promotion of decentralization in the country. However, current planning practices are not based on functional territories but some administrative boundaries in which a defined quota of arable land may not make sense today. Some cantons face housing shortages because of the inflexibility of the Sectorial Plan, for which the quality of LCRA remains uncertain and strict monitoring is not implemented. We put forward that the rationale behind arbitrarily decided quotas for each canton, with different development dynamics, is outdated. In that context, an exchange market between cantons could be envisioned. This would imply some level of coordination between cantons, which is not often achieved in the current framework, and more flexibility for the use of LCRA. However, we warn on two aspects which could impede the success of an exchange market: (i) the lack of accurate soil data at a national level, and (ii) the current use of LCRA as planning instrument to promote densification. The first aspect would not guarantee that the best arable land are preserved in a context of land exchange between cantons. One could easily build on good quality land, and the other compensate on a land of lesser quality. In addition, gathering data on soil quality could take years, especially for cantons with limited human and financial capacity. The current revision proposal does not mention a definite timetable for action. The second aspect means that the Federal Office for Spatial Development (ARE) would not be in favour of an exchange market as it would lose a major tool to push for denser urban areas. Thus, the immediate implementation of an exchange market appears to be a delicate matter.

6.2.1.5 Protected areas

In chapter 4 and 5, our findings demonstrate the importance of protected areas in the supply of ES, as well as the possible overestimation of the importance of cultural aspects linked to semi-natural (e.g. pastures) landscapes nature in current planning policies. We suggest that this link may be misused to justify human interventions in semi-natural or natural ecosystems. It appears more important to safeguard biodiversity and ecosystem functions than to use the potential of nature to provide services of outdoor activities and aesthetics. In addition, recent examples showed that national landscapes inventories, including protected wetlands, were subject to urbanization (e.g. Col des Mosses). The protection of cantonal inventories is not always binding. The legal framework around the integration and protection of protected areas and biodiversity in planning should be strengthened.

6.2.2 Future planning alternatives

Practically, a critical question for planners is how to integrate multiple ES while minimizing trade-offs. Over the years, the decision of landscape specialization made by some municipalities, especially in the lowlands (Plateau region), for a specific ES led to a stagnation or decrease in the supply of other ES. This land sparing management strategy was a combination of socio-economic and geographic conditions, but also the result of the inflexibility of the current Sectorial Plan on LCRA, which has limited power in ensuring the supply of multiple ES. On the contrary, we put forward in chapter 4 that no municipality in the canton of Vaud showed an increase in all ES. Therefore, it seems unrealistic in the current political settings to have multifunctional territories. In that respect, there could be two opposing alternatives for future planning paths: territorial land sparing and territorial land sharing.

6.2.2.1 Territorial land sparing path

The present thesis demonstrates that ensuring landscape multifunctionality at the municipal level seems unrealistic in the current political context. The lack of cooperation between sectorial policies, and coordination between planning levels (both horizontal and vertical) will not allow for the integration of multiple ES in planning and the minimization of trade-offs. In this context, a municipal land sparing alternative could be advisable to better protect ES and biodiversity. A land sparing approach concentrates intensive agriculture or urban development in a small area, leaving maximum space for conservation. It advocates dividing territories into separate areas for intensive farming to maximize biodiversity preservation and the supply of ES other than agricultural production.

A municipal land sparing path would be that some municipalities provide some services depending on their socio-economic and geographical conditions. We note that this already the case due to LCRA quotas. The rationale would be to apply the same principle to other services in a planned manner to optimize the supply value of ES at a supra-municipal level. It could typically be the case for forests or the delimitation of building zones, as our results show that population density is a driver of change of ES supply. Indeed, cultural ES and some regulating ES are very sensitive to changes in population density and the presence of protected areas, respectively. It shows that a land sparing approach could be beneficial for these services. Overall, the land sparing alternative would facilitate the planning process and alleviate the persisting challenge for municipalities to provide a multifunctional landscape (Zarrineh et al., 2018). However, it would entail agreements on key planning practices at supra-cantonal and supra-municipal level to clearly delineate areas that would remain dedicated to intensive farming, building zones and ones that would be used for nature restoration (passive or active). Agroecosystem restoration, after either intensive farming or land abonnement, could be used to enhance biodiversity and ES other than agricultural production. However, one should also bear in mind that restoration would entail a reduction in crop production.

6.2.2.2 Territorial land sharing path

The possibility of an alternative path to ensure landscape multifunctionality requires territories to adopt a land sharing practices whereby multiple ES are provided on the same land. It advocates conserving and improving the level of ES supply and biodiversity on farmed land.

It reflects the paradigm of multifunctional agriculture, which assigns a series of function to the same land including food production, regulating attributes and cultural aspects. It also falls within Art. 104 of the Constitution and the new agricultural policy (PA 14-17) aiming at a more multifunctional agriculture. Despite the appealing nature of land sharing practices, it requires drastic revisions of current planning policies and merging of sectorial policies leading to low population density changes in rural areas, the promotion of extensive agriculture and forest multifunctionality on the same territory.

6.2.2.3 Arbitration: land sharing or land sparing?

In Switzerland, spatial planning largely adopted a land sparing strategy, particularly in the lowlands, since the entry into force of the Federal Act on Spatial Planning by portioning the territory in distinct uses. The inclusion of stakeholders' perspectives was crucial to determine credible, legitimate and salient policy implications of this thesis. Based on our findings, we conclude that the dichotomy of land sharing and land sparing is too simplistic for Switzerland. Our quantitative and qualitative results showed that the two strategies are not necessarily mutually exclusive, but could be complementary in a territory with diverse geographical, cultural and socio-economic settings. Human interventions on natural ecosystems are already several and the different drivers of ES change identified in this work make a more differentiated approach necessary. Therefore, we suggest using both land sparing and land sharing principles to guide future planning depending on the territory.

In the Plateau region, land scarcity is a key issue. ES trade-offs are multiple, and the strong focus on agricultural production despite the loss of arable land, requires immediate action. Therefore, we recommend a stepwise approach to face the urgency of preserving multiple ES in the region. Based on our results and the reflection on reforms at the national level, we first propose to freeze the quotas of LCRA and offer them strict protection, similar to forests with very limited margin for future development. Exceptions would only be granted for development projects of national interests. This initiative would be paired with two paradigm changes (see previous section), and therefore, the adoption of a land sharing approach in these areas. In the Plateau region, where most LCRA are located, the land sparing strategy translated through agricultural intensification since the second half of the 20th century did not manage to decrease the trend of fast urbanization and the loss of LCRA, and led to a decrease in most ES. We suggest that adopting an opposing strategy such as land sharing practices is essential while ensuring that natural or semi-natural ecosystems exist and provide their functions in the lowlands. Only on this basis, an exchange market between LCRA and a revision of the inventories could be discussed subsequently, should critical issues of development arise.

Mountainous and hilly regions areas are supplying a large share of regulating and cultural ES, which are largely impacted by the presence of protected areas and population density changes. Land abandonment and the development of winter tourism highly impact these areas. Our findings suggest that these areas should receive high level of protection, advocating a land sparing approach. We recommend a two-step approach where the principle of precaution is applied towards the preservation of ecosystem functions. Our qualitative analysis revealed that people would be ready to give away some of their privileges, especially winter tourism to safeguard ecosystem functions. Natural ecosystems should exist and function properly. Then,

if and only if the two first conditions are met, should we consider gaining benefit from them economically. Nevertheless, this ideal approach would entail both passive restoration measures (e.g. the creation of protected areas) and active measures (e.g. adding in desired plant species, amending the soil), which could be difficult because of land ownership and decentralised responsibilities. It may also not be in line with the need of local population already impacted by rural exodus and agricultural land abandonment. Whether new protected areas are created and new economic activities are developed such as eco-friendly tourism is a matter of political choice.

The idea of a multifunctional landscape with different territories producing ES determined by their comparative advantage and the further implementation of land sharing or land sparing strategies appears logical. In practical terms, it would be necessary to go beyond market mechanisms, as many ES are unlikely to fall within standard monetary valuation as shown in this work. Market forces will tend to foster profitable activities such as urban development, intensive agriculture or winter tourism. Therefore, working alternatives suggested in this thesis are dependent on political will and the improvement of governance mechanism. There is an urgency to avoid further trade-offs, and promote a change in planning practices. The adoption of complementary planning alternatives and key reforms at the federal level could permit a smoother transition towards optimum land allocations for the preservation of ES.

6.3 Outlook for future research in the field

In this work, we explored various aspects of the concept of ES to understand the role of such services for spatial planning in Switzerland. For the purpose of clarity and completeness, we detailed the research's methodological limitations in individual chapters.

Despite, being comprehensive on the assessment of supply as well as considering demand through stakeholder's perspectives, this study suggests two main outlook for future research on the relationships between ES and spatial planning.

First, land use in any given region, including in Switzerland, is increasingly influenced by distant factors in globalized markets. In that respect, many commodities including food, are traded globally or at least at a continental scale. For example, the trade-off between agricultural production and other ES could take place in different locations. Implementing a land sparing or a land sharing strategy could have implications elsewhere by the displacement of one or multiple services supply. This "leakage" effect occurs through trades and distant linkages called "teleconnections". In order to understand, quantify and value these teleconnections, there is need for reproducible methods which could be applied in different contexts but still be comparable. This brings another level of complexity, especially in the Global South, where leakages could occur but data access to assess them could be limited (Jaligot et al., 2018a). In the context of Switzerland, it is likely that services supply would be displaced to neighbouring countries such as France, Germany or Italy, especially for food production. Therefore, assessing the consequences of the main output of this research at the European scale would be useful on the medium term.

Second, and on a rather qualitative aspect, the impact on human well-being of changes in ES is not yet totally understood. Current discussions on a paradigm change to measure progress

and development from GDP to alternative measures, including well-being, require a better understanding of the impact of our recommendations on well-being. Inter- or transdisciplinarity is therefore crucial in future planning decisions. This should go beyond participatory approaches and include specific disciplines such as sociologists, psychologists and potentially neuroscientists to obtain a fine-tuned comprehension of the implications on well-being.

Chapter 7

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Chapter 8

Appendices

Appendix A - Historical dynamics of ecosystem services and land management policies in Switzerland

A.1. Quantification of dependent variables

A.1.1 Cultural ecosystem services (ha)

Cultural ecosystem services (CES) embed social complexity that cannot be easily understood using sys-tem based approaches. De Vreese et al. (2016) use the term 'social mapping' to describe the mapping of subjective perceptions and intangible ES. Estimates of five CES values have been calculated using participatory mapping and land use / land cover (LULC) data. Then, historical values of CES were estimated using a benefit transfer approach where weights (i.e. ratio of CES point count per LULC type to the total CES point count) were kept constant over the years.

The following methodology was used for CES:

- Location of provisioning areas

- Five CES were selected based on literature review expert elicitation (Table A). Public participation geographic information systems (PPGIS) is a useful tool to include residents' perceptions, uses and values in a spatially explicit approach (Brown and Kyttä, 2014). Web-based mapping was preferred to hard copy mapping because it gave the flexibility to work at the national scale, and to engage with participants speaking one of the three national languages (i.e. French, German, and Italian).

Table A. Description of cultural ecosystem services

Cultural ecosystem service	Description
Heritage	I appreciate the local customs, traditions and cultural heritage linked to the place
Landscape aesthetics and landmark	I enjoy the landscape for it beauty or the landmark associated with it.
Outdoor activities	I enjoy spending time outside after work or on week-ends where I practice outdoor sports, walking, hiking, biking walking the dog, etc.
Inspiration, spiritual and religious	I am inspired by feelings, new thoughts, religious or spiritual meaning.
Simple nature value	I simply appreciate this place just because of its existence regardless of its benefits for me.

- The softGIS survey tool Maptionnaire developed by the Finnish company Mapita (https://maptionnaire.com/) was used to conduct the study.

- Switzerland was divided into eights regions based on the official division from the Department of Home Affairs (Schüler et al., 1999). The official division set seven regions. For practical reasons related to map visualization, we decided to exclude Valais from the Leman region and make it an eighth region. The regions are groups of cantons based on administrative boundaries and functional territories. Regions were preferred to cantons because it allowed the participants to have an extended view of potential CES provisioning areas instead of establishing a spatial constraint.
- A database of 11,300 email addresses from academic institutions, city councils, cantonal offices and environmental / planning associations was put together from the Internet. Low population density regions were also targeted. We acknowledge that population representativeness was not entirely achieved but the sample was considered large enough to ensure an adequate diversity of educated responses.
- After a welcome screen detailing the survey aim, time estimation to complete (approximately 20-25 min), and contact information, participants were asked to select one of the eight regions where they lived and to locate their residence. A pop-up instruction box indicated the five CES and descriptions prior to locating CES. The survey was structured into six sections – one for each CES and one for personal data at the end. The default base map was a normal Bing Map, but the user could switch to a satellite or roads and terrain map.
- For each CES section, participants were asked systematically to locate service provisioning areas meaningful to them with a pin. A sample question asked to the user was "*Please locate the areas for which you appreciate the local customs, traditions and related cultural heritage. The geographical center is of interest here.*"
- In general, the participants were asked to locate areas in which a service is provided. This method allowed to assess CES supply. A minimum zoom function was set to ensure the positional accuracy of CES points. Points are usually less cognitively challenging to locate.
- We considered "valid responses" as those with at least two different CES located.

- Estimation of current land use / land cover area

- The nomenclature of the Swiss Land Use Statistics (AREA) evaluated by the Swiss Federal Statistical Office is the basis for the categorization of land use / land cover (LULC) used in our assessment (SFSO, 2006). Every hectare is assigned to one of 72 categories of LULC (nomenclature NOAS04). LULC data are provided for the entire country over three time periods "1979/1985" (AS79/85), "1992/1997" (AS92/97) and "2004/2009" (AS04/09). A partial dataset was available for the period "2013/2018" (AS13/18), where 50% of the territory has been processed.
- CES provisioning areas were located in present days, hence current LULC, it was necessary to perform the analysis with current LULC data. However, AS13/18 was partially complete. Instead, we used a combination of AS04/09 and the 2D, small-scale landscape model of Switzerland, VECTOR200, updated annually by the Federal Office of Topography to reconstruct LULC data for present day. We performed two set of calculations to build an updated LULC dataset:

1. Set current boundaries of primary land cover to update the latest complete version of areal statistics (AS04/09). It corrected for changes in primary land cover that occurred between the aerial photo interpretations and current times. Although only the extent of primary land cover was available for current times, most transitions occured between agricultural areas, forests and urban areas. VECTOR200 provided the current extent of forests and urban areas with enough details to consider most transitions.

2. Within the new boundaries, LULC types from AS04/09 were kept constant. For example, the location of urban parks within the reclassified dataset was the same, provided that it was within the class 'urban areas' of VECTOR200. Similarly, other LULC categories from AS04/09 were kept constant when no data was available in the landscape model. Finally, the overlap exercise led to some transition areas where a change occurred from some LUCL categories of AS04/09 to a primary land cover of VECTOR200. Here, the type of LULC was set to the one of VECTOR200.

- Estimation of current cultural ecosystem services value

- PPGIS activities provided the location of 4,342 CES provisioning areas (Table B).
- A spatially explicit estimate of the current LULC has been calculated in the previous step. The responses were interpolated with the land cover dataset to understand how CES were related to land cover types. For each CES and in each region, the ratio of points associated with each land cover category to the total point count was calculated (r_j). Once the ratio was calculated for each region and each CES, we calculated CES potential supply for each canton belonging to the region. The ratio was multiplied by the area of LULC types in a canton ($LULC_i$). We summed the result for each LULC and relativized the proportion of total point count located in the region (Eq. 1).

$$V_{CES} = \left(\sum_1^i LULC_i \times r_j \right) \times w_j \qquad \text{Equation (1)}$$

Where i is the LULC type, j is one of the eight region, V_{CES} is the value of a CES in a canton, $LULC_i$ is the area of a LULC type in a canton (ha), r_j is the ratio of the point count associated to each land use / land cover category to the total point count recorded for a CES in a region, and w_j is the proportion of total point count in the region.

Table B. General output of participatory mapping activities

Region	Total n° of respondents	Valid n° of respondents	"Heritage" point count	"Landscape aesthetics and landmark" point count	"Outdoor activities" point count	"Inspiration, spiritual and religious" point count	"Simple nature value" point count
Central	85	21	46	57	59	21	48
East	200	62	120	178	149	46	115
Leman	398	98	255	254	253	83	164
Mittelland	349	99	192	287	265	93	198
North-West	184	43	92	78	91	18	31
Ticino	138	41	106	94	77	37	53
Valais	87	26	73	113	56	32	86
Zurich	185	59	96	110	124	24	67
TOTAL	1626	449	980	1171	1074	354	763

- Estimation of historical land use / land cover

- Based on the methodology for historical LULC interpolation from the Swiss Greenhouse Gas Inventory, we performed a primary stratification between cantons, elevation and forest production regions with three datasets: cantonal boundaries, elevation and forest production regions to account for sub regional differences in LULC change (FOEN, 2017). First, AS79/85, AS92/97, AS04/09, and AS13/18 were stratified by cantons. Then, three elevation zones were differentiated: <601 meters above sea level, 601-1200 meters above sea level, and >1200m above sea level. Elevation data was retrieved from the Federal Office for Topography in the form of a 25x25 m raster file (DHM25). Five forest production regions have been defined by the National Forest Inventory (NFI) (EAFV/BFL 1988; Brassel and Brändli 1999; Brändli 2010). The NFI regions are: 1. Jura, 2. Central Plateau, 3. Pre-Alps, 4. Alps, and 5. Southern Alps.

- We further stratified our dataset with the survey year group of NOAS04 statistics. Here we defined a year group as the years at which a specific area was surveyed to complete the statistics. For example, part of the canton of Vaud was surveyed in 1979 for AS79/85, 1992 for AS92/97, 2004 for AS04/09, and 2012 for AS13/18. This year group was used to further stratify the dataset to obtain strata with a single association of canton, elevation, NFI region and year group.

- Consistent data across the territory for the period of interest (1986-2015) was required but 50% of the last survey AS13/18 was missing. The values had to be calculated to create a virtual AS13/18 in the zones were not yet covered by the survey. In addition, some survey years of AS13/18 correspond to 2012, 2013 or 2014. A virtual statistic for a fifth survey period was estimated to get LULC data until 2015. The Markov chain approach has been widely used to retrieve missing LULC data. A cellular-automata element may be added to build the spatial component, but this was not required here (Weng, 2002; López et al., 2001; Halmy et al., 2015; Olmedo and Mas, 2018). Two sets of analysis were performed:

  1. For strata without data in AS13/18, we created a virtual AS13/18 based on the transition probability distribution between AS92/97 and AS04/09 for each point per stratum.
  2. For strata with data in all survey periods for which the fourth survey took place in 2012, 2013, or 2014, we created a virtual LULC statistics based on the transition probability distribution between AS04/09 and AS13/18 for each point per stratum.

- The Kappa coefficient was used to validate the approach for the actual AS04/09 dataset and a virtual AS04/09 dataset calculated based on the transition probability distribution between AS79/85 and AS92/97 for each point per stratum. It performs a cell-to-cell comparison between the observed map AS04/09 and the predicted map of AS04/09 based on the Markov chain approach (Chaudhuri and Clarke, 2011; Rutherford et al., 2007; Visser & De Nijs, 2006).

According to Landis & Koch (1960), the interpretation of the kappa indices is summarized in the table below (Table C). The correspondence was over 95% which showed the suitability of the Markov chain approach to estimate LULC statuses.

Table C. Interpretation of Kappa statistics

Kappa indices	Agreement between two maps
< 0.00	Poor
0.00 – 0.20	Slight
0.21 – 0.40	Fair
0.41 – 0.60	Moderate
0.61 – 0.80	Substantial
0.81 – 1	Perfect

- The methodology set out by the IPCC to obtain missing LULC data was used. The LULC status between two survey periods was linearly interpolated for each stratum (IPCC, 2006). Finally, the area of each LULC category was aggregated for each canton for each year.

- Estimation of historical cultural ecosystem services supply

- An extrapolation method was used, where r_j and w_j (Eq. 1) were kept constant over a region and the period of interest (1986-2015). Equation 1 was used to estimate the value of CES in each region and then in each canton.

A.1.2 Carbon stock (t Carbon / ha)

Carbon stock (C stock) is a regulating ES. In Switzerland, the main providing areas are forests but it is key to account for other LULC categories. Estimates of annual carbon stocks have been calculated following guidelines and methods from the Guidelines for National Greenhouse Gas Inventory (IPCC, 2006) and the Swiss Greenhouse Gas Inventory (FOEN, 2017).

The following methodology was used for C stocks:

- Primary stratification: canton, organic soil, elevation and forest production region

- The nomenclature of the Swiss Land Use Statistics (AREA) evaluated by the Swiss Federal Statistical Office is the basis for the categorization of LULC used in our assessment (SFSO, 2006). Every hectare is assigned to one of 47 categories of land use (nomenclature NOLU04) and to one of 27 categories of land cover (nomenclature NOLC 04). LULC data were provided for the entire country over three time periods "1979/1985" (AREA 1), "1992/1997" (AREA 2) and "2004/2009" (AREA 3). A partial dataset available for the period "2013/2018" (AREA 4), where 50% of the territory has been processed. Both NOLU04 and NOLC04 nomenclatures have been reclassified according to the main categories provided by the IPCC (IPCC, 2006;

FOEN, 2017). A total of 18 LULC categories were used for the assessment of C stocks. The methodology proposed in the Swiss GHG Inventory was followed to quantify C stocks as accurately as possible (FOEN, 2017).

- The territory was stratified with four data datasets: canton, soil type (mineral or organic), elevation and forest production regions. Wüst-Galley et al. (2015) elaborated a digital map showing the location of organic soil, integrating intact and degraded peaty soils. The map was kept constant over the entire period as in the Swiss GHG Inventory due to data limitation (FOEN, 2017). Three elevation zones were differentiated: <601 meters above sea level, 601-1200 meters above sea level, and >1200m above sea level. Elevation data was retrieved from the Federal Office for Topography in the form of a 25x25 m raster file (DHM25). Finally, five forest production regions have been defined by the National Forest Inventory (NFI) (EAFV/BFL 1988; Brassel and Brändli 1999; Brändli 2010). The NFI regions are: 1. Jura, 2. Central Plateau, 3. Pre-Alps, 4. Alps, and 5. Southern Alps.

- • Interpolation of annual LULC data

- We further stratified our dataset with the survey year group of AREA statistics. Here, we define a year group as the years at which a specific area was surveyed to complete the AREA statistics. For example, part of the canton of Vaud was surveyed in 1979, 1992, 2004, and 2012. Finally, we obtained strata with a single association of canton, organic soil, elevation, NFI region and year group.

- 50% of the last survey AREA 4 was still missing. The values had to be calculated to create a virtual AREA 4 for the zones that were not yet covered by the survey. In addition, some surveys of AREA 4 were done in 2012, 2013 or 2014, which meant a virtual land use statistics (AREA 5) had to be calculated. The Markov chain approach has been widely used to retrieve missing LULC data. A cellular-automata element may be added to build the spatial component, but this was not required here (Weng, 2002; López et al., 2001; Halmy et al., 2015; Olmedo and Mas, 2018). Two sets of analyses were performed:

1. For strata without data in AREA 4, we created a virtual AREA 4 based on the transition probability distribution between AREA 2 and AREA 3 for each point per stratum.
2. For strata with data in all survey periods for which the fourth survey took place in 2012, 2013, or 2014, we created a virtual AREA 5 based on the transition probability distribution between AREA 3 and AREA 4 for each point per stratum. We obtained a value of LULC for the virtual next survey period.

- We validated the approach using Kappa coefficients as in section A.1.1. The correspondence was over 95%, which showed the suitability of the Markov chain approach to estimate LULC statuses (Table C).

- Finally, the methodology set out by the IPCC to obtain missing LULC data was used. The LULC status between two survey periods was linearly interpolated for each stratum (IPCC, 2006).

- • Calculation of historical carbon stocks

- The Swiss GHG Inventory defined four pool of carbon from 1990 to 2015 for each association of NFI production region and elevation (15 combinations in total): (i) carbon stock in living biomass, (ii) carbon stock in dead wood, (iii) carbon stock in litter, and (iv) carbon stock in soil (either mineral or organic) (FOEN, 2017).
- C stock variables varied annually for carbon in living biomass and carbon in dead wood in productive forests, as well as carbon in living biomass in cropland (FOEN, 2017). They were fixed for other LULC categories. Although stocks are in reality not fixed for a given LULC, the Swiss GHG considers that applying a Tier 1 approach and keeping C stocks in equilibrium for some LULC is appropriate.
- Values of carbon stocks between 1986 and 1989 were estimated. Annual variability of carbon stocks in dead wood was low so we used 1990 values for the period 1986-1989. A similar observation could be made for carbon stocks in living biomass in cropland. Because the annual change in carbon stock in living biomass can be greater than 2 tons per hectare in productive forests, we linearly extrapolated stocks based on the stock between 1990 and 1997, which showed a linear trend for all associations of NFI regions and elevation. This outcome was preferred rather than setting the stocks equal to 1990 values.
- Finally, we calculated the total annual carbon stocks for each stratum and aggregated the results by canton to get annual carbon stocks at the cantonal level. All spatial and statistical analysis were performed using Python 3©.

A.1.3 Flood regulation (δ(max-mean))

Each river has its own discharge threshold, which changes over time depending on the river channel capacity, and the damage potential along the river. Therefore, it is challenging to compare the absolute number of floods recorded for different catchments (Schmocker-Fackel and Naef, 2010). Working at the cantonal scale does not integrate the catchment boundaries so the number of records in each canton may integrate flood events from different catchments. Therefore, we used the methodology presented in Renard et al. (2015) to estimate historical value of flood regulation supply at the cantonal scale. We estimated the amplitude of flooding events as the ecosystem capacity to buffer variation in flood events through time.

The following methodology was used for flood regulation:

- Historical flood records often mentioned damages caused by them (Schmocker-Fackel and Naef, 2010). The Federal Institute of Forests and Snow (WLS) has been collecting data on the financial damages of flood events and landslides since 1972 through newspaper and internet

reports (Hegg et al., 2002; Hilker et al., 2009). We used the number of events per year and aggregated it for each canton. In addition, data access improved over the years (e.g. internet) and small events were less likely to be recorded in the past. After discussions with experts at WSL, flood events with financial damages lower than CHF 0.25 million were excluded.

- Short-term fluctuations in the number of flood events through the time series were smoothed out by calculating a moving average over two-year periods (Renard et al., 2015).

- We calculated the difference between the maximum number of events over the time series and the annual number of flood events per canton, to reflect the amplitude of flood events during the period 1986-2015. Here flood regulation is the amplitude of events, not the direct number of floods. High amplitude values reflect a high ecosystem capacity to buffer variations in flood events.

It is acknowledged that all cantons have rivers that are capable of flooding, and the amplitude approach limits the effect of river size on the ecosystem capacity to buffer variations in flood events through time. However, we were not able to account for the probability of flooding for all rivers in each canton over the period under study.

A.1.4 Food production (t/ha)

In Switzerland, land crop rotation areas (LCRA) are the best arable land, which provide a large share of food production. Historical values on the extent of LCRA, and other arable land were not available between 1986 and 2015 (SFSO, 2018a). However, data on cropland, which are the largest component of LCRA, were available. We used the annual yields of cropland areas in tonnes per hectare in each canton as in previous work (Renard et al., 2015).
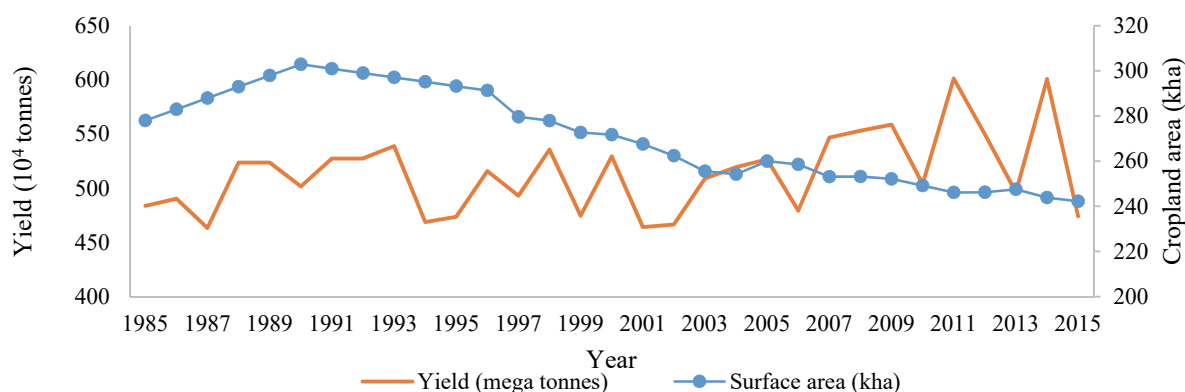

Figure A. Evolution of cropland yields and surface area in Switzerland from 1985 to 2015

The following methodology was used for food production:

- The Swiss Farmer's Union publishes annual reports on agriculture including the extent of cropland, and yields in decitonne per hectare for a variety of crops at the cantonal scale (SFU,

2018). However, it was not possible to retrieve the annual extent of cropland prior to 1996 directly from the reports as the accounting method changed in 1995.

- The Swiss Federal Statistical Office provided harmonized data on the extent of cropland areas between 1996 and 2015, as well as in 1985 and 1990. An estimate of cropland surface areas was retrieved by linear interpolation for each canton (Figure A). Fifteen crop types were used to calculate an average annual yield of cropland areas per canton in tonnes per hectare (t/ha) (Table D).

Table D. Area of crops used in the assessment in 2015

Crop type	Area in 2015 (ha)	Percentage
Wheat	82,312	33.98
Silage maize	45,904	18.95
Barley	27,986	11.55
Rapeseed	23,316	9.63
Sugar beets	19,759	8.16
Maize	15,322	6.33
Potatoes	10,891	4.50
Triticale	8,090	3.34
Spelt	3,907	1.61
Rye	1,889	0.78
Oat	1,556	0.64
Fodder beet	529	0.22
Tobacco	478	0.20
Meslin and other feed grains	191	0.08
Meslin and other bread cereals	99	0.04
TOTAL	242,233	100

A.1.5 Timber production (m^3/ha)

About one third (31.3%) of the Swiss territory is covered by wooded areas (SFSO, 2015). Indeed, the total surface area of forests increased by 4.1% between 1985 and 2009, with the largest increase in the canton of Valais (9.6%) and Uri (9.4%) (SFSO, 2015). The second national forest inventory showed that coniferous forests accounted for 65% of the growth (Brassel and Brändli, 1999). In 2011, the Federal Council adopted the Forest Policy 2020, which aimed to harmonize cantonal policies in terms of forest resource exploitation, optimize timber production, to ensure the multifuntionality of forests and to protect it against the effects of climate change (Baranzini et al., 2017). One of the measure involves the rise of forest reserves to 10% of the total forested area in 2030 (Gattlen, 2012). The intermediary objective of 5% was already successfully achieved (FOEN, 2014). In that context, the use of forests as an economic resource is likely to drop. Timber production is an important provisioning ecosystem service to be included in a historical assessment n Switzerland. The volume of wood produced per hectare is the indicator of timber production (Burkhard et al., 2014).

The following methodology was used for timber production:

- The Swiss Federal Statistical Office provided annual data on timber production for period 1986-2015 at the cantonal scale (SFSO, 2018b). Timber production was divided by the surface area of forests in each canton.

A.2. Quantification of independent variables

A.2.1 Settlement outside building zones (δ(density BZ- density canton))

The variable "Settlement outside building zones" is an indicator of the effectiveness of the Federal Act on Spatial Planning of 1979 (*Loi fédérale sur l'aménagement du territoire)*, which sets out the division of the territory into building zones and non-building zones (BZ) (Mahaim, 2014). Poor data availability limited the possibility to check whether settlements had occurred mainly inside or outside building zones. For example, a study from the environmental organization, Pro Natura, estimated the surface area of infrastructures outside BZ for each land use survey period (1979/1985, 1992/1997, 2004/2009) (Pro Natura, 2017). Nevertheless, the extent of BZ in 2012 was kept constant over all periods. Therefore, the results underestimated the extent of constructions outside BZ for the first survey period because BZ were smaller in 1979 than 2012, but overestimated it for the second survey period because BZ were larger in 1989 than in 2012 (Federal Office for Spatial Development, 1989; Leuzinger and Matthey, 1977; SFSO, 2017).

An indicator that accounts for changes in BZ extent was required to estimate more accurately settlements outside building zones.

The following methodology was used for the indicator:

- The extent of building zones was available at the cantonal scale for five years: 1979, 1989, 2007, 2012, and 2017 (Federal Office for Spatial Development, 1989; Leuzinger and Matthey, 1977; SFSO, 2017). A linear interpolation was performed to get annual estimates of the area of BZ for each canton between 1986 and 2015. The objective of Federal Act on Spatial Planning is to prevent constructions outside building zones. In that respect, we calculated the population density inside BZ assuming that all residents settled inside them. The population living in each canton was divided by the total surface area of BZ for that year. Lastly, we divided the results by the proportion of BZ area in the canton account for the relative area of BZ compared to the canton area, and allow comparison in density changes.

- The cantonal population was divided by the cantonal surface area, excluding lake areas, to get population density.

- The difference between annual changes in population density in building zones and in the cantons were computed. The resulting values showed whether settlements occurred mainly inside or outside building zones. For example, if the density change was greater in the canton than in the building zone, it yielded a negative value showing that changes mainly occurred outside building zones.

A.2.2 Organic farming (% land for organic farming)

Two main revisions of the Swiss agricultural policy framework came into force in 1992 and 1999 (El Benni and Finger, 2013). The "pre-revision" political framework included public market support to maintain high output production prices. With the first reform in 1992, market price support was reduced and area-based payments were introduced (Lehmann and Stucki, 1997). The second reform in 1999 linked the area-based payment system to a cross-compliance approach that integrated compulsory production requirements. For example, farmers have to set aside 7% of their land as ecological compensatory area to receive financial support from the government (Mann, 2003).

Although direct payments would have been a relevant indicator of the main agricultural policy for the last 30 years, the data gap prior to 1992 limited its suitability. A key modification of the agricultural policy was the introduction of direct payments for environmental friendly production. Studies have shown that organic farming benefits biodiversity and soil chemical properties better than conventional agriculture (Cederberg and Mattson, 2000; Mäder et al., 2002; Clark et al., 1998). In this study, the variable "Organic farming" is an indicator of the effectiveness of the agricultural policy to promote more sustainable agricultural production. In practice, the percentage of land for organic farming in each canton was used.

The following methodology was used for the indicator:

- The Swiss Federal Statistical Office (SFSO) provided yearly data on areas of organic farming between 1996 and 2015. Prior to 1996, data was only available for 1990 (SFSO, 2018a). The number of organic farms was available for the same period. The Swiss Organization for Agriculture and Rural Area Development (SOARD) monitors the number of organic farms in Switzerland on a yearly basis since 1981.

- The annual evolution of the number of organic farms for each canton. We retrieved the number of organic farms for the time interval 1986 – 1995. Between 1986 and 1989, we used the SFSO data to calculate the number of organic farms in each canton as the product of the ratio of organic farms in each canton to the total number of organic farms in Switzerland in 1990, and the total number of organic farms from the SOARD dataset (SOARD, 2017). The ratio was kept constant for the interval 1986 to 1989 due to the lack of data. Between 1991 and 1995, we reconstructed the average size in hectares of organic farms using the data from the SFSO. We linearly interpolated the average size of organic farms between 1990 and 1996. Then, we calculated the ratio of organic farms in each canton to the total number of organic farms in Switzerland between 1990 and 1996. We interpolated this ratio linearly between 1990 and 1996. The number of organic farms was the product of the ratio of organic farms interpolated previously, and the number of organic farms from the SOARD dataset.

- We calculated the total area of organic farming in each canton by multiplying the number of organic farms by the average size of organic farms in hectares interpolated previously. The

average size of organic farms was equal to 1990 values for the period 1986-1989 due to the lack of data.

-   Finally, the surface area of organic farming was divided by the canton surface area (excluding lake areas) to get the percentage of land for organic farming in each canton.

A.2.3 Population density (habitant/km^2)

An objective of the Federal Act on Spatial Planning of 1979 is to densify existing urban areas but with the increase in population density, humans tend to intensify their use of ecosystems for economic profit. The evolution of population density over time often results in changes in ES values, with greater increases most often leading to greater reduction in ES values (Rossi et al., 2008; Fei et al., 2016).
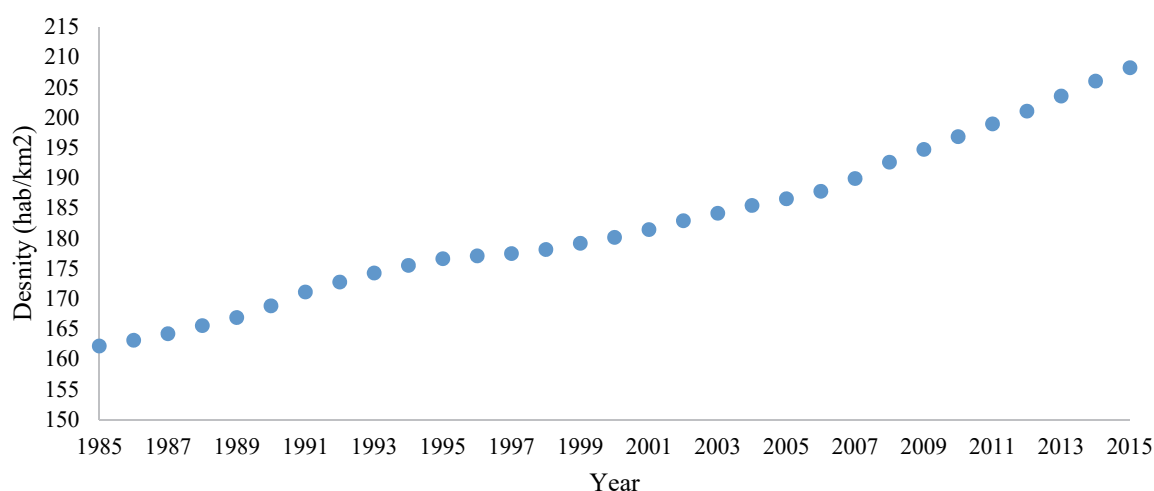
Figure B. Evolution of population density in Switzerland from 1985 to 2015

The following methodology was used for the indicator:

-   Population density was calculated annually between 1986 and 2015 in each canton. The Swiss Federal Statistical Office provided population statistics, and population counts were taken at the end of each year (SFSO, 2018c). An example of the evolution of population density is provided in Figure B.

-   We divided the population by the surface of each canton excluding lake areas as per the SFOS standards (SFSO, 2018d). The results provided an estimate of population density in permanent residents per kilometer squared (hab/ km^2).

Appendix B - Assessing spatial temporal patterns of ecosystem services in Switzerland

B.1. Methods

B.1.1 Cultural ecosystem services (dimensionless)

Cultural ecosystem services (CES) embed social complexity that cannot be easily understood using sys-tem based approaches. De Vreese et al. (2016) use the term 'social mapping' to describe the mapping of subjective perceptions and intangible ES. The following methodology was used for CES:

- Location of provisioning areas

- Five CES were assessed (Table E). Public participation geographic information systems (PPGIS) is a useful tool to include residents' perceptions, uses and values in a spatially explicit approach (Brown and Kyttä 2014). Web-based mapping was preferred to hard copy mapping because it gave the flexibility to work at the national scale, and to engage with participants speaking one of the three national languages (i.e. French, German, and Italian). We refer to Jaligot et al. (2018) for full methodological details on PPGIS.

Table E. Description of cultural ecosystem services

Cultural ecosystem service	Description
Heritage	I appreciate the local customs, traditions and cultural heritage linked to the place
Landscape aesthetics and landmark	I enjoy the landscape for it beauty or the landmark associated with it.
Outdoor activities	I enjoy spending time outside after work or on week-ends where I practice outdoor sports, walking, hiking, biking walking the dog, etc.
Inspiration, spiritual and religious	I am inspired by feelings, new thoughts, religious or spiritual meaning.
Simple nature value	I simply appreciate this place just because of its existence regardless of its benefits for me.

- Estimation of current cultural ecosystem services value

- PPGIS activities provided the location of 951 CES provisioning areas in the canton of Vaud (Table F).

- The responses were interpolated with the latest LULC dataset from the nomenclature NOAS04. LULC data were provided for Vaud over four time periods "1979/1985" (AREA 1), "1992/1997" (AREA 2), "2004/2009" (AREA 3), and "2013/2018" (AREA 4). The objective was to understand how CES were related to LULC types. For each CES, we calculated the ratio (r_j) of points associated with each land cover category in AREA 4 to the total point count. Once the ratio was calculated for each CES, we assigned this value to the respective LULC category in the four LULC dataset. The ratio was kept constant for each CES and LULC categories over the four time periods.

Table F. General output of participatory mapping activities in the canton of Vaud

Valid n° of respondents	*Heritage* point count	*Landscape aesthetics* point count	*Outdoor activities* point count	*Inspiration* point count	*Simple nature value* point count
108	217	271	238	73	152

B.1.2 Carbon stock (t ha−1 yr−)

Carbon stock (C stock) is a regulating ES. In Switzerland, the main providing areas are forests but it is key to account for other LULC categories. Estimates of annual carbon stocks have been calculated following guidelines and methods from the Guidelines for National Greenhouse Gas Inventory (IPCC 2006) and the Swiss Greenhouse Gas Inventory (FOEN 2017).

The following methodology was used for C stocks for each of time period:

- Primary stratification: canton, organic soil, elevation and forest production region

- The nomenclature of the Swiss Land Use Statistics (AREA) evaluated by the Swiss Federal Statistical Office is the basis for the categorization of LULC used in our assessment (SFSO 2006). Every hectare is assigned to one of 47 categories of land use (nomenclature NOLU04) and to one of 27 categories of land cover (nomenclature NOLC 04). LULC data were provided for Vaud over four time periods "1979/1985" (AREA 1), "1992/1997" (AREA 2), "2004/2009" (AREA 3), and "2013/2018" (AREA 4). Both NOLU04 and NOLC04 nomenclatures have been reclassified according to the main categories provided by the IPCC (IPCC, 2006; FOEN, 2017). A total of 18 LULC categories were used for the assessment of C stocks. The methodology proposed in the Swiss GHG Inventory was followed to quantify C stocks as accurately as possible (FOEN 2017).

- The canton was stratified with four data datasets: canton, soil type (mineral or organic), elevation and forest production regions. Wüst-Galley et al. (2015) elaborated a digital map showing the location of organic soil, integrating intact and degraded peaty soils. The map was kept constant over the entire period as in the Swiss GHG Inventory due to data limitation (FOEN 2017). Three elevation zones were differentiated: <601 meters above sea level, 601-1200 meters above sea level, and >1200m above sea level. Elevation data was retrieved from the Federal Office for Topography in the form of a 25x25 m raster file (DHM25). Finally, five forest production regions have been defined by the National Forest Inventory (NFI) (EAFV/BFL 1988; Brassel and Brändli 1999; Brändli 2010). The NFI regions are: 1. Jura, 2. Central Plateau, 3. Pre-Alps, 4. Alps, and 5. Southern Alps.

- We further stratified our dataset with the survey year group of AREA statistics. Here, we define a year group as the years at which a specific area was surveyed to complete the AREA statistics. For example, part of the canton of Vaud was surveyed in 1979, 1980 and 1981 in

AREA 1. Finally, we obtained strata with a single association of canton, organic soil, elevation, NFI region and year group.

- Calculation of historical carbon stocks

- The Swiss GHG Inventory defined four pools of carbon from 1990 to 2015 for each association of NFI production region and elevation (15 combinations in total): (i) carbon stock in living biomass, (ii) carbon stock in dead wood, (iii) carbon stock in litter, and (iv) carbon stock in soil (either mineral or organic) (FOEN 2017).

- C stock variables varied annually for carbon in living biomass and carbon in dead wood in productive forests, as well as carbon in living biomass in cropland (FOEN 2017). They were fixed for other LULC categories. Although stocks are in reality not fixed for a given LULC, the Swiss GHG considers that applying a Tier 1 approach and keeping C stocks in equilibrium for some LULC is appropriate.

- Values of carbon stocks between 1979 and 1989 were set to the value of carbon stocks in 1990 to avoid extrapolating data more than ten years in the past.

- Finally, we calculated the total annual carbon stocks for each stratum and aggregated the results by canton to get annual carbon stocks in Vaud. All spatial and statistical analysis were performed using Python 3©.

B.1.3 Flood regulation (index - dimensionless)

STREAM (Spatial Tools for River basins and Environment and Analysis of Management options) is a GIS based spatially distributed rainfall runoff model for simulating the impact of land use changes and climate change on the freshwater hydrology of river basins (Aaerts et al., 1999). The water balance is calculated per grid cell based on the Thornthwaite and Mather equation (1957). The methodological approach to build a flood regulation supply index was similar to Stürck et al. (2014) who used STREAM to assess the flood regulation service supply in Europe. The index is based on the response of hydrographs to environmental variables derived from hydrological experiments carried out using STREAM, where the effects of three environmental variables on discharge volumes following precipitation events were estimated (Table G). A supply index is derived from translating the outcome of these experiments conducted on a test catchment to the extent of Vaud, based on spatial maps of the environmental variables explored in the experiments.

Table G. Environmental variables used for the application of the flood regulation supply index

Environmental variables	Input	Resolution	Sources
Catchment zones	River catchment map		FOEN(2016)
	DHM 25	~ 25 m	Swisstopo (2001)
Crop factor			
WHC	NOAS04 (72 categories)	~ 100 m	SFSO (2015)
	Biophysical table		Allen et al. (1998), Nistor (2016), Nistor and Porumb (2015), Stürck et al. (2014)
	Total available water content	~ 1 km	Hiederer (2013)

The following methodology was used to calculate the flood regulation supply for each of time period:

- Environmental variables and catchment subdivision

- Characteristics of intensive rainfall vary across regions and environmental variables may have different responses which the resulting flood regulation supply index should account for (Stürck et al., 2014). Based on the approach detailed in Stürck et al. (2014) and data from Umbricht et al. (2013), we identified that the precipitation regime in the canton was five-days wet.

- The position within a catchment is a determinant of the influence of land use effects on flood regulation. Therefore, it is possible to divide the catchment into five equally sized zones depending on their elevation and slope factor (Aaerts et al., 1999), to reflect the steepness and the proximity of each location to the river network. In other words, the catchment is subdivided in upstream and downstream areas.

- Crop factors (CF) are used to determine the actual evapotranspiration from the potential evapotranspiration dependent on land use, land cover and management characteristics based on the Thornthwaite (1948) equations. Crop factors were assigned to each one of the 72 categories of the land use / land cover statistics (NOAS04), and kept constant for the four periods. The crop factors were retrieved from a review of work focusing on hydrological models (Allen et al., 1998; Nistor 2016; Nistor and Porumb 2015; Stürck et al., 2014).

- The water holding capacity (WHC) reflects the impact of soil hydraulic properties on water storage and retention. In Switzerland, a vector map of soil properties (BEK2000, 1:200,000) classified hydrologic retention capacities in six classes. However, the format and precision was not suitable for our application. A European map was retrieved from the European Soil Database (Hiederer 2013). In Vaud, WHC values go from 35 mm to 120 mm. We note that these values are in accordance with the map BEK2000.

- Flood regulation supply index

- A representative catchment was selected based on its central location in the canton, the presence of sufficient gauge data, and the absence of large-built up areas in the canton (Stürck et al., 2014). The characteristics of the catchment is presented in table H.

Table H. Characteristics of the Broye river catchment

Gage station	Payerne
Area (km²)	392
Highest point (m)	1504
Lowest point (m)	441
Mean elevation (m)	710
Mean slope (degree)	5.6
Min. discharge rate[a] (m³.s⁻¹)	1.27
Max. discharge rate[a] (m³.s⁻¹)	12.8
Max. discharge rate[a] (m³.s⁻¹)	5.92

- The next step involved the calibration of the hydrological model for the test catchment. STREAM has been calibrated for the Broye catchment using daily discharge data observed at the Payerne gauge station at the catchment outlet provided by the Federal Office of Environment (FOEN 2018). The model is initially designed to work with monthly data so we adjusted the model to work with daily data (full code is freely available upon request).

- The input for the model are daily precipitation and temperature at high resolution (1 km x 1 km) (MeteoSwiss 2018), a digital elevation model (Swisstopo 2001), a map of WHC (Hiederer 2003) and a crop factor map. We refer to Bouwer et al. (2008) for a detailed explanation of calibration parameters. The calibration was conducted for the year 2016 and validated for the year 2017 (MeteoSwiss, 2018). The resolution of all input layers was scaled down to 25-m.

We note that we also calibrated the model using monthly data for the period 2005-2010 to assess the difference in model performance.

- The model aimed to optimize the Nash-Sutcliffe efficiency coefficient (NSE) (Nash and Sutcliffe 1970) in accordance with other work (Milano et al., 2015; Ward et al., 2007). Perfect agreement between the observed and simulated discharges yields a value of 1. Figure C shows the hydrograph for observed and simulated discharge at the outlet of the Broye catchment for the calibration year 2016. After a warm-up period of 180 days, the model simulates flow dynamics with an NSE value of 0.52, which is satisfactory (Moriasi et al., 2007; Lin et al., 2017). An NSE coefficient of 0.87 was obtained with monthly data. Although Stürck et al. (2014) use monthly calibrated parameters, we decide to use the parameters calibrated daily to be consistent with the rest of the approach, which uses daily data.
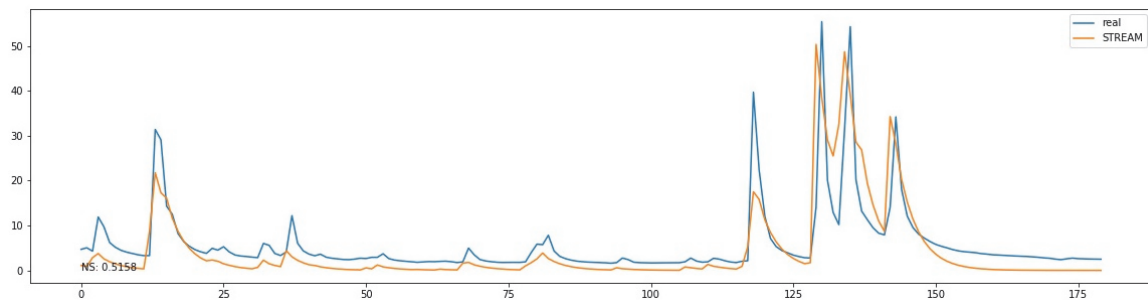
Figure C. Calibration of the STREAM model with daily data

- The model simulates flow dynamics with an NSE value of 0.74 for the validation period, meaning that the model is appropriate (Figure D).
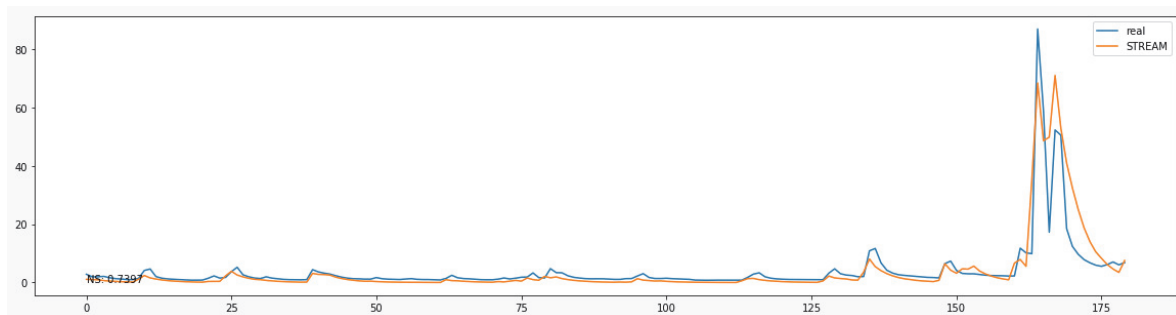

Figure D. Validation of the STREAM model with daily data

- For the calibrated model, hydrological experiments were run following the approach from Stürck et al. (2014) to estimate flood regulation supply. According the precipitation type five-days wet, one design event was tested in the STREAM experiment in the catchment. The precipitation quantity of the event was 50 mm.d^{-1} with 2 mm.d^{-1} antecedent precipitation in prior 5 days (Stürck et al., 2014; Umbricht et al., 2013). For all experimental runs, seven crop factors (0.4-1.1) and nine WHC values (0 – 80 mm) were iteratively adjusted in one catchment zone, while the remaining were set to the lowest values of crop factor and WHC. After each simulation, the discharge record at the catchment outlet was retrieved. We refer to Stürck et al. (2014) for full methodological details.

- The final step is to create a flood regulation index. We quantified the effect of environmental factors on river discharge. The flood regulation supply indicator (IFS) is calculated by normalizing the river discharges at the catchment outlet after the precipitation event by scaling the results between 0 and 1 resulting in a dimensionless factor.

- The values retrieved were entered in a look-up table, which distinguishes the IFS, catchment zone, crop factor and WHC. A linear regression was performed after normalizing the variables (R-squared =0.77). Equation 2 reflects the relative impact of each variable on the flood regulation index IFS. It was applied to other areas in the canton to obtain a flood regulation supply index at the cantonal scale and for each time period. It shows the impact of LULC change on the flood regulation supply (Stürck et al., 2014).

$$IFS = 0.1254 * Crop\ Factor + 0.4097 * WHC + 0.4168 * Catchment\ zone + 0.048 \qquad Equation\ (2)$$

B.1.4 Food production (t ha^{-1} yr^{-})
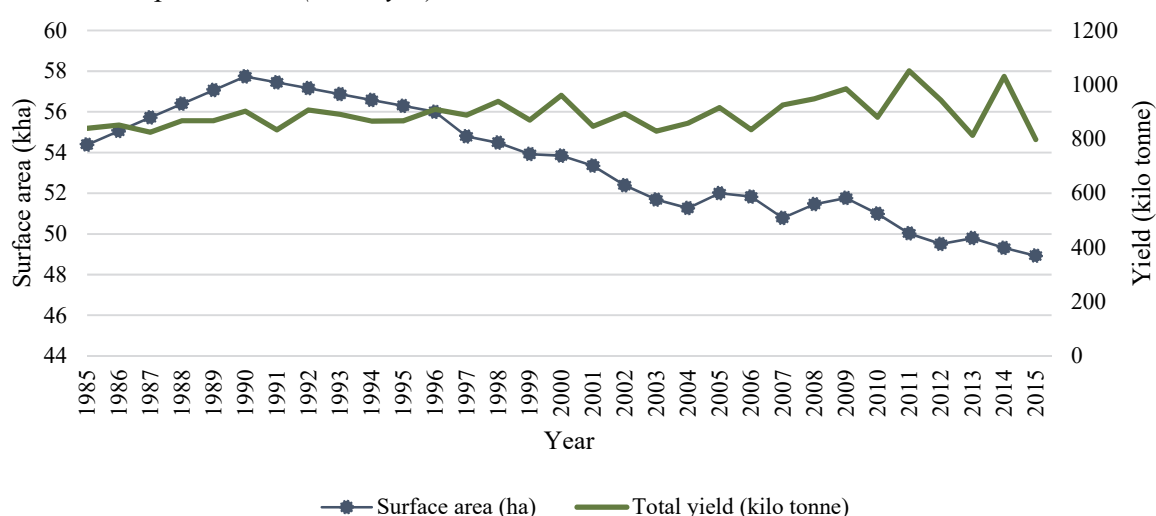
Figure E. Evolution of cropland yields and surface area in Vaud from 1985 to 2015

Food production is quantified using annual yields of cropland areas (Figure E), fruits orchards and vineyards in tonnes per hectare in the canton (Courzat et al., 2015). The following methodology was used for each of time period:

- The extent of cropland, fruit orchards and vineyards is determined by the nomenclature of the Swiss Land Use Statistics evaluated by the Swiss Federal Statistical Office (SFSO 2006).

- The Swiss Farmer's Union publishes annual reports on agriculture including yields in decitonne per hectare for a variety of crops at the cantonal scale (SFU 2018). The report also includes fruit orchards and vineyards.

- Fifteen crop types, seven fruit types and vineyards were used to calculate an average annual yield per canton in tonnes per hectare (t/ha). Table I shows an example of the distribution of crop types in the canton in 2015. We stratified the values by altitudes to account for the variation in yields for the same crop type depending on altitude (Crouzat et al., 2015). The

stratification was done in three categories: < 600m, 601-1200m, and > 1200m. The resulting yields were assigned respectively to the cropland, fruit orchards and vineyards.

Table I. Area of crops used in the assessment in 2015

Crop type	Area in 2015 (ha)	Percentage
Wheat	20,319.13	41.53
Rapeseed	7,118.43	14.55
Sugar beets	4,779.02	9.77
Barley	4,392.49	8.98
Silage maize	4,354.19	8.90
Maize	3,345.30	6.84
Potatoes	2,010.45	4.11
Triticale	1,661.70	3.40
Rye	368.81	0.75
Oat	259.99	0.53
Tobacco	161.50	0.33
Fodder beet	75.49	0.15
Spelt	33.51	0.07
Meslin and other feed grains	25.63	0.05
Meslin and other bread cereals	20.54	0.04
TOTAL	48,926.18	100

B.1.5 Pollination (index – dimensionless)

The methodology to assess pollination supply as the Relative capacity of ecosystems to support crop pollination was derived from the InVEST model version 3.4.4 (Sharp et al., 2018). The model focuses on wild bees as key for pollination. It estimates the availability of nesting sites and floral abundance within bee flight ranges to derive an indicator of the abundance of bees nesting within a LULC cell. Then, it predicts the relative abundance of different pollinator species visiting each cell based on the floral resources, foraging activity, flight range information and abundance within each cell (Lonsdorf et al., 2009).

- Model parameterization

- The model requires three compulsory input: a LULC map, a guild table with properties about active seasons, nesting preferences, mean flight distances, and relative abundances for each pollinator species; and a biophysical table with nesting suitability and floral resources across seasons for all LULC types.

Guild table

- Based on an extensive literature review, we identified 23 important pollinator species in Vaud. Table J provides information on the nesting ground, the foraging activities, the flight range and

the relative abundance of these species in the canton. Foraging distances were either from field measurements or calculated using an allometric equation based on species intertegular span and measure of body size (Greenleaf et al., 2007).

Biophysical table

- As in previous models, the nomenclature of the Swiss Land Use Statistics (AREA) was used. The base map for the assessment of nesting suitability and floral availability was the NOAS04 classifying LULC in 72 categories at a resolution of 100 m. It was preferred to other classification because it distinguishes dense canopy with less dense woodlands at the boundary with other land cover types. For example, many herbaceous species and shrubs are a good source of pollen and/or nectar for honeybees (Cho et al., 2017; Cunningham et al., 2018). It also distinguishes green elements in urban settings (e.g. public parks). First, nesting suitability and floral availability were assigned to each LULC category based on an extensive literature review in the European context (Groff et al., 2016; Kammerer et al., 2016; Lonsdorf et al., 2009; Meehan et al., 2013; Zulian et al., 2013). LULC data were subsequently combined with other datasets in a composite model to account for the management intensity of cropland and the split between broadleaf and coniferous forests (Verhagen et al., 2018; Zullian et al., 2013).

- Field studies across Europe showed that pollination supply was affected by the proximity of habitat areas and management intensity of cropland (Hendrickx et al., 2007). We used typical value of fertilizer application on crops in the Leman region to account for management intensity on crops (low < 50 kg/ha, medium: 50-150 kg/ha; and high > 150 kg/ha) (Klein et al., 2007). In accordance with Verhagen et al. (2018), we assumed that low intensity cropland had 100% contribution of pollinators to surrounding cells, medium intensity had 75% contribution and high intensity had 50% contribution. Therefore, scores of habitat suitability and floral availability were increased in agricultural areas under extensive farming (Zullian et al., 2013).

- Forest and woodland are key providers of nesting and floral resources for pollinators. We reclassified forest and woodland areas to account for the division between broadleaf and coniferous forests (Groff et al., 2016; Meehan et al., 2013; Zulian et al., 2013). Waser et al. (2017) provided a tree map with a resolution of 3 m with the distinction between broadleaf and coniferous trees. We interpolated the LULC maps with the tree type map and reclassified forested areas with more than 50% broadleaf trees as broadleaf forests and less than 50% as coniferous. The tree map was constant for all periods.

- Verhagen et al. (2016) argue that accounting for landscape configuration is key in ES assessments. Following Zullian et al. (2013) and Verhagen et al. (2016, 2018), we accounted for forest edges adjacent to more open land as they have a positive impact on pollination and small patches are important for pollination. We assigned a separate value to nesting suitability

and floral resource availability for forest interior and edge cells. Forest edge cells were defined as those cells within 100 m from other LULC types.

Table J. Modelling reference values for pollinator species

Species	Nesting suitability				Foraging activity			Flight Distance (m)	Relative abundance	References
	Cavity	Wood	Stem	Ground	Spring	Summer	Autumn			
Lasioglossum malachurum	0	0	0	1	0.8	1	0.5	500	1	Buri et al. (2014), Carrié (2016), Greenleaf et al. (2007)
Halictus.simplex group	0	0	0	1	0.8	1	0	494.2	0.45	Buri et al. (2014), Carrié (2016), Fortel et al. (2014)
Apis mellifera (honey bees)	1	0	0	0	1	1	0.5	1091	0.40	Buri et al. (2014), Couvilon et al. (2015), Eyer et al. (2017), Lonsdorf et al. (2009)
Lasioglossum laticeps	0	0	0	1	0.8	1	0.5	343	0.34	Buri et al. (2014), Carrié (2016), Fortel et al. (2014), Gérard et al. (2018), Greenleaf et al. (2007)
Lasioglossum calceatum	0	0	0	1	0.8	1	0.5	1000	0.33	Buri et al. (2014), Carrié (2016), Lonsdorf et al. (2009), Zurbuchen et al. (2010)
Halictus tumulorum	0	0	0	1	0.8	1	0.5	346	0.20	Buri et al. (2014), Carrié (2016), Fortel et al. (2014), Greenleaf et al. (2007), Lonsdorf et al. (2009), Wright et al. (2015)
Lasioglossum pauxillum	0	0	0	1	0.8	1	0.5	480	0.18	Buri et al. (2014), Carrié (2016), Greenleaf et al. (2007)
Bombus sensus stricto group	1	0	0	0	0.8	1	0.5	2851	0.12	Buri et al. (2014), Gerard et al. (2018), Lonsdorf et al. (2009), Pyke et al. (2011), Zurbuchen et al. (2010)
Lasioglossum lineare	0	0	0	1	0.8	1	0.5	323	0.077	Buri et al. (2014), Carrié (2016), Fortel et al. (2014), Gerard et al. (2018), Lonsdorf et al. (2009)
Bombus lapidarius	0	0	0	1	1	1	0.5	1500	0.054	Buri et al. (2014), Lonsdorf et al. (2009), Walther-Hellwig and Frankl (2000)
Lasioglossum morio	0	0	0	1	1	1	0.6	217	0.052	Buri et al. (2014), Carrié (2016), Fortel et al. (2014), Greenleaf et al. (2007), Wright et al. (2015)
Lasioglossum villosulum	0	0	0	1	0.8	1	0.8	293	0.044	Carrié (2016), Fortel et al. (2014)
Lasioglossum leucozonium	0	0	0	1	0.8	1	0.5	498	0.039	Carrié (2016), Fortel et al. (2014)
Lasioglossum glabriusculum	0	0	0	1	0.5	1	0	122	0.039	Carrié (2016), Fortel et al. (2014)
Megabombus group	0	0	0	1	1	1	0.3	1945	0.038	Carrié (2016), Fortel et al. (2014)
Thoracobombus group	1	0	0	1	0.8	1	0	1743	0.030	Carrié (2016), Fortel et al. (2014)
Halictus scabiosae	0	0	0	1	0.8	1	0.3	712	0.029	Buri et al. (2014), Carrié (2016), Greenleaf et al. (2007), Fortel et al. (2014), Lonsdorf et al. (2009)

Species										References
Lasioglossum zonulum	0	0	0	1	0.8	1	0.5	943	0.025	Buri et al. (2014), Carrié (2016), Lonsdorf et al. (2009), Meehan et al. (2016)
Lasioglossum fulvicorne	0	0	0	1	0.8	1	0.5	1250	0.021	Carrié (2016), Fortel et al. (2014)
Andrena dorsata	0	0	0	1	1	1	0.8	544	0.019	Carrié (2016), Fortel et al. (2014)
Andrena flavipes	0	0	0	1	1	1	0.8	653	0.018	Carrié (2016), Fortel et al. (2014)
Halictus maculatus	0	0	0	1	0.8	1	0.5	367	0.017	Carrié (2016), Fortel et al. (2014)
Halictus rubicundus	0	0	0	1	0.5	1	0.3	604	0.017	Carrié (2016), Fortel et al. (2014), Potts and Willmer (1997)

B.1.6 Erosion control (t ha⁻¹ yr⁻)

In Switzerland, soil erosion has been recognized as a problem since the mid-1970s. A number of studies have been performed to quantify soil erosion using high-resolution data (Gisler al. 2010; Meusburger et al., 2010; Prashun et al., 2012; Prashun et al., 2013; Rüttiman et al., 1995). Prashun et al. (2013) presented a high-resolution (2 m × 2 m grid) potential soil erosion risk map using the software AVErosion. For the purpose of this study, such a resolution was not necessary as all modelling results are presented at the municipal scale. Here, we use the Sediment Retention model from InVEST 3.4.4 modelling suite to calculate erosion control in Vaud (Table K) (Grafius et al., 2016; Hamel et al., 2015). We only use the first part of the model, which computes the amount of annual soil loss per pixel. The amount of annual soil loss per pixel i_i, $usle_i$ (tons·ha⁻¹yr⁻¹), is given by the revised universal soil loss equation (RUSLE): (Sharp et al., 2018).

- Model parameterization

Table K. InVEST sediment retention model input

Environmental variables	Input	Resolution	Sources
Watersheds	River watershed map		FOEN(2016)
Digital elevation model	DHM 25	~ 25 m	Swisstopo (2001)
Rainfall erosivity (R)	Annual R factor map	~ 100 m	Schmidt et al. (2016)
Soil erodibility (K)	K factor map	~ 500 m	Schmidt et al. (2018)
LULC	NOAS04 (72 categories)	~ 100 m	SFSO (2015)
USLE C factor	See biophysical table below		
USLE P factor	See biophysical table below		
Threshold accumulation value (tfac)	200		Calibrated
k	2.0		Calibrated
IC_0	0.5		Calibrated
SDR_{max}	0.75		Calibrated

Support practice factor P

- The support practice factor USLE *P* is an index value between 0 and 1, where 1 has no effect on the equation and values less than 1 represent standard agricultural management practices. It was set to 0.5 of urban areas (Chaplin-Kramer et al., 2016; Hamel et al., 2015; Hamel et al., 2017), and 1 for all classes except agricultural areas (Grafius et al., 2016; Prashun et al., 2007; Wanner 2013). *P* factor can be calculated based on the slope (Clark et al., 2015; Prashun et al., 2013). Here *P* = 0.4 x (0.02 x slope (%)). It was calculated for each time period based on the average slope of agricultural land use classes.

Cover management factor C

- A *C* (cover) factor was assigned to each LULC based on the literature. The values were kept constant throughout time. Table L provides an example of the model parameters used in the model for the last period (2012-2014) using the LULC dataset AREA 4.

Table L. Input biophysical table in InVEST SDR for soil erosion prevention

LULC code	LULC	*P*	*C*
1	Industrial and commercial buildings	0.5	0
2	Surrounding of industrial and commercial buildings	0.5	0.1
3	Surroundings of one- and two family houses	0.5	0
4	Surroundings of one- and two family houses	0.5	0.1
5	Terraced housed	0.5	0
6	Surroundings of terraced houses	0.5	0.1
7	Blocks of flats	0.5	0
8	Surroundings of blocks of flats	0.5	0.1
9	Public buildings	0.5	0
10	Surroundings of public buildings	0.5	0.1
11	Agricultural buildings	0.5	0
12	Surroundings of agricultural buildings	0.5	0.1
13	Unspecified buildings	0.5	0
14	Surroundings of unspecified buildings	0.5	0.1
15	Motorways	0.5	0
16	Green motorways environs	0.5	0.1
17	Roads and paths	0.5	0
18	Green road environs	0.5	0.1
19	Parking areas	0.5	0
20	Sealed railway	0.5	0
21	Green railway environs	0.5	0.1
22	Airports	0.5	0
23	Airfield, green airport environs	0.5	0.1
24	Energy supply plants	0.5	0
25	Waste water treatment plants	0.5	0
26	Other supply or waste treatment plant	0.5	0
27	Dumps	0.5	0
28	Quarries, mines	0.5	0
29	Construction sites	0.5	0

30	Unexploited urban areas	0.5	0
31	Public parks	0.5	0.1
32	Sport facilities	0.5	0.1
33	Golf courses	0.5	0.1
34	Camping areas	0.5	0.1
35	Garden allotments	0.5	0.1
36	Cemeteries	0.5	0
37	Intensive orchards	0.50	0.2188
38	Field fruit trees	0.61	0.2188
39	Vineyards	0.8	0.3527
40	Horticulture	0.51	0.2188
41	Arable land	0.52	0.344
42	Meadows	0.68	0.0012
43	Farm pastures	0.71	0.0903
44	Brush meadows and farm pastures	0.92	0.0903
45	Alpine meadows	0.87	0.0903
46	Favourable alpine pastures	0.92	0.0903
47	Brush alpine pastures	1	0.0903
48	Rocky alpine pastures	1	0.0903
49	Sheep pastures	1	0.0903
50	Normal dense forest	1	0.0011
51	Forest strips	1	0.0011
52	Afforestation	1	0.0011
53	Felling areas	1	0.0011
54	Damaged forest areas	1	0.3427
55	Open forest (on agricultural areas)	1	0.0011
56	Open forest (on unproductive areas)	1	0.0011
57	Brush forest	1	0.0219
58	Groves, hedges	1	0.0011
59	Cluster of trees (on agricultural areas)	1	0.0881
60	Cluster of trees (on unproductive areas)	1	0.0219
61	Lakes	1	0

62	Rivers	1	0
63	Flood protection structures	1	0
64	Scrub vegetation	1	0.003
65	Unproductive grass and shrubs	1	0.003
66	Avalanche and rockfall barriers	1	0
67	Wetlands	1	0
68	Alpine sport facilities	1	0
69	Rocks	1	0.45
70	Screes, sand	1	0.45
71	Landscape interventions	1	0
72	Glaciers, perpetual snow	1	0

- Soil erosion prevention supply (t ha^{-1} yr$^-$)

- Soil erosion prevention was computed using Equation 3 as avoided soil erosion provided by land use and land cover (Crouzat et al., 2015; Luo et al., 2019).

$$EC = RKLS - RUSLE \quad \text{Equation (3)}$$

Where EC is the erosion control, a measure of the gap between potential and actual soil erosion; RKLS is the potential soil loss with no vegetation coverage or support practice (t ha^{-1} yr^{-1}); R is rainfall erosivity, from daily rainfall (MJ mm ha^{-1} h^{-1} yr^{-1}) data (Schmidt et al., 2016); K describes a soil erodibility factor (t ha h MJ^{-1} ha^{-1} mm^{-1}) (Schmidt et al., 2018); LS is a slope length and steepness factor; and $RUSLE$ is the revised soil loss equation representing the annual soil loss (t ha^{-1} yr^{-1}).

B.1.7 Water purification (index – dimensionless)

The use of fertilizers in Swiss agriculture has been the major contributor to air and water pollution through the conversion of nitrogen intro ammonia, nitrates and nitrites. Although nitrogen exceedance decreased from to 130,000 tonnes in 1990 to 100,000 tonnes today, the levels of pollution remain high in many watercourses (FOEN 2014; Rihm and Achermann 2016).

Water purification was calculated using the InVEST 3.4.4 Nutrient Delivery Ratio model (NDR), to estimate the amount of nitrogen retained in the landscape based on runoff, elevation, soil characteristics, nitrogen export, and filtration coefficients linked to LULC types (Table M) (Sharp et al., 2018).

Table M. InVEST nutrient delivery ratio model input

Environmental variables	Input	Resolution	Sources
Watersheds	River watershed map		FOEN(2016)
Digital elevation model	DHM 25	~ 25 m	Swisstopo (2001)
Nutrient runoff proxy	Precipitation	~ 1000 m	MeteoSwiss (2018)
LULC	NOAS04 (72 categories)	~ 100 m	SFSO (2015)
Nutrient load	See biophysical table below		
Maximum retention efficiency	See biophysical table below		
Critical retention distance	See biophysical table below		
Proportion of subsurface nutrient	See biophysical table below		
Threshold accumulation value (tfac)	200		Calibrated
k	2.0		Calibrated
Subsurface critical length	100 m		Calibrated
Subsurface Maximum Retention Efficiency	0.75		Calibrated

- Model parameterization

Nitrogen loads (kg/ha)

The nitrogen loads encompass mostly manure, mineral fertilizers and atmospheric deposition. Maps of nitrogen atmospheric deposition were retrieved for the years 1980, 1990, 2005 and 2010, and assigned to each time period modelled (Rihm and Achermann 2016). The average deposition was calculated for each LULC category in the canton of Vaud. For agricultural areas, nitrogen loads were estimated from an extensive literature review of guidelines and agriculture statistics reports for each time period (Bertschinger et al., 2003; Cornaz et al., 2005; Hürdler et al., 2015; FOEN, 2014; Peter et al., 2006; SFU 2018; Spiess 1999). We note that data of nitrogen load per culture type and canton are not available in Switzerland.

Retention efficiency

Conceptually, this value represents the maximum retention efficiency that can be expected from a given LULC type. Natural vegetation types (e.g. forests, natural pastures, etc.) are usually assigned high values. Based on the literature, we estimated the parameters for each LULC type. We note that these parameters were adjusted during model calibration and remained constant for simulations over time (Bai et al., 2018; Berg et al., 2016; Chaplin-Kramer et al., 2017; Redhead et al., 2018, Salata et al., 2017).

- Model calibration and validation

- The main model output is the total nitrogen (TN) export from each watershed in kg/year. For consistency with the flood regulation model, calibration was conducted on the Broye

watershed. Observed nitrogen export data from the watershed were used to calibrate and validate the results of the NDR module. Total N (mg.L-1) was converted to kg/year to be comparable with model output by multiplying the nitrogen concentration by the annual water discharge in the watershed (FOEN 2018).

- InVEST cannot account for nitrogen input from point sources such as waste water treatment plants. An additional value was added to the TN export modelling output (Yan et al., 2018). 2009 was used as the year of calibration and 2012 as the year of validation due to data availability. TN from point sources were retrieved from the Wastewater treatment balance report in Vaud for 2009 and 2012. (Vioget et al., 2010; Vioget et al., 2013). Modelled TN export was 7% lower than the observed value for the calibration year, and 15% higher than the observed value for the validation year (Figure F). Therefore, the model displays good performance.
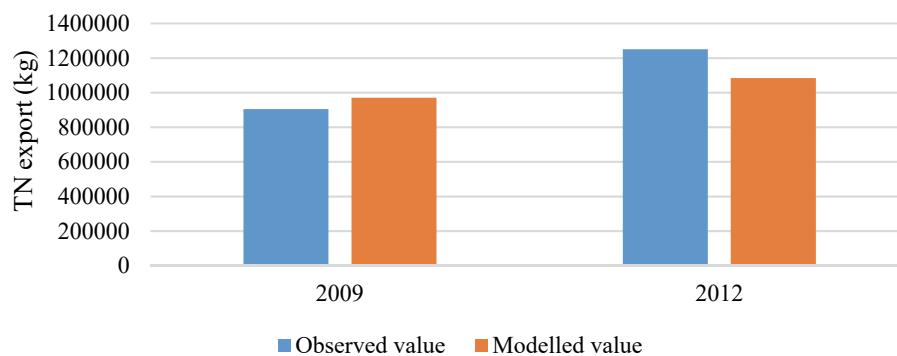

Figure F. Calibration (2009) and validation (2012) of InVEST NDR model.

The model parameters used to model water purification in last period (2012) are shown below (Table N).

Table N. Input biophysical table in InVEST NDR for water purification for the last simulation period

LULC code	LULC	TN load (kg/ha)	Retention efficiency	Proportion subsurface nitrogen
1	Industrial and commercial buildings	17.6	0.1	0
2	Surrounding of industrial and commercial buildings	17.8	0.1	0
3	Surroundings of one- and two family houses	16.8	0.1	0
4	Surroundings of one- and two family houses	16.4	0.4	0
5	Terraced housed	15.6	0.1	0
6	Surroundings of terraced houses	16.4	0.4	0
7	Blocks of flats	16.0	0.1	0
8	Surroundings of blocks of flats	16.2	0.4	0
9	Public buildings	16.0	0.1	0
10	Surroundings of public buildings	16.5	0.4	0

11	Agricultural buildings	18.0	0.1	0
12	Surroundings of agricultural buildings	18.3	0.4	0
13	Unspecified buildings	15.9	0.1	0
14	Surroundings of unspecified buildings	16.3	0.4	0
15	Motorways	18.4	0.1	0
16	Green motorways environs	18.1	0.4	0.4
17	Roads and paths	16.6	0.1	0
18	Green road environs	17.8	0.4	0.4
19	Parking areas	16.5	0.1	0
20	Sealed railway	16.8	0.1	0
21	Green railway environs	17.2	0.4	0.4
22	Airports	16.0	0.1	0
23	Airfield, green airport environs	15.9	0.4	0.4
24	Energy supply plants	16.8	0.1	0
25	Waste water treatment plants	16.7	0.1	0
26	Other supply or waste treatment plant	16.9	0.1	0
27	Dumps	17.0	0.1	0
28	Quarries, mines	18.7	0.1	0
29	Construction sites	17.2	0.1	0
30	Unexploited urban areas	17.3	0.1	0
31	Public parks	15.7	0.4	0.4
32	Sport facilities	17.3	0.1	0
33	Golf courses	14.6	0.1	0
34	Camping areas	18.1	0.1	0
35	Garden allotments	17.1	0.4	0.4
36	Cemeteries	16.8	0.1	0
37	Intensive orchards	74	0.65	0.5
38	Field fruit trees	18.3	0.65	0.5
39	Vineyards	74	0.65	0.5
40	Horticulture	74	0.65	0.5
41	Arable land	155	0.65	0.5
42	Meadows	74	0.65	0.5
43	Farm pastures	18.5	0.65	0.5
44	Brush meadows and farm pastures	16.8	0.65	0.5
45	Alpine meadows	12.6	0.65	0.5
46	Favourable alpine pastures	13.2	0.65	0.5
47	Brush alpine pastures	10.4	0.65	0.5
48	Rocky alpine pastures	10.3	0.65	0.5
49	Sheep pastures	9.3	0.65	0.5
50	Normal dense forest	16.8	0.9	0
51	Forest strips	16.2	0.9	0
52	Afforestation	16.9	0.9	0
53	Felling areas	18.2	0.9	0
54	Damaged forest areas	14.7	0.4	0
55	Open forest (on agricultural areas)	14.3	0.9	0
56	Open forest (on unproductive areas)	14.3	0.9	0

57	Brush forest	10.3	0.9	0
58	Groves, hedges	16.7	0.9	0
59	Cluster of trees (on agricultural areas)	14.7	0.9	0
60	Cluster of trees (on unproductive areas)	11.0	0.9	0
61	Lakes	11.4	0.05	0
62	Rivers	17.1	0.05	0
63	Flood protection structures	18.9	0.1	0
64	Scrub vegetation	11.0	0.1	0
65	Unproductive grass and shrubs	9.2	0.1	0
66	Avalanche and rockfall barriers	10.5	0.1	0
67	Wetlands	16.7	0.5	0
68	Alpine sport facilities	11.9	0.1	0
69	Rocks	7.3	0.1	0
70	Screes, sand	7.4	0.1	0
71	Landscape interventions	18.1	0.1	0
72	Glaciers, perpetual snow	5	0.1	0

- Water purification index

As the loads vary for each time period, a water purification index was computed using Equation 4 adapting the approach of Schirpke et al. (2019).

$$WP = \frac{(TN - NS)}{TN} \quad \text{Equation (4)}$$

Where *WP* is the water purification index, *TN* is the loads for surface transport per pixel (kg/year) and *NS* is how much load from each pixel eventually reaches the stream (kg/year). *WP* values are comprised between 0-1 where a high value means high water purification and low value means low purification, as most of the load would reach the stream.

B.2. Maps of ES supply variations
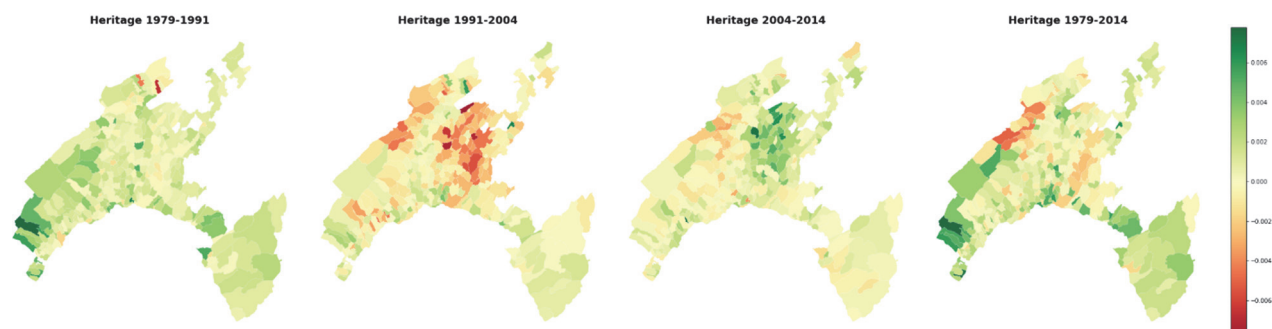
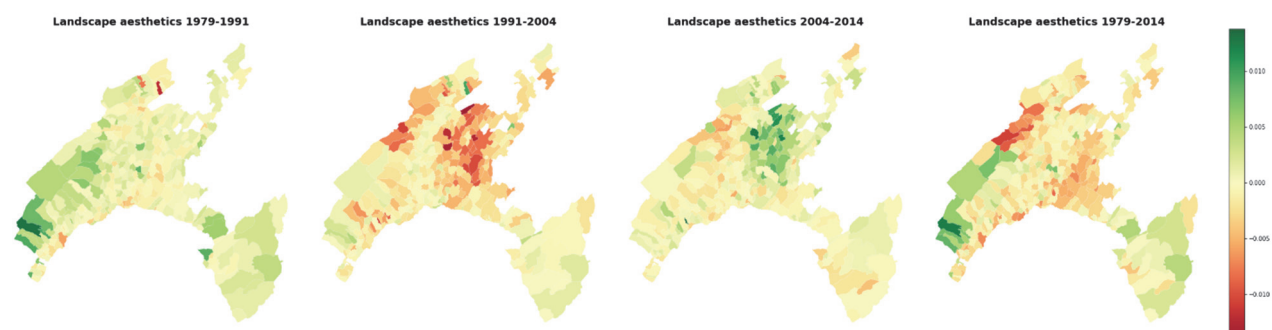**Figure G. Changes in heritage for the period 1979-2014 (dimensionless)**

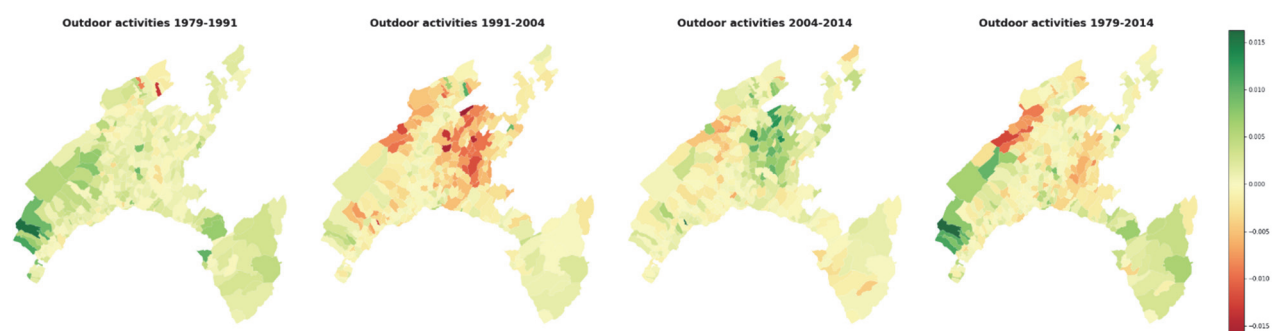**Figure H. Changes in landscape aesthetics for the period 1979-2014 (dimensionless)**

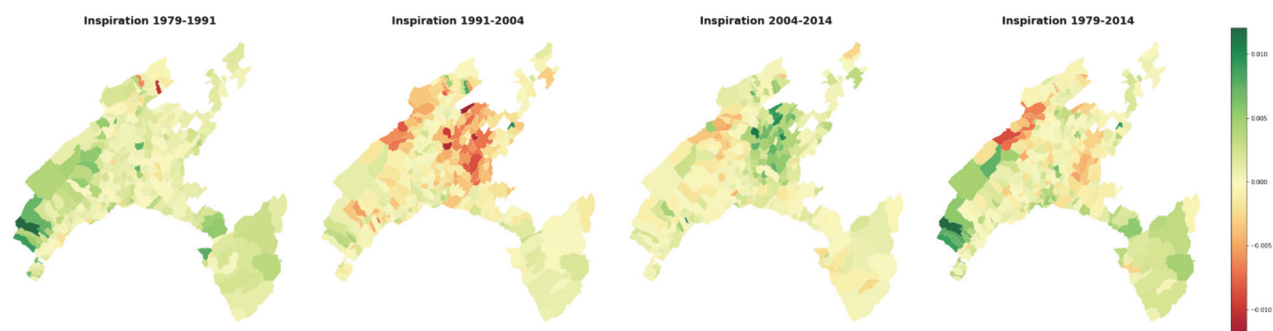**Figure I. Changes in outdoor activities for the period 1979-2014 (dimensionless)**

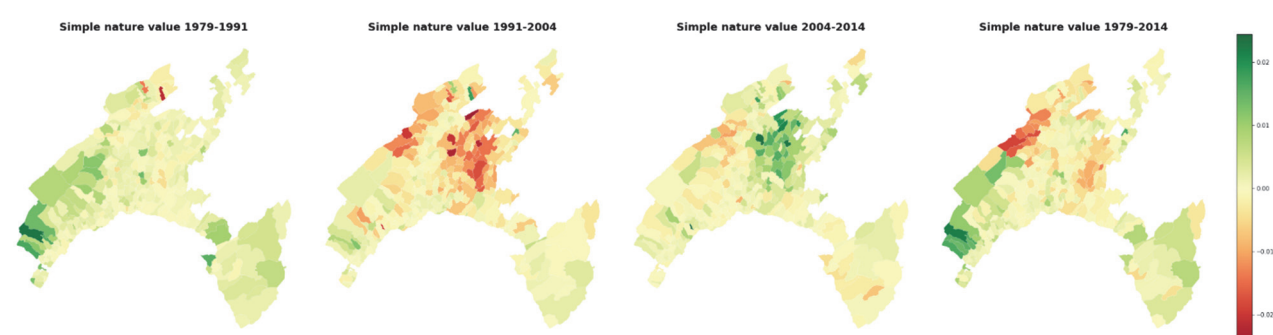**Figure J. Changes in inspiration, religious and spiritual for the period 1979-2014 (dimensionless)**

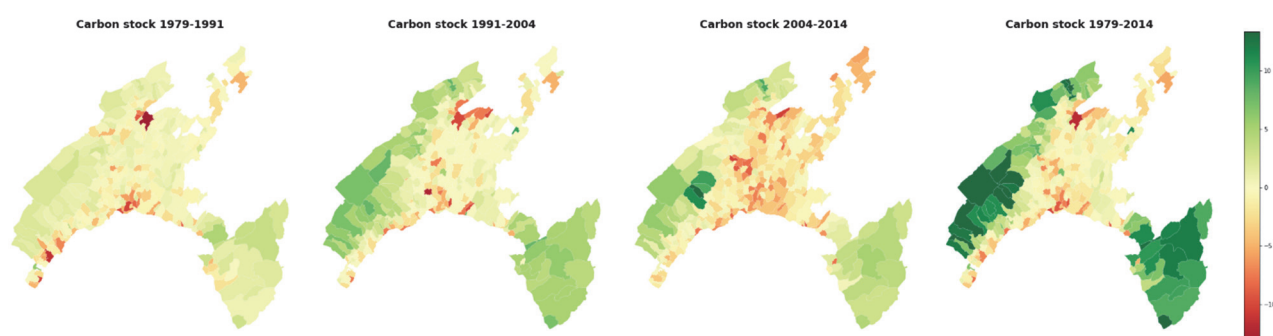**Figure K. Changes in simple nature value for the period 1979-2014 (dimensionless)**

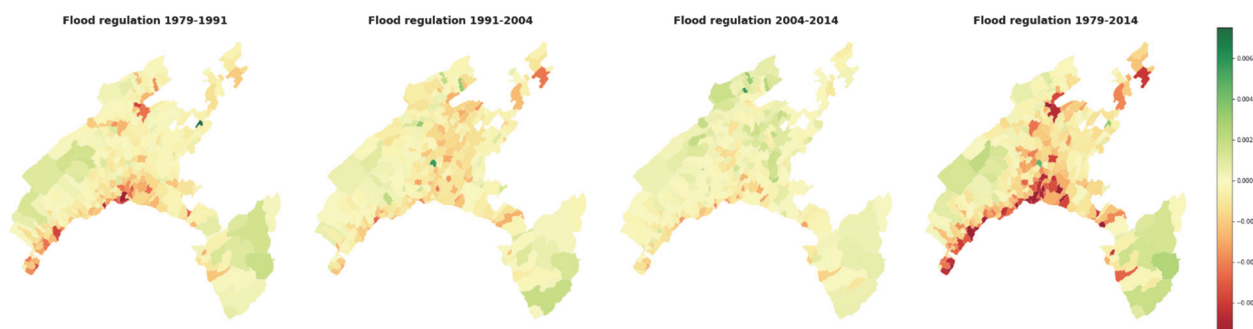**Figure L. Changes in carbon stock for the period 1979-2014 (t ha−1 yr−)**

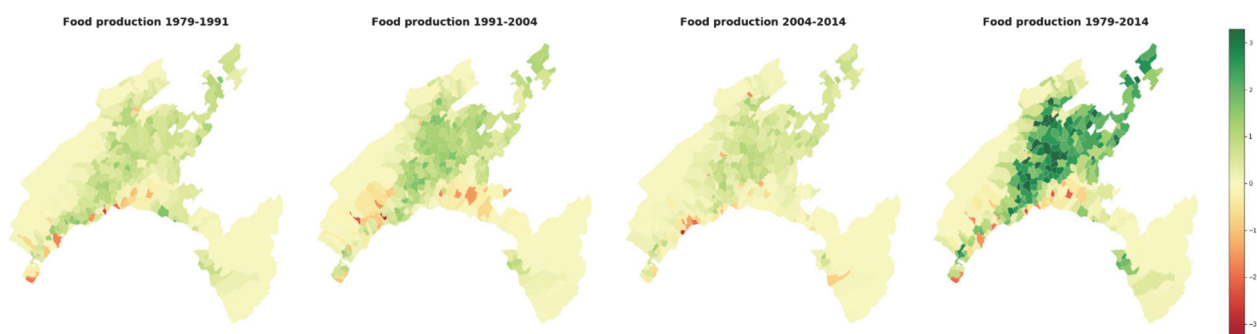**Figure M. Changes in flood regulation for the period 1979-2014 (dimensionless)**

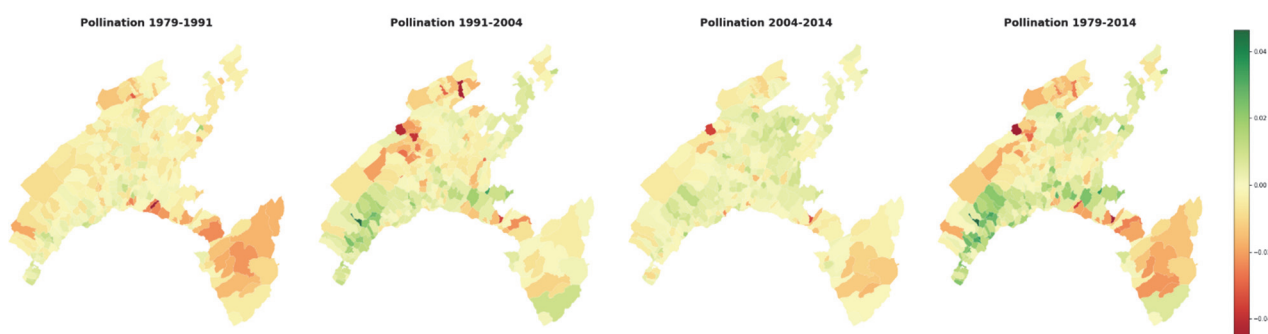**Figure N. Changes in food production for the period 1979-2014 (t ha−1 yr−)**

Figure O. Changes in pollination for the period 1979-2014 (dimensionless)

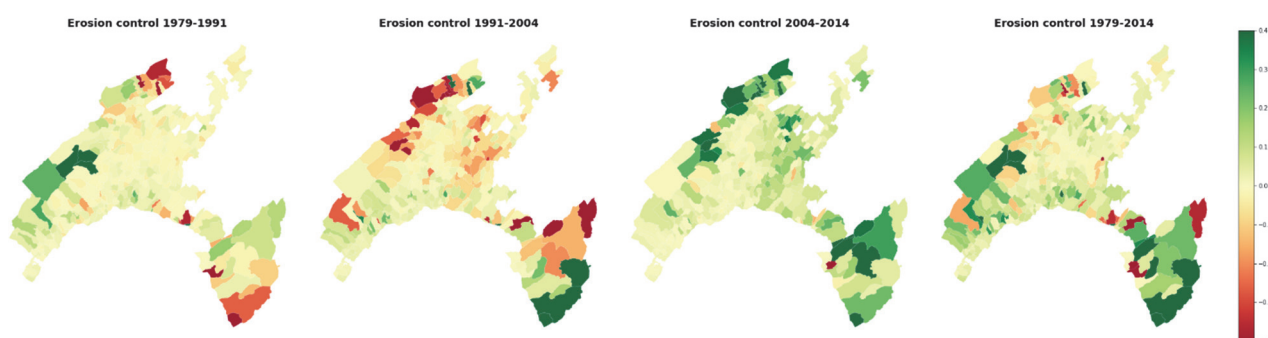**Figure P. Changes in erosion control for the period 1979-2014 (t ha−1 yr−)**
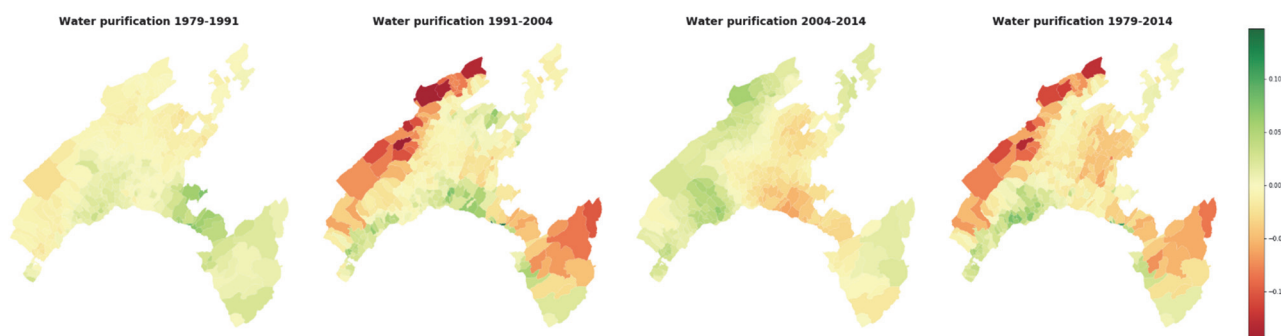
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Figure Q. Changes in water purification for the period 1979-2014 (dimensionless)

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Curriculum vitae

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1012, Lausanne, VD
Switzerland

EDUCATION

Feb 2017 – Fed 2020 / Ecole Polytechnique Fédérale de Lausanne, Switzerland
PhD candidate – New perspectives for spatial planning in Switzerland: the role of ecosystem services

Other projects:
- SINERGIA – African contributions to Global Health
- FORT – Future of rural territories (spatial planning and ecosystem services in Cameroon and Switzerland)
- Assistant editor of the journal African Cities Journal
- MOOC instructor – African Cities I: an introduction to urban planning

Oct 2014 - Sept 2015 / Imperial College London, UK
MSc Environmental Engineering and Sustainable Development with Distinctions

- Thesis - Value Chain Analysis to build on existing informal recycling systems: a case study of Egypt.
Project done in partnership with the German Corporation for International Cooperation (GIZ) including fieldwork in Egypt.

2011 - 2014 / University of Manchester, UK
BSc Hons Geology/Geography with a Second Class Division one Honours

WORK EXPERIENCES

Feb 2017 – Feb 2020 / PhD candidate - EPFL, Switzerland

- Funding proposal write-ups for research in Africa;
- Liaise with multilateral organizations, local authorities, NGOs, and universities for proposal; write-ups and data access in Kenya and Morocco;
- Development and management of academic partnerships in Kenya;
- Field research in Cameroon on environmental planning and motorcycle taxi research.

Jan 2017 - Feb 2017 / Waste management consultant – Disaster Waste Recovery, Jordan

- Develop an integration strategy for the informal sector at the Syria / Jordan border;
- Liaise with multilateral organizations, local authorities and NGOs to implement the strategy.

February 2016 – December 2016 / Health, Safety and Environmental Advisor – **Jan De Nul Group, Worldwide**

- Management of HSE aspects on the 260 MW Burbo Bank Wind Farm Extension, UK;
- Negotiate contractual arrangements with the network of partners;
- Coordination and execution of working plans;
- Administrative follow-up of HSE aspects;
- Formulate environmental assessments, hazard Identification and Risk assessment.

June 2015 - August 2015 / Researcher on Solid Waste Management - **German Corporation for Cooperation (GIZ) in Egypt and Imperial College, London**

- Value chain analysis of informal recycling in Egypt;
- Assess the barriers and constraints to knowledge transfer between informal communities;
- Fieldwork in the Zabaleen community.

AWARDS

- **Black and Veatch Prize**
  Awarded annually to the top student in MSc Environmental Engineering.

PUBLICATIONS

Jaligot, R., & Chenal, J. (2019). Stakeholders' Perspectives to Support the Integration of Ecosystem Services in Spatial Planning in Switzerland. *Environments*, *6*(8), 88.

Jaligot, R., Chenal, J., & Bosch, M. (2019). Assessing spatial temporal patterns of ecosystem services in Switzerland. *Landscape Ecology*, 1-16.

Kemajou, A., Jaligot, R., Bosch, M., & Chenal, J. (2019). Assessing motorcycle taxi activity in Cameroon using GPS devices. *Journal of Transport Geography*, *79*, 102472.

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Jaligot, R., & Chenal, J. (2018). Decoupling municipal solid waste generation and economic growth in the canton of Vaud, Switzerland. *Resources, Conservation and Recycling*, *130*, 260-266.

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Jaligot, R., Wilson, D. C., Cheeseman, C. R., Shaker, B., & Stretz, J. (2016). Applying value chain analysis to informal sector recycling: A case study of the Zabaleen. *Resources, Conservation and Recycling*, 114, 80-91.

CONFERENCES

Jaligot, R., Bosch, M., & Chenal, J. (2019). On the use of historical patterns of ecosystem services in Switzerland to inform spatial planning. *Ecosystem Services Partnership regional conference: World 2019*

Jaligot, R., Mbianda, K., Firmin, A., & Chenal, J. (2018). Applying participatory geographic information systems to evaluate cultural ecosystem services in Yaoundé, Cameroon. In *International Meeting on Mapping Techniques and Citizenship Sao Paulo*.

Jaligot, R., Hasler, S., & Chenal, J. (2018). Conducting participatory mapping of cultural ecosystem services at the national scale: a case of Switzerland. In *Ecosystem Services Partnership regional conference: Europe 2018*.

Jaligot, R. (2018). Valuing waste as resource: Mechanisms of change in developed and developing countries. *World Congress on Biopolymers and Bioplastics and World Congress on Recycling*.

Jaligot, R., & Chenal, J. (2017). Ecosystem services and federalism: a case study of Switzerland. In *2017 International Conference on Sustainable Development and Green Technology*.

Jaligot, R., Mbianda, K., Firmin, A., & Chenal, J. (2017). A spatial analysis of motorcycle taxis activities for environmental planning–the case of Port-au-Prince, Haiti. In *Proceedings of the Seventh International Conference On Advances in Applied Science and Environmental Technology-ASET 2017*.

OTHER COMPETENCES

- **French**: Native language
- **English**: Bilingual proficiency
- **German**: Basic understanding and writing
- **Portuguese:** Elementary

- **Informatics skills**: Python, R, QGIS, ArcGIS, Pack Office

INTERESTS

- Sports (cycling, skiing, football, basketball, rugby and table tennis)

- Travelling (North America, Caribbean, South America, Thailand, Europe, Iceland, Australia, Africa)