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Translating global commitments into national actions: A framework for
identifying the ecological infrastructure in Switzerland

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FACULTÉ DES SCIENCES

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**TRANSLATING GLOBAL COMMITMENTS INTO NATIONAL ACTIONS
A FRAMEWORK FOR IDENTIFYING THE ECOLOGICAL INFRASTRUCTURE IN
SWITZERLAND**

THÈSE

présentée aux Facultés de médecine et des sciences de l'Université de Genève
pour obtenir le grade de Docteur ès sciences en sciences de la vie,
mention Ecologie et évolution

par

Nathan KÜLLING

de

Wilchingen (Schaffouze)

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MENTION ECOLOGIE ET ÉVOLUTION

Thèse de M. Nathan KÜLLING

intitulée :

**« Translating global commitments into national actions:
A framework for identifying the ecological infrastructure in
Switzerland »**

Les Facultés de médecine et des sciences, sur le préavis de Monsieur Anthony LEHMANN, Professeur associé et directeur de thèse (Département F.-A. Forel des sciences de l'environnement et de l'eau), Madame Adrienne GRÊT-REGAMEY, Professeure ordinaire et co-directrice de thèse (Department of Civil, Environmental and Geomatic Engineering, ETH Zürich, Zürich), Monsieur Nadir ALVAREZ, Professeur titulaire (Département de génétique et évolution), Monsieur Alessandro GIMONA, Docteur (The James Hutton Institute, Dundee, Scotland) et Madame Perrine HAMEL, Professeure (Nanyang Technological University, The Asian School of the Environment, Singapore) autorisent l'impression de la présente thèse, sans exprimer d'opinion sur les propositions qui y sont énoncées.

Genève, le 6 février 2025

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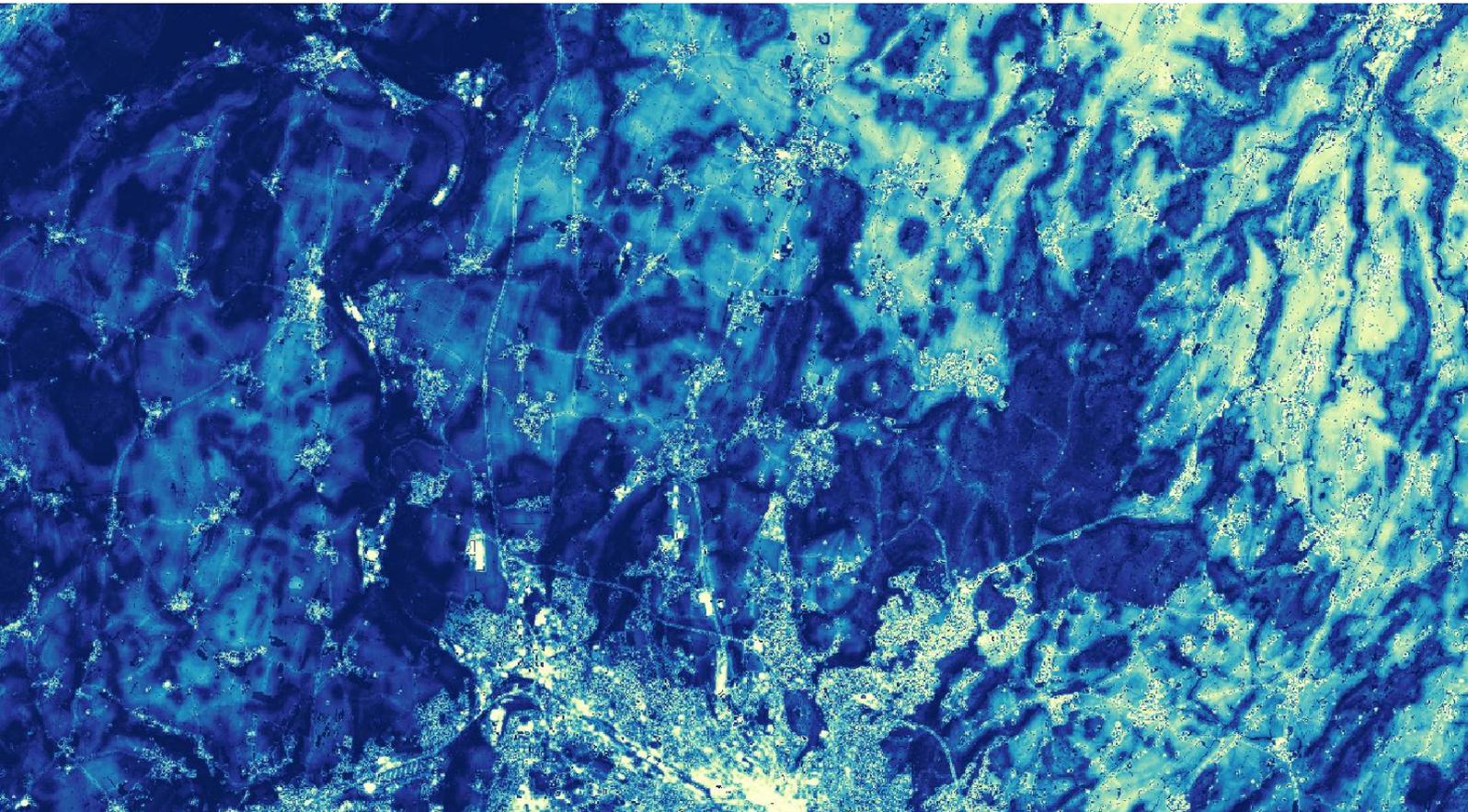
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“Je suis persuadé que le rapport de l’homme et de la nature ne peut être compris et réglé que dans la perspective d’une philosophie de la complémentarité: tu n’es que par rapport à ce qui n’est pas toi; et tu es d’autant plus intensément que tu aimes et connais mieux autrui et que tu respectes mieux sa nature propre.”

Expansion et nature, Robert Hainard, éd. Le courrier du livre, 1972, p. 18



Detail from a prioritized ecological infrastructure, N. Külling

Abstract

The Earth system is undergoing unprecedented changes, with six out of nine planetary boundaries already crossed. This poses severe risks globally to biodiversity and ecosystem services (ES) supply, and therefore represents a major challenge for Humans. Key pressures such as habitat loss, pollution, climate change, and invasive species have contributed to the rapid degradation of ecosystems, impacting their ability to support human well-being. Addressing this crisis requires conservation approaches that integrate ecological, social, and economic dimensions. Switzerland, despite its rich biodiversity and diverse ecosystems, faces significant challenges in meeting international conservation targets. With nearly half of its native species threatened and a comparatively low percentage of protected areas, there is an urgency for a functioning ecological infrastructure (EI).

The EI represents the key components of natural and semi-natural ecosystems that are necessary for maintaining ecological functions and biodiversity, and delivering services that support human well-being. The Swiss Biodiversity Strategy, adopted in 2012, aims to establish a functioning EI made of networks of core and connecting habitats by 2040. However, delays in implementation and difficulties to meet international commitments highlight the need for more effective and integrated conservation planning tools. The overarching goal of this thesis is to reflect on the ways to translate global conservation commitments into actions at the national level. To contribute to this goal, this thesis proposes and applies a framework for the identification and prioritization of the EI in Switzerland, divided in three parts:

- 1) Theoretical and technical foundations
- 2) Indicators development
- 3) Integration and prioritization

In the first part, we reviewed existing methods to spatially link biodiversity and ES, which are essential elements of the EI. We also produced novel spatially explicit data, including a downscaled Swiss land-use and cover map and a raster database comprising over 5'000 geospatial layers.

This foundational data and knowledge enabled the second part, where we developed ES supply maps and biodiversity indicators. We analysed their relationships and spatial distribution in Switzerland, and the key drivers influencing their patterns.

In the final part, we combined biodiversity ES, and landscape structure indicators in a spatial conservation prioritization (SCP) analysis. We assessed the sensitivity of the SCP results to different weighting approaches, compared the SCP with the current protected area network, and provided insights on its future suitability for biodiversity.

The proposed framework shows a way of integrating biodiversity and ES into spatial planning, and can help bridge gaps between traditional conservation approaches and strategies that address human needs. Ultimately, this work provides Switzerland with practical tools to accelerate progress toward achieving its conservation goals, aligning national efforts with global commitments.

Résumé

La Terre subit actuellement des changements sans précédent, avec six des neuf limites planétaires ayant déjà été franchies. Cela pose de graves risques mondialement pour la biodiversité et l'approvisionnement en services écosystémiques (SE), et représente donc un défi majeur pour les humains. Des pressions majeures telles que la perte d'habitat, la pollution, le changement climatique et les espèces envahissantes ont contribué à la dégradation rapide des écosystèmes, ce qui a eu un impact sur leur capacité à soutenir le bien-être humain. Pour faire face à cette crise, il faut adopter des approches en matière de conservation qui intègrent les dimensions écologiques, sociales et économiques. Malgré la richesse de sa biodiversité et la diversité de ses écosystèmes, la Suisse doit relever d'importants défis pour atteindre les objectifs internationaux en matière de conservation. Avec près de la moitié de ses espèces indigènes menacées et un pourcentage relativement faible de zones protégées, il est urgent de mettre en place une infrastructure écologique (IE) fonctionnelle.

L'IE représente les composantes clés des écosystèmes naturels et semi-naturels qui sont nécessaires au maintien des fonctions écologiques et à la fourniture de services qui soutiennent le bien-être humain et la biodiversité. La stratégie biodiversité Suisse, adoptée en 2012, vise à établir une IE fonctionnelle constituée par des réseaux d'habitats centraux et d'aires de mise en réseau d'ici à 2040. Cependant, les retards dans la mise en œuvre et les difficultés à respecter les engagements internationaux soulignent la nécessité de disposer d'outils de planification de la conservation plus efficaces et plus intégrés. L'objectif principal de cette thèse est de réfléchir à la manière de traduire la stratégie de l'IE en outils de planification de la conservation plus efficaces et plus intégrés. L'objectif principal de cette thèse est de réfléchir aux moyens de traduire les engagements mondiaux en matière de conservation en actions au niveau national. Pour contribuer à cet objectif, cette thèse propose et applique un cadre pour l'identification et la priorisation de l'IE en Suisse, divisé en trois parties :

- 1) Fondements théoriques et techniques
- 2) Développement d'indicateurs
- 3) Intégration et priorisation

Dans la première partie, nous avons passé en revue les méthodes existantes pour relier spatialement la biodiversité et les SE. Nous avons également produit de nouvelles données spatialement explicites, notamment une carte de l'utilisation et de la couverture des sols en Suisse à résolution augmentée, et une base de données comprenant plus de 5'000 couches géospatiales.

Ces données et connaissances fondamentales ont permis de réaliser la deuxième partie, dans laquelle nous avons élaboré des cartes d'approvisionnement en SE et des indicateurs de biodiversité. Nous avons analysé leurs relations et leur distribution spatiale en Suisse, ainsi que les principaux facteurs influençant leur répartition.

Dans la dernière partie, nous avons combiné les indicateurs de biodiversité, de SE et de structure du paysage dans une analyse de priorisation spatiale de la conservation (SCP). Nous avons évalué la sensibilité des résultats de la SCP à différentes approches de pondération, comparé la SCP avec le réseau actuel de zones protégées en Suisse, et fourni des indications sur son adéquation future pour la biodiversité.

Le cadre proposé démontre une manière d'intégrer la biodiversité et les SE dans l'aménagement du territoire, et peut aider à combler les lacunes entre les approches traditionnelles de conservation et les stratégies transformatives qui répondent aux besoins humains. En fin de compte, ce travail fournit à la Suisse des outils pratiques pour accélérer les progrès vers la réalisation de ses objectifs en matière de conservation, en alignant les efforts nationaux sur les engagements mondiaux.

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Abbreviations

EI: Ecological Infrastructure

GI: Green Infrastructure

SCP: Spatial Conservation Prioritization

ES: Ecosystem services

BD: Biodiversity

NCP: Nature's Contributions to People

SDM: Species Distribution Models

NbS: Nature-Based Solutions

OECMs: Other Effective area-based Conservation Measures

FOEN: Federal Office for the Environment

IPBES: Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services

CBD: Convention on Biological Diversity

List of publications

Peer reviewed

Külling, N., Adde, A., Lambiel, A., Wicki, S., Guisan, A., Grêt-Regamey, A., & Lehmann, A. (2024). **Nature's contributions to people and biodiversity mapping in Switzerland: spatial patterns and environmental drivers.**

Ecological Indicators, 163, 112079. <https://doi.org/10.1016/j.ecolind.2024.112079>

Külling, N., Adde, A., Fopp, F., Schweiger, A. K., Broennimann, O., Rey, P.-L., Giuliani, G., Goicolea, T., Petitpierre, B., Zimmermann, N. E., Pellissier, L., Altermatt, F., Lehmann, A., & Guisan, A. (2024). **SWECO25: A cross-thematic raster database for ecological research in Switzerland.**

Scientific Data, 11(1), Article 1. <https://doi.org/10.1038/s41597-023-02899-1>

Adde, A., Külling, N., Rey, P.-L., Fopp, F., Brun, P., Broennimann, O., Lehmann, A., Petitpierre, B., Zimmermann, N. E., Pellissier, L., Altermatt, F., Guisan, A. (2024). **Projecting Untruncated Climate Change Effects on Species' Climate Suitability: Insights from an Alpine Country.**

Global change biology. <https://doi.org/10.1111/gcb.17557>

Black, B., Adde, A., Farinotti, D., Guisan, A., Külling, N., Kurmann, M., Martin, C., Mayer, P., Rabe, S.-E., Streit, J., Zekollari, H., & Grêt-Regamey, A. (2024). **Broadening the horizon in land use change modelling: Normative scenarios for nature positive futures in Switzerland.**

Regional Environmental Change, 24(3), 115. <https://doi.org/10.1007/s10113-024-02261-0>

Adde, A., Rey, P.-L., Brun, P., Külling, N., Fopp, F., Altermatt, F., Broennimann, O., Lehmann, A., Petitpierre, B., Zimmermann, N. E., Pellissier, L., & Guisan, A. (2023). **N-SDM: A high-performance computing pipeline for Nested Species Distribution Modelling.**

Ecography, 2023(6), e06540. <https://doi.org/10.1111/ecog.06540>

Giuliani, G., Rodila, D., Külling, N., Maggini, R., & Lehmann, A. (2022). **Downscaling Switzerland Land Use/Land Cover Data Using Nearest Neighbors and an Expert System.**

Land, 11(5), Article 5. <https://doi.org/10.3390/land11050615>

Not peer reviewed

Rey, P.-L., Külling, N., Adde, A., Lehmann, A., & Guisan, A. (2022). **Mapping linkages between biodiversity and nature's contributions to people: A ValPar.CH perspective.**

<https://doi.org/10.5167/UZH-213594>

Guisan, A., Rey, P.-L., Külling, N., & Lehmann, A. (2022). **Biodiversité et services écosystémiques pour les humains.** In SANTÉ ET ENVIRONNEMENT VERS UNE NOUVELLE APPROCHE GLOBALE (RMS éditions / Médecine et Hygiène).

<http://dx.doi.org/10.53738/REVMED.95022>

In preparation

Wicki, S., Black, B., Külling, N., Kurmann, M., Wang, J., Lehmann, A., Grêt-Regamey, A. (submitted). **Temporal Archetypes of Nature's Contributions to People for Sustainable Landscape Development.**

Rey, P.L., Adde, A., Külling, N., Petitpierre, B., Vittoz, V., Lehmann, A., Guisan, A. (submitted). **Predicting the spatial distribution of nature's contributions to people from individual species.**

Külling, N., Adde, A., Waller, N., Lambiel, A., Moilanen, A., Guisan, A., Grêt-Regamey, A., Lehmann, A. (in preparation). **Reaching conservation targets: Spatial prioritization of national ecological infrastructure.**

Lambiel, A., Gerber, L., Schweiger, A., Mariethoz, G., Lehmann, A., Külling, N. (in preparation). **Tree species classification in the Gruyère Pays-d'Enhaut regional nature park using AVIRIS-NG hyperspectral data.**

Gerber, L., Lambiel, A., Külling, N., Mariethoz, G. (in preparation). **A method for gap-filling very large spatial datasets: application to AVIRIS-based airborne data**

Rey, P.-L., Külling, N., Adde, A., Lehmann, A., & Guisan, A. (in preparation). **Improving the linkage between biodiversity and nature's contributions to people.**

Adde, A., Rey, P.-L., Külling, N., Chauvier-Mendes, Y., Fopp, F., Popp, M. R., Brun, P., Broennimann, O., Petitpierre, B., Lehmann, A., Zimmermann, N. E., Pellissier, L., Guisan, A., & Altermatt, F. (in preparation). **SDMapCH: A Comprehensive Database of Modelled Species Habitat Suitability Maps for Switzerland.**

Introduction

1. Background and current developments

1.1. Direct and indirect drivers

The Earth system is currently undergoing unprecedented changes driven by human activities, and the outlook for the future remains uncertain (Rockström et al., 2024; Steffen et al., 2016; Vitousek et al., 1997). As of 2023, we have already crossed six of the nine planetary boundaries (K. Richardson et al., 2023), a set of critical thresholds beyond which the Earth's stability is at risk (Rockström et al., 2009). The impact of humans on the environment is mainly expressed through overexploitation of natural resources, pollution, climate change, habitat loss, and disruptions to ecological communities- e.g. by the spread of invasive species (Fig. 1.1.).

Since the mid-20th century, humanity has been consuming the Earth's resources at a rate that exceeds its capacity for renewal, leaving an ever-growing environmental footprint (Catton, 1982; Wackernagel & Rees, 1998). The long-term effects of ecosystem exploitation are already visible, as ecosystems once degraded may either fail to recover or do so only at a significantly slower pace, reducing their capacity to provide essential services (Moreno-Mateos et al., 2017; Trombulak et al., 2004). Moreover, species responses to these changes often occur with considerable delay, exacerbating the challenges of managing and mitigating these impacts (Cornford et al., 2023).

Indirect drivers

Indirect drivers of environmental changes (Fig. 1.1.) are factors at the basis of direct pressures that influence ecosystems and biodiversity. These drivers shape human activities and decision-making processes through institutional, economic, demographic, and socio-cultural systems (Pörtner et al., 2021). Public institutions and governance play a major role in influencing how private actors drive environmental change, either through the implementation and enforcement of environmental policies or the lack of it.

Increasing market traffic and changing consumption patterns, linked to globalization, intensify economic actors' incentives to overexploit resources for economic profit. Examples include the extraction and use of fossil fuels, deforestation, mining, intensive agriculture, or land-use change. The current environmental crisis is deeply tied to how nature is valued by decision-makers within public and private governance frameworks. Indeed, while a diversity of nature's values exist, including cultural, intrinsic, and spiritual values, the current globalized system disproportionately emphasizes a subset of values at the expense of both nature and society (IPBES,

2022). Indirect drivers constantly influence one another, creating feedback loops that exacerbate environmental challenges. Addressing these drivers thus requires a holistic understanding of their complex interplay.

Direct drivers

Pollution, frequently overlooked in discussions of human-induced environmental changes, remains a significant threat to both human and planetary health. It contributes to millions of deaths annually, primarily through air pollution and toxic chemicals, with over 8 million deaths attributed to it each year (Fuller et al., 2022). Another form of pollution, eutrophication - caused by excessive nutrient loading (e.g., nitrogen and phosphorus) - disrupts the chemical balance of ecosystems, with widespread effects on water quality (Bouwman et al., 2002). This problem has worsened with the global rise in fertilizer use since the agricultural and industrial revolutions.

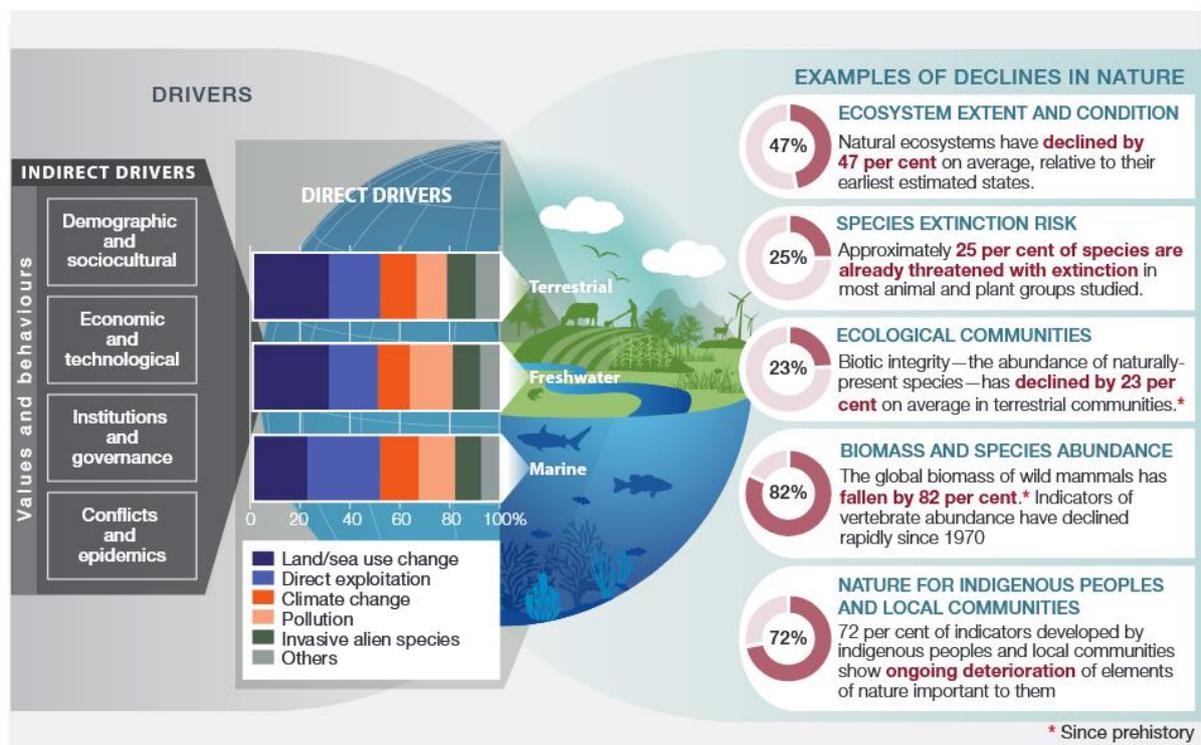


Figure 1.1. Source: IPBES (2019b) – Figure SPM2: “ Examples of global declines in nature, emphasizing declines in biodiversity, that have been and are being caused by direct and indirect drivers of change.”

Climate change is driving a broad range of impacts, including global temperature increases, more frequent extreme weather events, rising sea levels, and ocean acidification. Over 3 billion people now live in regions extremely vulnerable to climate change, and irreversible damage has already been caused to ecosystems and biodiversity (IPCC, 2023). The growing risk of reaching climate tipping points leaves a

unpredictable climatic future that is expected to impact the entire globe (Armstrong McKay et al., 2022).

Ecosystems are also impacted by non-native species. Invasive alien species in particular can outcompete native species for resources, disrupt trophic interactions, prey on native organisms, and are generally regarded as detrimental to biodiversity. They are responsible for approximately 16% of global plant and animal extinctions and pose a threat to the provision of essential ecosystem services (ES) (Gallardo et al., 2024; IPBES et al., 2023). However, some non-native species can contribute to different types of ES and could be considered useful in conservation strategies, highlighting their potential value (Schlaepfer et al., 2011, 2020).

Finally, land use change, according to the latest IPBES report (2019), is the leading pressure on natural ecosystems, followed by resource overexploitation. More than one-third of the Earth's land surface is now used for agriculture, with urbanization and infrastructure development contributing to further habitat loss.

1.2. Impacts on biodiversity

The global impacts of these drivers on biodiversity and human populations are deeply concerning. Experts estimate that 30% of species have gone extinct or are at risk of extinction over the last 500 years (Isbell et al., 2023). While the loss of biodiversity is undeniable, its magnitude remains difficult to assess. The extent of species extinction and their threat status are particularly hard to estimate, as only a small fraction of species have been formally evaluated for conservation concern (Díaz et al., 2019; Mora et al., 2011), and disparities in data on species from different regions make it difficult to draw a clear state of the biodiversity worldwide (Tydecks et al., 2018).

Biodiversity

The concept of biodiversity is also challenging to define, as the subjects studied and metrics types vary, and no consensus on what is referred to when studying or reporting about biodiversity exists. Often used as an umbrella term, it is defined as “the sum total of all biotic variation from the level of genes to ecosystems” by Purvis & Hector (2000). Biodiversity thus includes genetic diversity, which is vital for the adaptation and evolution of species; species diversity, which supports a range of ecological systems with each species filling a unique ecological role; and ecosystem diversity, which reflects the adaptation of life to various environments, fostering various ecological processes, communities, and habitats. While biodiversity is most associated with species diversity, it can also be measured in terms of species abundance (relative or absolute) or distinctiveness (Trombulak et al., 2004).

Many studies on biodiversity focus on species richness (i.e. number of species within a given area). While this metric is fundamental, it does not account for the abundance of those species. Common indices such as the Shannon and Simpson diversity indices are often used to capture both richness and abundance, with the former being more

sensitive to rare species present (linked to the relative abundance) and the latter being more influenced by dominant or most abundant species over the area (Shannon, 1948; Simpson, 1949). Methods for assessing or estimating species richness and or abundance typically start with direct species counts in a specific plot. Although highly accurate, this approach is difficult to scale to large areas. Remote sensing technologies, including satellite and airborne imagery, offer a way to collect data over much larger regions. These tools enable direct observations, such as identifying large species like trees (Yang & Kan, 2020), or vegetation communities in grasslands (Zhu et al., 2023), based on the spectral signature of their leaves, with reference points used for calibration, but these assessments are generally restricted to vegetation.

Other methods involve fitting statistical models to sampling data collected across an area and then extrapolating these findings to estimate richness (e.g. Pineda & Lobo, 2009) or abundance (e.g. Young & Carr, 2015) for larger landscapes based on environmental covariates. Species distribution models (SDMs, Guisan & Thuiller, 2005) are often used to estimate richness, and by aggregating multiple SDMs, we can derive a proxy of species richness across large areas, offering a practical tool for biodiversity assessment using existing observational data.

1.3. Ecosystem services

Throughout this thesis, I primarily use the term **ecosystem services (ES)** for consistency, clarity, and aligning with its widespread use in policy contexts and most scientific literature. However, in sections [1.1](#), [2.1](#), and [3.1](#), I use the terminology **nature's contributions to people (NCP)** as these sections are based on published (or in preparation) papers where adopting the NCP framework aligns with promoting the more inclusive vision advocated by IPBES.

The concept of “nature's services” to humans was introduced by Westman (1977), who emphasized the interest of ecosystems not only for the extraction of materials, but also for their role in regulating processes essential for human survival. The term “ecosystem services” (ES) was introduced later and gained significant global attention following the 2005 publication of the Millennium Ecosystem Assessment (MA, 2005), which examined the consequences of ecosystem changes on human well-being and laid the groundwork for strategies aimed at conserving nature and promoting the sustainable use of natural resources for human benefit. ES are defined by Fisher et al. (2009) as “...*the aspects of ecosystems utilized (actively or passively) to produce human well-being.*”. The concept was further solidified with the adoption of the Aichi Targets under the Convention on Biological Diversity (CBD, 2010), which formally recognized the need to conserve nature in ways that maintain ES. In 2012, the creation of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services

(IPBES) significantly advanced the global dialogue by providing reports on the state of biodiversity and ES globally. More recently, the framework of “Nature’s Contribution to People” (NCP), introduced by Díaz et al. (2015, 2018), has broadened the understanding of ES to include a more comprehensive, less utilitarian, and more inclusive perspective. This shift reflects an evolving recognition that ES are not just about human benefits, but also about the interconnectedness of people with nature. NCP has since become the preferred terminology of IPBES and is widely used as a surrogate for ES.

The ES concept is a useful approach for guiding policymakers and conservationists in protecting ecosystems (Grêt-Regamey et al., 2017). By highlighting the value of ecosystems (whether in monetary or biophysical terms), it shows the crucial role nature plays in supporting human well-being, and underscoring the need for nature conservation. ES are closely linked with biodiversity, with it supporting ES through ecosystem functions (EF) such as resource capture, biomass production, and nutrient recycling (Cardinale et al., 2012). Their relationships operate at all the levels of biodiversity (Harrison et al., 2014) and knowledge of these relationships are fundamental to understand and promote the protection of biodiversity and ES (Bastian, 2013). Naturally, ES provision is therefore also affected by current changes in the earth system. Since the end of the 20th century, provisioning ES have increased drastically through agricultural production, bioenergy production, harvest of fish and materials. However, out of the 18 ES categories assessed by the IPBES, 14 have been declining on a 50 year trend (IPBES, 2019a). There is now a consensus by experts in the field that the loss of biodiversity will drive the loss of ES (Isbell et al., 2023). Similarly to biodiversity, the assessment of ES presents significant challenges due to the wide range of available methods and the ongoing evolution of the field (Burkhard & Maes, 2017). Martínez-Harms and Balvanera (2012) identify five main approaches for spatially assessing ES supply: “look-up tables”, “expert knowledge”, “causal relationships”, “extrapolation of ES values from primary data”, and “regression models”. Some tools such as the InVEST (Integrated Valuation of Ecosystem Services and Tradeoffs) suite allow researchers or landscape planning stakeholders to model ES distribution and assess how changes in land use and management practices affect the delivery of multiple ES (Natural Capital Project, 2022). A major limitation in ES assessment is the availability of data, and there is often a lack of consensus on the appropriate ES indicators to use. Furthermore, ES can be categorized by their potential (supply/provision), their flow (the actual use of the service), and their demand (the need for ES, whether met or unmet) (Burkhard et al., 2014; Schröter et al., 2016). However, many assessments focus primarily on the supply of ES, often neglecting the flow and demand aspects. All elements - supply, flow, and demand - are however critical to assess and are represented by very different indicators, and their assessment addresses different societal challenges, such as resource access, equity, and sustainability.

1.4. Nature conservation

Over the past decades, shifting perspectives on the relationship between humans and nature have given rise to various frameworks for nature conservation, as summarized by Mace (2014). The “People and Nature” vision (Mace, 2014) describes an integrated approach to conservation that seeks to protect both nature and human well-being simultaneously, rather than addressing them as separate challenges. This framework was revisited by Reyers & Bennett (Fig. 1.2., 2024) with the “People with Nature” vision, that emphasizes the importance of relationships and processes in conservation, yielding and aiming for transformative change, and thinking conservation as a collaborative, societal effort. The concept of ecological infrastructure (EI) can be linked to this vision, by offering a useful framework for managing landscapes considering both biodiversity and its contributions to people, as it highlights the functional connections between natural, semi-natural, and artificial systems (F. Li et al., 2017). The IPBES defines the EI as “The natural or semi-natural structural elements of ecosystems and landscapes that are important in delivering ecosystem services” (IPBES, 2018), emphasizing on the importance of the EI for ES provision, thus closer to an instrumental vision of nature.

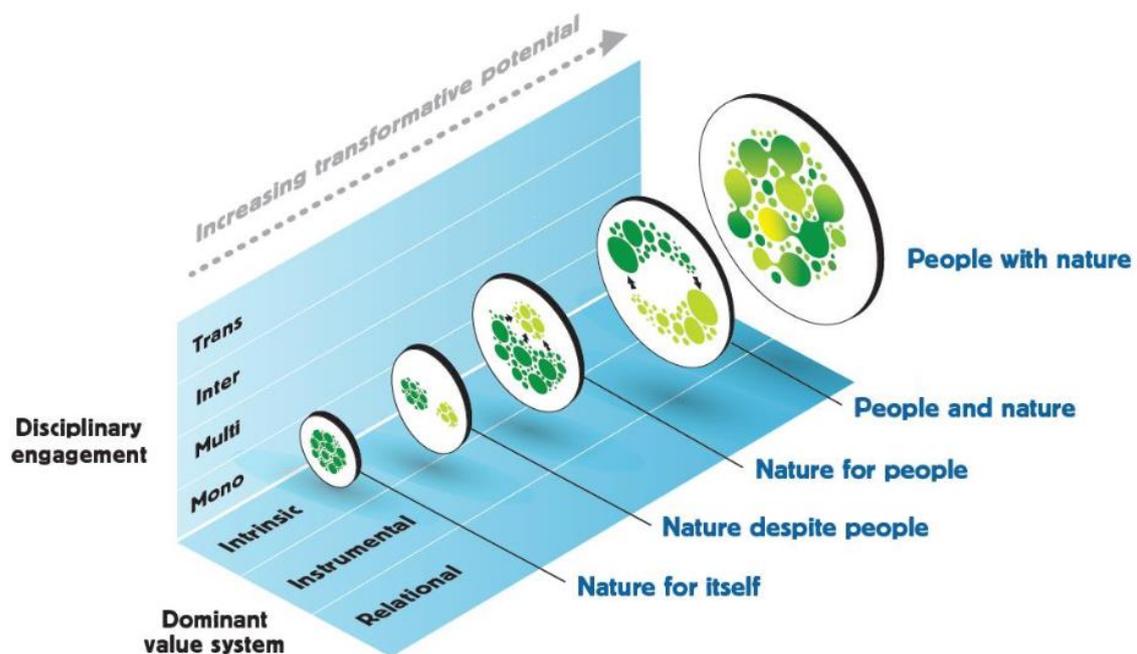


Figure 1.2. source: Reyers & Bennett (2024) - Figure 1. Conservation practices have evolved from emphasizing intrinsic, to instrumental, to relational values of Nature, in the “people with nature” framing. This shift also goes from single disciplinary fields to inter-, to transdisciplinary approaches that include different knowledge systems. This promotes a system-wide transformative change in the relationship of people with nature.

1.5. Ecological infrastructure

The EI is managed (or not) in diverse ways and at various scales around the world. International agreements and collaborative frameworks play an important role in the definition of global management currents. For example, the Ramsar Convention on Wetlands, signed in 1971, is a treaty that aims at the sustainable use of wetlands, which has been ratified by 171 countries (UNESCO, 1971). More recently, the Kunming-Montreal Global Biodiversity Framework (GBF) was ratified by 196 countries as a global commitment to protect the environment. This agreement includes 23 targets for 2030 aiming to halt and reverse biodiversity loss, with key goals including conserving 30% of land and marine areas (“30 by 30” initiative), but also reducing threats to biodiversity (e.g. reduce pesticide use), and investing in preserving sustainable ES in developing countries (UN CBD, 2022). In addition to protecting ecosystems, there is an increasing focus on restoring degraded habitats. The UN Decade on Ecosystem Restoration, launched in 2021, seeks to prevent, halt, and reverse ecosystem degradation on a global scale (UN, 2023). Notable achievements attached to this initiative include the Altyn Dala Conservation Initiative (ADCI) in Kazakhstan, a national program dedicated to conserving and restoring grasslands, wetlands, and deserts across an area of 750,000 km², more than ten times the size of Switzerland (ADCI, 2006).

While such initiatives are vital, they often reflect a dichotomous view of nature conservation (“nature for itself” or “nature despite people”, Fig. 1.2), that seeks to separate human activities from “untouched” ecosystems. However, protecting and restoring areas alone may not be sufficient to prevent species loss in protected areas (G. Li et al., 2024), and thus priorities of conservation might need to be reevaluated (Schlaepfer & Lawler, 2023). Some initiatives adopt a more holistic approach to the management of the EI. For example, UNESCO’s “Man and the Biosphere” (MAB) Program, with 136 member countries, focuses not just on strictly protected areas, but on the management of a wider area composed of three distinct zones with varying levels of protection (UNESCO, 2022). Over 260 million people live within UNESCO biosphere reserves, promoting the integration of human activities into conservation efforts.

The European Union’s Green Infrastructure (GI) strategy is comparable to the EI strategy as defined by IPBES. GI and EI as terms are closely related and often used interchangeably. In the EU, the GI strategy aims to establish a network of natural and semi-natural areas that provide essential ecosystem services (European Commission, 2013) and is supported by *Natura 2000*, the EU network of protected areas (Evans, 2012). By promoting the GI strategy, the EU recognizes the crucial role that nature plays in achieving economic and policy goals, and one kind of measure proposed by the EU is using Nature-based Solutions (NbS) (Cohen-Shacham et al., 2016; European Commission, 2015). NbS address the social and environmental challenges related to

ES provision, while simultaneously enhancing or preserving biodiversity. These solutions offer a practical way to meet economic and social development goals by implementing projects that enhance the health and functioning of the EI. NbS can be seen as a shift towards using ES more sustainably, reducing reliance on non-renewable natural resources (Maes & Jacobs, 2017). For example, in modern agro-industrial farming, intensive cultivation often increases short-term yields but diminishes soil carbon content and introduces excess chemical (nutrients, pesticides), threatening long-term food security. In contrast, cover crops, a form of NbS, restore soil fertility, increase carbon content, reduce erosion, and create natural habitats, enhancing productivity with fewer external inputs (Daryanto et al., 2018).

In an effort to help governments meet conservation targets such as the “30 by 30”, the CBD introduced the concept of Other Effective Area-Based Conservation Measures (OECMs, CBD, 2018). OECMs are located outside of protected areas, and managed in ways that can achieve long-term biodiversity conservation, along other purposes (cultural, economic), making them useful for a sustainable EI. OECMs need to be identified and defined geographically, and voluntarily reported by the governing authority, whether private or public (Jonas et al., 2024).

1.6. Spatial conservation prioritization (SCP)

To identify and map the EI, several approaches exist, often with focuses on specific features from the EI (landscape structure, habitat networks, biodiversity, ES). Methods for mapping EI have evolved rapidly and vary consequently on their aims, data, and knowledge requirements. The overlay analysis is a straightforward technique that combines multiple spatial datasets to identify EI areas by stacking and weighting geospatial layers. While data-intensive, it is efficient for small-scale applications (Rodríguez-Espinosa et al., 2020; Shi & Qin, 2018). Minimum path models, in contrast, focus on horizontal ecological processes and connectivity by simulating movement across the landscape. This method emphasizes structural connections but requires detailed species data and knowledge (Adriaensen et al., 2003). Other structural methods include graph-based analysis, which simplifies the landscape into a network of nodes and connections, using graph theory to quantify connectivity (F. Kong et al., 2010). Similarly, the morphological spatial pattern analysis (MSPA), which divides the landscape in key EI structural components like core areas, islets, corridors, and can rely only on land cover data, making it less data-intensive (Vogt et al., 2007). These methods can be integrated with other approaches, such as circuit theory, to optimize biodiversity connectivity measures (Huang et al., 2024), but these are not ideal to detect synergies between EI components, which are essential for decision support in conservation planning (Chan et al., 2006).

Spatial Conservation Prioritization (SCP) is a set of methods and computational tools designed to efficiently identify priority areas for conservation actions, to optimize the use of limited monetary and human resources (Kukkala & Moilanen, 2012; Moilanen

et al., 2009). High-priority areas are identified considering features deemed relevant to be preserved, and based on scientific data (such as GIS layers), making it particularly useful for designing the EI (Andrello et al., 2022; Snäll et al., 2016). Honeck et al. (2020), outline a three-pillar framework for the identification of the EI, which includes species diversity, ES supply, and ecological connectivity. SCP is usually used as part of a conservation plan, which includes specific objectives and targets that can range from expanding protected area networks, allocating habitat restoration efforts, balancing habitat conservation with other uses (e.g. agriculture, human infrastructure development). Several software tools have been developed for SCP, here is a summary of the most popular and recent ones.

Marxan

Recognized as one of the most popular tools for conservation planning, Marxan has been extensively used for tasks such as designing protected area networks, ecosystem restoration, and identifying management priorities related to biodiversity and ES (Crouzeilles et al., 2015; Egoh et al., 2011; Watson et al., 2019). The software uses a simulated annealing optimization algorithm that iteratively explores various combinations of spatial units (protected areas) to identify the most cost-effective solutions that meet conservation targets for biodiversity features (Ball et al., 2009). While Marxan accounts for connectivity between selected units, it does not integrate species-specific connectivity requirements. However, it does allow for the inclusion of ecological processes, site conditions, and socio-political factors (e.g., land ownership or cultural significance) as cost considerations.

Zonation

Zonation has been used in conservation projects at multiple spatial scales (e.g. Di Minin et al., 2019; Jalkanen et al., 2020; Lehtomäki et al., 2019). It uses an algorithm called “iterative conditional sort” for spatial prioritization. The algorithm begins by generating an initial ranking of landscape features (spatial layers) based on potential weighted criteria such as rarity or conservation status. The process then refines this ranking through iterations, adjusting priorities according to a selected marginal loss rule. After each iteration, the algorithm reassesses the grid cells, ensuring that areas are ranked in terms of their marginal loss, from least to most important. The result is a continuous priority ranking, represented as a raster map with values ranging from 0 (lowest priority) to 1 (highest priority) (Moilanen, Kohonen, et al., 2022). While Marxan identifies discrete conservation areas, Zonation main output is a continuous priority ranking across the entire landscape.

One of Zonation’s key strengths is its ability to incorporate various constraints, such as human activities, land use, or socio-economic factors, making it a flexible tool for balancing ecological goals with practical considerations. These features allow Zonation to create a prioritization map that maximizes ecological outcomes while accounting for spatial context and trade-offs.

Emerging Tools

Recent alternatives to these tools include CAPTAIN (Silvestro et al., 2022), a software that utilizes reinforcement learning to simulate an artificial environment where species are exposed to human pressures and climate change. CAPTAIN optimizes the placement of protected areas over time, considering dynamic changes in biodiversity and environmental conditions. This makes it particularly useful for adaptive conservation planning, as it allows for adjustments as conditions change, and integrates progressive conservation measures.

Another notable tool is the Prioritizr R package (Hanson et al., 2024), which offers a flexible solution for SCP using mixed integer linear programming (MILP) techniques. It can handle complex conservation planning problems and allows the integration of Marxan outputs. The integration in the R programming language can facilitate custom studies and modifications (as opposed to Marxan and Zonation).

1.7. Spatial data

Spatial data is essential for identifying and mapping the EI and integrating it into spatial planning and decision-making processes, for example through SCP. Consistent data on biodiversity, ecosystems, and ES indicators is crucial, yet much of the available data is scattered, non-standardized, making it difficult to use (European Commission, 2013). Advances in open science and the establishment of public data repositories have improved access to ecological data, enabling large-scale, reproducible analyses. For instance, the global biodiversity information facility (GBIF) provides free access to biodiversity data (Telenius, 2011), and the Sentinel and Landsat programs offer widely used high-resolution, multi-spectral remote sensing imagery, now freely accessible (ESA, n.d.; NASA, n.d.). Despite, challenges remain, including inconsistencies in data generation and varying regional standards (Michener, 2015). Initiatives like the Swiss Data Cube aim to address these issues by standardizing and facilitating access to spatial data for applications such as remote sensing in Switzerland (Chatenoux et al., 2021).

2. Specific context and objectives

2.1. The need for a functioning EI in Switzerland

Switzerland's geological features and geographical position makes it a place with exceptional biodiversity, despite its relatively small size. Indeed, the diverse topography includes an elevation gradient ranging from 193 to 4'634 meters, two distinct mountain ranges (the Alps and the Jura), and the Plateau valley in between. These features create a wide variety of climates, from perennial snow at the highest peaks to subtropical conditions in parts of the Ticino canton. This diversity fosters a rich array of ecosystems, hosting 230 natural habitats and around 56'000 known species of plants, animals, and fungi (FOEN, 2023a).

However, nearly half of Switzerland's native species are facing significant threats: 35% are either extinct or endangered, and another 12% are classified as vulnerable (FOEN, 2023a). Despite its rich biodiversity, Switzerland's proportion of protected areas is comparatively small to that of neighbouring countries (OCDE, 2017). The Swiss Federal Office for the Environment (FOEN) is aware and took measures to protect Swiss biodiversity. The Swiss Biodiversity Strategy (FOEN, 2012) aims, among other things, at developing the Swiss EI to enhance ecological connectivity by linking existing protected areas (PA) through networks of natural and semi-natural habitats (FOEN, 2017). FOEN defines the EI as "Switzerland's web of life", highlighting its importance for maintaining biodiversity and ES through core habitats and connected areas (FOEN, 2021b).

Adopted in 2012 to address the ongoing biodiversity crisis, the Swiss Biodiversity Strategy faced delays in implementation, with an action plan taking five years to develop. The associated action plan aims to establish a functional EI by 2040, with responsibility for its planning and implementation assigned to the Swiss cantons (FOEN, 2017a). Given the urgency of the biodiversity crisis, concerns remain about how effectively Switzerland can meet its conservation targets and safeguard its natural heritage.

2.2. The ValPar.CH project

The ValPar.CH project, launched in 2020 as part of the Swiss Biodiversity Strategy, is an inter- and transdisciplinary initiative that brings together researchers from diverse fields, including natural sciences, social sciences, economics, and policy studies. The aim of the project was to evaluate the values and services provided by the EI in Switzerland, contributing to a more comprehensive understanding of its importance and providing tools for its identification and promotion. Outcomes from it allowed to produce recommendations designed for different governance levels, spatial scales and audiences, reinforcing the current planning efforts done for the EI (Steiger et al., 2024). This thesis was conducted within the framework of the ValPar.CH project,

specifically as part of the subgroup dedicated to assessing the current state of biodiversity and ES.

2.3. Switzerland's policy dissonance

Switzerland ratified the Kunming-Montreal Global Biodiversity Framework (GBF) in 2022, which includes the "30 by 30" goal. Prior to this, Switzerland had ratified the Nagoya Protocol under the Convention on Biological Diversity (CBD) in 2010, which set a target of 17% protected areas (Aichi target 11, CBD, 2010). The 2012 biodiversity strategy has been developed in response, demonstrating Switzerland's will to respect its commitments through comprehensive, strategic planning.

Despite these commitments, recent assessments of biodiversity continue to reveal concerning trends in biodiversity loss (FOEN, 2023a). Notably, the original target of having a fully functional EI by 2020, has been delayed to 2040 in the biodiversity strategy action plan (FOEN, 2017a). Additionally, the 30% protected area target from the Kunming-Montreal agreement has been incorporated into Switzerland's broader EI planning: the plan now envisions one-third of the country's landscape dedicated to EI, with 17% specifically designated for protected areas that safeguard core biodiversity areas (FOEN, 2023c).

These discrepancies highlight a dissonance between Switzerland's actions and its commitments. The country is renowned for its natural landscapes and takes pride in its general management. However, as noted, Switzerland lags behind most European countries in terms of protected areas (OCDE, 2017). This gap extends beyond protected areas; for instance, Switzerland is not on track to meet its greenhouse gas emission reduction targets for 2030, having already missed its 2020 goal under the Paris Agreement (UN, 2015). Similarly, after committing to a 30% reduction in methane emissions by 2030 at the COP26 (UN, 2021), no significant action has been taken to address this target. Switzerland's system of direct democracy means that the implementation of national strategies can be subject to popular or governmental initiatives, with the public voting on key policies. One of the reasons Switzerland is falling short in meeting its environmental commitments is the repeated rejection of carbon reduction and biodiversity-oriented laws by Swiss voters, a stance that was also supported by the government (e.g.: DETEC, 2024; Federal Council, 2021a, 2021b). This reflects a disconnection between Switzerland's international commitments and the public's willingness to support the necessary legal and policy measures to fulfill them.

This dissonance may stem from a lack of awareness about the ongoing biodiversity loss and climate change by the population, as these issues often don't have immediate, visible impacts on daily life. This is probably also linked to the evolving relationship between Swiss inhabitants and the environment. People and nature relationships are well encapsulated by the Nature Futures Framework (NFF),

developed by the IPBES (2023), conceptualizing human-nature relationships as guidelines for the development of scenarios of desirable futures. The NFF outlines three key perspectives on nature: “nature for nature”, which emphasizes the intrinsic value of biodiversity and ecosystems; “nature for society”, which highlights the instrumental benefits nature provides to humans; and “nature as culture”, which focuses on the cultural and relational values that link human traditions and nature (IPBES, 2023). Historically, Switzerland's conservation approach has aligned with the “nature for nature” perspective, focusing on the intrinsic value of ecosystems and biodiversity.

Research has shown that higher urbanization, increased consumption, and greater reliance on technology are linked to lower levels of nature connectedness (Richardson et al., 2022). A global study across 65 countries revealed that while Switzerland scores above average for nature exposure, it fares worse than average for nature connectedness (Swami et al., 2024). This decline in nature connectedness has been observed worldwide (Soga & Gaston, 2023) and is particularly marked in Switzerland, where 74% of the population lives in cities and urbanization continues to grow (FSO, 2024). As urbanization increases and people have fewer direct experiences with nature, there is a growing decline in “connectedness” to the natural world.

However, to better the relationship between Swiss inhabitants and nature, recent shifts have led to the adoption of new conservation frameworks, and visions encompassing “nature for nature”, but also “nature as culture”, and “nature for society”. Since 2007, the Swiss Confederation has supported the creation of “Parks of national importance”, now numbering 18, with goals to preserve and enhance cultural and natural landscapes, promote sustainable economies, and increase environmental education and awareness. This approach has proven effective, as strengthening the human-nature connection is shown to enhance sustainability (Barragan-Jason et al., 2023). In addition, the Swiss Biodiversity Strategy integrates the EI approach, going beyond the sole creation of protected areas and integrating ES and human activities in the preservation of the environment. These efforts are encouraging but they will have to yield rapid results to match the urgent pace of habitat degradation, climate change, and biodiversity loss, necessitating a faster shift in both public perception and human involvement in conservation efforts.

2.4. Current methods for EI identification in Switzerland

To meet its commitments, the first step for Switzerland is to design and plan its functioning EI. As per the Swiss Biodiversity Strategy action plan, Cantons are mandated to plan their EI by 2025 (FOEN, 2017a). The Federal Office for the Environment (FOEN) provides official guidelines for identifying the EI, through a look-up table, categorizing existing geospatial data in two categories: core areas and networking areas. Core areas are vital biodiversity reservoirs, providing enough space to protect species and habitats at the national level (FOEN, 2021b). Networking areas,

while not of the same ecological quality or protection status, are crucial for the overall functioning of the EI. This approach relies on the reclassification of existing data, for each Canton to identify the current status of the EI.

To assist in EI planning, the FOEN has mandated *InfoSpecies* (<https://www.infospecies.ch/>), the Swiss organization responsible for data management and information about species, with evaluating a way to plan the Swiss EI. *InfoSpecies'* approach builds upon the spatial analysis mentioned above (assess the current state of EI) and identify the areas needed to complete it to enhance the EI (Rutishauser et al., 2023). This method utilizes existing national inventories and species observation data, which are grouped into ecological guilds - species with similar ecological requirements. These guilds are defined based on the typology of Swiss natural habitats (Delarze et al., 2015), with expert consultation guiding species classification within each guild.

Alternatively, an approach to EI evaluation was employed locally by the *GE-21* group (<https://www.ge21.ch/>), a network of experts in different fields from public policies to ecology, in the Canton of Geneva. Their approach followed the methodology from Honeck et al. (2020) and has been implemented in 2023 for the greater Geneva region (cross-border region between Switzerland and France, Sanguet et al., 2023). This approach integrates four key pillars, each representing a set of indicators that define biodiversity quality spatially. The Zonation software (Moilanen, Lehtinen, et al., 2022a) was used for spatial conservation prioritization (SCP), generating a hierarchical ranking of the landscape. This SCP method, which we have adopted for our national-scale prioritization, is detailed further in section [3.1](#).

A comparative analysis of these methods at the canton of Geneva level was conducted by Lambiel et al. (2024), who found that the SCP approach using Zonation provided the most optimized results for biodiversity conservation. While the FOEN method relies on existing geodata, and *InfoSpecies* adds field observations of species, the SCP method offers a more holistic perspective including a wide array of indicators, including ES. The SCP approach seeks to integrate human activities and needs in EI planning. However, it is important to note that this method is based on modeled outputs, which inherently carry uncertainties and limitations that must be accounted for in the decision-making process (Muscatello et al., 2021).

3. Thesis main goals

Thesis overarching question

The overarching goal of this thesis is to reflect on the paths and ways to **translate global conservation commitments into actions at the national level.**

Specific contributions

To contribute to this goal, this thesis proposes and applies **a framework for the identification and prioritization of the ecological infrastructure** in Switzerland.

As highlighted through the introduction, there is an urgent need for actionable support in conservation planning to accelerate the identification and design of Switzerland's EI. The current state of biodiversity is concerning, and traditional conservation measures alone are insufficient to halt the rapid loss of biodiversity. To address this, our research aims to develop a set of indicators that not only assess biodiversity but also ecosystem services, allowing for a more holistic approach to identifying and prioritizing the EI. The tools, indicators, and final outputs developed in this thesis are intended to serve as resources for future ecological research and policy planning in Switzerland. Our work is focused on helping design conservation strategies through data and indicators that offer practical, actionable insights. Ultimately, this thesis aims to provide Switzerland with the tools necessary to meet its need for a functional and comprehensive EI, accelerating progress toward achieving the nation's biodiversity and conservation goals.

Results: research contributions

The specific contributions of this thesis were realized through a series of scientific studies. Together, these research contributions form the core of this thesis, offering a structured approach to identify and prioritize the ecological infrastructure in Switzerland.

Part 1: Theoretical and technical foundations

- 1.1. Mapping linkages between biodiversity and nature's contributions to people: a ValPar.CH perspective (Rey et al., 2022).
- 1.2. Downscaling Switzerland Land Use/Land Cover Data Using Nearest Neighbors and an Expert System (Giuliani et al., 2022).
- 1.3. SWECO25: a cross-thematic raster database for ecological research in Switzerland (Külling et al., 2024a).

Part 2: Indicators development

- 2.1. Nature's contributions to people and biodiversity mapping in Switzerland: spatial patterns and environmental drivers (Külling et al., 2024b).
- 2.2. 2.2. N-SDM: a high-performance computing pipeline for Nested Species Distribution Modelling (Adde, et al., 2023).

Part 3: Integration and prioritization

- 3.1. Reaching conservation targets: Spatial prioritization of national ecological infrastructure (Külling et al., in preparation).

Part 1: Theoretical and technical foundations

In the first section ([1.1](#)), we conducted a comprehensive review of the approaches and methods used to explore the relationships between biodiversity and ecosystem services. Presented as a working paper, this section offered recommendations to improve the study of these relationships and detailed the ValPar.CH project's roadmap for EI mapping and stakeholder engagement.

In the following sections ([1.2-1.3](#)), we focused on foundational data generation and standardization. First, we developed a higher-resolution land-use map of Switzerland, which serves as the basis for multiple analyses presented in later chapters ([1.2](#)). Following this, we created and published a standardized raster database ([1.3](#)), also serving as a basis for multiple later analysis in this thesis, and for many other ecological research studies in Switzerland.

1.1. Mapping linkages between biodiversity and nature's contributions to people: a ValPar.CH perspective

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As co-first author of this study, I contributed to the original idea and conceptualization, co-led the literature review, the writing of the original draft, and the original visualization.

1. Defining a common understanding of the theoretical linkages between BD and NCP

Since the 2000s, many conservationists adopted the concept of Ecosystem Services in the hope to convince a wider audience about the importance of "Nature for people" (Costanza et al., 1997), using monetary or other values. With the launch of IPBES in 2012, the focus has evolved toward a less utilitarian vision where both "People and Nature" must live in harmony in sustainable and resilient socio-ecological systems (Mace, 2014). In accordance with recent publications and current terminology used by IPBES, this working paper will use the term "Nature's contribution to people" (NCP) instead of "Ecosystem Service" (Díaz et al., 2018), even though the latter is still widely used in the scientific literature and in the communication to the public.

ValPar.CH explores the benefits and values of the ecological infrastructure (EI) in Switzerland and its regional parks (Reynard et al., 2021). EI is defined as a network of natural and semi-natural habitats with high quality and functionality (FOEN, 2021b). By identifying and preserving these habitats, the EI is assumed to be essential to promote and protect biodiversity and ensure the supply of NCP (Grêt-Regamey et al., 2021). Within ValPar.CH, the valuation of EI is carried out through multiple inter- and transdisciplinary processes, including a mapping of biodiversity (BD) and NCP. This working paper focuses on the different mapping methods relating BD and NCP.

The relationships between BD and NCP are numerous and complex, operating at multiple levels from genes to ecosystems, through species and communities (Harrison et al., 2014). The study of these relationships is important for promoting the role of nature conservation in NCP supply (Bastian, 2013). As a result, the amount of research focusing on the relationships between BD and NCP has increased in recent years. In particular, the direct links between BD and NCP that arise from ecosystem functions (EF, e.g. resource capture, biomass production, decomposition, nutrient recycling) were extensively studied and reviewed by Cardinale et al. (2012). EF are precursors of NCP supply and sometimes are a NCP themselves (Costanza et al.,

2017). However, the relationship between BD and NCP supply is more difficult to determine than that of BD and EF because the complexity of processes and interactions present in ecosystems cannot be completely encompassed, and has accordingly remained understudied (Harrison et al., 2014; Ricketts et al., 2016; Smith et al., 2017).

In addition to the complexity of the relationships between BD and NCP, the spatial and temporal scales in which studies are conducted can vary greatly (Isbell et al., 2017). Given that assessments of NCP are often prompted by the need for immediate or near future decision-making, they typically adopt short temporal scales, often focused on a small geographical extent. By contrast, the time scale of biological extinctions or the estimated regeneration time (Delarze et al., 2016) of ecosystems and habitats necessitate studies considering a similar scale (decades or centuries; Birkhofer et al., 2018; Isbell et al., 2017). These reasons could help explain the poor accounting for direct links between BD and NCP in many studies (Bateman, et al., 2013; de Groot & Harrison, 2016). Using tiered (i.e. “multi-levels hierarchical”) approaches for representing BD, NCP, and their relationships over multiple relevant spatio-temporal scales can be of major interest for overcoming these challenges (Grêt-Regamey et al., 2015). The direct relationships between BD, EF and NCP can be difficult to demonstrate, especially through maps. Additionally, strong and intricate links exist between ecosystems, biodiversity, and functions and processes to supply services that meet societal demands (e.g. Ceașu et al., 2021; Isbell et al., 2017; Lefcheck et al., 2015; Maes et al., 2012).

The terminology used around NCP can be confusing and therefore is best clarified at the start of a project (see Appendix 1, 1A. [Definition box](#)). These definitions allow us to propose an integrated representation of these important concepts and their relationships (Figure 1).

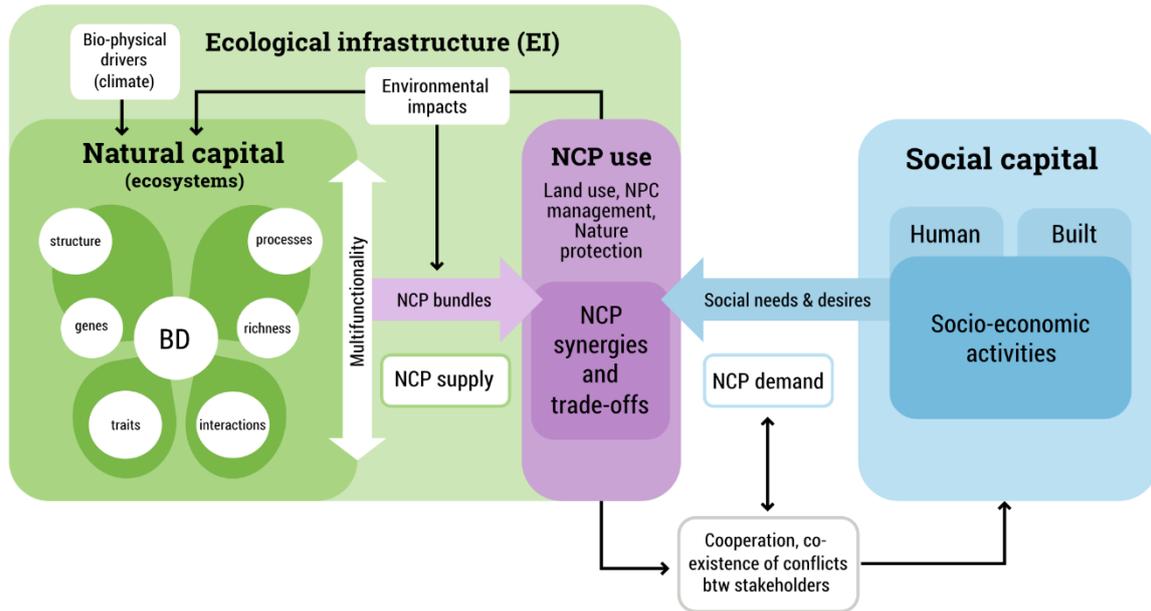


Figure 1: From Biodiversity (BD) to Nature’s contributions to people (NCP) synergies and trade-offs, where bundles of NCP supply meet NCP demand, and where ecosystems and their biodiversity components are multifunctional. Adapted from: European Commission (2013); Turkelboom et al. (2016).

2. Identifying the main methods to link BD and NCP

Despite the recognised evidence that BD is the basis for NCP provision and for the maintenance of ecosystem processes (Díaz et al., 2006; MA, 2005), the way ecosystems are used can also influence their species composition, so that the relationships between BD and NCP remain difficult to quantify (Harrison et al., 2014). To grasp the complexity of these relationships, we propose a modified version of a two-way table published by Smith et al. (2017) to display which nature (here biodiversity) characteristics are hypothetically related to NCP supply (here restricted to NCP that will be mapped in ValPar.CH - Module A; Figure 2).

		C Nature's contribution to people (NCP)																
		C2 Regulating								C3 Material				C4 Non-material			C1 Option	
		Habitat creation and maintenance	Pollination	Air quality	Climate	Water supply	Water quality	Soil	Natural Hazards	Pest and disease	Energy	Food and feed	Material and assistance	Medicinal, biochemical and genetic resources	Learning and inspiration	Physical and psychological experiences	Supporting identities	Maintenance of options
N Biodiversity characteristics	N1 Species																	
	N2 Biophysical assemblages																	
	N3 Biophysical processes																	
	N4 Biodiversity																	

Figure 2: Hypothetical relationships between biodiversity (BD) characteristics (i.e. IPBES’ biotic characteristics N1 to N4) and nature contributions to people (NCP). Modified from Smith et al. (2017) to account for IPBES new NCP definitions (IPBES, 2018) and restricted to those BD components and NCP considered within the ValPar.CH project - Module A.

We identified four main linkage methods in the literature to connect BD and NCP (Figure 3). Each of these four methods can be applied at different BD and NCP levels (Figure 2), such as individual species or groups vs communities for BD, or single vs bundles (i.e. groups) for NCP (Raudsepp-Hearne et al., 2010), and through either direct or indirect analyses. The direct analysis aims at demonstrating a causal relationship between biodiversity (e.g. species, community, functional group, etc.) and the provision of NCP, whereas the indirect analysis aims at linking BD and NCP either through a relevant indicator or proxy, or through the comparative response of BD and NCP to the same variable. Indirect analyses are expected to remain more speculative (i.e. less causal) links between BD category and NCP provision.

Although we introduce them independently here, these distinct linkage methods have strong interdependencies. Despite only one linkage method having an explicit mapping purpose (i.e. the “spatial” linkage), all of them can be used for mapping the BD-NCP relationship. Within ValPar.CH, the spatially explicit assessment is mainly done within Modules A and C, and is our main focus here.

The four methods (detailed below) are: I “spatial”; II “functional”; III “valuation (economic/social)”; and IV “management”. Linkage methods of type I, II and IV directly echo the spatial, functional and management linkages of Ricketts et al. (2016), whereas we added III to account for the socio-economic valuation of this linkage (e.g. Alemu I et al., 2021; Jaligot, Hasler, et al., 2019; Nahuelhual et al., 2013; Schirpke et al., 2018).

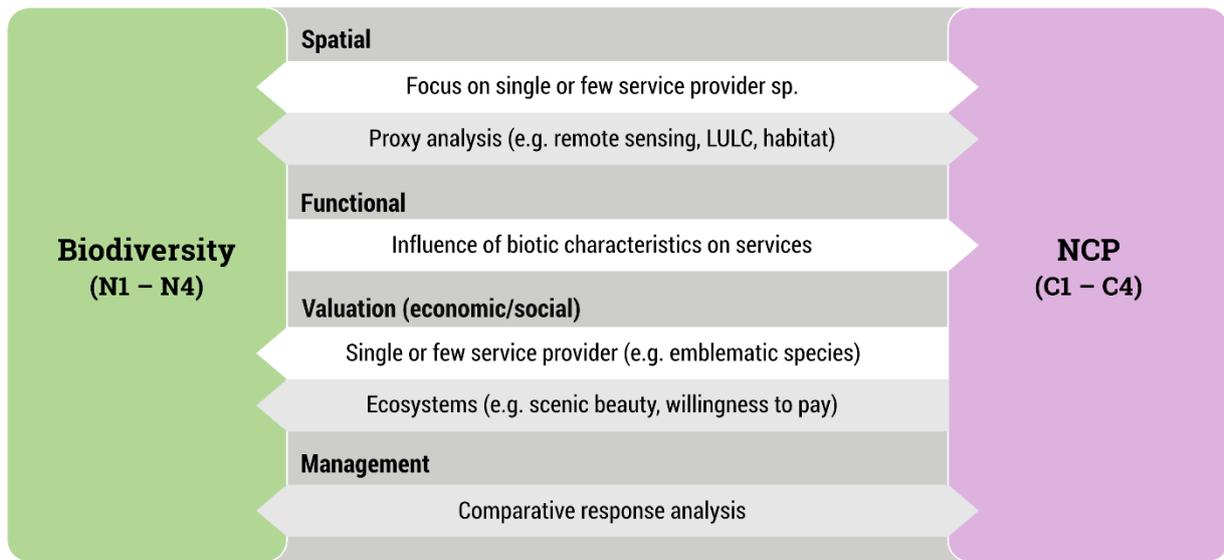


Figure 3: Possible expression of the relationships between biodiversity (BD) and Nature Contributions to People (NCP). Linkage methods adapted from Ricketts et al. (2016) to account for social/economic valuation (e.g. Schirpke et al., 2018). Directional arrows represent the direction in which the relationship is established (e.g. for functional linkage, the relationship is established from the species to the service provided).

I. The “Spatial” linkage method focuses on searching for common spatial patterns between BD and NCP levels. This linkage method assesses the spatial correlation between BD and NCP. BD and NCP may be linked by mechanistic or functional processes, or they may respond in a similar way to spatial variables like environmental conditions.

This method relies mainly on “indirect analysis” as it makes use of empirical correlations and proxy metrics for BD and NCP derived from spatial layers such as land use/land cover classifications, vegetation maps or remote sensing indices assumed to be informative about the quality of the habitat/ecosystem, its contributions to people, and its ability to support the species.

Within the ValPar.CH project, an important use is made of spatial analysis software and methods, such as Zonation (Lehtomäki & Moilanen, 2013a) or machine learning clustering techniques, respectively. Zonation is a powerful tool for systematic conservation planning based on an optimization algorithm. As such, it can facilitate spatial targeting of conservation actions and resource allocation for ecosystem preservation, and accordingly contribute to consider BD and NCP in a common conservation prioritization scheme. However, it does not really assess the intrinsic nature of the linkage between species and NCP, which requires backing up spatial correlations with more in-depth investigations (e.g. literature, expert knowledge, etc.). While species-level metrics should provide us with a more precise picture of the BD-NCP relationships, upper-level metrics' (e.g. community, habitat area, structure, production, etc.) estimation can provide a simpler and potentially valuable alternative (Harrison et al., 2014). This explains why the indirect analysis approach is currently popular among researchers seeking to establish a link between BD and NCP (Smith et al., 2017). Although species and community-level characteristics allow to assess positive or negative impacts on NCP, Kleijn et al. (2015) demonstrated that species occurrence, abundance or richness were not necessarily sufficient to infer meaningful conservation strategies for both BD and NCP. A better understanding of the processes underlying these empirical observations would require working with “functional linkage” methods.

Kong et al. (2018) use the spatial linkage approach to analyse trade-offs and synergies between a set of NCP and biodiversity in the Yangtze river basin, China. They found significant synergies between regulation services and biodiversity, as well as synergies among regulation services (NCP bundles).

II. The “Functional” linkage method assumes that NCP are a direct or mechanistic function of BD. This link can be identified by conducting in-situ experiments aimed at evaluating NCP response to controlled changes in BD (Ricketts et al., 2016), or through expert knowledge (e.g. based on species functional traits or ecological roles). A direct link between BD and NCP can be easily identified when a specific species or group corresponds directly to a material service, as in the case of species identified through

ethnobotany (e.g. Abbet et al., 2014; Dal Cero et al., 2014; Oka et al., 2019). For example, Schulp et al. (2014) identified wild garlic (*A. ursinum*) as one of the most consumed wild plants in Europe, and mapped its distribution and abundance along with other common wild plants to obtain a spatially explicit representation of this material NCP. The study of Civantos et al. (2012) is one of the few examples using a functional relationship between species (vertebrates) and NCP in the context of climate change. Results from this study are anticipating a significant drop in the richness of species contributing to pest control across Europe. The paper by de Bello et al. (2010) is another example where the relationship between BD and NCP is approached through the analysis of species traits that provide specific ecosystem functions. However, this study is an exception as this type of linkage tends to be mostly reported at fine scales (e.g. in experimental plots, Balvanera et al. (2006). Metrics and knowledge derived from the functional linkage method are key inputs for direct spatial linkage analyses and economic/social valuation analyses, such as Benefit Transfer calculation (BT; Costanza et al., 1997; Grêt-Regamey et al., 2014). The functional linkage method is an excellent basis for the economic/social valuation in ValPar.CH, especially to transpose these results into a spatially explicit representation.

Oka et al. (2019) is to date one of the most comprehensive studies to highlight the functional services of trees (171 tree species for 15 NCP). It offers a new functional group approach based on the relationships between species and NCP.

III. The “Valuation (social/economic)” linkage is done through the extrapolation of qualitative (e.g., description of perceptions and experiences) and quantitative (e.g. price, frequency, absence/presence, etc.) values which link BD to NCP.

“Social” valuation is a way to understand the values of stakeholders in conservation processes (Omoding et al., 2020). Methods such as interviews and surveys are used to establish the link between BD and NCP, or to address social and ethical issues related to BD (Jetzkowitz et al., 2018). Social valuation can be used to assess non-material NCP (Jaligot, Hasler, et al., 2019) and can also be translated into maps (Richards & Friess, 2015). In ValPar.CH, qualitative methods (micro-narrative analysis, go-along interviews, focus groups and participatory mapping, geosemantic analysis, etc.) are used to assess these social valuation links between BD and NCP.

“Economic” valuation methods can link BD to NCP by estimating a market value for NCP that are provided by biodiversity characteristics (Figure 2). Although economic valuation methods are useful to highlight the multifunctional role of ecosystems, and thus defining NCP bundles (Ojea et al., 2016), their final aim remains to obtain the stocks and flow of Natural Capital (Banerjee et al., 2016; Sharp et al., 2020). Natural Capital Accounting can be assessed using different economic valuation approaches, such as: i) direct market evaluation (market price, cost-based, production function,

meta-analysis methods); ii) indirect market valuation (hedonic pricing, travel cost, meta-analysis methods); or iii) non-market valuation (contingent valuation, choice experiment, meta-analysis methods) (Koetse et al., 2015). The indirect market valuations are mainly oriented towards non-material NCP (e.g. scenic beauty) and generally rely on social valuation methods (e.g. surveys, geolocalised activities, etc.). In ValPar.CH, the economic benefits of NCP are calculated through the “exchange value approach”, which is used for the valuation of ecosystem services in the United Nations System of Environmental Economic Accounting (SEEA) (UN DESA, 2019), and can also be translated into maps (as in Ramel et al. 2020).

Based on the opinions of their study participants, Schirpke et al. (2018) have listed symbolic plant and animal species in the Alpine region. They validated the resulting list by screening for websites referring to the target species. Based on these results, they produced a cartography of cultural NCP associated with these symbolic plants and animals.

IV. The “Management” linkage method establishes the link between BD and NCP through the comparative analysis of their individual responses to the same management intervention. As for “spatial linkage”, this type of linkage is most often expressed at larger scales than functional linkages and there is no specific hypothesis as to its nature (Ricketts et al., 2016). Land management policies have a straightforward link to certain NCP (e.g. forests or agriculture in Switzerland) and to BD (e.g. protected areas). However, the effect of certain policies, for example intended to protect target species or to maximize specific types of services, can generate unexpected trade-offs and/or synergies (Turkelboom et al., 2018). For instance, biological farming has been shown to host greater amounts of NCP and BD relative to conventional farming, and to increase the resilience of the ecosystem to climate change (Kremen & Miles, 2012). In ValPar.CH, this linkage method is used in particular by comparative analysis of the effect of changes in land use on BD and NCP from the past to the present (module A) and between the present and future scenarios (module C).

Häger (2012) observed the effect of management of agroforestry systems in terms of ecosystem service supply and plant diversity. He compared the estimated carbon content as well as the number of tree species and their density in organic farms and in conventional farms to observe the response of ES (carbon storage) and BD to these two kinds of management.

3. Main gaps in the identified linkage approaches and proposed solutions

Substantial progress has been made on linking BD and NCP since the Millennium Ecosystem Assessment (MEA, 2005), and the recent assessments by the IPBES (Jetzkowitz et al., 2018). Nevertheless, large gaps remain in the data, models/analyses, and temporal/spatial scales used to assess these linkages, but also in their complexity, uncertainty and interpretation by scientists, and ultimately use by stakeholders (Table 1). This section elaborates on the gaps, as identified by IPBES (2018) and other references (see Table 1), and offers potential solutions developed in ValPar.CH.

Table 1: Synthesis of the main gaps in the identified BD-NCP linkage approaches. Green text in bold corresponds to the potential solutions that will be used in the ValPar.CH project. Dark red text highlights recommendations on appropriate linkage methods for the identified gaps (method I= “spatial”; II= “functional”; III= “valuation (economic/social)”; and IV= “management”). References highlight key literature.

Gaps	Identified issues	Potential solutions	References
Data	<ul style="list-style-type: none"> . spatial & temporal data gaps for (a)biotic sources 	<ul style="list-style-type: none"> . remote sensing . citizen science . collect data on species (functional capacity, genetic resource, ...) <p style="text-align: center;">Method II, III</p>	(Burkhard & Maes, 2017; Ferrier et al., 2016; Jaligot et al., 2019; Randin et al., 2020)
Models	<ul style="list-style-type: none"> . plurality of methods of BD and NCP assessment, making it difficult to compare / extrapolate the results . ecological processes at temporal and spatial scales relevant for decision making . inability to identify tipping points 	<ul style="list-style-type: none"> . incorporate species interactions and community dynamics . use of clearly defined metrics and methods for BD/NCP assessment . develop integrated socio-ecological models (with prioritizations’ scenarios, direct and indirect drivers of species, BD, NCP) <p style="text-align: center;">Method I, III</p>	(D’Amen et al., 2017; Ferrier et al., 2016; Rounsevell, 2018; RUBICODE, 2009)
Scales	<ul style="list-style-type: none"> . scale conflict between management (large scale) and functional (small scale) studies 	<ul style="list-style-type: none"> . work with various scales and build complex models (both - BD and NCP) <p style="text-align: center;">Methods I, IV</p>	(Grêt-Regamey et al., 2015; Hauck et al., 2013; Martinez-Harms et al., 2015; Mateo et al., 2019; Ricketts et al., 2016;

	. BD-NCP relationships are spatial-scale dependant		M. G. Turner et al., 2013)
Complexity of the linkages	. difficulty of identification of interdependencies between BD & NCP . studies focus on small subset of interactions between BD & NCP . difficulty of identifying equilibrium between BD & NCP	. develop integrated socio-ecological approaches (with prioritizations' scenarios, direct and indirect drivers of species, BD, NCP) . identify (in)direct links between BD & NCP . identify multifunctionalities of species, community & bundles of NCP Methods I, II, III, IV	(Maes et al., 2012; Ramel et al., 2020; Turkelboom et al., 2018)
Interpretations of the BD-NCP relationships	. NCP do not solely depend on BD, but also on abiotic factors . most relationships studied between BD & NCP focus on positives links . complexity of relationship for decision-making (when trade-offs exist between NCP/BD)	. identify (in)direct links between BD & NCP . consider abiotic factors as non-dependant of the BD to assess NCP . interpretation of potential results with the support of stakeholders to support national conservation objectives Methods III, IV	(Gray, 2011; Harrison et al., 2014; Kleijn et al., 2015; Smith et al., 2017)
Stakeholder's involvement	. Practical Insights on BD - NCP linkages could be contributed by stakeholders, but they are often involved too late in the process	. integrate stakeholders throughout the BD-NCP linkage assessments (as advocated in related fields, e.g. biodiversity modelling) Method III	(Ferrier et al., 2016; Guisan et al., 2013; Mouquet et al., 2015)

Data

The IPBES report on scenarios and models (Ferrier et al., 2016) highlighted important spatial and temporal data gaps to properly assess BD and NCP and their linkages from biotic and abiotic data sources. While Switzerland is rightly considered as a data rich country, our capacity to model BD and assess NCP is still largely dependent on the availability and access to all existing data (e.g. soil data not nationally available at fine scale). In some instances, remote sensing can be used to fill specific data gaps, even though there are limitations on what can be captured from the sky (Randin et al., 2020; Skidmore et al., 2021; Vihervaara et al., 2017; Wüest et al., 2020).

Although some material services can be directly quantified to some extent (e.g. crop, wood, drinking water) without being directly related to specific species, there are others that need such direct link with BD, and are often less documented (e.g. medicinal plants, traditional goods, decoration, energy, wild food; Smith et al., 2017). The underlying reason is that the functional characteristics of these species are often not described. Similarly, regulating services would benefit from more advanced analyses of life cycle maintenance and gene pool protection, however these services need additional data on life history and ecological traits that are not readily available (Burkhard & Maes, 2017). In recent years, the collection of data (e.g. Jaligot et al., 2019) has been greatly increased by the rise of citizen science, an efficient process but one that can be biased and requires time before gathering a significant amount of data.

In ValPar.CH, we provide an extensive set of 25-m resolution abiotic variable layers at different temporal scales, including downscaled land-use map (from 100m to 25m) for three periods between 1992 and 2018. Species' data provided by Infospecies are also included in this work and related to the abiotic variables to parametrize species distribution models. In addition, an hyperspectral remote sensing campaign conducted in two of the four pilot parks (Jurapark Aargau and Parc naturel Gruyère Pays d'Enhaut) will allow deriving the potential benefit of using high-resolution spectral images to map BD and NCP. For the functional approach, a direct linkage between 2,000 species (vascular plants and vertebrates) and 17 NCP has been established (Rey et al., 2023). We are also exploring the potential of using species' genetic data; yet we expect the latter data to cover only a limited geographical extent for a small number of species.

Models

Modelling can help us exploring and understanding the complex multi-scale linkages that exist between BD and NCP. The IPBES report on models and scenarios (Ferrier et al., 2016) highlights three main modelling approaches that are currently under-utilized for studying the BD-NCP relationships: (i) models that explicitly link BD to NCP, especially models to predict NCP from BD; (ii) models that address ecological processes (i.e. underlying ecosystem functions and NCP, based on BD) at temporal and spatial scales relevant for decision making; and (iii) models that are able to identify tipping points (e.g. extinction of key species) in the BD-NCP relationship (RUBICODE, 2009). Although these three modelling approaches would individually benefit from improvements, a necessary next step will be to develop integrated socio-ecological models that explicitly integrate prioritizations' scenarios, direct and indirect drivers of species, BD, NCP, and good quality of life to better account for important relationships and feedback between those components (Rounsevell, 2018). Importantly, these models should incorporate species interaction and community dynamics (Ferrier et al., 2016, D'Amen et al., 2017).

In ValPar.CH we propose an innovative way to combine species distributions models (SDMs; Guisan et al. 2013) with the geographical distribution of NCP in Switzerland (as done regionally in Honeck et al. 2020, Ramel et al. 2020; Module A). The underlying goal is to obtain a better understanding of the BD-NCP relationships through the assessment of the ecological infrastructure under multiple scenarios (Module C). Integrating interactions between species and establishing community dynamics are perspectives that we would like to explore further in the future.

Scales

A literature review by Ricketts et al. (2016) shows that depending on the linkage method used to study BD-NCP relationships, the resulting outputs can vary greatly. In this regard, several studies have shown how the main factors driving the BD-NCP relationship are spatial-scale dependant (Hauck et al., 2013; Turner et al., 2013; Martinez-Harms et al., 2015). Although it was shown that the choice of the scale (e.g. landscape scale) can be crucial when analysing the relationships between BD and ecosystem functions (EF; Isbell et al., 2018; Thompson et al., 2018), these relationships can be underestimated at the time of decision-making because management trade-offs are not necessarily considered at the same scale (Vallet et al., 2018). Along the same lines, Cordingley et al. (2016) suggested that it is more appropriate to work at the landscape scale rather than at the individual patch scale for assessing BD-NCP relationships, as it allows to implement contrasting management strategies to enhance preservation of BD and human well-being in landscapes where trade-offs occur. This further emphasizes the importance of considering different linkage methods and relevant scales to assess this link.

In ValPar.CH, modules A and C will build models based on multi-scale approaches. For BD, spatially nested species distribution models (European and National scales) will allow accounting for niche truncation issues (Chevalier et al., 2021). For NCP, a tiered approach will be used to assess NCP at two scales (national and parks who are more fine), with varying scale-dependant objectives and levels of complexity (Grêt-Regamey et al., 2015). Further investigations on the scale effect on the BD-NCP relationships is needed (Birkhofer et al., 2018).

Complexity of the linkages

The BD-NCP relationships can be more complex than simple pairwise interactions (1:1). Maes et al. (2012) illustrated this point through the example of the geographical co-occurrence of BD and different bundles of NCP analysed in function of land protection status across Europe. Results showed that habitats benefiting from "favourable" conservation status (see Epstein et al., 2016) provide more BD and have a higher potential to supply regulating and non-material NCP (Maes et al. 2012). In addition, several studies showed the necessity of BD for the provision of NCP in the long term (e.g. Isbell et al., 2011; Soliveres et al., 2016). However, focusing on NCP for promoting BD conservation can be hazardous, as over-emphasising NCP can, in some

instances, reduce BD conservation (Ramel et al., 2020). Indeed, some NCP were shown to rely mostly on a small subset of species (Kleijn et al., 2015), whereas many rare or endemic species of high conservation value might have no clear link with NCP (Balvanera et al., 2014). Moreover, an uninformed use of NCP (i.e. which does not account for BD) in operational frameworks (e.g. spatial planning, EI planning, water management or forestry) could result in counter-productive results both in terms of BD and NCP (Turkelboom et al., 2016).

In ValPar.CH, Module A makes use of all four linkage methods introduced above to account for the diversity of possible interactions between BD and NCP. In addition, other modules are enlarging the scope of analysis using other methods without a spatially explicit aim (social interpretations of nature; incl. linkage method III). This will provide Module C team with an integrated overview, useful for developing future scenarios of a functional ecological infrastructure.

Interpretation of the BD-NCP relationships

An update of the initial review by Harrison et al. (2014) on the links between BD attributes and NCP (conducted by Smith et al. (2017)) highlighted the multiple interpretations of the relationships between biotic characteristics (i.e. functional group, diversity, population dynamics, etc.; Figure 2) and NCP. These two reviews emphasized the importance of considering the landscape and all its characteristics (biotic and abiotic) as a whole system rather than focusing only on some specific species or functional groups. In addition, one of their main findings is that there are mostly reports of positive links between either species, functional groups or traits and NCP. This is probably related to the fact that most studies are designed with the objective of establishing positive BD-NCP relationships, at the expense of potentially hiding negative (e.g., from deleterious invasive species) or neutral (e.g. from non-structural species) relationships. We stress here the importance, when designing a framework aimed at establishing BD-NCP links, of being equally able to study the positive, neutral and negative aspects of these relationships. (e.g. using a synthetic contingency table to link species and NCP, with all above types of relationships explicitly identified; Rey et al., in prep. - Module A).

In ValPar.CH, Modules A and B assess BD-NCP relationships from an ecological, a social and an economic perspective. The interpretation and use of identified relationships will be discussed between different stakeholders (within and outside academia).

Stakeholders' involvement

Several authors recognize the need to improve the link between policy maker requirements (e.g. conservation objectives) and research outputs (e.g. Guisan et al., 2013; Mouquet et al., 2015; Ferrier et al., 2016), and this similarly applies to the linkages between BD and NCP. The challenge is to create fit-for-purpose BD-NCP linkage outputs (e.g. maps) that are scientifically robust and stakeholder-friendly by

improving the communication between scientists and end users, and by making the underlying scientific process more transparent and reproducible (Burkhard & Maes, 2017). There is thus also a gap in the abilities of stakeholders to use and interpret scientific outputs.

In ValPar.CH, module C will mobilize stakeholders for the evaluation and proposal of an operational EI (i.e. providing: (i) an inventory of policy objectives and instruments, (ii) reports policy design and (iii) reports park financial costs; incl. linkages method IV). The weighting of the BD and NCP inputs in the EI prioritization will also be based on a large consultation of stakeholders (incl. the main data providers, Infospecies.ch).

4. Conclusions and ways forward for ValPar.CH

Summarizing, the ValPar.CH project aims to identify a functional ecological infrastructure at two scales (selected regional parks and country-wide) by linking BD and NCP through modelling, mapping and prioritization analyses, where both direct (e.g. species-related) and indirect (e.g. landuse-related) relationships are considered. As detailed in table 1, cutting-edge methods will be applied with the aim of overcoming the identified gaps in BD-NCP linkages, to yield five main and complementary outputs (from modules A.1, A.2, for the present, and C.3 for future scenarios):

- i. Spatial predictions of aquatic and terrestrial species distribution associated with NCP;
- ii. Identification of synergies and trade-offs between BD and NCP ;
- iii. Spatial planning of a functional EI using a weighted joint prioritisation of BD and NCP
- iv. Archetypisation of NCP resulting from a landscape-based upscaling of BD and NCP indicators.

As a potential framework within which to embed these outputs, ValPar.CH will further consider Petchey et al. (2015) proposed roadmap for ecological predictability research, emphasizing the need for an integrated approach with resulting models meeting the predictive requirements of stakeholders and policy, additionally promoting the development of consistent and replicable BD/NCP linkage protocols, and their integration in EI mapping, that also better address model uncertainty (Ferrier et al., 2016; Burkhard & Maes, 2017).

To conclude, the proposed developments for spatially linking BD and NCP will open exciting new perspectives to improve the mapping of a functional infrastructure in Switzerland and help pave the way toward a better accounting of BD and NCP in spatial conservation planning.

1.2. Downscaling Switzerland Land Use/Land Cover Data Using Nearest Neighbors and an Expert System

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While not the primary author of this study, I actively contributed by conducting data curation, formal analysis, model validation, and visualization. The following summary reflects the study's main outcomes and their role in this thesis.

Summary

Land use and cover (LU/LC) maps form the foundation of many spatial analyses, playing an important role in applications such as ES mapping, species distribution modelling, and land-use change assessments. Widely available datasets exist, such as the CORINE land cover at European scale (EEA, 2011).

In Switzerland, national LU/LC statistics are collected approximately every 10 years with a high thematic resolution (72 categories) on a 100 m lattice (FSO, 2021c). Additionally, Swiss topographic base maps at a 1:25,000 scale are available, albeit with a reduced number of categories and recorded using varying intervals and methods (swisstopo, 2007, 2021). In this study, we combined these topographic base maps with national LU/LC statistics to produce a set of downscaled LU/LC maps with a 25 m spatial resolution and 62 land-use categories (Fig. 1). The methodology employed an approach that integrated inverse distance weighting and an expert system for category correspondence.

The resulting maps were validated by comparing the outputs to the original LU/LC statistics, achieving high overall accuracy with F1-scores and a kappa coefficient of 0.69 and 0.67, respectively. However, a limitation of this study lies in its temporal comparability: changes in the methods used to produce the Swiss national base maps over time rendered the results inconsistent across the three assessed time periods. Despite this limitation, the maps for the latest time period (2013–2018) demonstrated good accuracy and have since been effectively applied in several research projects (Adde et al., 2023; Külling et al., 2024a; Külling, et al., 2024b; Rey et al., 2023). These spatial outputs were also essential data for the ES indicator mapping done in this thesis (2.1.), and were further developed and included in part 1.3.

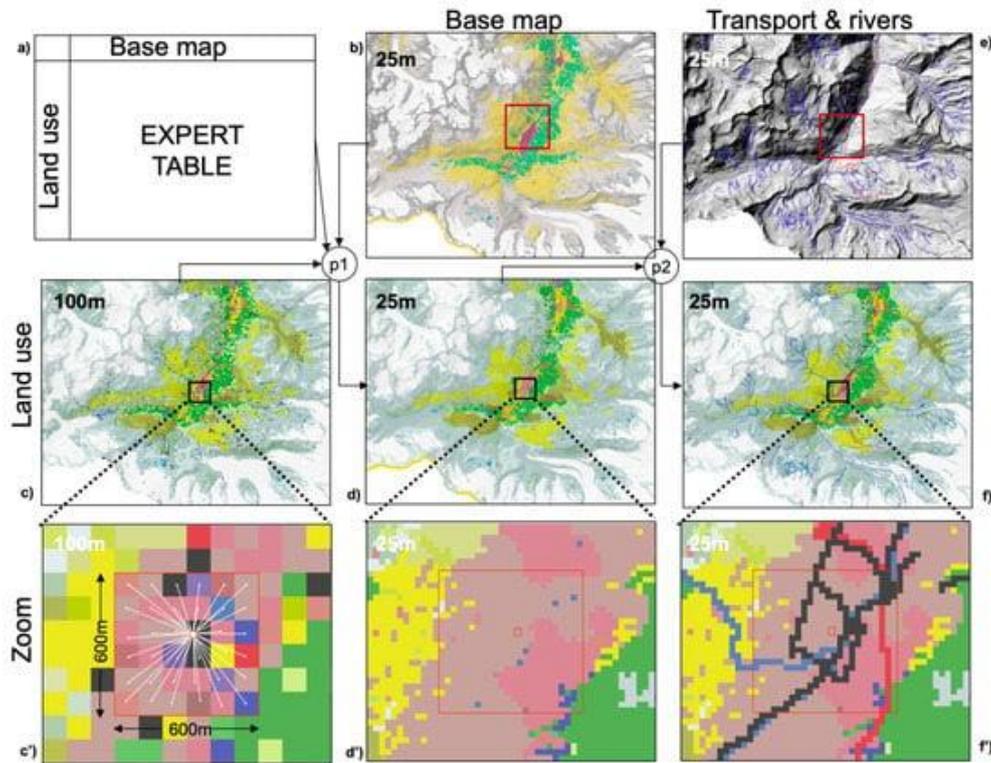


Figure 1: Source: Giuliani et al. (Fig. 3, 2022). “Downscaling land use statistics (2013–2018) in the area of Zermatt from 100 m to 25 m resolution using inverse distance weighting, expert knowledge, national base map, transport and river information at 25 m. (a) Expert system (details in [Figure 4](#)), (b) 1:25,000 base map, (c,c') hectare land use information, (d,d') downscaled land use, (e) 1:25,000 linear features (rivers, roads and rails), (f,f') overlay of linear features to downscaled land use at 25 m resolution. Downscaling process (p1) and linear features addition (p2).”

1.3. SWECO25: a cross-thematic raster database for ecological research in Switzerland

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As co-first author of this study, I contributed to the conceptualization and co-lead the technical preparation of the database (all datasets), the validation, statistical analysis, online upload of the data, visualizations, and the writing of the original draft.

1. Background & Summary

Spatial ecology has benefited from growth in data availability, geostatistical methods, and computing facilities, and is now central for a wide range of applications including public health (Dlamini et al., 2019; Jamison et al., 2015; Meentemeyer et al., 2012), agriculture (Cambouris et al., 2014; Mathenge et al., 2022; Oliver, 2010), and biological conservation (Fletcher & Fortin, 2018; Moilanen et al., 2009; W. Turner et al., 2015). Because the targets of such applications (e.g., water quality, soil nutrients, species' environmental suitability) are controlled by multiple environmental drivers (e.g., climate, vegetation, land use and cover), their study requires working with cross-thematic data. However, in most countries, thematic data are often scattered across computer servers of different institutions (e.g., universities, federal and state offices, non-governmental organizations), and are generally lacking spatial standards, whether in terms of resolution, extent, or projection system. Consequently, a significant effort for data compilation and standardization is usually required prior to using them, which implies a non-sustainable use of time and resources, but also hinders comparisons and cross-project usage of data.

In Switzerland, many spatial datasets are publicly available from university and governmental computer servers and cover a wide range of themes including topography (swisstopo, 2016), hydrography (swisstopo, 2007), land use and cover (FSO, 2021c), transportation (swisstopo, 2021), and several others. Although there has been recent efforts for developing web portals aimed at gathering the increasing volume of new data, such as the Swiss Data Cube (<https://www.swissdatacube.org/>) for remote sensing data (Chatenoux et al., 2021), or [opendata.swiss](https://opendata.swiss/en) (<https://opendata.swiss/en>) for Swiss government data, available layers are rarely provided in standard formats, so their joint use can require tedious data management and heavy geomatic operations. Currently, a ready-to-use, standard, cross-thematic, geospatial database gathering key layers for ecological research in Switzerland is lacking. Yet, thanks to the large amount of available data and the diversity of

landscapes to study and protect, Switzerland is an ideal candidate to promote greater standards in scientific data, which is essential for advancing research in ecology and can inspire similar initiatives worldwide. Here we introduce SWECO25, a 25-meter resolution raster database gathering 5,265 layers on 10 main environmental categories. The 25-meter resolution was chosen as a trade-off between spatial accuracy, resolution of input sources, and size of output database. Layers available in SWECO25 were standardized to a common spatial grid covering all of Switzerland so they all share the same spatial resolution, extent, and geographic coordinate system. SWECO25 includes both the standardized sources and newly calculated layers, such as those obtained by computing focal or distance statistics. By providing standardized spatial data for a large range of environmental themes, SWECO25 stands as a foundational contribution for more effective analyses, informed decision-making, collaboration, and sustainable development across various sectors. It should help streamlining stakeholder workflows and support them in making more accurate decisions. The variety of potential applications of national interest for Switzerland includes, but is not limited to, biodiversity conservation, glacier and snowmelt modelling, tourism and recreation management, natural hazard mitigation, energy transition planning, or ecosystem services assessment. The SWECO25 database and associated metadata are openly available on Zenodo (<https://zenodo.org/communities/sweco25/>).

2. Methods

The development of SWECO25 followed four main steps (Fig. 1): (1) dataset identification, (2) dataset selection, (3) layer processing, and (4) public upload on Zenodo (<https://zenodo.org/communities/sweco25/>).

Dataset identification. We identified candidate datasets for SWECO25 by screening academic geodata servers (e.g., University of Lausanne UnilGis, Zurich Polytechnic GeoVITe, University of Bern GIUBGIS, and University of Geneva GRID), Swiss governmental geodata (<https://opendata.swiss/en>), and consulted with a panel of ~20 scientists involved in ecological research in Switzerland. Discussions among panel members allowed sharing unpublished data and identifying gaps in available datasets (e.g., missing themes or coarse spatial resolutions). When these gaps were not solvable by applying basic geomatic operations (e.g., resampling or reprojection), research initiatives involving more advanced computational techniques were started. This was the case for developing the high-resolution climate (Broennimann, 2021), and land-use and cover (Giuliani et al., 2022) datasets.

Dataset selection. Three main criteria were used for deciding on the selection of an existing dataset for SWECO25: (i) its relevance for ecological research, (ii) a spatial extent covering all of Switzerland, and (iii) a minimum input resolution of 100 meters to preserve data accuracy after resampling.

Layer processing. Individual layers from selected datasets were processed following an eight-step standardization procedure: (i) rasterization of vector layers, (ii) reprojection to the CH1903 +/LV95 (<https://epsg.io/2056>) geographic coordinate system, (iii) resampling to a common spatial grid of 25-meter resolution (bilinear and nearest neighbor methods for continuous and categorical layers, respectively), (iv) transformation of discrete data to continuous values (e.g. converting discrete land use and cover classes within a grid cell to percentage cover for a particular class), (v) computation of distance statistics for linear features (e.g., Euclidean and path distance to roads and rivers), (vi) computation of focal statistics by applying a cell-level function calculating the average value in a circular moving window of 13 radii ranging from 25 meters to 5 kilometers, (vii) conversion of decimals to integer values for storage efficiency, and (viii) saving the final raster layers as GeoTIFF files.

3. Data Records

Following our dataset selection criteria, 16 datasets were collected (Table 1). The source datasets consisted predominantly of raster files (10 out of 16) with a mean \pm standard deviation (SD) spatial resolution of 32.5 ± 34.8 meters and most of them were already projected in the CH1903+/LV95 geographic coordinate system (10 out of 16). Most of the datasets were available for a single time step (static), except the *chclim25*, *geostat25*, *statpop*, and *sdv* datasets that contained layers for several time steps. In addition, the *chclim25* dataset included layers for three future greenhouse gas concentration trajectories, or representative concentration pathways (RCPs) (Van Vuuren et al., 2011), RCP2.6 (“Very Low Carbon”), RCP4.5 (“Low Carbon”), and RCP8.5 (“High Carbon”). After running the standardization procedure, a total of 5,265 layers was produced and compiled together in SWECO25 (v1.0.0) for a total size of 157 GB. Figure 2 provides an overview of the diversity of layer types available in SWECO25. All SWECO25 layers and files are following a standard naming scheme, which is also used for folder organization (Fig. 3). The tree structure of SWECO25 folders can be developed to a maximum of six levels: category, dataset, period, sub-period, scenario, and variable (Fig. 3). At its top level SWECO25 is divided into ten main environmental categories: geologic (“*geol*”)18, topographic (“*topo*”)19, bioclimatic (“*bioclim*”)20, hydrologic (“*hydro*”)21, edaphic (“*edaph*”)22, land use and cover (“*lulc*”)23, population (“*pop*”)24, transportation (“*trans*”)25, vegetation (“*vege*”)26, and remote sensing indices (“*rs*”)27. The environmental category with the most layers was land use and cover (3,304), followed by bioclimatic (428) and geologic (420). For each environmental category, the detailed list of layers can be found in the *SWECO25_data\layers_details_categoryname.csv* file available in its respective Zenodo repository.

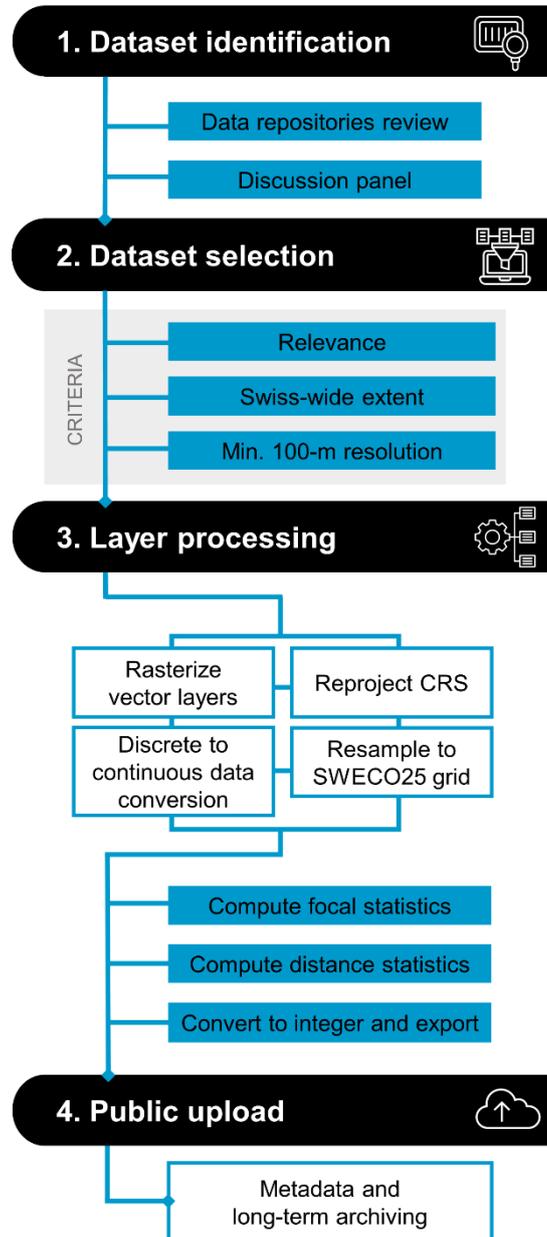


Figure 1: SWECO25 development workflow. 1) Identification and panel discussion about existing datasets. 2) Selection of ecologically relevant datasets meeting spatial requirements. 3) Standardization of selected datasets to SWECO25 standards. 4) Public upload on Zenodo (<https://zenodo.org/communities/sweco25/>).

4. Technical Validation

SWECO25 was technically validated through an automated procedure during which all layers were checked for their standard format (reference system, spatial resolution,

and extent), folder structure, naming scheme, and data integrity (count of NA cells, range of values, and integer format). All layers successfully passed the validation procedure, except for several from the remote sensing category that contained a higher number of NA cells, as well as very high or low values. The propagation of errors inherent to the source data to SWECO25 is difficult to avoid and to measure. For instance, reason for NA cells is most likely artefacts from satellite imagery, whereas very high or low values arise because remote sensing vegetation indices were computed for all of Switzerland, including areas not covered by vegetation. We did not mask very high and low values, as they might still be informative for some users (e.g. provide information on the presence or absence of vegetation). The supplementary file SWECO25_datalayers_details_rs.csv available on the SWECO25 remote sensing Zenodo repository (<https://zenodo.org/record/7994481>) allows identifying these layers. In addition, we assessed the potential effects of spatial resampling on SWECO25 layers by comparing the values of 15'000 random points extracted from the source and resampled layers. This analysis was conducted for source layers from all datasets, except the gwn07 and tlmd3D datasets that consisted of linear features (i.e., river and road networks, respectively) from which distance layers were computed directly on the SWECO25 grid. The chclim25 dataset was also excluded from this analysis as the source dataset used the SWECO25 grid. For the "sdc" dataset, due to the number of source layers in it, only three time-steps were randomly tested for each spectral index. Results from the resampling analysis indicated very low differences between source and resampled values, with a median coefficient of variation $28 \pm$ standard deviation of 0.0066 ± 0.0348 for continuous data (32 source layers evaluated), and a median Dice coefficient $29 \pm$ standard deviation of 0.9906 ± 0.0793 for discrete data (7 source layers evaluated). A detailed version of the technical validation procedure with additional results can be found on the SWECO25 GitHub repository (https://github.com/NKulling/SWECO25/tree/main/database_validation).

Table 1: Summary characteristics of the bioclimatic, topographic, geologic, hydrologic, edaphic, land use and cover, population density, transportation, vegetation, and remote sensing datasets included in SWECO25 (v1.0.0).

Results: research contributions

Category	Dataset	Short description	Temporal resolution	Input spatial resolution or precision	Number of layers	Reference
Bioclimatic ("bioclim")	chclim25	Climatic (temperature and precipitation) and bioclimatic WorldClim (https://www.worldclim.org/data/bioclim.html) parameters	Present: annual (1981–2017) and 30-y averages (1981–2010); Future: 30-y averages (2020–49, 2045–70 and 2070–99) for three scenarios (RCP2.6, RCP4.5 and RCP8.5)	25 m (raster)	428	(Broenniman, 2021)
Topographic ("topo")	alti3d	Topography without vegetation and development	Static (2016)	2 m (raster)	224	(swisstopo, 2016)
Geologic ("geol")	geotechnic	Subsoil classified according to lithological criteria (30 classes)	Static (1967)	0.02 m (vector precision)	420	(swisstopo, 1967)
Hydrologic ("hydro")	gwn07	Distance to hydrological network (10 river and 4 lake classes)	Static (2007)	3 to 8 m (vector precision)	14	(swisstopo, 2007)
Hydrologic ("hydro")	morph	Ecomorphological state of the rivers (5 classes)	Static (2009)	3 to 8 m (vector precision)	71	(FOEN, 2009)
Hydrologic ("hydro")	swisstopo	Watercourse steepness	Static (2015)	3 to 8 m (vector precision)	28	(Kaelin & Altermatt, 2016)
Edaphic ("edaph")	eiv	Ecological indicator values for soil properties	Static (1938–2018)	93 m (raster)	112	(Descombes et al., 2020)
Edaphic ("edaph")	modiffus	Nitrogen and phosphorus loads	Static (2015)	100 m (raster)	28	(Hürdler et al., 2015)
Land use and cover ("lulc")	geostat25	Land-use and cover classification (65 classes)	6-y periods (1992–1997, 2004–2009 and 2013–2018)	25 m (raster)	2730	(Giuliani et al., 2022)

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Land use and cover ("lulc")	wslhabmap	Natural habitats classification (41 classes)	Static (2020)	0.2 to 3 m (vector precision)	574	(Price et al., 2021)
Population density ("pop")	statpop	Human population density	Annual (2010–2020)	25 m (raster)	297	(FSO, 2021b)
Transportation ("trans")	tlmd3D	Distance to transportation network (5 classes)	Static (2013–2020)	0.2 to 1.5 m (vector precision)	12	(swisstopo, 2021)
Transportation ("trans")	sonbase	Exposure to noise levels	Static (2015)	25 m (raster)	14	(FOEN, 2018)
Vegetation ("vege")	nfi	Vegetation height	Static (2019)	10 m (raster)	42	(Ginzler, Christian, 2019)
Vegetation ("vege")	copernicus	Dominant leaf type	Static (2018)	10 m (raster)	28	(EEA, 2018)
Remote sensing indices ("rs")	sdc	Remote sensing indices (EVI, GCI, LAI, NDVI, NDWI)	Annual (1996–2021)	10 m (raster)	243	(Chatenoux et al., 2019)

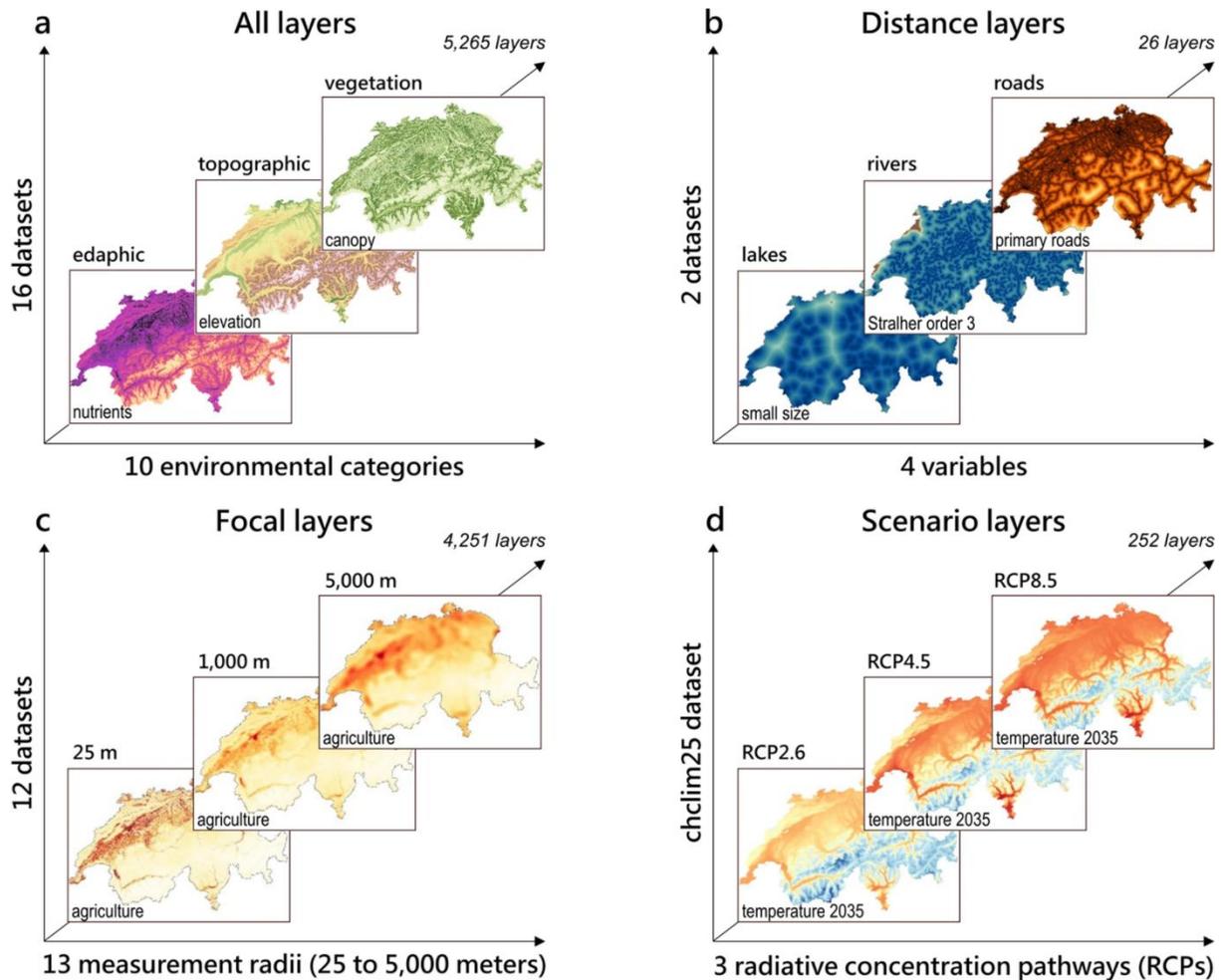


Figure 2: Overview of SWECO25 layer diversity and example illustrations. (a) Example layers extracted from three environmental categories, out of the ten available. (b) Example distance statistics layers made available for linear features (i.e., transportation and hydrological networks). (c) Example focal statistics layers computed using 13 measurement radii for 12 datasets. (d) Example scenarios layers for the chclim25 dataset for three radiative concentration pathways (RCPs).

All SWECO25 layers and files are following a standard naming scheme, which is also used for folder organization (Fig. 3). The tree structure of SWECO25 folders can be developed to a maximum of six levels: category, dataset, period, sub-period, scenario, and variable (Fig. 3). At its top level SWECO25 is divided into ten main environmental categories: geologic (“geol”), topographic (“topo”), bioclimatic (“bioclim”), hydrologic (“hydro”), edaphic (“edaph”), land use and cover (“lulc”), population (“pop”), transportation (“trans”), vegetation (“vege”), and remote sensing indices (“rs”). The environmental category with the most layers was land use and cover (3,304), followed by bioclimatic (428) and geologic (420). For each environmental category, the detailed list of layers can be found in the SWECO25_datalayers_details_categoryname.csv file available in its respective Zenodo repository.

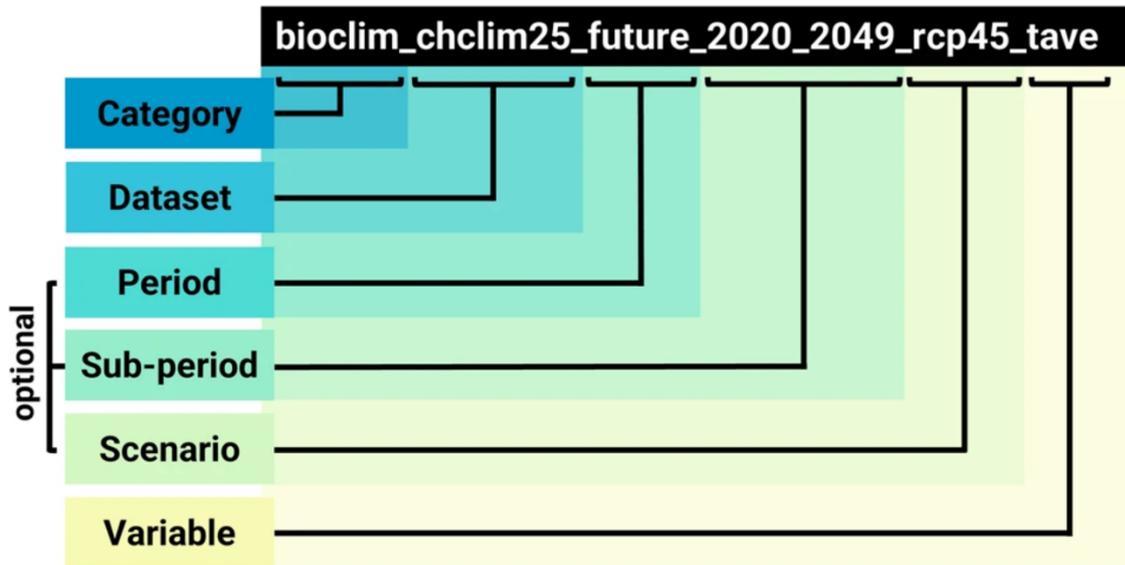


Figure 3: SWECO25 folder and file naming structure. In this example, the “tave” (temperature average) variable, from the “bioclim” (bioclimatic) category, in the “chclim25” dataset, for the “future” period, “2020_2049” sub period, and the “rcp45” scenario is stored in the folder “bioclim/chclim25/future/2020_2049/rcp45/tave”. The filename for this variable is “bioclim_chclim25_future_2020_2049_rcp45_tave.tif”.

5. Code availability

The R-code and ArcGIS toolboxes allowing to reproduce the standardization procedure, the computation of focal and distance statistics, and the technical validation are openly available on the SWECO25 GitHub repository

<https://github.com/NKulling/SWECO25>.

Part 2: Indicators development

In this part, we developed novel indicators for ecosystem services and biodiversity in Switzerland. These indicators were designed to serve as building blocks for the identification of the ecological infrastructure pursued in subsequent analyses.

In the first section ([2.1](#)), we created 15 ES supply indicators and one indicator for threatened species. We further examined the trade-offs and synergies among these indicators and identified their spatial bundling patterns across Switzerland.

In the second section ([2.2](#)), we established a streamlined pipeline for species distribution modelling, enabling the mapping of current and future distributions for over 7,000 species in Switzerland. This pipeline allowed the generation of biodiversity indicators, which were used in sections [2.1](#) and [3.1](#).

2.1. Nature's contributions to people and biodiversity mapping in Switzerland: spatial patterns and environmental drivers

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As first author, I led the conceptualization of the study, the literature review, methodology, software development, formal analysis, and the writing of the original draft.

1. Introduction

Ecosystems are facing severe threats worldwide, compromising the supply of many life-supporting goods and services to people. These threats, driven by human activities, are currently posing a greater risk of global extinction to more species than at any previous time (IPBES, 2019b; Canadell & Jackson, 2021). The erosion of habitats and biodiversity leads to the decline, alteration, and shift in the provision of nature's contributions to people (NCP) (Janssen et al., 2021; Walsh et al., 2016), thereby endangering the stability of human livelihood. The challenges of preserving biodiversity and NCP thus require multifaceted approaches that address social, environmental, and economic aspects (Biber-Freudenberger et al., 2020; de Queiroz-Stein & Siegel, 2023). Numerous attempts at protecting biodiversity have failed to slow down the rate of biodiversity loss (IPBES, 2019b; Mace et al., 2018), emphasizing that conservation efforts should now be planned holistically, understanding and considering both the interdependence of species as well as the necessity to accommodate human needs (Mace, 2014; Schlaepfer & Lawler, 2022). Indeed, biodiversity carries a major role in the supply of multiple NCP (Bastian, 2013; Harrison et al., 2014; Rey et al., 2023), thus the importance to consider both for conservation initiatives. In this context, the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) introduced multiple values of nature in its assessments, encompassing nature's values (i.e. biodiversity), nature's contributions to people (NCP; i.e. ecosystem services), and good quality of life (IPBES, 2018).

Evidence reporting the state of these values of nature is essential for designing policies, implementing strategies and practices, and driving behaviours to help achieve the Sustainable Development Goals (UN DESA, 2016), the Aichi Biodiversity Targets (Convention on Biological Diversity, 2016) and the Paris Agreement on Climate change (United Nations Environment Programme, 2015).

In particular, spatially explicit information across large scales reveals patterns that allow moving beyond site-specific understanding to design policies and institutions that work across administrative borders, and focus on ecosystem functionalities and the long-term supply of their services. Mapping NCP and biodiversity plays an important role in supporting effective management processes (e.g.: Beier et al., 2008; Daily et al., 2009) and landscape planning (e.g. Frank et al., 2012; Honeck et al., 2020; Koschke et al., 2012). It also facilitates the assessment of trade-offs and synergies among different NCP and biodiversity components (Ramel et al., 2020; Sylla et al., 2020; Yan et al., 2021; Zhao & Li, 2020), which is crucial for optimizing resource allocation in conservation initiatives (Aryal et al., 2021; Bennett et al., 2009) and to better understand the different relationships between biodiversity and NCP. In addition, mapping of NCP and biodiversity allows, through clustering in bundles, the identification of their joint supply providing a spatial representation of their co-occurrence (J. D. Karimi et al., 2021a; Qiu & Turner, 2013; Zhang et al., 2022). Bundles were defined by Raudsepp-Hearne et al. (2010) as “sets of ecosystem services that repeatedly appear together across space or time”, and allow to pinpoint the key drivers of their distribution. Furthermore, understanding which drivers impact the distribution of NCP and biodiversity bundles is necessary to predict their future evolution (Meacham et al., 2022; Spake et al., 2017).

Biodiversity underpins ecosystems, which in turn provide NCP. Overall, reported relationships between NCP and biodiversity tend to be positive, but are shown to depend on location, specific indicators, and scale of analysis. Global studies (worldwide or continental level) have generally identified positive relationships (i.e. synergies) between biodiversity and NCP, particularly in regulating NCP (Cimatti et al., 2023; Ricketts et al., 2016; Soto-Navarro et al., 2020). For example, it was shown that higher levels of biodiversity can increase NCP provision of carbon sequestration, water quality regulation, and protection from organisms detrimental to humans (Cardinale et al., 2012; Hooper et al., 2005; Tilman et al., 2014). However, more diverse results are shown in regional assessments. For instance Crouzat et al. (2015) showed a positive spatial correlation between plant diversity and crop/wood production in the French Alps, while Kong et al. (2018) showed a negative relationship (i.e. trade-off) between biodiversity and material NCP in China. In addition, although research on functional relationships between biodiversity and NCP is scarce, positive relationships are generally found (Finney & Kaye, 2017; Isbell et al., 2018b; Waldén et al., 2023), but not necessarily (e.g. Kleijn et al. (2015) and Winfree et al. (2015), for pollination). This emphasizes the need to integrate NCP and biodiversity considerations in conservation strategies (as shown in Peru by Móstiga et al., 2023) and across relevant scales (Chaplin-Kramer et al., 2022).

This is particularly applicable in Switzerland, where the landscape has been extensively shaped by human activities, necessitating the promotion of coexistence between humans and nature due to their spatial proximity. Switzerland exhibits

commitment and interest in integrating NCP in nature conservation. In particular, the nationwide biodiversity strategy explicitly states the conservation of ecosystem services in its overall objective (FOEN, 2012). Investigations of NCP in Switzerland have been undertaken through several research studies, with diverse approaches, scales, and resolutions. At the national level, Braun et al. (2018) mapped four NCP indicators, revealing synergies among the majority of them. Jaligot et al. (2019) identified distinct and complementary bundles of NCP supplied by different Swiss cantons. Additionally, researchers have investigated regional scales, providing insights into the spatial and temporal dynamics of NCP. For instance, these studies show that the distribution of NCP supply has not been constant over time in the *Vaud* Canton (Jaligot et al., 2019), and that potential shifts are expected in the future due to land use and climate change in mountainous regions (Briner et al., 2012). Moreover, they show the possibility of integrating NCP with biodiversity in regional spatial conservation planning, underscoring that excessively prioritizing specific NCP could increase threats on biodiversity (Ramel et al., 2020). Stritih et al. (2021) also highlighted possible changes in NCP provision by mapping risks and uncertainties associated with NCP supply in mountain forests.

Yet, a comprehensive assessment of NCP and their relationship with biodiversity was still lacking in Switzerland. Our study bridged this gap by mapping a set of 15 NCP indicators, as well as a biodiversity indicator based on the modeled distribution of 1482 threatened species. Our specific objectives were to:

- 1) Create high-resolution models and maps for NCP supply indicators and one biodiversity indicator in Switzerland
- 2) Assess the relationships - trade-off or synergies - among NCP and between NCP and biodiversity
- 2) Identify bundles of NCP and biodiversity and their main drivers

These analyses enhance our understanding of the relationship between NCP and biodiversity at a national scale, offering insights of their spatial patterns across Switzerland. Moreover, these spatial outputs can prove valuable within Switzerland in the context of multi-level planning (Albert et al., 2016). With this work, we aim to contribute to more efficient landscape management and effective conservation strategies.

2. Material and methods

2.1. Study area

Switzerland is a landlocked country located in Europe whose landscape is largely influenced by human activities. Switzerland is showing a tendency towards more settlements, urban areas, and forests and fewer agricultural areas (FSO, 2021a). One

prominent feature of Switzerland is its large elevation gradient, spanning from a minimum altitude of 193m to the Alps' highest summit at 4634 m. The country has been divided into five distinct ecoregions referred to as production region, as identified by the national forestry inventory (Figure 1, FOEN, 2020a): the *Plateau*, Jura, Pre-Alps, Alps, and Southern Alps, each with specific ecological and topographic characteristics.

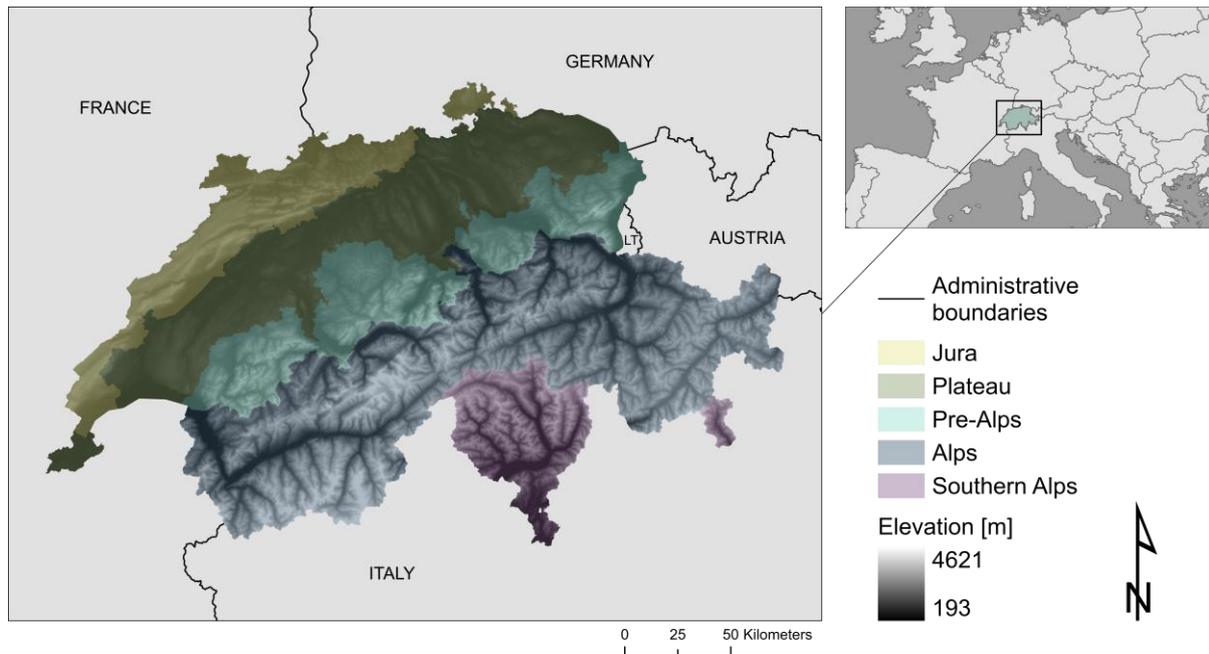


Figure 1: Map of Switzerland with ecoregions (production regions) and elevation.

2.2. NCP mapping

We mapped the supply of 15 nature's contributions to people (NCP) indicators and one biodiversity indicator guided by the IPBES' classification (IPBES, 2018). Eight regulating NCP, four material NCP, three non-material NCP, and one biodiversity

indicator were investigated (Table 2). We produced spatially explicit outputs in the form of raster maps with a 25 m resolution for all of Switzerland. The methodology used for mapping NCP indicators was based on different approaches, reflecting the evolving nature of NCP research (Burkhard & Maes, 2017; Martínez-Harms & Balvanera, 2012). Part of the mapping was based on causal relationships between biophysical information tables derived from primary data (e.g. field surveys) and land use, climatic, and topographic data. We also used regression models for several NCP, for example using niche-based models (Lavorel et al., 2017), which rely on the landscape suitability for a selected set of species associated with certain NCP (Rey et

al., 2023). See 2.2.1 to 2.2.15 and Appendix A. Input data used for the mapping is listed in Table 1.

Table 1: Input data used for NCP mapping.

Description	Values range / number of classes	Year	Resolution (data type)	Source
Land use map of Switzerland	65 classes	2013 – 2018	25 m (raster)	Giuliani et al. (2022)
Leaf-area Index	0 – 4.57 (index)	2014 – 2018	300 m (raster)	European Union (2014)
Forest dominant leaf type	2 classes	2018	10 m (raster)	European Union (2018)
Digital elevation model	193.39 – 4632.51 m	2020	2 m (raster)	swisstopo (2020a)
Swiss production regions (ecoregions)	1 class	2020	~25 m (vector precision)	FOEN (2020a)
Roads	1 class	2013 – 2020	0.2 to 1.5 m (vector precision)	swisstopo (2021)
Average annual precipitations	447.70 – 3805.96 mm	2013 – 2017	25 m (raster)	Broennimann (2023b)
Medium water catchments	1 class	2018	~25 m (vector precision)	Schwanbeck & Bühlmann (2018)
Soil erodibility	0.0 – 0.088 $t \cdot ha \cdot h \cdot ha^{-1} \cdot MJ^{-1} \cdot mm^{-1}$	2014	500 m (raster)	Panagos et al. (2014)
Rainfall erosivity	117.2 – 6500 $MJ \cdot mm \cdot ha^{-1} \cdot h^{-1} \cdot yr^{-1}$	2012	500 m (raster)	Panagos et al. (2017)
Root penetration depth	0 – 1450 mm	1980	~200 m (vector precision)	FOAG (1980a)
Potential evapotranspiration	0 – 709.52 mm	1981 – 2010	25 m (raster)	Broennimann (2023c)
Water availability for plants	0 – 100 (index)	1980	~200 m (vector precision)	FOAG (1980b)
Slope	0 – 89.9 °	2020	2 m (raster)	swisstopo (2020a)
Soil pH	4.71 – 7.1	2020	93 m (raster)	Descombes et al. (2020)
Average monthly precipitations	17.54 – 525.30 mm	2013 – 2017	25 m (raster)	Broennimann (2023d)
Average monthly temperature	-19.02 – 24.1 °C	2013 – 2017	25 m (raster)	Broennimann (2023a)
Population density	0 – 1096 inhabitants	2021	25 m (raster)	FSO (2021)
Protected areas	1 class	2020	20 to 60 m	swisstopo (2020b)

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			(vector precision)	
Lakes and rivers	2 classes	2020	20 to 60 m (vector precision)	swisstopo (2020b)
Alluvial zones	1 class	2017	~25 m (vector precision)	FOEN (2017)
Natural hazards	5 classes	2012	~50 m (vector precision)	Losey & Wehrli (2013)

Table 2: List of nature's contributions to people (NCP) indicators, biodiversity (BD) indicator, and codes used in this study. See 2.2.1 to 2.3 and appendix A.1 to A.2 for mapping methods.

Type of value	IPBES denomination	Indicator	Code
Nature / non anthropocentric	Biodiversity	Red list species	BD
Regulation NCP	Habitat creation and maintenance	Habitat quality	HAB
	Pollination and dispersal of seeds	Pollinator abundance	POL
	Regulation of air quality	Removal of PM ₁₀ by vegetation	AIR
	Regulation of climate	Carbon stored in biomass	CAR
	Regulation of freshwater quality	Nutrient retention by landscape	NR
	Formation, protection and decontamination of soils	Sediment retention by landscape	SR
	Regulation of hazards and extreme events	Protective forests and floodplains	HAZ
Material NCP	Regulation of organisms detrimental to humans	Pest control species	PC
	Regulation of freshwater quantity, location and timing	Annual water yield	WY
	Energy / materials and assistance	Wood provision potential	MAT
	Food and feed	Landscape suitability for agriculture	FF
Non-material NCP	Medicinal, biochemical and genetic resources	Medicinal plants	MED
	Learning and inspiration	Landscape suitability for picture-taking	LI
	Physical and psychological experiences	Recreation potential	REC
	Supporting identities	Emblematic species	ID

2.2.1. Habitat quality (HAB)

HAB informs on the repartition of natural habitats and their state of degradation. This NCP indicator was computed using InVEST habitat quality module (Natural Capital

Project, 2022), which calculates an index value for each raster cell based on a relative habitat score, and its sensitivity and proximity to threats. Habitat scores (ranging from 0 for artificial to 1 for natural; see Table A.2) were set for each land use class using a classification done in Switzerland (GE-21, 2020), based on the urbanity index from O'Neill et al. (1988). Five binary threat layers were generated using land use, population density, and road networks. "Urban" threat layer was created selecting settlements and urban land use classes in municipalities exceeding 10'000 inhabitants or densities surpassing 100 inhabitants/km², while the "Rural residential" layer was based on the same land use classes but for municipalities falling below these thresholds. "Primary roads" and "secondary roads" threat layers were generated by rasterizing road network vectors. Habitats sensitivity to threats was defined based on values from the literature (see A.1.1.).

2.2.2. Pollinator abundance (POL)

POL describes the potential for presence of wild pollinators species in a pixel, given the habitat nesting suitability based on land use, and the floral resources available within flying range. Pollinators species were selected based on Kleijn et al. (2015; see table A.4 for the list). Output map was produced using InVEST pollination module (Natural Capital Project, 2022).

2.2.3. Removal of PM₁₀ by vegetation (AIR)

AIR describes the potential regulation of air quality through removal by vegetation of PM₁₀ (particulate matter with a diameter $\leq 10 \mu\text{m}$). We used a formula of PM₁₀ removal adapted from Nowak et al. (2006) based on Braun et al. (2018). It estimated the quantity of PM₁₀ filtrated by vegetation based on the pollutants deposition rates per leaf area surface (Table A.5, values from Remme et al., 2014), the type of land use, and the resuspension rate of PM₁₀ (see appendix A.1.3.). We coupled land use classes with the dominant leaf-type layer of forests, as well as a digital elevation model, to distinguish broadleaved from coniferous forests.

2.2.4. Carbon stored in biomass (CAR)

CAR estimates the amount of carbon stored in vegetation and soil, thus contributing to the regulation of climate. We used InVEST carbon module (Natural Capital Project, 2022), which attributes a value of elemental carbon stored in each raster cell based on a land use map and a correspondence table containing the mass of carbon stored by land use categories (table A.6). The values of carbon stored per land use categories were based on the Swiss greenhouse gas inventory of the period 1990-2018 (table 6-4, FOEN, 2020b). The Swiss territory was divided by production region (FOEN, 2020a) and elevation regions (<601m, 601-1200m, >1200m), and each combination (15 total) was computed individually to fit with the values provided by the greenhouse gas inventory.

2.2.5. Nutrient retention by landscape (NR)

NR describes the environment's filtration capability of nitrogen annually, as an indicator of the regulation of water quality. We used InVEST nutrient delivery ratio module (Natural Capital Project, 2022) to estimate the quantity of nitrogen retained by each pixel and thus not reaching the water streams. This was computed using a land use map, corresponding nutrient loads and retention properties, as well as annual water runoff and elevation data. We used information from Jaligot et al. (2019) for land use biophysical table as well as model parametrization (table A.7 and A.8).

2.2.6. Sediment retention by landscape (SR)

SR estimates the yearly amount of sediment that is retained by each pixel in the Swiss landscape, thus regulating the erosion of soils. We used InVEST sediment delivery ratio module (Natural Capital Project, 2022), which computes sediment retention using an elevation map, soil properties (erosivity and erodibility) as well as a land use map with corresponding biophysical properties of land use classes. Values of model parameters and biophysical table (table A.9 and A.10) were based on the study done by Jaligot et al. (2019).

2.2.7. Protective forests and floodplains (HAZ)

HAZ shows the location of forests and floodplains providing potential protection against natural hazards. The SilvaProtect-CH project provided modeled natural hazard data on rockfall, avalanches, landslides, flood, and debris flow (Losey & Wehrli, 2013). This data was overlaid with forested areas from the Swiss land use map (table A.11) to identify protective forests potential. In addition to that, alluvial zones representing floodplains (FOEN, 2017b) were added to the indicator map.

2.2.8. Pest control species (PC)

PC describes the combined habitat suitability of species identified as predator species to main agricultural pests. To map this indicator, we used a list of 50 predators (table A.12), based on the study done by Civantos et al. (2012). It includes 2 amphibian, 2 reptile, 34 bird, and 12 mammal species. Invertebrates were not included in this analysis. We modelled the habitat suitability of each of these species and averaged the prediction maps to get the mean suitability value for predator species. The detailed species distribution modelling process is described in section 2.3, and specific model performances are reported in Appendix A.2.

2.2.9. Annual water yield (WY)

WY describes the relative contribution of each pixel to the water yield of the watershed the pixel is on. This indicator was computed with InVEST water yield module (Natural Capital Project, 2022) using annual precipitations, evapotranspiration, soil properties (depth and water availability), and land use. The model was calibrated using data at the watershed level from official hydrological surveys (Schädler & Weingartner, 2002),

for 287 available watersheds (Figure A.1), by modifying the K_c parameter (crop coefficient) in the biophysical table (table A.13).

2.2.10. Wood provision potential (MAT)

MAT shows an estimation of annual forest growth, as an indicator of the potential supply of wood-based energy and material. We used annual forest growth data from the Swiss greenhouse gas inventory (table 6-15, FOEN, 2020b) to map this indicator. Values of average wood increment in m^3 (table A.15) were attributed to each pixel of land use corresponding to productive forest (table A.14). Switzerland was divided in elevation and production region to use the corresponding value of forest growth (similarly to 2.2.4 – CAR). Pixels located on a slope superior to 110% were not considered in the analysis as they are not suitable for wood harvesting (Dupire et al., 2015).

2.2.11. Landscape suitability for agriculture (FF)

FF describes the landscape climatic and edaphic suitability to cultivate crops. We selected a list of the most cultivated crops in Switzerland (table A.16) based on data from the Swiss Farmers Union (USP, 2021). We used the ECOCROP database (FAO, 2007) to extract species-specific optimal growing conditions (monthly precipitations, temperature, and soil pH), similarly to Briner et al. (2012). We modeled optimal growing conditions maps for each species using the “Recocrop” package on R (Hijmans, 2021). The obtained maps represented climatic and edaphic suitability for the selected crops and were aggregated by averaging the value of crop maps. They were then masked to be applied only to food and feed production land use classes (table A.17).

2.2.12. Medicinal plants (MED)

MED describes the combined habitat suitability of 380 wild plant species identified as having a medicinal potential. A list of medicinal plants was created based on studies from Dal Cero et al. (2014) and Rey et al. (2023) (table A.18). We modelled the habitat suitability of each of these species and averaged the prediction maps. The detailed species distribution modelling process is described in section 2.3, and specific model performances are reported in Appendix A.2.

2.2.13. Landscape suitability for picture-taking (LI)

LI represents the modeled landscape potential for picture-taking linked with nature. We used publicly accessible data from two photo sharing apps for photography (*Flickr*) and naturalist observations (*iNaturalist*). We collected geolocation of pictures taken between 2006 and 2021 (*Flickr*) and 2010 and 2021 (*iNaturalist*), for a total of 6855 and 3719 observations, respectively. We used automatic image annotation (Schwemmer, 2021) on the geo-referenced pictures to remove pictures not depicting natural elements (e.g. drawings, vehicle pictures), enhancing the general quality of the observations (Fox et al., 2021). We then explained the distribution of these geolocated

pictures using a set of environmental predictors (table A.20), by building a regression model using the “randomForest” R package (Liaw & Wiener, 2002). We used this model to predict the landscape potential suitability for nature picture-taking to the entire Swiss territory. We conducted the analysis with 5-fold cross-validation. For each fold, we assessed the model's performance through area under the curve (AUC), mean square error (MSE) and R-squared. Model performances are shown in table A.19.

2.2.14. Recreation potential (REC)

REC describes the landscape potential for outdoor recreation. This indicator was mapped similarly to ESTIMAP’s “recreation potential” geomatic model done for the European union (European Commission, 2013). Mapping was based on three landscape characteristics: degree of naturalness (DN), natural protected areas (NP), and water components (W). DN was generated by attributing habitat scores to land use categories, as in section 2.2.1 – HAB. NP was created using areas of protected areas of Switzerland, from the *TLM_PA* item of *swissTLMRegio* database (swisstopo, 2020b). *W* was assessed by computing an inverse relative distance to lake coasts, getting the highest value at lake coast and a decreasing value for 2km. The REC map is a normalized aggregate (sum) of the three landscape characteristics maps.

2.2.15. Emblematic species (ID)

ID describes the combined habitat suitability of 15 species identified as emblematic/iconic, and thus contributing to support cultural identity. The list of species was based on the study from Schirpke et al. (2018) conducted in the Alpine region and shown in table A.21. We modelled the habitat suitability of each species and averaged the prediction maps to get the mean suitability value map. The detailed species distribution modelling process is described in section 2.3, and specific model performances are reported in Appendix A.2.

2.3. Species distribution modelling and biodiversity indicator mapping

We constructed species distribution models (SDMs) for 1482 terrestrial species that have been identified as threatened and classified in the red list by the Swiss government (red list species). The selection of these species for conservation efforts in Switzerland is based on an assessment of the threat level to their populations within the country (FOEN, 2021c). Selected species consist principally of vascular plants (n=596), arthropods (n=369), fungi (n=267), birds (n=83), and ferns and mosses (n=62) (see Figure A.2), and the complete list of selected species along with a detailed description of the method are available in appendix section A.2.

SDMs were built using the N-SDM software (Adde et al., 2023), which allows the integration of a “global” model, quantifying the species response to bioclimatic conditions across its entire distribution range, with a “regional” model incorporating finer-scale habitat predictors in Switzerland. Ensemble SDMs were computed using the five modelling algorithms available in N-SDM (Generalized Linear Model (GLM),

Generalized Additive Model (GAM), Maxnet (MAX), Random Forest (RF), and light Gradient Boosted Machine (GBM)). Candidate environmental predictors used for modelling the distribution of each species were extracted from the “SWECO25” database (v.1.0) (Külling, Adde, et al., 2024) and automatically selected using the “covsel” procedure (Adde et al., 2023). Model selection and evaluation was achieved using a consensus ‘Score’ metric averaging the AUC’ (or Somers’ D, such as $AUC' = AUC * 2 - 1$), the maxTSS, and the CBI (Adde et al. 2023). Results from the modelling algorithms were mapped over Switzerland on a 25 m resolution grid and ensembled together by averaging the five maps for each species. All information on the parameters used to fit and evaluate the models was stored using the ODMAP protocol (Zurell et al., 2020; appendix B)

Individual species maps were aggregated using the Zonation 5 (v.1.0) prioritization software (Moilanen, Lehtinen, et al., 2022b). Zonation is originally designed to support ecologically based landscape planning, in combining different landscape elements by an algorithm that systematically removes grid cells with the smallest aggregate loss of conservation values in each iteration. By prioritizing areas based on their relative importance for the conservation objective (in our case, red list species), Zonation produces a hierarchical spatial priority map ranging from 0 for minimum priority to 1 for maximal priority (Lehtomäki & Moilanen, 2013b). Here, it was used to aggregate the individual red-list species maps produced by the SDMs into a biodiversity indicator (BD). This aggregation was done using the Core-Area zonation 2 (CAZ2) algorithm. The choice of this algorithm was made to strike a balance between achieving high average coverage across all species and capturing the high-occurrence areas of each individual species (Moilanen, Lehtinen, et al., 2022b).

2.4. Relationship and bundle analysis

To investigate the relationship between NCP and between NCP and BD, we conducted a correlation analysis to identify potential trade-offs or synergies between the 120 possible pairs of the NCP and BD indicators. We applied min-max normalization to the NCP maps and the BD map to ensure comparability (e.g. Yu et al., 2022) and performed random sampling to select 15,000 points from the study area. To assess the correlations, we conducted Spearman rank correlation (ρ) between each pair of variables (e.g. Zhang et al., 2022). The alpha level for statistical significance was set at 0.05.

We employed a bundle analysis to discern distinct patterns of NCP supply and BD across the landscape (Raudsepp-Hearne et al., 2010). Here, bundle analysis allows to assess how these elements co-occur and interact over a given area. To do this, we used the *k*-means clustering algorithm, which has been employed widely in similar analysis (e.g. Cusens et al., 2023; Schirpke et al., 2019; Zhang et al., 2022). To determine the optimal number of bundles, we used the silhouette coefficient method

from the “factoextra” R package (Kassambara & Mundt, 2020), by selecting the number of bundles showing the highest average silhouette width. Clustering was done using the “RStoolbox” R package (Leutner et al., 2022) with a sampling of 15000 points. Built-up areas were masked from the maps used in both the relationship analysis and the bundle analysis. The mask used was based on built areas outlined by the Swiss building zone statistics (ARE, 2022).

To better understand the driving factors behind the identified bundle patterns, we performed a classification analysis using environmental predictors to predict bundles membership, following a methodology similar to that employed by Schirpke et al. (2019). To do that, we selected a set of predictors from the “SWECO25” database (v.1.0) (table A.25, Külling, Adde, et al., 2024) from a range of topographic, edaphic, habitat type and climatic datasets, similarly to what was done previously in Switzerland in similar large scale environmental clustering study (Lehmann et al., 2010). We extracted values from the bundle map and the predictors using random-stratified sampling, with 10000 points per bundle category. We excluded predictors displaying a high correlation ($|r| > 0.7$) (Dormann et al., 2013) and used a random forest classification algorithm using the “ranger” implementation in the “caret” package in R (Wright & Ziegler, 2017; Kuhn, 2008, respectively). We assessed model performance on 30% of the dataset using several evaluation metrics including Cohen’s Kappa, multiclass AUC of ROC, and confusion matrix, where high values of these metrics (>0.8) represent strong agreement between predicted and observed classifications (Fielding & Bell, 1997).

From the model, we identified the most influential predictors based on the mean decrease in accuracy, both for individual bundle classes and for the overall classification model. A higher mean decrease in accuracy for a predictor indicates that its inclusion improves the model's ability to make accurate classification (Archer & Kimes, 2008). We then calculated the marginal effects of the most important variables using the “pdp” R package (Greenwell, 2017) and displayed it with partial dependence plots, which illustrate the relationship between each predictor and the predicted outcome of the classification model, to visualize their individual effect on the prediction. To display the distribution of climatic and land use predictors by bundles, we used density plots for continuous predictors and cumulative barplots for discrete land use/cover classes.

3. Results

NCP and biodiversity maps

We produced maps of 15 NCP and one BD indicator, among which distinct spatial patterns emerged (Figure 2). Pollinator abundance, protective forests and floodplains, sediment retention by landscape, and emblematic species exhibited analogous

distributions, primarily associated with mountainous regions (Alps, Southern Alps, Prealps, and Jura), yet limited to moderate elevations. In contrast, other services, such as habitat quality and recreation potential, revealed a more uniform spread across the mountainous areas. Similarly tied to these regions, annual water yield and sediment retention by landscape displayed higher supply at greater elevations. The *Plateau* region displayed a higher supply of NCP linked to agricultural production: landscape suitability for agriculture, pest control species, as well as medicinal plants. In contrast, removal of PM₁₀ by vegetation, carbon stored in biomass, and wood provision potential collectively exhibited similar distributions aligned with forest presence. Lastly, landscape suitability for picture-taking illustrated a relatively consistent and unique distribution throughout Switzerland, closely linked to human infrastructure such as cities and roads.

The BD indicator map displayed scattered patterns covering all regions of Switzerland, with high values of priority score given in Alpine valleys (especially in the *Rhône* valley), and mean values of 0.62 ± 0.3 for the Jura, 0.41 ± 0.32 for the *Plateau*, 0.44 ± 0.28 for the Pre-Alps, 0.44 ± 0.3 for the Alps and 0.41 ± 0.3 for the Southern Alps. The mean score metric for all modeled SDMs was 0.88 ± 0.06 (Figure A.3).

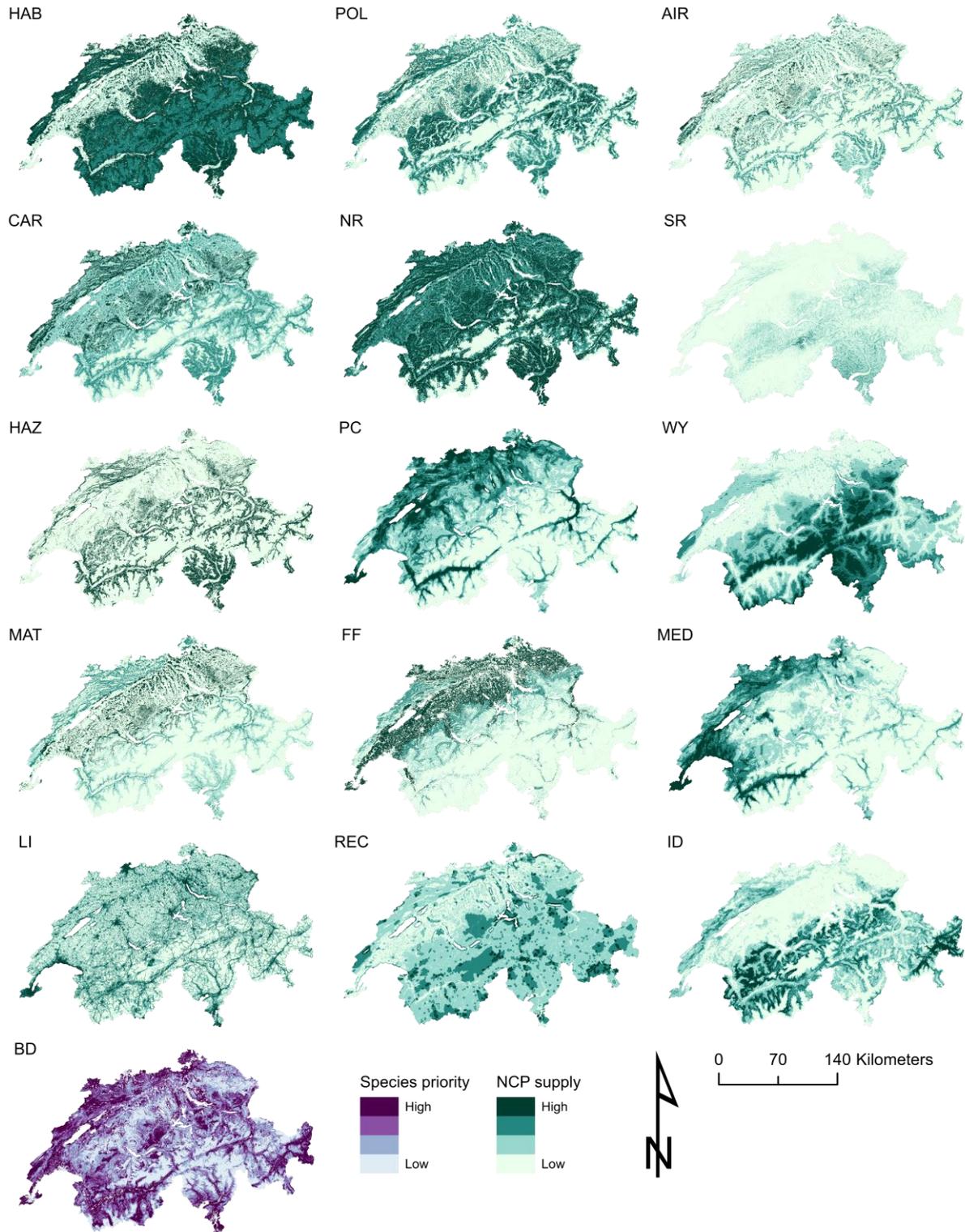


Figure 2: Normalized distribution of indicators maps. Color schemes defined by Jenks natural breaks. **BD** - Red list species, **HAB** - Habitat quality, **POL** - Pollinator abundance, **AIR** - Removal of PM_{10} by vegetation, **CAR** - Carbon stored in biomass, **NR** - Nutrient retention by landscape, **SR** - Sediment retention by landscape, **HAZ** - Protective forests and floodplains, **PC** - Pest control species, **WY** - Annual water yield, **MAT** - Wood provision potential, **FF** - Landscape suitability for agriculture, **MED** - Medicinal plants, **LI** - Landscape suitability for picture-taking, **REC** - Recreation potential, and **ID** - Emblematic species.

Relationship and bundle analysis

Significant correlations were observed between 116 out of the 120 pairs of NCP and BD indicators (Figure 3). Most correlations among NCP and between NCP and BD were positive, although among significant correlations, 85 were weak ($\rho < 0.4$) while 32 were stronger ($\rho \geq 0.4$). Among identified synergies, the strongest occurred between carbon stored in biomass (CAR) and removal of PM₁₀ by vegetation (AIR) (correlation coefficient $\rho = 0.91$), CAR and wood provision potential (MAT) ($\rho = 0.78$), medicinal plants (MED) and pest control species (PC) ($\rho = 0.76$), and CAR and pollinator abundance (POL) ($\rho = 0.7$). The strongest trade-offs occurred between annual water yield (WY) and PC ($\rho = -0.75$), WY and MED ($\rho = -0.53$), landscape suitability for agriculture (FF) and MAT ($\rho = -0.47$), and FF and WY ($\rho = -0.44$). BD had positive correlation with most NCP (11 /15), the strongest occurring with MED ($\rho = 0.48$) and PC ($\rho = 0.4$), and trade-off relationships occurring with WY ($\rho = -0.26$) and Sediment retention by landscape (SR) ($\rho = -0.15$).

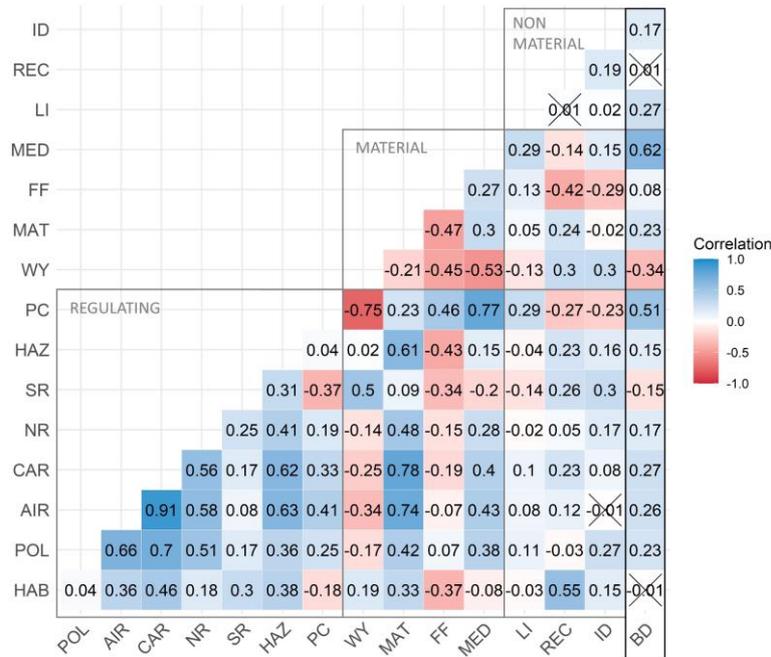


Figure 3: Correlogram depicting the relationships between nature’s contributions to people (NCP) and biodiversity indicators. Each cell represents the Spearman correlation coefficient (ρ), with non-significant relationships indicated by a cross. **BD** - Red list species, **HAB** - Habitat quality, **POL** - Pollinator abundance, **AIR** - Removal of PM₁₀ by vegetation, **CAR** - Carbon stored in biomass, **NR** - Nutrient retention by landscape, **SR** - Sediment retention by landscape, **HAZ** - Protective forests and floodplains, **PC** - Pest control species, **WY** - Annual water yield, **MAT** - Wood provision potential, **FF** - Landscape suitability for agriculture, **MED** - Medicinal plants, **LI** - Landscape suitability for picture-taking, **REC** - Recreation potential, and **ID** - Emblematic species.

Based on the silhouette coefficient, the optimal number of bundles was found to be four, with an average silhouette width of 0.38 (Table A.26). Figure 4.A provides a visual representation of the analysis outcome, in which all NCP and BD pixel values are projected to their corresponding bundle centers. Spatial distribution of these 4 bundles across the Swiss landscape revealed uneven patterns. Bundle 1 predominated in steep and mountainous regions, while bundle 2 was prevalent in the *Plateau* region and Alpine valleys. Bundle 3 displayed a distribution across the *Plateau* and Jura regions, and bundle 4 was notably dominant in higher-elevation alpine areas, and some Jura regions.

Figure 4.B provides a heatmap displaying the mean values of NCP and BD per bundle and the distribution of land use categories in each bundle. Bundles 1 and 3 primarily included forested areas, encompassing diverse NCP. Bundle 2 was primarily composed of NCP associated with agricultural land, including FF and PC, but also included MED and LI. Bundle 4 was made of a broader range of land use categories, including non-vegetated natural areas such as scree, rocks, and glaciers, as well as agricultural lands. This bundle comprised primarily regulating NCP (HAZ, HAB, SR, WY), along with non-material NCP such as REC and ID. The BD indicator was represented in all bundles but the 4th, with the highest mean value in the 3rd bundle.

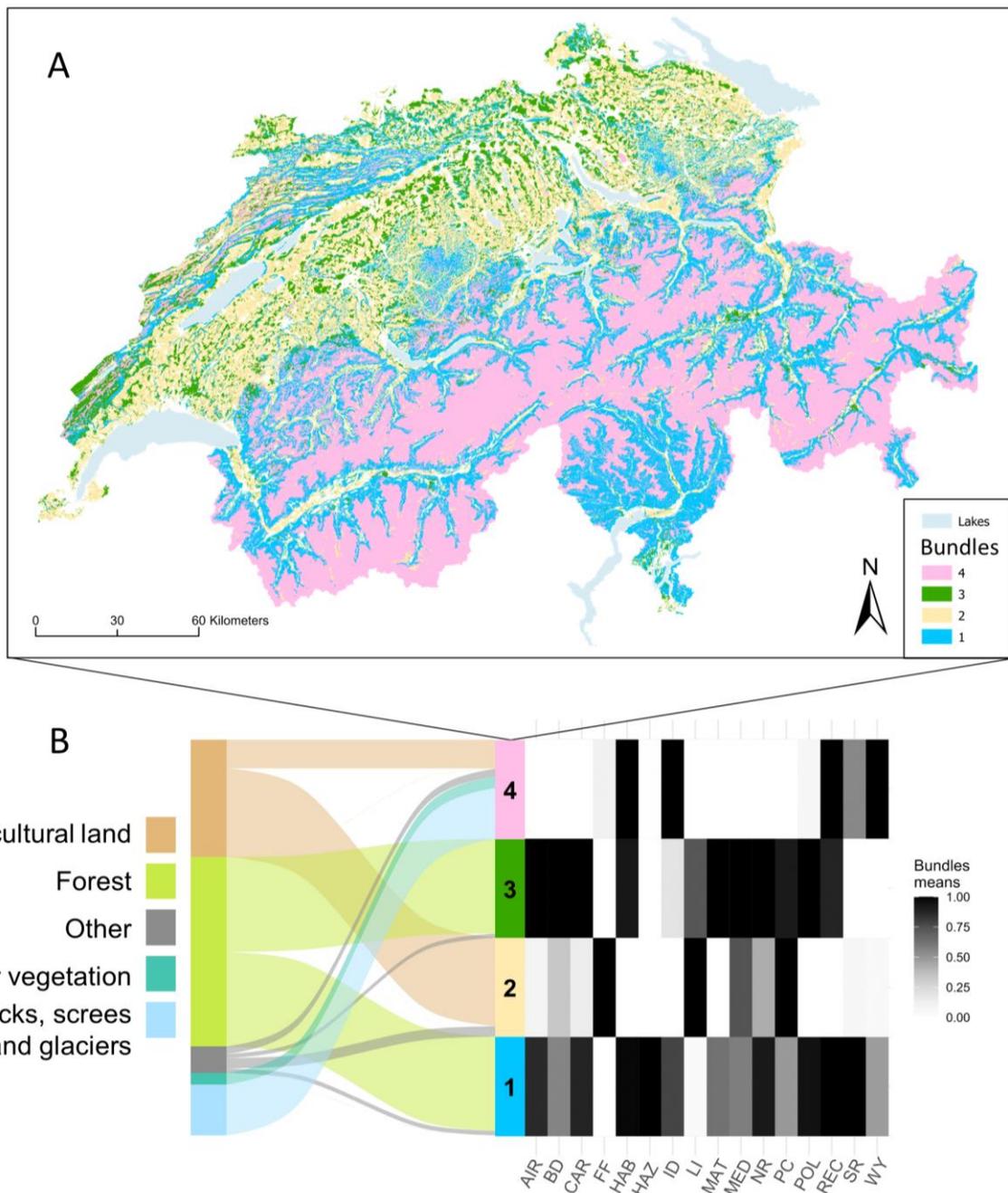


Figure 4.A: Spatial distribution of the four bundles across Switzerland. **4.B (left):** Alluvial diagram with flow thickness indicating the distribution of land use categories repartition in each bundle, with **4.B (right):** a heatmap indicating bundles mean values for the nature's contributions to people (NCP) and biodiversity indicators. **BD** - Red list species, **HAB** - Habitat quality, **POL** - Pollinator abundance, **AIR** - Removal of PM10 by vegetation, **CAR** - Carbon stored in biomass, **NR** - Nutrient retention by landscape, **SR** - Sediment retention by landscape, **HAZ** - Protective forests and floodplains, **PC** - Pest control species, **WY** - Annual water yield, **MAT** - Wood provision potential, **FF** - Landscape suitability for agriculture, **MED** - Medicinal plants, **LI** - Landscape suitability for picture-taking, **REC** - Recreation potential, and **ID** - Emblematic species.

Using environmental predictors to explain and predict bundle classification, our random forest analysis accurately classified 86.03% of the original bundle labels.

Evaluation of the model's predictions showed a value of Cohen's kappa of 0.81 and a multiclass AUC of ROC of 0.86. The confusion matrix and per-bundle metrics are shown in table A.23 and A.24. Predictors displaying the highest correlation (mean decrease in accuracy values) with the spatial distribution of the four bundles were slope, vegetation height, average annual temperature, and light availability (Figure 5.A). The computation of marginal effects of the six main variables is shown in Figure 5.B through partial dependence plots. Bundles 1 and 3 displayed contrasting responses to topographical and climatic conditions (slope, temperature), but shared similar ecological features in term of vegetation composition, especially in the presence of high vegetation, through "beech forests" (*Fagus sylvatica*) habitat (especially for bundle 3) and "highland coniferous forest" habitat (for bundle 1), as opposed to bundles 2 and 4 which showed a similar response to low vegetation, and a habitat type of "grassland and meadows".

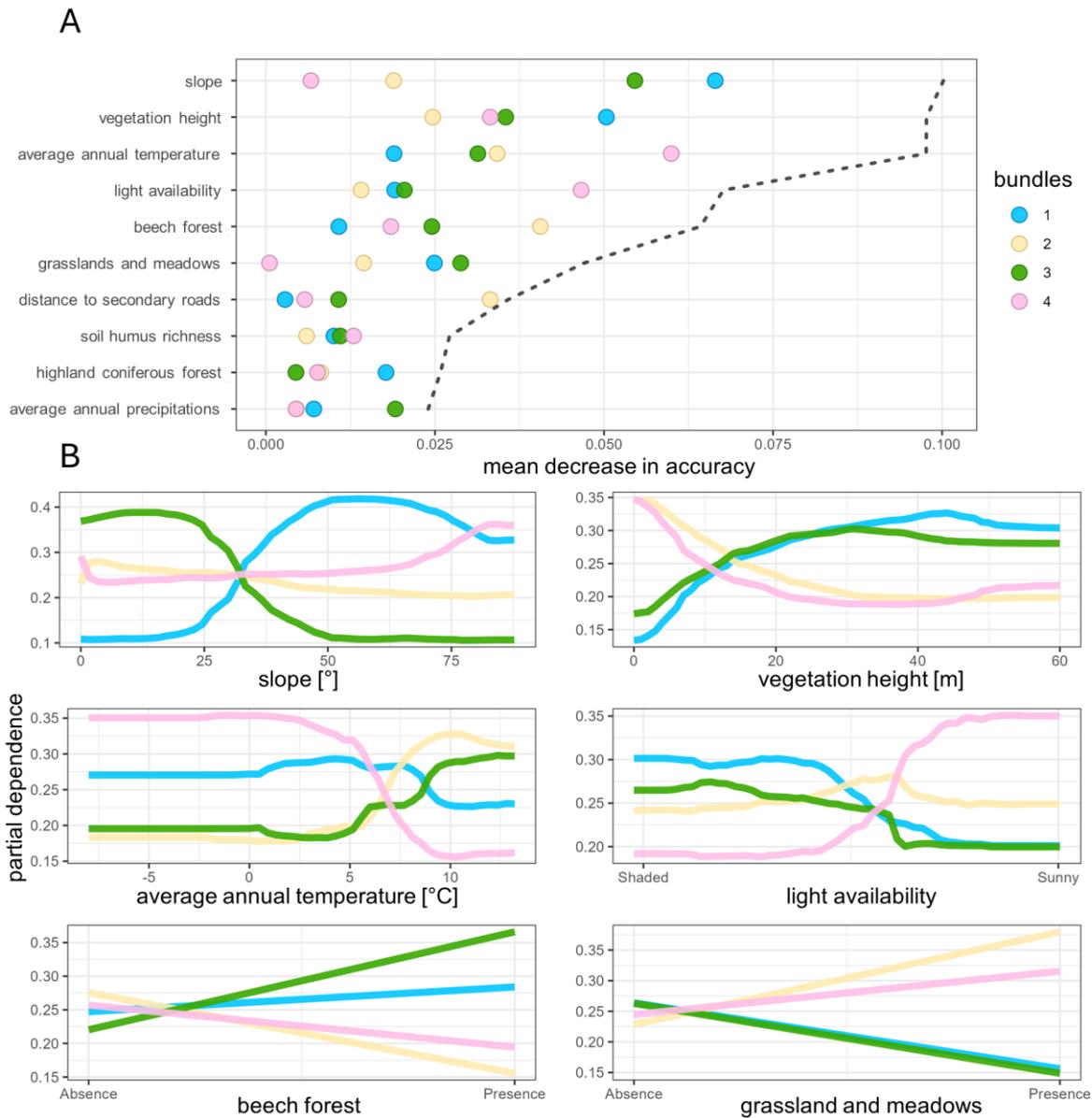


Figure 5.A: Predictors importance for random forest bundle classification. The ten most important variables are shown, with the mean decrease in accuracy for the classification model indicated by the dashed black line, and the colored dots representing the mean decrease in accuracy for each bundle. A higher mean decrease in accuracy indicates that its inclusion improves the model's ability to make accurate classification. **5.B:** Partial dependence plots for the six most important variables. Colored lines display bundle-specific responses to the selected variables over their value range.

The per-bundle distributions of main identified climatic and land use predictors are displayed in Figure 6. Continuous predictors were precipitation, temperature, and vegetation height (Figure 6.A-C). The highest mean value for temperature was in bundle 3 (9.16°C), while the lowest was in bundle 4 (2.65°C). For precipitation, the highest mean value was in bundle 4 (1323 mm), while the lowest was in bundle 3 (984 mm). bundle 3 had the highest mean vegetation height (28 m), whereas bundle 4 had the lowest (4 m) (see table A.27 for all descriptive statistics per bundle). For discrete

land use predictors, “beech forest” predominantly occurred in bundles 1 and 3, “grassland and meadows” in bundles 2 and 4, and “highland coniferous forest” in bundle 1 (Figure 6.D).

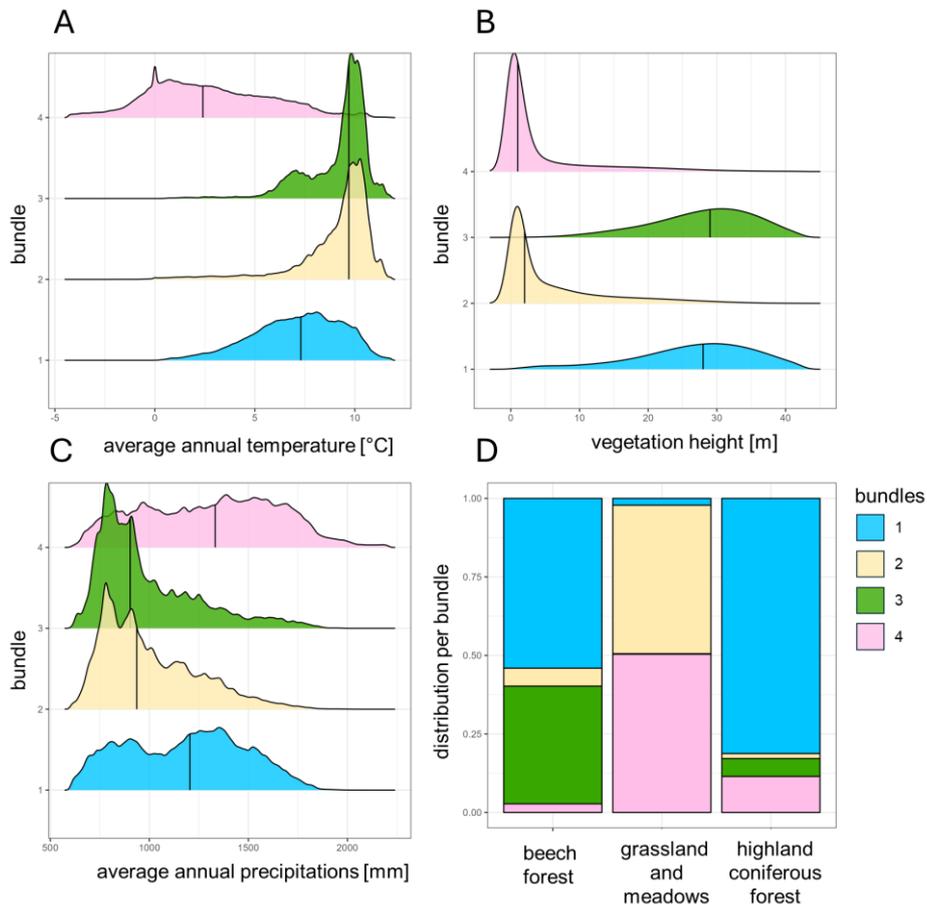


Figure 6.A-C: Density plots showing the distribution of temperature, precipitation, and vegetation height per bundle. Vertical black line represents the median value. **6.D:** Cumulative barplot showing the relative distribution of land use categories per bundle.

4. Discussion

Implications for conservation planning

We provided a first comprehensive set of 16 high-resolution maps of indicators of NCP supply and BD, based on the IPBES regional assessment of values of nature (IPBES, 2018). This development of spatially explicit indicators is essential for achieving a more effective balance between ongoing land use changes and ecological integrity, as highlighted in previous research (e.g. Bateman et al., 2013; Grêt-Regamey et al., 2017).

We identified three target levels at which our results can be practically used by stakeholders: cantonal, national, and European.

At the cantonal level, the Swiss government has mandated all cantons to identify, plan and develop their ecological infrastructure (EI) in order to ensure the protection of

biodiversity (FOEN, 2021a). This task will benefit from the availability of our NCP in complement to a biodiversity-only approach (as in e.g. Vincent et al., 2019). For example, the canton of Geneva is using NCP indicator maps for the planification of its EI (DETA-DGAN et al., 2018).

At the national level, we provided here the first national-scale assessment for Switzerland, based on a comprehensive list of NCP at high resolution and including an index of biodiversity based on a large number of endangered species, paving the road for a nation-wide spatial prioritization. In practice our maps could be used as an input for a nation-wide prioritization of the EI, as approaches which encompass both NCP and biodiversity indicators for the identification of the EI through weighted spatial prioritization have been tested regionally in Switzerland (e.g. Honeck et al., 2020, Ramel et al., 2020), but not at the national level like done in India (Srivathsa et al., 2023) or at European scale (Kukkala & Moilanen, 2017). NCP maps and knowledge on their synergies and trade-offs have been shown to be valuable to guide the planning and management of the EI at large scales (Chen et al., 2024; Liqueste et al., 2015; Ramyar et al., 2020).

Finally, our assessment aligns with the "EU Biodiversity Strategy to 2020" goals, which emphasizes the mission of member states to "map and assess the state of ecosystems and their services" (European Commission. Joint Research Centre., 2020). Switzerland, not being an EU member, was not part of this specific initiative. Nevertheless, the data and insights derived from our assessment can play an important role by inspiring similar initiatives across Europe and supporting the objectives set forward in the European "EU Biodiversity Strategy for 2030" (European Commission. Directorate General for Environment., 2021).

BD and NCP relationship

We assessed the relationships between NCP and BD maps following the "spatial linkage" approach, comparing values of NCP and BD across space (Rey et al., 2022; Ricketts et al., 2016). Our analysis revealed a positive correlation between the spatial distribution of the BD indicator and most of the NCP indicators. This was expected as several studies have shown the positive relationship between biodiversity and NCP supply in different ways (Isbell et al., 2018b; Ricketts et al., 2016; Waldén et al., 2023). Notably, our results show the strongest correlation between BD and two NCP – medicinal plants and pest control species - which are niche-based models (Lavelle et al., 2017), derived from SDMs and sharing very similar input data. While other correlations are noteworthy positive, they are relatively modest. Thus, our findings highlight the significant yet partial link between BD and NCP supply in Switzerland. This result is congruent with previous studies, and encourages targeted approaches for conservation of both biodiversity and NCP (Cimon-Morin et al., 2013; Larsen et al., 2011; Naidoo et al., 2008; Xu et al., 2017).

Relationship between NCP, bundles, and drivers

Our findings indicated significant relationships among the spatial distribution of most NCP in Switzerland, which is coherent with what was found in similar studies (Crouzat et al., 2015; L. Kong et al., 2018; Raudsepp-Hearne et al., 2010; Schirpke et al., 2019). Our results regarding water yield (WY) diverge somewhat from existing studies conducted in the Alpine region. For example, Crouzat et al. (2015) reported a mild yet significant synergy between water quantity regulation and the pest control NCP (PC), and Schirpke et al. (2019) display differing results regarding the relationship between WY and wood provision potential (MAT), carbon storage (CAR) and soil erosion prevention (SR). These contrasts likely stem from variations in scale, geographical region (especially latitude) and resolution used in our analysis. Specifically, highest WY values in Switzerland were most concentrated in places characterized by limited vegetation and species diversity (high altitudes, glaciers, see Figure 2), and thus appear in a trade-off with NCP linked to forests (CAR, MAT), vegetation in general (SR) and cropland-specific species (PC).

We identified four distinct bundles of NCP and BD for Switzerland in our analyses. This number aligns with Schirpke et al. study (2019), which employed a similar methodology. Dittrich et al. (2017), in the context of a national-scale assessment for Germany, identified eight bundles, by using the same methodology as Crouzat et al. (2015) who found five bundles. This study-specific difference in the number of bundles may be influenced by the spatial extent of the study area. In our case, Switzerland (four bundles) is of a much smaller size compared to Germany (eight bundles). We explored the repartition of bundles based on the approach of Raudsepp-Hearne et al. (2010), including NCP and biodiversity components, as recommended by Crouzat et al., (2015). This approach facilitates the overall understanding of NCP and BD distribution. This distribution in each bundle was found to be very diverse, highlighting the multiplicity of roles of supply played by ecosystems. However, each bundle appeared to be supported by specific types of land use, suggesting the vulnerability of their provision to changes in land use, which has been shown in Austria by Schirpke et al. (2023).

Our bundle classification model performed well, allowing us to efficiently highlight the main drivers of bundle's distribution. These drivers are predominantly associated with climate, topography, and vegetation. Notably, temperature and precipitation emerged as key drivers influencing the bundle assignment, aligning with findings from Braun et al. (2019) who observed similar patterns for three NCP in Switzerland. Furthermore, "beech forest" habitat was identified as significant driver, particularly for Bundle 3. Beech forests are one of the main type found in the *Plateau* region (Brändli et al., 2020), and have been shown to decline in Europe due to climate change (Martinez Del Castillo et al., 2022). Coupled with the alteration of temperature and precipitation patterns, we

can anticipate changes in the spatial distribution of NCP and BD bundles in the future, similarly to what has been shown on individual NCP (Sun et al., 2023). Our BD indicator being based on a spatial prioritization, high BD values were not expected at higher elevation, as species diversity decreases with altitude (Sanders & Rahbek, 2012). However, Bundle 4 (linked to high elevations) having the highest habitat quality (HAB) value, remains crucial for biodiversity (e.g. for alpine species, Vittoz et al., 2013), although having low values for our red list species prioritization.

Our bundle approach allows to consider simultaneously NCP and BD in a holistic view (Saidi & Spray, 2018), with one single geographic information layer for the Swiss landscape. Our work can help promote social and ecological considerations in nature conservation (Dias et al., 2022), for example highlighting the diverse NCP and BD features provided by one area (as shown in forests by Deal et al., 2012). Here, our results underscore the importance of “beech forest” and “grassland and meadows” as habitats in Switzerland, which are main drivers to the distribution of all four NCP and BD bundles identified. These informations can be leveraged for landscape management decisions that protect both NCP and BD. Indeed, this approach of landscape characterization in bundles has been shown as an efficient way to communicate the numerous functions of the landscape and can be used for the development of informed landscape management plans (Bai et al., 2021; Liao et al., 2023; Malmberg et al., 2021).

Limitations of the study

Our NCP supply assessment does not capture the actual benefits of NCP to people, hindering our ability to identify gaps (e.g. in land use policies) (Mandle et al., 2021). The development of spatially explicit demand indicators (e.g. Schirpke et al., 2019) for Switzerland is necessary to further the connection between human well-being and natural environment.

Large-scale NCP assessments are necessary (Albert et al., 2016; Schröter et al., 2016), but can lack crucial information necessary at smaller scales. For instance, analyses of socio-ecological-technological systems in Geneva canton showed varying drivers and archetype (comparable to bundles) numbers, highlighting a need for more archetypes than at Swiss level (Wicki et al., 2023). A complementary alternative lies in tiered assessments at different spatial scales, allowing to better understand the variety of NCP provided and to design conservation strategies accordingly, with adapted methods for regional and national needs (Grêt-Regamey et al., 2015).

Additionally, though we use a comprehensive list of NCP defined by the IPBES, the choice of NCP and BD indicators are subject to data availability and technical limitations, and model outputs often lack uncertainty measures. This complicates comparability between NCP assessments (Schirpke, Ghermandi, et al., 2023), and we thus advocate for an open access to scripts and data in such assessments, as done here. Finally, although an assessment of NCP and BD was necessary to identify the

current drivers of their spatial distribution in the landscape, a look into the future evolution of the identified drivers and bundles is needed to ensure the preservation of NCP and BD supply, and to forecast potential changes (Schirpke et al., 2023)

5. Conclusions

In this study, we show significant correlations among the spatial distribution of NCP and BD indicators studied in Switzerland. Although closely linked, NCP and BD are not entirely collinear, emphasizing the importance of informed and targeted approaches in the conservation of both NCP and BD supply. We identified four bundles that represent NCP and BD supply in the landscape, and we showed that they are reliably correlated to a set of environmental predictors. Our findings reveal that climatological drivers, such as temperature and precipitation, along with habitat types (forests and meadows), play a major role in the distribution of these four bundles. This indicates that future global changes will likely have a significant impact on the spatial distribution of BD and NCP supply. Finally, we provide a set of spatially explicit outputs and methods, which could serve as valuable inputs to refine conservation priorities in Switzerland by promoting the integration of NCP, particularly through weighted spatial prioritization.

2.2. N-SDM: a high-performance computing pipeline for Nested Species Distribution Modelling

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While not the primary author of this study, I actively contributed by participating the conceptualization, data curation, formal analysis, model validation, visualization, and article writing. The following summary reflects the study's main outcomes and their role in this thesis.

Summary

Predicting current and future species distributions is crucial for both scientific research and decision-making processes. However, generating high-resolution spatial predictions for diverse taxonomic groups and regions remains challenging due to the limited scalability of existing modelling tools. In this study, we developed N-SDM, a species distribution modelling (SDM) platform optimized for high-performance computing environments, designed to produce reproducible models for biodiversity assessments (Fig. 1). N-SDM's framework allows the integration of species occurrence data from multiple sources and spatial scales. This approach facilitates the combination of two models fitted with data ranging from global to regional scales (nested), effectively addressing spatial niche truncation. We generated a metric score ("Score") combining three common SDM metrics. We tested N-SDM on 1500 species and obtained a median "Score" value superior to 0.85, which indicates high performance. N-SDM is available on GitHub, and has been successfully used for the generation of SDM maps in different instances (e.g. Adde et al., 2024; Brantschen et al., 2024; Steen et al., 2024). N-SDM allowed to produced essential data for this thesis, used for the mapping of ES and biodiversity indicators (2.1.), and the prioritization of the Swiss ecological infrastructure (3.1.).

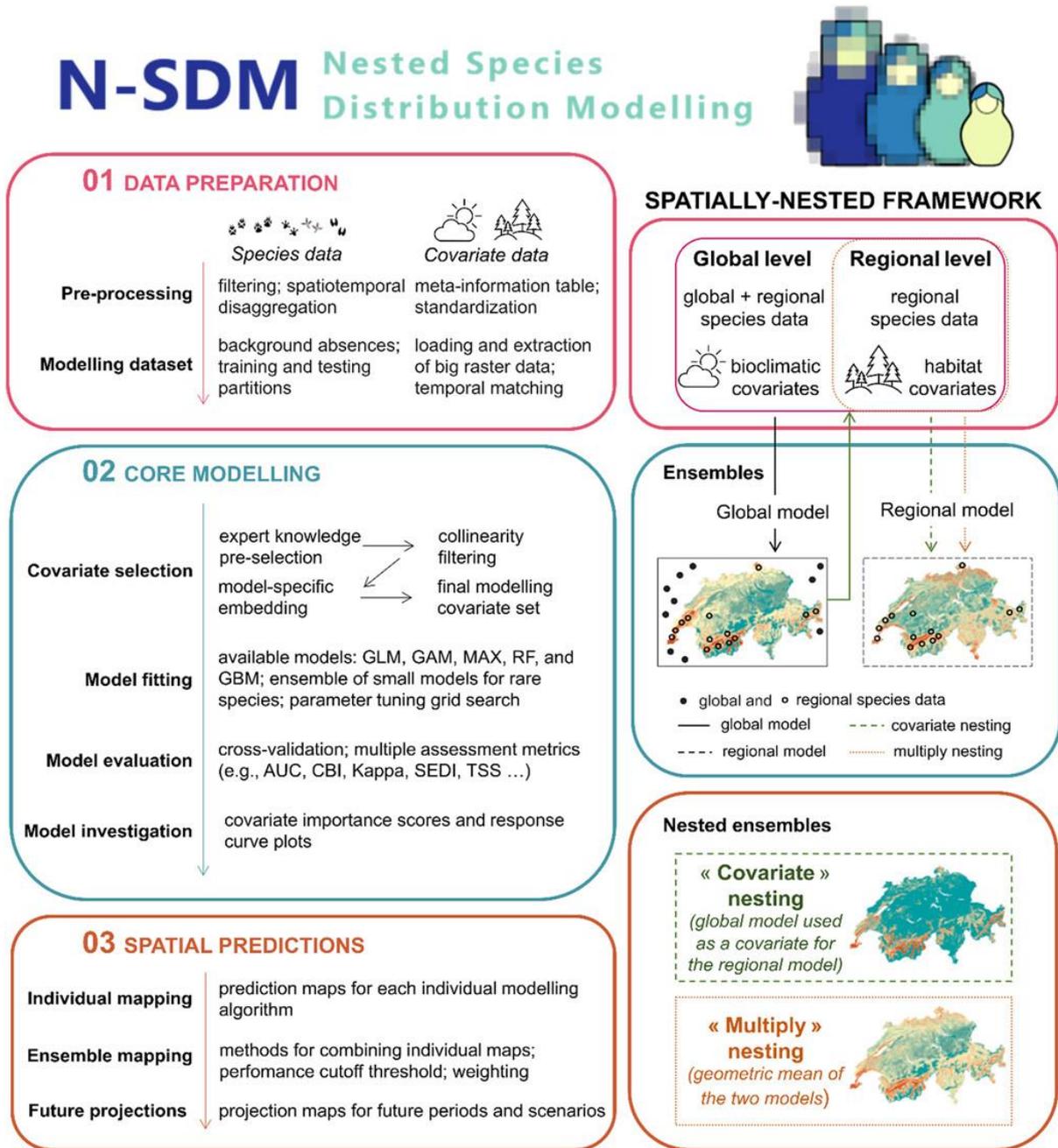


Figure 1 : source : Adde et al. (Fig.1, 2023): “N-SDM overview. Panels on the left display the sequence of tasks performed during each of the three main stages (Data preparation, Core modelling, and Spatial predictions). Panels on the right provide a graphical representation of the spatially-nested framework used in N-SDM. All the complementary information required for the installation and use of N-SDM, along with data for an example N-SDM run, are available on the N-SDM GitHub repository <https://github.com/N-SDM/N-SDM>. GLM: Generalized Linear Model; GAM: Generalized Additive Model; MAX: Maxnet; RF: Random Forest; GBM: (light) Gradient Boosted Machine; AUC: Area Under the Curve; CBI: Continuous Boyce Index; Kappa: Cohen’s Kappa coefficient; SEDI: Symmetric Extremal Dependence Index; TSS: True Skill Statistic.”

Part 3: Integration and prioritization

In this section, we build upon the knowledge and data generated in previous parts to develop a spatial conservation prioritization (SCP) framework for Switzerland. Specifically, we explored the sensitivity of SCP outcomes to varying weightings of three key EI components: biodiversity, ecosystem services, and landscape structure. Additionally, we analysed the alignment between the current protected area network and the prioritization of these component groups. Lastly, we assessed the effectiveness of the SCP framework in supporting a sustainable EI under future conditions by comparing species distribution model coverage across the current period and two future scenarios.

3.1. Reaching conservation targets: Spatial prioritization of national ecological infrastructure

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(in preparation).

As first author, I led the conceptualization of the study, the literature review, methodology, software development, formal analysis, and the writing of the original draft.

1. Introduction

Ecosystems and biodiversity are under unprecedented stress worldwide due to human activities (Barnosky et al., 2011; IPBES, 2019a; Vitousek et al., 1997). Species extinction rates are high and increasing, due to habitat loss, pollution, overexploitation of resources, climate change, and invasive alien species (Finn et al., 2023; Mantyka-pringle et al., 2012; Un Environment, 2019). This biodiversity loss poses a significant threat to human well-being, as we depend on the equilibrium of ecosystems for numerous ecosystem services (ES), or nature's contribution to people (NCP) to sustain our livelihoods (NCP, Brauman et al., 2020; Díaz et al., 2019).

In response to this crisis, several global initiatives have been launched to combat biodiversity erosion. Among these, an important effort to mitigate habitat degradation is the Convention on Biological Diversity (CBD). The CBD's Strategic Plan for Biodiversity 2011-2020 included the 20 Aichi biodiversity Targets, one of which aimed to protect 17% of terrestrial and inland water areas globally (CBD, 2016). This target, along with all others, was not met by 2020 (Maney et al., 2024). The Kunming-Montreal Global Biodiversity Framework is a more recent landmark, adopted in 2022, which includes the "30 by 30" initiative aiming at protecting 30% of the world's land and oceans by 2030 (CBD, 2022). At the European level, the EU Biodiversity Strategy for 2030 aligns with this goal, focusing on establishing protected areas through restoration and conservation efforts, and also seeking to integrate biodiversity considerations across all sectors of the economy and society (European Commission, 2021).

Recent conservation programs emphasize integrating nature into human landscapes and activities, rather than strictly preserving it with no human access. For example UNESCO's "Man and the Biosphere" program, which establishes reserves with varying levels of protection with none to dense human presence (UNESCO, 2022). These initiatives reflect a shift in modern conservation strategies, moving from a focus on solely protecting nature to recognizing and integrating the contributions nature makes

to people, acknowledging human needs in the process of nature conservation (Freudenberger et al., 2013; Mace, 2014; Schlaepfer & Lawler, 2023). This paradigm shift is reflected in the concept of ecological infrastructure (EI), defined by the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) as “the natural or semi-natural structural elements of ecosystems and landscapes that are important in delivering ecosystem services” (IPBES, 2018).

Identifying the EI is thus critical for nature protection and to achieve latest conservation objectives. A key step in this process is determining which areas should be included in the EI and how to manage them. One effective method for this is spatial conservation prioritization (SCP), a systematic approach that identifies and allocates areas for conservation efforts to maximize biodiversity protection and NCP efficiently. However, this process remains challenging due to the lack of consensus on methodologies and the complexity of accessing spatial data on EI components, such as biodiversity, NCP, or landscape structure indicators (Bartesaghi Koc et al., 2017; Honeck, et al., 2020; Wang & Banzhaf, 2018). At a global level, Neugarten et al. (2024) have made a substantial effort to map top areas for biodiversity and NCP, finding that conserving approximately 44% of global land area could provide 90% of current levels of ten NCP, and meet minimum representation targets for over 26'000 terrestrial vertebrate species, but also find out that only 18% of the prioritized areas are currently protected. At a continental level, O'Connor et al. (2021) and Liqueste et al. (2015) both analysed the priority areas in the European union, and declare that there is an urgent need to protect key areas for biodiversity, NCP, and landscape connectivity, and that we should include more than just biodiversity in the establishment of protected areas. At national scales, Eckert et al. (2023) prioritized the EI of Canada based on species distribution models and concluded that a national scale analysis is better for overall species protection coordination rather than province or region specific analysis. Srivathsa et al. (2023) did a similar exercise for India, including NCP and habitat information layers, and showed that only 15% of the identified priority areas were included in the current protected area network. El-Gabbas et al. (2020) observed a similar trend in Egypt, concluded that current protected areas are insufficient for preserving fauna.

Switzerland is a small alpine country with a landscape significantly shaped by human activities. It was a pioneer in conducting conservation efforts by establishing one of the first national park of Europe, in 1914. However, the country also experienced significant environmental degradation throughout the 19th and 20th centuries due to intense agricultural, industrial, and urban development practices, making the landscape highly modified with half of habitat types currently endangered (FOEN, 2023b). In response, Switzerland has adopted a nation-wide biodiversity strategy in 2012 and a related action plan in 2017. A key component of this plan is the creation of a functional EI at national, regional (cantonal), and municipal levels (FOEN, 2017a). The Swiss government declares that the EI “secures habitats that are capable of

functioning and regenerating over the long term. [...] ensuring the basis for a rich biodiversity that is responsive to change. In this way, the Ecological Infrastructure, as "Switzerland's web of life", also makes a significant contribution to safeguarding the central services of nature for society and the economy" (FOEN, 2021a). Given the nation's mandate and the global need for conservation efforts, Switzerland serves as an ideal case study to demonstrate how SCP of the national EI can help achieve conservation targets.

Although no national-level spatial prioritization exercise currently exists to guide EI planning at the Swiss scale, several studies have been dedicated to identify and prioritize EI in specific Swiss regions. For instance, Vincent et al. (2019) suggested that current protected areas in an alpine area of Switzerland are not ideally located to sustain high species richness, and that climate change is expected to make these areas less and less effective. In contrast, in the canton of Geneva, a highly urbanised and densely populated area, Honeck et al. (2020) concluded that the protected areas are well placed according to their prioritization, which also included ES. In particular, they found that optimizing both NCP and species indicators was possible, conversely to Ramel et al. (2020) who found in an alpine region of Switzerland that prioritizing certain NCP could be a threat to biodiversity. This highlights that synergies and trade-offs between biodiversity and NCP vary spatially, emphasizing the need for a comprehensive country-wide analysis.

In this study, to demonstrate how conservation targets can be achieved through the spatial conservation prioritization (SCP) of national ecological infrastructure (EI), we conducted SCP analysis integrating three key components of the EI: biodiversity (including habitat and species distribution), NCP, and landscape structure indicators. Our specific objectives and research questions are as follows:

- 1) How sensitive is the national-scale prioritization analysis to the weighting of different EI component groups?
- 2) Are protected areas effectively located in relation to the prioritized EI, and where might expansions be needed?
- 3) How resilient is the identified prioritized EI for species in the context of climate change?

Our novel methods, results, and highly resolved spatial outputs are of prime importance in the current context of land degradation and the biodiversity crisis. They provide valuable insights into a national-level approach to SCP. While particularly relevant for the Swiss context of EI identification and development, our findings also aim to enhance landscape management practices and to inspire the integration of socio-ecological components into SCP.

2. Material and methods

We developed and gathered spatial data on biodiversity, nature's contributions to people (NCP), landscape structure, and ecosystem condition to conduct a spatial conservation prioritization analysis at Swiss scale (Fig.1). This analysis was carried out at a 25-m resolution and included a sensitivity analysis, an evaluation of the effectiveness of current protected areas, and of the adaptation of the SCP to climate change. All the R code (R Core Team, 2020) used to perform the analyses is available on GitHub (link to be provided).

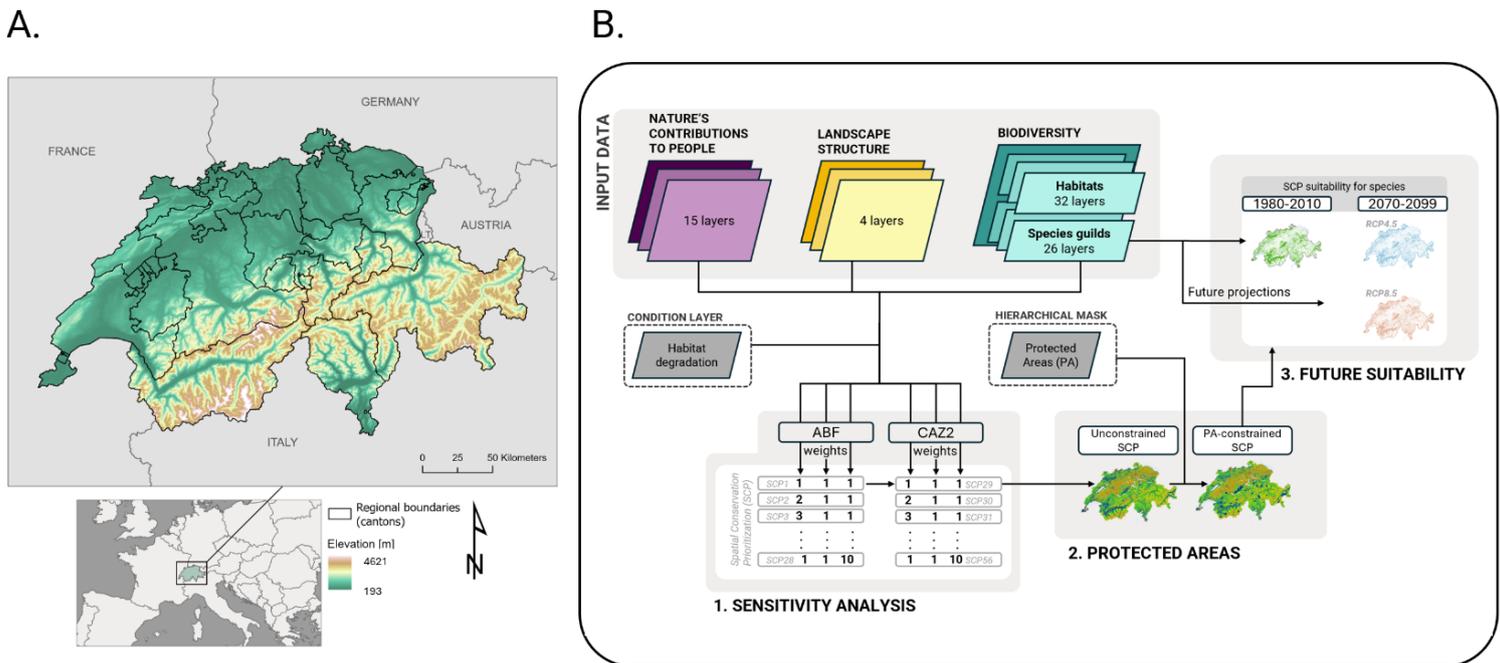


Figure 1. A. Map of Switzerland with European context, regional boundaries (cantons) and elevation. **B.** Diagram of the study framework outlining the three main ecological infrastructure (EI) components (nature's contributions to people (NCP), biodiversity, and landscape structure) and the three main analyses done for spatial conservation prioritization (SCP): 1. Sensitivity Analysis: SCP is conducted with varying weights assigned to three input components groups under two marginal loss rules - Additive Benefit Function (ABF) and Core-Area Zonation 2 (CAZ2) (see section 2.3 for a detailed explanation of the rules). 2. Protected Areas (PA): the SCP is constrained with PA boundaries, and the resulting outputs are compared between unconstrained and PA-constrained SCP. 3. Assessment of future suitability: this analysis aims to determine whether the areas prioritized by the SCP remain suitable for selected species during the current (1980-2010) and future (2070-2099) periods, using two Representative Concentration Pathways (RCP4.5 and RCP8.5).

2.1. Study area

Switzerland is a mountainous country in Europe (Fig.1. A.) characterized by two major mountain ranges, the Jura and the Alps, with a relatively flat Plateau region in between. This distinctive geography, marked by steep elevation gradients and diverse climatic

and geological conditions, has fostered a variety of heterogeneous landscapes that have been cultivated for thousands of years. As a result, Switzerland is exceptionally rich in both habitat types and species (FOEN, 2023a). Nonetheless, Switzerland's limited available space has led to significant urbanization and extensive landscape modification, representing a major pressure on natural habitats. Switzerland is divided in 26 member states called cantons, which each have their own constitution, laws and government.

2.2. Data

2.2.1. Biodiversity

Two types of layers were used to represent biodiversity, species habitat suitability maps, and habitat types maps.

First, we included species habitat suitability maps of 2'181 species from 10 taxonomic groups (Appendix A) averaged at the level of 26 ecological guilds (i.e., groups of species with similar ecological needs, based on the typology of Swiss natural habitats, fig. 2; Delarze et al., 2015; Rutishauser et al., 2023). A detailed list of species within each guild can be found in Appendix A. The species maps were sourced from the "SDMapCH" database, a Swiss-wide raster database of modelled species habitat suitability maps at a 25-m resolution, with each map composed of habitat suitability values (HSV) ranging from 0 for not suitable area to 1 for highly suitable habitat. This dataset was developed using the N-SDM modelling pipeline, an end-to-end modelling platform built around a spatially-nested hierarchical framework (Adde et al., 2023). The maps covered the current period (1980-2010) and included projections for the period 2070-2099, under two representative concentration pathways (RCP4.5 and RCP8.5; Van Vuuren et al., 2011). RCP4.5 expects moderate greenhouse gas emission to peak around 2040 and then reduce. RCP8.5 predicts a continuous increase in greenhouse gas emissions until the end of the century.

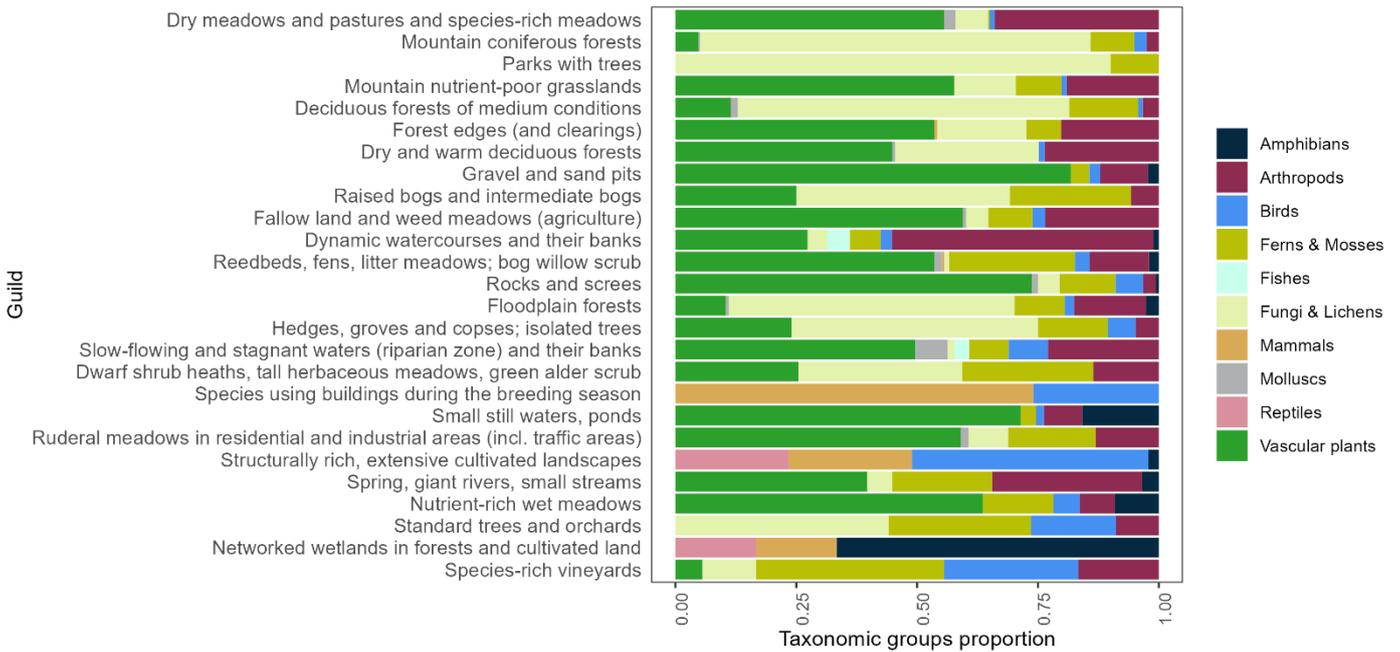


Figure 2: Bar chart listing the 26 ecological guilds, along with the taxonomic groups of the species that were used to generate the guild aggregates.

Also, to account for Switzerland’s high species diversity, which is largely attributable to its variety of habitats, we included maps of habitat types ($n=32$). These habitats correspond to the second classification level from the “TypoCH” classification (Delarze et al., 2015). The habitat maps were developed by Price et al. (2021) and obtained from the “SWECO25” database (Külling, et al., 2024). The complete list of habitats is available in Appendix A.

2.2.2. Nature’s contributions to people

We used 15 NCP supply indicators maps developed for Switzerland by Külling et al. (2024b) and covering 8 regulating, 4 material, and 3 non-material NCP (Table 1), built upon IPBES’ NCP classification (IPBES, 2018).

Table 1. List of nature’s contributions to people (NCP) indicators.

Category	Indicator	IPBES label
Regulation	Habitat quality	Habitat creation and maintenance
	Pollinator abundance	Pollination and dispersal of seeds
	Removal of PM ₁₀ by vegetation	Regulation of air quality
	Carbon stored in biomass	Regulation of climate
	Nutrient retention by landscape	Regulation of freshwater quality
	Sediment retention by landscape	Formation, protection and decontamination of soils

	Protective forests and floodplains	Regulation of hazards and extreme events
	Pest control species	Regulation of organisms detrimental to humans
Material	Annual water yield	Regulation of freshwater quantity, location and timing
	Wood provision potential	Energy / materials and assistance
	Landscape suitability for agriculture	Food and feed
	Medicinal plants	Medicinal, biochemical and genetic resources
Non-material	Landscape suitability for picture-taking	Learning and inspiration
	Recreation potential	Physical and psychological experiences
	Emblematic species	Supporting identities

2.2.3. Landscape structure

We calculated four landscape structure indices from the habitat map of Switzerland (Price et al., 2021) in a raster format with a 25-m resolution (Table 2). These indices differs from the biodiversity indices in that it describes the characteristics of ecosystem through the spatial arrangement and state of the landscape, and not through specific species group or habitat types (Syrbe et al., 2013; Walz & Syrbe, 2013). They are designed so that high values of these indices indicate a better state of the EI, and are therefore prioritized in the SCP. Original vector data was rasterized, and each indicator was derived using a circular moving window with a 200-meter radius. To optimize calculations, geoprocessing was performed for each of the 26 cantons individually before merging them to create a comprehensive map of the country, incorporating a 200-meter buffer to account for edge effects. Preprocessing was conducted using ArcGIS Pro (Esri Inc., 2020), and all input tables for indices computation are available in appendix A.

Table 2. List of landscape structure indicators.

Index	Description	Calculation method
Habitat diversity	Corresponds to the Shannon diversity index (Shannon, 1948). It considers the abundance and distribution of habitat types. A high value indicates that all kind of habitats are present and distributed in the neighbourhood.	Habitats were aggregated into 8 natural habitat categories (see appendix A), and Shannon index is calculated using FragStats' Shannon's Diversity Index function (v 4.2.1, McGarigal, 1995) with a moving window sampling strategy, applying a circular radius of 200 meters.
Fragmentation	Represented by the effective mesh size, the fragmentation index classifies habitats as barriers or non-barriers for wildlife movement. A high value indicates that the landscape is not fragmented.	Calculated using FragStats' Effective Mesh Size function (v 4.2.1, McGarigal, 1995) with a moving window sampling strategy, applying a circular radius of 200 meters.

Naturality	Reflects habitat's capacity to host biodiversity. Classified into five naturality categories, with higher values indicating less human impact. Classification based on Geneva's natural habitat map (SIPV, 2024, appendix A)	Rasterized habitats were smoothed with ArcGIS Pro's Focal Statistic tool, calculating the mean of cells in a circular radius of 200 meters.
Core Area	Describes the extent of habitats that are unaffected by the adjacent environment, identifying "core areas". The index value at a pixel reflects the number of surrounding pixels that belong to a central zone of interest, with higher values indicating a greater presence of habitats shielded from edge effects.	Habitats were aggregated into 8 natural habitat categories (see appendix A). The influence buffer of each habitat is then computed using an <i>FME</i> model (Safe Software Inc., 2023), based on an asymmetric matrix of influence (appendix A). The influence is then erased and only core areas are retained. The result is rasterized and smoothed using ArcGIS Pro's Focal Statistic tool, calculating the mean of cells in a circular radius of 200 meters.

2.2.4. Habitat degradation

Soil artificialisation was used as a proxy for habitat degradation and integrated in the SCP as a condition layer, as it is considered detrimental to the maintenance and development of the EI (FOEN, 2020b). Soil artificialisation impacts ecological processes by altering water flow and hinders environmental measures. The habitat map of Switzerland (Price et al., 2021) was classified into binary categories – artificial or non-artificial – based on the "permeability" attribute from Geneva's natural habitat map (SIPV, 2024, appendix A). The resulting raster was smoothed by calculating the mean value of cells within a 200-meter circular radius.

2.3. Spatial prioritization

We performed spatial conservation prioritization (SCP; Fig. 1.B.) analyses using the Zonation 5 software (v1.0; Moilanen et al., 2022). Zonation is a powerful software allowing to process numerous spatial datasets at high resolution. The main algorithm of Zonation 5 starts by creating an initial pixel-level priority ranking that combines all input components (spatial layers) based on weighted range size rarity, a measure that prioritizes components according to their geographic range and rarity, giving more weight to those that are rarer and have smaller ranges. The algorithm then calculates the marginal losses of removing each pixel based on this initial ranking and reorders the pixels using a marginal loss rule (i.e., a rule that aggregates pixel values from different input components into a single numerical value) allowing the pixels to be ranked again. The process continues until the marginal loss values consistently increase from the lowest to the highest ranked cells. At this point, the algorithm terminates, and the final ranking is retained, represented as a raster map with priority

values ranging from 0 (low priority) to 1 (high priority) (Moilanen, Kohonen, et al., 2022).

In this study, SCP analyses were conducted on two marginal loss rules: the additive benefit function (ABF) and core-area zonation 2 (CAZ2). The main effect of these rules is how the final priority ranking prioritizes input components (biodiversity, NCP, and landscape structure). For instance, the rule may aim to maximize overall average coverage across all components (as in ABF), or to improve coverage for worst-off components resulting in a slightly lower average coverage (as in CAZ2).

2.4. Sensitivity analysis

Weights can be attributed to input layers, or to the component groups, to adjust their relative importance in the SCP. Previous studies have defined weights through expert surveys (e.g. Bai & Guo, 2021; Sanguet et al., 2023), or based on input components threat level (e.g. El-Gabbas et al., 2020). Here, we examined the sensitivity of our analyses to different weightings strategies on the three input component groups - biodiversity, NCP, and landscape structure. This was done by gradually increasing the weight of one component from one to ten while keeping the other fixed at one. These sensitivity analyses were done for the two marginal loss rules, ABF and CAZ2.

To evaluate the impacts of individual component weight groups, we analysed the differences between an unweighted SCP map output obtained using equal weights of 1 for the three components, and the 54 SCP maps with weights (9 weights x 3 components x 2 marginal loss rules). We conducted two analyses to assess pairwise differences: first, we conducted Spearman correlation based on 10'000 randomly sampled points from the study area. The Spearman correlation coefficient ranges from -1 to 1, with values near 0 indicating no correlation, values close to 1 indicating a positive correlation, and values near -1 indicating a negative correlation. Second, we assessed pixel-level overlap using the Jaccard index (Jaccard, 1912), which ranges from 0 to 1, with higher values indicating greater overlap between two maps. To compute the Jaccard index, binarization of the SCP maps were required. This was done using the surface area of current protected areas in Switzerland as the threshold. The Jaccard index thus compares the top priority areas from the SCP, whereas the Spearman coefficient compares the entire range of SCP values.

2.5. Protected areas (PA) analysis

Switzerland's protected area (PA) network is managed through a complex framework of regulations and protection statuses that vary across municipal, regional (cantonal), and national levels. This complexity makes it difficult to assess the actual degree of protection of different PA classes. We compiled all available geospatial data for PA in Switzerland and kept only areas granted with a comprehensive protection, meaning

legally binding measures that enforce strict conservation regulations, prohibiting activities that could harm the environment. These protected areas include the national park, national and private reserves, parts of federal hunting reserves, and specific federal inventories. The complete list of PA and their source is available in Appendix A.

We integrated PA into the SCP process in Zonation using a hierarchical mask (PA-constrained). This allowed to assign the highest priority values to the already protected pixels, permitting to maintain and potentially expand the existing PA network. Additionally, we produced an unconstrained version of the SCP without the PA mask, for comparison. To evaluate the relationship between priority values and the presence or absence of PA, we examined the pixel-level point-biserial Pearson correlation between the two, over 10'000 randomly sampled points from the study area. This comparison was also conducted using the Jaccard index on the binarized versions of the SCP maps, thresholded using the value of the current PA area size.

Performance curves from Zonation were extracted to compare the mean SCP value along with the three individual EI components, between the PA-constrained and unconstrained SCP outputs. Performance curves illustrate the extent of component distribution coverage achieved by protecting map pixels in order of their priority rank. To evaluate the difference in prioritization performance, we compared these performance curves using the area under the curve (AUC) computed using trapezoidal integration (Borchers, 2023), with high values indicating better overall prioritization performance. We used a downscaled land-use map of Switzerland (Giuliani et al., 2022) to assess the land use categories associated with a theoretical expansion of the PA network, based on our SCP. We then reported the corresponding surface area and the primary land use categories.

2.6. Future habitat suitability of species under climate change

To evaluate the performance of the SCP in supporting a sustainable EI in the future, we compared habitat suitability values (HSV) from species maps (see section 2.2 – biodiversity) for both present and future scenarios with the SCP values. Specifically, for each species guild, we performed two related analyses: 1) We calculated the sum of HSV across different fractions of the SCP (e.g., top 1%, top 10%, etc.) in 1% increments, covering the entire 0-100% range, to generate comparable performance curves. 2) For the same fractions of the SCP (e.g., top 1%, 10%, etc.) we calculated the relative proportion of remaining HSV, comparing the sum of HSV within each fraction of the SCP to the total sum of HSV across the entire map. This allowed to evaluate how much habitat suitability is maintained in the highest-priority areas, relative to the original range. We conducted these analyses for both the current baseline period (1980-2010) and the two future climate scenarios (RCP4.5 and RCP8.5) for the period 2070-2099, and compared the performance using the AUC.

3. Results

3.1. Sensitivity analysis

Results from the sensitivity analysis aimed at comparing the overlap (Jaccard index) and the correlation (Spearman coefficient) of the SCP outputs with different weights on EI components groups, and with two different marginal loss rules, ABF and CAZ2 (Fig. 3). Jaccard index compares the overlap of the highest ranked priority areas of the SCP, whereas Spearman coefficient compares all SCP values.

Changes in the weights of components groups had an impact on the SCP output, especially under the CAZ2 rule (Fig.3). The overlap analysis revealed that assigning a weight to a component rapidly affected the SCP output, with the most substantial changes occurring up to a weight of approximately 5, before reaching a plateau. This plateau was less pronounced in the correlation analysis compared to the overlap analysis. On average (\pm std dev), for a weight of 5, using the ABF and CAZ2 marginal loss rules, we obtained a Jaccard index of 0.64 ± 0.02 and 0.52 ± 0.04 , respectively, and a Spearman correlation coefficient of 0.86 ± 0.02 and 0.79 ± 0.02 , respectively.

In the overlap analysis, increasing the weight of the biodiversity component had the least effect on the SCP outputs differences, followed by NCP and landscape structure (mean Jaccard values across weights: ABF/CAZ2 – biodiversity = 0.71/0.62; NCP = 0.67/0.57; structure = 0.66/0.54). This pattern was consistent across both the ABF and CAZ2 rules. In the correlation analysis, assigning higher weights to NCP had the least effect on the SCP outputs correlations, followed by biodiversity and landscape structure which displayed similar patterns (mean Spearman coefficient values across weights: ABF/CAZ2 – biodiversity = 0.85/0.79; NCP = 0.88/0.82; structure = 0.85/0.79) (Fig. 3).

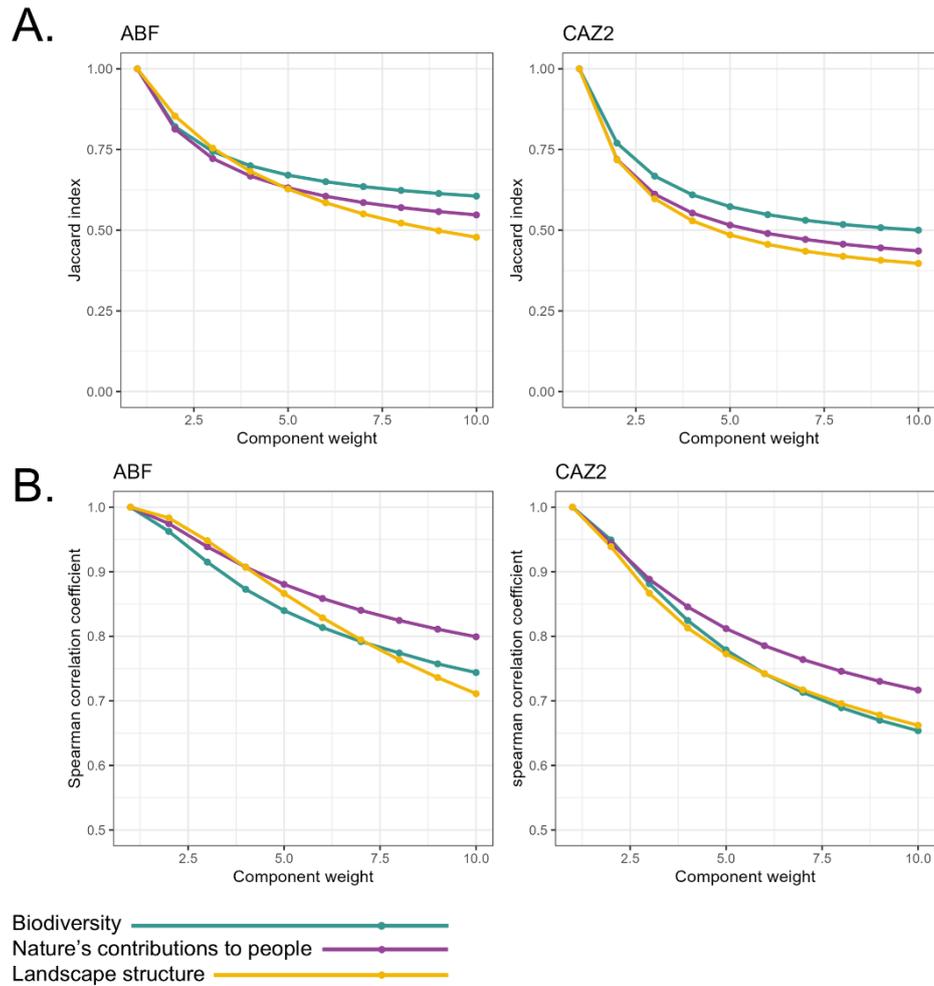


Figure 3. Sensitivity analysis of spatial conservation prioritizations (SCP), comparing how changes in the weights of ecological infrastructure (EI) components affect the differences in SCP output maps under two marginal loss rules: Additive Benefit Function (ABF) and Core-Area Zonation 2 (CAZ2). **A.** Jaccard index of overlap, indicating the similarity between the highest ranked priority areas across SCP outputs with different component weights; with higher values indicating greater overlap. **B.** Spearman correlation coefficients, indicating the correlation between SCP outputs with different component weights; with higher values indicating a stronger positive correlation.

3.2. Current protected area (PA) network and expansion

After gathering protected areas (PA) distribution data, we identified that 8.08 % of Switzerland's land is protected under strong legal measures, amounting to 3234 km². The point-biserial correlation analysis aimed at assessing the relationship between SCP values and the presence or absence of PA, analyses presented are made using the additive benefit function (ABF) marginal loss rule, see appendix A for results from CAZ2. Results revealed that SCP values were significantly higher in protected pixels. This result was consistent across both unconstrained and PA-constrained SCP ($p < 0.001$, correlations: 0.13 and 0.47, respectively; Fig. 4B). The overlap analysis between the current PA and the corresponding size top priority areas revealed a

Jaccard index of 0.11 for the unconstrained SCP, with 19.68% of PA included in the SCP. For the PA-constrained SCP, we obtained a Jaccard index of 1, with 100% of the PA included in the SCP.

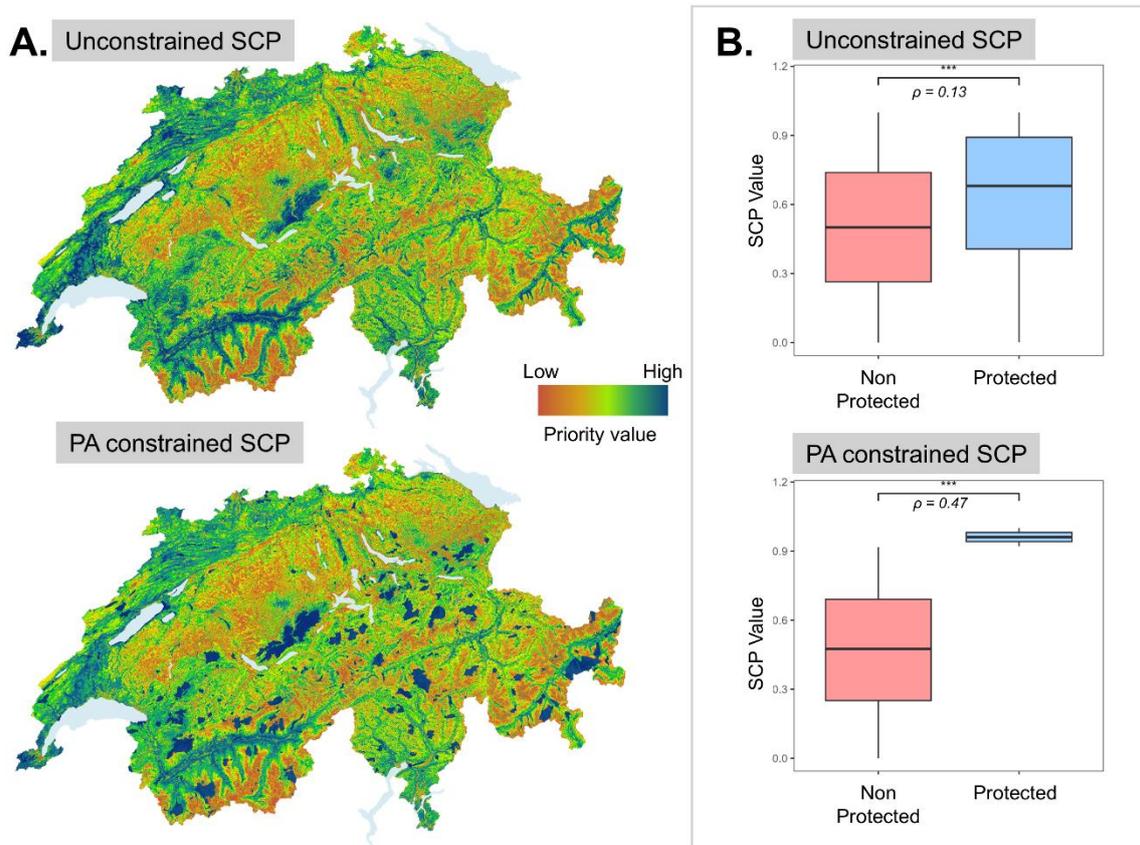


Figure 4. Analysis of Spatial conservation prioritization (SCP) outputs and their relationship with protected areas (PA), using the additive benefit function (ABF) marginal loss rule. **A.** SCP map based on biodiversity, nature's contributions to people (NCP), and landscape structure, displaying priority values across Switzerland. The "Unconstrained SCP" prioritizes the three components with equal weights. The "PA-constrained SCP" prioritizes the three components with equal weights and integrates protected areas (PA) as a hierarchical constraint, assigning highest-priority values to PA pixels. **B.** Pixel-level point-biserial Pearson correlation (ρ) between SCP values and the presence or absence of PA (***: $p < 0.001$).

Comparing the performance curves from the unconstrained and PA-constrained SCP outputs, we found that current PA are not optimal to preserve priority areas of the three input components (Fig. 5). In the top 8.08 % of the SCP (current PA surface, Fig.5, vertical grey line), we found that a mean \pm std dev of 22.8% \pm 22.2% of the EI components was preserved in the unconstrained SCP, while it was 15.3% \pm 18.9% in the PA-constrained SCP. Additionally, the AUC of the mean value (Fig. 5, black curve) was the highest for the unconstrained SCP, with a value of 0.63, against a value of 0.614 for the PA-constrained SCP. The full table of output values is available in Appendix A. We also observed in both SCP that landscape structure and NCP have

higher values in the top 70-100% of the EI, and that this tendency inverts afterwards with biodiversity components having higher values.

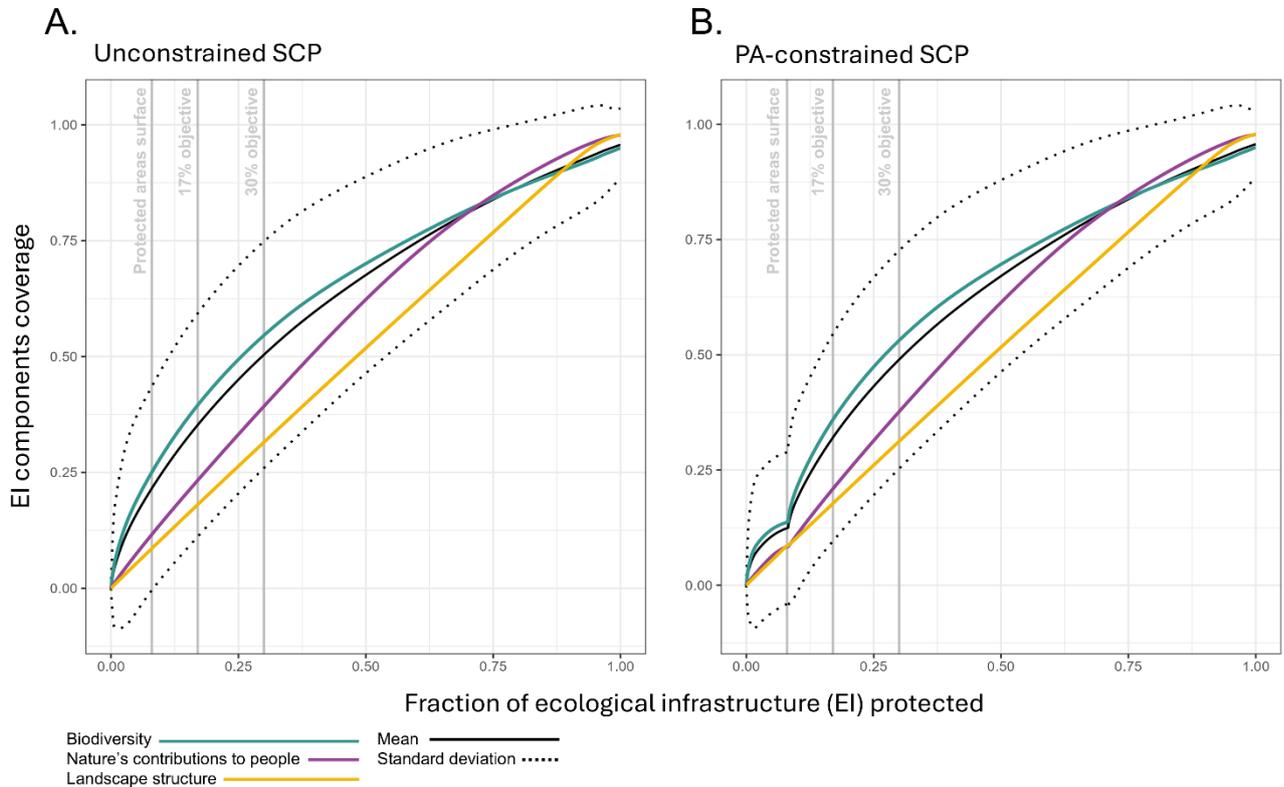


Figure 5. Performance curves from the spatial conservation prioritization (SCP) analysis obtained using the Zonation software. These curves show the extent of the components (biodiversity, nature's contributions to people (NCP), and landscape structure) distribution coverage achieved by protecting map pixels in order of their priority rank, using the additive benefit function (ABF) marginal loss rule. **A.** The "Unconstrained SCP" prioritizes the three components with equal weights. **B.** The "PA-constrained SCP" prioritizes the three components with equal weights and integrates protected areas (PA) as a hierarchical constraint, assigning highest-priority values to PA pixels. Black lines indicate the mean value across all input components, while the dotted lines represent the standard deviation from the mean. Grey vertical lines indicate the current proportion of PA in Switzerland, along with protection objectives.

To support the objective of expanding the current PA network to cover 17% and 30% of the terrestrial land, our analysis compared land use and cover classes with SCP values. Results indicated that the five land use and cover categories most suitable for the EI components were forests, arable land, alpine meadows, meadows and pastures, and brush forests. Together, these categories accounted for 81% of the prospective expanded area. Specifically, to reach the 17% (30%) objective, it would require 1906 km² (4417 km²) of forest, 477 km² (1024 km²) of arable land, 350 km² (922 km²) of alpine meadows, 307 km² (815 km²) of meadows and pastures, and 247 km² (417 km²) of brush forest (Fig. A2).

3.3. Future habitat suitability of species under climate change

Considering the PA-constrained SCP for the current period (see appendix A for unconstrained SCP), we examined the differences in HSV for 26 species guilds under climate change scenarios RCP4.5 and RCP8.5 for the 2070-2099 period. Our results indicated that the HSV proportion in the prioritized area relative to the original range, averaged across the 26 guilds, was highest in the current period, with an AUC of 0.62, compared to 0.55 for RCP4.5 and 0.52 for RCP8.5, respectively (Fig. 6.A).

However, the summed HSV values, averaged across the 26 guilds, were higher under both climate change scenarios, with an AUC of 0.55 and 0.48 for RCP4.5 and RCP8.5, respectively, compared to the one of the current period which had an AUC of 0.30 (Fig. 6.B). Predictions show that the average sum of HSV was highest under RCP4.5, followed by RCP8.5, and consistently remained higher than the current period across the entire range of priority area.

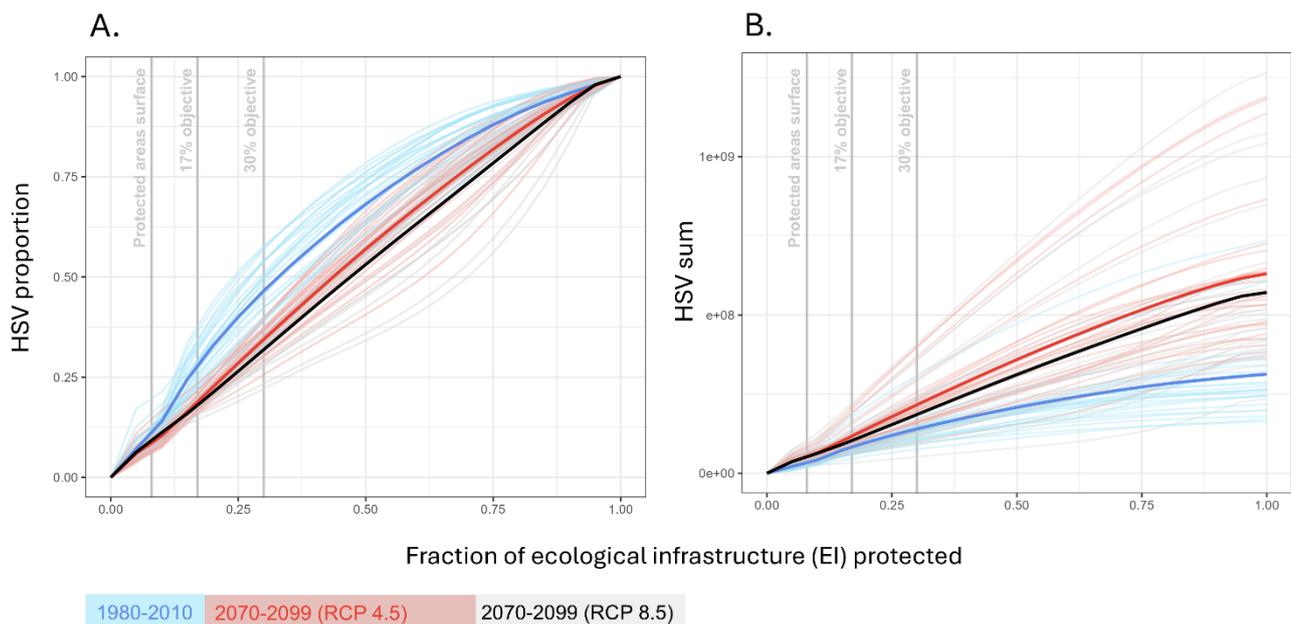


Figure 6: Performance curves showing the spatial distribution of habitat suitability values (HSV) for 26 species guilds in relation to spatial conservation prioritization (SCP) values. SCP values were derived using biodiversity, nature's contributions to people (NCP), and landscape structure as input components, with equal weights and constraining protected areas (PA). The curves compare the relationship between the SCP priority ranking and HSV distribution under current conditions (1980-2010, blue line) and future scenarios (RCP8.5, black line; RCP4.5, red line) for the period 2070-2099. Bold lines represent mean values, while lighter lines show individual guild performances. Grey vertical lines indicate the current proportion of PA in Switzerland, along with protection objectives. **A.** Proportion of HSV relative to its original range. **B.** Summed HSV.

4. Discussion

4.1. Implications for conservation planning

Our study represents the first comprehensive country-scale spatial conservation prioritization assessment, conducted at a high resolution and encompassing habitats, species, NCP, and landscape structure indicators in Switzerland.

At the global scale, our study provides valuable insights for improving sustainable management practices based on integrated models, aligning with recent global efforts (Chaplin-Kramer et al., 2024). Indeed, our analysis addresses a data gap by complementing the European Union's "green infrastructure strategy" that Switzerland is not part of (European Commission, 2013). Furthermore, this study's methodology and results serve as a guide for other countries and organizations in developing integrated models for SCP by demonstrating the relative importance of various EI input components, weighing methods, and marginal loss rules at a national scale.

At the national scale, by providing a nation-wide EI priority map and insights into expanding and connecting existing PA, our study provides policymakers with decision tools necessary for landscape management and conservation strategies. Our outputs can also help prioritize management decisions, extending beyond PA, to identify areas of interest for the national EI.

At the regional scale, Swiss cantons can use the findings of this study to support their planning of the EI, as required by the Swiss government (FOEN, 2017a). The high-resolution SCP output data is available through Zenodo (link to be provided), providing a valuable resource for cantons that lack the capacity to develop their own SCP-based EI assessment. Additionally, it can serve as a comparative tool for cantons that have adopted alternative methodologies for their EI evaluations.

4.2. Sensitivity analysis

When comparing the highest ranked priority areas using the Jaccard index, our results show that prioritizing landscape structure has the most significant effect on the SCP outputs (i.e. the output differs most), followed by NCP and biodiversity. This may be due to landscape structure being less tied to specific landscape types (such as forests, meadows, etc.), and rather focusing on the overall configuration of the landscape. In the continuous ranking of the SCP outputs, both structure and biodiversity exhibit the highest effect with lower correlations of the outputs. Overall, the CAZ2 marginal loss rule is more sensitive to weight variations in the component groups than ABF. This is because CAZ2 prioritizes worst-off input layers, compared to ABF which maximizes overall coverage, leading to a more balanced response to weight adjustments.

Our results indicate that the SCP map outputs are generally robust to weight changes; but that substantial changes occur when component weights are strongly adjusted (e.g., a 5:1:1 ratio). However, such ratios are rarely used in similar studies (e.g. Honeck

et al., 2020; Sanguet et al., 2023; Srivathsa et al., 2023). These results align with the findings from Koschke et al. (2012), who found that the method used to define weights has minimal effect on the SCP output. Notably, the SCP outputs are more sensitive in highest ranked priority areas (as measured by the Jaccard index) compared to the overall prioritization (Spearman correlation coefficient), highlighting the need for careful consideration in conservation planning, as the highest ranked areas could be the ones considered for PA expansion, for example. Additionally, the choice of marginal loss rules should align with specific conservation objectives, although minimal differences were found between the two tested marginal loss rules.

4.3. Current protected area (PA) network and expansion

According to our analysis, 8% of Switzerland's landscape is currently under robust protection, which falls between the 7.82% reported by the NGO *Pro Natura* (2023) and the 13.4% by the Federal Office for the Environment (2023a). This amount is however below the 17% target set by the Swiss Biodiversity Strategy (FOEN, 2017a) and less than one-third of the 30 by 30 objective from the UN CBD (2022). This highlights the urgent need for improved management of PA in Switzerland.

Interestingly, our results indicate that our SCP has significantly higher values within PA, indicating that PA could be more effective at conserving biodiversity, NCP, and landscape structure than non-protected areas in general. However, only 19% of the highest ranked priority areas are located in current PA, an observation similar to that done in India and Egypt (El-Gabbas et al., 2020; Srivathsa et al., 2023), which indicates that although more effective, current PA are not optimized for conservation of biodiversity, NCP and landscape structure indicators. Indeed, a side-by-side comparison (Fig. 5) reveals that the PA-constrained SCP is less effective at preserving the EI input components than the unconstrained SCP.

Our findings further indicate that the SCP is particularly performant in covering biodiversity within the highest-priority areas (represented by low x-axis values in Fig. 5), more so than NCP or landscape structure. These results underscore the importance of considering both NCP and landscape structure as essential components of the EI, that extend beyond the boundaries of PA. While PA play a crucial role in conservation, they alone may not sufficiently address the complex needs of a functioning EI network, and the SCP approach presented here can help identify interactive or buffer zones around PA (Blanco et al., 2020). A comprehensive approach to landscape planning should incorporate structural elements such as networking areas, core habitats, and natural spaces throughout the entire landscape to ensure its ecological functionality (J. D. Karimi et al., 2021b). For instance, the provision of material NCP (e.g. timber, crops plantations) often requires areas that are accessible and exploitable for human use, which may not align with strict protection measures typically associated with PA. The "Swiss Parks" program exemplifies this approach, aiming to preserve natural landscapes and promote sustainable management,

economy, education, and tourism without imposing strict protection measures (FOEN, 2024).

Finally, our findings highlight that a relatively modest increase in the protected area network - from the current 8% to the overdue 17% - would result in a significant improvement in the protection coverage of key components. Specifically, this expansion would increase the remaining proportion of protected components from 12% under the current PA system to 32%, underscoring the potential for substantial gains in EI protection through targeted PA expansion.

4.4. Future habitat suitability of species under climate change

In this part of the study, we evaluated the suitability of the SCP for species guilds under climate change scenarios projected for 2070-2099. While this analysis provides valuable insights into a key component of the EI and its response to climate change, it has limitations. Specifically, we did not include the full range of input components that the SCP was designed to incorporate - habitats, NCP, and landscape structure. Additionally, our focus was solely on climatic changes, which are not the only factors affecting species. Despite these constraints, this analysis offers insightful information on potential effects of climate change on species distributions within the EI framework. Understanding these dynamics is essential for developing adaptive management strategies and ensuring the resilience of the EI in the face of environmental change (Bryce & Hunter, 2024; Wiens et al., 2009).

Our results indicate that the SCP may become less efficient in the future for species coverage under both RCP scenarios, compared to the current period (proportion of HSV, Fig. 6.A.). However, we also observe a projected increase in overall suitability (sum of HSV, Fig 6.B), aligning with findings from other studies that explore the impacts of climate on species distributions in similar regions (Adde et al., 2024; Chauvier-Mendes et al., 2024; Gebert et al., 2022). This trend can be attributed to the range expansion to higher altitude of species as climate conditions change (Petitpierre et al., 2016; Scheffers et al., 2016; Vitasse et al., 2021).

Indeed, planning of the EI and PA expansion must account for the rapid changes that will occur in the landscape. For example, biomes such as the temperate conifer forests, prevalent in the Swiss Alps, are predicted to see their climatic conditions change drastically (Hoffmann et al., 2019). While static approaches of SCP may be insufficient in the face of rapid climate change (Elsen et al., 2020), prioritizing areas for current and future EI remains crucial to create a resilient network and facilitate species movement in face of climate change (Carroll et al., 2018). SCP output maps can help enhance landscape's climate resilience by expanding current PA, to include a broader range of elevations and ecosystem diversity (Carroll & Noss, 2021). Furthermore, climate changes also affects NCP, which are projected to have various both positive and negative responses (Schirpke et al., 2024; Schirpke & Tasser, 2024). This highlights the importance of developing future predictions for NCP and other

landscape metrics, ensuring their integration into comprehensive landscape planning efforts.

The current SCP provided for Switzerland is thus a necessary, overdue foundation to identify priority areas of the Swiss EI, and guide conservation efforts. Future projections, once available, will serve as additional information used to refine and adapt conservation strategies over time.

Limitations

This study has several limitations, some of which have been mentioned in relevant sections. Here, we highlight additional general limitations. While multiple input layers were used in the SCP, there is an imbalance in their quantities inside EI components, which should be considered when interpreting the results. For instance, the biodiversity component includes 26 guild layers and 34 habitat layers, while the landscape structure component is based on 4 layers. Since these inputs are generated by models with inherent uncertainties, using only a few indices increases the risk of data not fully representing the EI component, which can significantly impact the SCP outputs (Muscatello et al., 2021). Furthermore, a single habitat condition layer (soil artificialization) is used in the prioritization of all other layers, making it highly influential in the final output (Kujala et al., 2018). Additionally, some studies suggest that including other components, such as intraspecific variation (Thomassen et al., 2011) or genetic data (Andrello et al., 2022), would improve the resilience of the EI.

5. Conclusions

In this study we show several key findings related to SCP of the EI in Switzerland. First, we show that the outputs of the SCP are generally not highly sensitive to the weighting of different EI components groups (biodiversity, NCP, and landscape structure). We also show that increasing the PA in Switzerland from 8% to 17%, in line with the Swiss objective, would expand the coverage of EI components from 12% to 32%. Furthermore, we show that while the current PA network in Switzerland is significantly more efficient than other areas in covering EI components, it only covers 19.7% of the highest-ranked priority areas. We also find that NCP and landscape structure indicators are underrepresented in these high-priority areas. This suggests that an effective EI strategy should integrate both PA networks and broader landscape-scale planning to support biodiversity conservation and human well-being. Finally, we emphasize the importance of integrating future scenarios in EI planning, though challenges remain in obtaining robust data for all components. Preserving current EI is essential to allow species and ecosystems the opportunity to adapt and move. Therefore, we advocate for adaptive management strategies that combine current approaches, such as ours, with future scenarios to guide necessary modifications (Allan & Stankey, 2009; Holling & United Nations Environment Programme, 1978). Finally, we provide a set of spatially explicit SCP maps and methods that can be used at different decision-making levels in Switzerland for the ongoing planning of the EI.

Thesis discussion

1. Overview of thesis main goals and key findings

The main objective of this work was to develop and apply a framework for the identification and prioritization of the ecological infrastructure (EI) in Switzerland. To achieve this, the thesis focused on gathering the necessary data, developing relevant indicators, and exploring the links between biodiversity and ecosystem services (ES).

The key findings and contributions of this research thesis are as follows:

- Several complementary ways to map the linkages between ES and biodiversity exist and were identified and described (Rey, et al., 2022).
- Through spatial linkage, biodiversity and ES appear significantly correlated in Switzerland, though not collinear, emphasizing the importance of targeted approach to conservation for biodiversity and ES (Külling et al., 2024b).
- Climatic and land-use drivers are the primary factors influencing the spatial distribution of ES bundles in Switzerland (Külling et al., 2024b).
- Current protected areas are not optimally located relative to identified priority areas which optimize the spatial repartition of biodiversity, ES, and structure indicators (Külling et al., in preparation).
- Meeting Switzerland's protected area (PA) objectives (going from 8% to 17%) would increase the coverage of biodiversity, ES, and landscape structure in the PA network from 12% to 32% (Külling et al., in preparation).
- 15 indicators for ES in Switzerland, one indicator for threatened species, four structure indicators, and spatial prioritization maps were developed and made publicly available (Külling et al., 2024b; Külling et al., in preparation).
- A spatial database containing over 5'200 raster layers, made to facilitate and encourage ecological research in Switzerland was developed and made publicly available (Külling et al., 2024a).

2. Biodiversity – ecosystem services linkages and indicators

Biodiversity and ES indicators, along with assessment of their interrelationships, are necessary for achieving conservation objectives. In the context of the EI, they provide the foundation for informed decision-making and sustainable management strategies. This thesis contributed to the growing body of knowledge on the links between biodiversity and ES, by examining spatial linkages within Switzerland (Ricketts et al., 2016), confirming that biodiversity generally exhibits positive associations with ES. This finding is consistent with previous research demonstrating that biodiversity mostly underpins the supply of various ES (Cimatti et al., 2023; Ricketts et al., 2016; Soto-Navarro et al., 2020).

Future studies could expand the range of biodiversity metrics to include functional diversity, genetic diversity, and other indicators that may reveal additional patterns or trade-offs. Moreover, this thesis focused on ES potential supply, and did not incorporate ES demand. Previous research has shown that accounting for demand can lead to more efficient outcomes without compromising biodiversity (Watson et al., 2019), and integrating both supply and demand perspectives could provide a more comprehensive understanding of how ES are distributed and utilized, as well as how they interact with biodiversity conservation goals. Despite the general positive trends observed, there are numerous cases where optimizing the supply of certain ES negatively impacted biodiversity, such as intensive forestry, farming, pastures, and croplands (Foley et al., 2005). Indeed, some provisioning services may require reduced biodiversity to maximize short term production. These trade-offs underscore the importance of the interpretation of ES indicators, and the contextualisation of their values relative to management practices and large temporal scales. The spatial and temporal scale at which these indicators and relationships are assessed is particularly important, as local dynamics may differ significantly from regional or national patterns, and effects from biodiversity loss may take a lot longer to affect ES than the time needed to see ES gains, for example (Grêt-Regamey et al., 2015; Lira et al., 2019).

To advance our understanding of biodiversity-ES relationships in Switzerland and beyond, future research should address several key gaps:

- Diversity of indicators: incorporate multiple biodiversity metrics (e.g., functional diversity, species richness) to capture a broader range of interactions.
- Supply vs. demand: include ES demand indicators alongside supply, to identify areas where conservation efforts can align with societal needs more effectively.
- Develop the assessment of relationships through spatial, functional, social and management linkages between biodiversity and ES.

- Analyse biodiversity-ES relationships across multiple spatial and temporal scales to account for local variability and broader regional trends.

By addressing these gaps, we can develop and strengthen the bond between society (as represented by ES) and biodiversity. This will not only enhance our ability to preserve species and ecosystems but also ensure that they continue to provide critical services for human well-being.

3. Pathways for transformation

Transformative change appears as essential to address the environmental crisis, as short-term adaptations are insufficient (Díaz et al., 2019; IPBES, 2019b; Park et al., 2012; Schlaepfer & Lawler, 2022). Governance structures must promote biodiversity and ES through innovative policies and collaborative mechanisms (e.g. NbS, Cohen-Shacham et al., 2016). Switzerland's commitment to achieving the "30 by 30" objective, including 17% strict protected areas and 13% networking areas (FOEN, 2023c), reflects the importance of integrating diverse conservation approaches. However, the weakness of political commitment, and the postponement of the establishment of a functioning EI to 2040 in the Swiss biodiversity action plan underscores significant challenges in implementation. Accelerating progress requires clear governance pathways, including defining the EI status and realising actionable steps to ensure its functionality.

This thesis advances that the EI approach is an effective pathway to reach Swiss conservation commitments. It positions EI as a potential transformative tool to bridge traditional conservation approaches visions (strict PA) with holistic approaches addressing human needs (e.g. including ES in SCP). Here we contributed to these efforts by publishing data, indicators, and methods for EI identification and prioritization. Complementary actions that could be implemented, listed from individual efforts to broader governance strategies, are listed in figure 3.1., and developed further in in the following paragraphs.

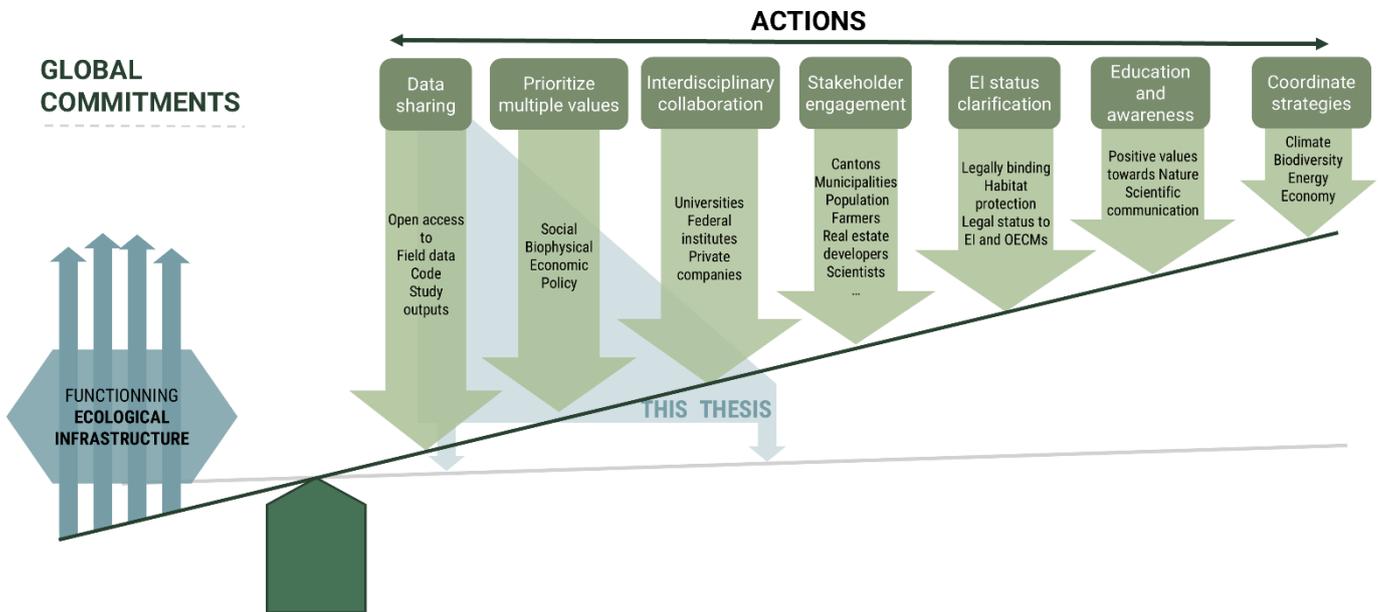


Figure 3.1. Potential actions to promote a functioning ecological infrastructure in Switzerland, and help reach global commitments. Figure inspired from IPBES (Figure SPM.7, 2022).

1. Data sharing

The generation of spatial data products has increased significantly, and data sharing is becoming a more common practice. However, some argue that data should be formally published rather than shared informally or through limited channels (Costello et al., 2015). Additionally, even when data is seemingly available, researchers often face barriers such as mandatory logins or formal requests, which can discourage its use. Also, data producers (governmental or not) sometimes withhold data, impose extensive conditions for access, and delay the data-sharing process through lengthy and complex negotiations. Finally, as developed in section 1.3., there is a need for standardized data outputs and format on accessible platforms, which can enable researchers to build upon existing datasets more efficiently.

2. Prioritize multiple values

Biophysical assessments of biodiversity and ES are necessary. However, for landscape conservation to be effective within allocated budgets, it is important to consider different value types that can impact conservation practices. Considering people's values in SCP can enhance social acceptability and reduces stakeholder conflicts, as demonstrated e.g. by Whitehead et al. (2014) in Australia, where incorporating social values guided more effective conservation planning. Additionally,

with economic interests being major drivers of land use change, SCP programs should consider integrating economic aspects. For example, Naidoo et al. (2006) incorporate economic costs in conservation planning to achieve more cost-effective outcomes, and other studies also show the importance of balancing ecological, economic and policy interests in SCP (Guerrero et al., 2010; Nieminen et al., 2021).

Unfortunately, integrating diverse values into SCP is challenging due to limited data availability and the complexity of quantifying social and economic values spatially. To address these challenges, participatory mapping tools have been developed to engage stakeholders in co-creating spatial data (Baker-Médard et al., 2024; A. Karimi et al., 2015).

3. Interdisciplinary collaboration

This previous paragraph highlights the difficulty of tackling such complex systems, and underscores the necessity of both inter- and transdisciplinarity (see below). For conservation, interdisciplinarity would mean integrating ecological, social, economic, political and communication dimensions, which cannot be effectively addressed by a single discipline. Interdisciplinarity is important to gain a holistic understanding of the system to preserve, and the development of optimized conservation strategies (Sato et al., 2023). The ValPar.Ch project, to which this thesis contributed, aimed to evaluate the diverse values of nature in Switzerland through collaboration among scientists from various fields (Reynard et al., 2021). The outputs from this project aspire to incorporate a broader range of values into decision-making processes.

4. Stakeholder engagement (transdisciplinarity)

The engagement of stakeholders is equally as important, as they are the ones making, contributing and directly affected by decision-making in the landscapes. Transdisciplinarity is thus essential for bridging empirical knowledge with stakeholder engagement to address challenges in policy, behavior change, and value integration, and to create more effective and contextually relevant conservation strategies (Hirsch Hadorn et al., 2006; Reyers et al., 2010). In the context of the framework we developed, different stakeholders could be engaged on the choice of weights for the spatial prioritization of the EI, ensuring that their perspectives and values are incorporated into the prioritization process. Some challenges are however often found in transdisciplinary research, such as inequities among stakeholders and power imbalances between scientists and stakeholders, that should be tackled by implementing participatory methods and scientists showing critical reflexivity (De La Rosa et al., 2024).

5. EI Status clarification

The status of areas that are dedicated to biodiversity in Switzerland is misleading. Official reports suggest that 23% of the country is protected, comprising 11.1%

protected areas, 9.4% Other Effective Area-based Conservation Measures (OECM), and 2.9 % of internationally protected areas (FOEN, 2023c). However, this thesis, in line with findings from the NGO *Pro Natura* (Külling et al., in preparation; Pro Natura, 2023), reveals that only 8% of these areas meet international standards for effective biodiversity conservation. This discrepancy is due to the inclusion of minimally protected (international protected areas) and temporarily (biodiversity promotion areas – SPB in French) protected areas in statistics as OECMs. For Switzerland to effectively reach the “30 by 30” goal of dedicating 30% of landscape for biodiversity, it is thus necessary to clearly define and strengthen the protection status of the EI in Switzerland. Ensuring that the targeted 17% core areas and 13% networking areas are protected sufficiently to maintain a functioning EI is thus necessary, as shown in a country wide analysis showing that 30% of the landscape dedicated to biodiversity would be the minimum for its preservation (Rutishauser et al., 2023).

6. Education and awareness

According to the 2022 IPBES report on values, the global biodiversity crisis is deeply connected to how nature is valued in political and economic decision-making across all levels (IPBES, 2022). In order to orient the values of society towards a positive appreciation of nature (e.g. “nature positive”, NPI, 2023), similar to the current valuation of economic growth (Otero et al., 2020), it is important to implement education programs and increase public awareness to build transformative change for nature. Indeed, as shown in the ValPar.CH project, impacts from scientific research can be maximized through communication measures (Otero et al., 2024). There are examples of education programs that can encourage critical thinking and personal growth, to promote shifts in individual values and promote positive outcomes for a sustainable society (Hamel & Lee, 2024; Odell et al., 2019).

7. Coordinating strategies

Switzerland’s conservation efforts are consequent but fragmented across national strategies implementations, and governance levels. Different strategies (energy, biodiversity, climate, economy) are carried out somewhat separately while being inherently linked, and drivers behind current environmental problems are not enough considered in them (Brunner et al., 2024). The Swiss federal council adopted a sustainability strategy and action plan, with an agenda for 2030 aiming to reach sustainability objectives that would connect strategies within 1) consumption and production, 2) climate, energy and biodiversity, and 3) equality and social cohesion (Federal Council, 2022). However, the practical implementation is obviously complex, and each of these strategies often develop in silos that can hinder the overarching goal, as the pace of action implementation does not align with the rate of environmental change (Guerrero et al., 2013). At global scale, the IPBES recently released its Nexus assessment, highlighting critical interlinkages between biodiversity, water, food, health, and climate change. The report identifies that

fragmented approaches to these issues result in missed opportunities for synergies, and exacerbate environmental and economic costs, estimated between 10 to 25 trillion dollars annually (IPBES, 2024).

4. Limitations

Nature conservation in the 21st century indubitably presents complex challenges. A shift from traditional conservation methods to more integrated, inclusive approaches might help reach transformative change needed to halt the current environmental crisis. The "people with nature" vision (fig.1.2) offers promise by addressing environmental issues through multiple lenses, including economic and social dimensions. However, implementing this approach requires acknowledging and managing trade-offs between nature protection and human livelihoods. For instance, promoting society's autonomy by local consumption of resources to reduce environmental impact at large scale may lead to increased exploitation of nearby lands. While this can be managed in ways that support biodiversity, such as through sustainable agricultural practices, it diverges from the "ideal" of preserving pristine environments. This paradigm shift challenges traditional perceptions of conservation, mine included, and underscores the need for strategies that balance ecological integrity with human well-being, including all forms of ES. For example, research on integrated conservation and development projects indicates that while they aim to reconcile biodiversity conservation with human well-being, they often face challenges in balancing these objectives, leading to difficult choices and compromises (McShane et al., 2011).

The SCP approach, while valuable for achieving conservation objectives, is not without limitations. Despite significant progress in the field, simplifications are always necessary when modelling and analysing complex systems such as species and ES, meaning a comprehensive perspective is never obtained (Levin, 2005; Steinberg, 2004). One key limitation to the SCP approach is the reliance on data, SCP outputs are highly sensitive to the availability and reliability of input data, making the approach less applicable in data-poor regions where the risk of producing unreliable results is higher (Dormann et al., 2008). Additionally, SCP frameworks and procedures are inherently complex, which can hinder their practical application in real-world planning contexts. For instance, the EI approach has been criticized as being neither credible nor realistic as a planning tool (Monteiro et al., 2020). Finally, the SCP approach used in this thesis has the limit of providing relative values to the EI (ranks). Normalized indices (e.g., scaled from 0 to 1) are used rather than absolute values, such as species richness or ES provision quantities. This approach fails to provide absolute benchmarks that would help identify true hotspots or facilitate meaningful comparisons over time. For example, a prioritization map created today and another produced in 30 years may have the same relative rankings, as these are tied to the number of pixels analysed on the area, rather than reflecting changes in absolute

ecological and ES values. This can limit the utility of SCP for assessing trade-offs and long-term planning.

5. Conclusion and perspectives

Conclusion

This thesis aimed at exploring how global conservation commitments can be translated into actionable strategies at the national level, in Switzerland. We proposed and applied a framework for the identification and prioritization of the EI, as a pathway to bridge global goals, such as the “30 by 30” objective, in the frame of a national strategy for biodiversity. We highlighted existing knowledge and gaps in understanding the relationships between biodiversity and ES, and emphasized the relevance of spatial prioritization tools in identifying conservation priorities that balance ecological and societal needs. With most countries failing to meet their global commitments to nature conservation, this thesis underscores the urgent need for transformative changes led by conservation. We propose actionable pathways to promote this transformation across different levels of action (Fig. 3.1).

At the core of this work, the framework presented consisted in the development of novel data, indicators, and methods that enhance our understanding of biodiversity and ES linkages, and allow the spatial representation of landscape elements fundamental for biodiversity and society. We showed how SCP can be integrated in the EI approach, which itself can help translate global conservation commitments into actions in Switzerland.

In conclusion, we stated how Switzerland faces challenges in meeting its global sustainability and biodiversity commitments, requiring urgent and coordinated action. While Switzerland may succeed in preserving its own habitats and biodiversity, its high consumption, purchasing power, and global economic influence significantly contribute to global biodiversity loss, habitat degradation, and climate change through negative spillover effects (see *Sustainable Development Report*, Sachs et al., 2020). With one of the highest GDPs per capita (World Bank, 2023), Switzerland has a global responsibility to sustainability and must integrate its externalities, such as greenhouse gas emissions and habitat loss impacts, into its national strategy. This requires a holistic approach, including reducing its global ecological footprint, enforcing stricter regulations to stop harmful financial practices, investing in sustainability research and implementation, and adopting an ambitious, actionable strategy with clear financial planning and alignment with global commitments.

Perspectives

This work marks an advance in the application of SCP for the identification and conservation of the EI. This research will contribute to integrating the EI approach into landscape management and planning, optimizing resource allocation to preserve both environmental integrity and societal well-being. The EI mapping framework presented in this thesis provides a robust and necessary foundation, but several perspectives for

further development remain to enhance its adoption implementation by political authorities. These include:

Integrating social and economic values

Include social and economic data in the SCP process. This will necessitate working with other disciplines to gather spatially explicit models and data (e.g. Mangubhai et al., 2015; Sherrouse et al., 2022). For example, Fan et al. (2021) did a spatially explicit mapping of aquatic ES combined with economic cost layers reflecting water resource utilization and integrated it in a SCP process. This approach revealed how different economic valuations drastically altered spatial priorities.

Integrating landscape connectivity measures

Connectivity between habitat is an important aspect of the EI, which was not thoroughly assessed in this thesis. Developing measures of landscape connectivity for different species groups and ES would allow to identify pinch points in the landscape that must be preserved and prioritized in a SCP (see e.g. Kukkala & Moilanen, 2017).

Prioritizing future projections for a better adaptation

Including future projections of biodiversity and ES can guide better management strategies and ensure resilience against climate change impacts. Eckert et al. (2023) included both present and future species distribution models in a SCP design to advise for “30 by 30” conservation objective.

Exploring opportunities of restoration

The SCP framework proposed in this thesis provides EI ranking for the entire landscape but does not explicitly provide restoration opportunities, while also fundamental, especially for a better EI network and connectivity. Exploring ways for restoration of ecosystems would thus be a complementary way to design a functioning EI, and represents an objective of the Kunming-Montreal GBF in itself (CBD, 2022).

Comparing national and regional (cantonal) outputs

The SCP approach proposed in this thesis integrates extensive spatial data and indicators. With all Swiss cantons required to identify their EI by 2025, this presents an opportunity for resource-constrained cantons to leverage these national datasets. Cantons can use these freely available outputs as a baseline to compare, validate, or enhance their EI identification efforts.

Integrate ES flow and demand indicators into SCP

Similarly to integrating socio-economic values, designing specific ES flow and demand indicator maps (e.g., Schirpke et al., 2019) would enable their inclusion in the SCP framework. Incorporating ES demand indicators has proven effective in safeguarding ES without compromising biodiversity (Watson et al., 2019). Further investigation will

then be needed to develop a framework that integrates supply, flow, and demand indicators alongside other features in SCP design (see also Qiu & Mitchell, 2024).

Integrate the aquatic part of the EI

Although closely connected to terrestrial ecosystems, aquatic networks like lakes and rivers, which are abundant in Switzerland, were not comprehensively assessed in this study. Future research should focus on evaluating the aquatic component of the EI, developing relevant indicators, and integrating them with the terrestrial EI within the SCP framework.

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