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Nature-based Solutions in the Alps to adapt to climate change: from current implementation to future scaling

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THÈSE

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Spécialité : Biodiversité-Ecologie-Environnement

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Les solutions fondées sur la nature pour l'adaptation au changement climatique dans les Alpes : évaluer leur mise en oeuvre actuelle pour faciliter leur déploiement futur

Nature-based Solutions in the Alps to adapt to climate change: from current implementation to future scaling

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Abstract

Climate change impacts mountains by increasing the intensity and frequency of natural disasters, altering Nature's Contributions to People (NCP) and threatening biodiversity. Nature-based Solutions (NbS) are increasingly recognized to support local communities in adapting to climatic hazards and conserving biodiversity. These initiatives hold the potential to accelerate the transformative adaptation of social-ecological systems, addressing the interconnected crises of climate and biodiversity. However, there is a limited understanding of the current stage of NbS implementation, the main existing barriers to their adoption, and their linkages with spatial planning.

To address this knowledge gap, I first identified a portfolio of NbS for climate change adaptation in the European Alps and mapped their location. The database showcases a wide range of NbS interventions aimed at addressing a given hazard, with the potential for various NCP co-benefits. Then, I evaluated whether the NbS are located where they are the most needed according to the intensity of the climate hazards they aim to address and to the existing amount of supply, flow and demand of the NCP they aim to provide. The spatial analysis indicates few spatial correlations, suggesting that climate hazards and NCP may not be the primary drivers of NbS implementation.

To identify the main levers and barriers of already implemented NbS and guide enabling policies for scaling NbS, I conducted semi-structured interviews with NbS managers. I investigated their decision-making contexts through the values-rules-knowledge framework and by assessing the transformative characteristics of the initiatives. I identified three types of initiatives, namely local self-sufficient transformations; green deal practices based on incremental changes; and co-production initiatives involving various sectors at multiple scales. Individually, these groups show a limited potential for transformative adaptation. However, when considering their interplay, a co-produced regional strategy may hold the potential to foster transformative adaptation.

To support the scaling of NbS at the Alpine level, I identified where NbS should be prioritized in the Alps for adaptation to drought. This spatial modelling considered areas where there is a deficit or a surplus of groundwater, respectively aiming at enhancing or safeguarding this essential resource for adaptation. The spatial distribution indicates that priority areas concentrate in the southern and the northeastern lowlands and hillsides. A limited number of areas meet simultaneously priorities for biodiversity conservation, carbon sequestration and climate change adaptation. Priority areas are only partially located within protected areas, emphasizing the need to consider the diversity of situations when implementing NbS.

The findings from these three analyses acknowledge the potential of the NbS concept to engage local communities in adaptation initiatives that jointly address both climate and biodiversity crises. Some of the identified initiatives fostered the adoption of NbS by breaking down silos of governance and sharing experiences. However, some challenges persist for scaling NbS, including the delay before getting benefits, the other interacting local issues, the necessity to deal with uncertainty, and financial barriers. Disseminating NbS, both successful and unsuccessful, recognising their role in multifunctional landscape management, and designing new research protocols can foster their adoption.

Keywords

Nature-based Solutions, Nature's Contributions to People, Climate change, European Alps, Transformative adaptation.

Résumé

Le changement climatique se traduit dans les montagnes par l'augmentation en intensité et en fréquence de plusieurs aléas climatiques extrêmes, affectant les Contributions de la Nature aux Populations (CNP) et menaçant la biodiversité. Les Solutions fondées sur la Nature (SfN) gagnent en popularité par leur capacité à aider les populations locales à s'adapter aux impacts du changement climatique tout en préservant la biodiversité. Ces initiatives sont reconnues pour accélérer la mise en place d'une adaptation transformative des socio-écosystèmes aux crises interconnectées du climat et de la biodiversité. Cependant, l'état actuel de leur mise en oeuvre reste peu compris, ainsi que les principaux freins à leur adoption et leur rôle dans l'aménagement des territoires.

Pour combler ces lacunes, j'ai tout d'abord recensé et cartographié une centaine de SfN dans les Alpes visant à s'adapter au changement climatique. Cette base de données illustre la diversité de pratiques existantes pour faire face à un aléa donné et les nombreux CNP qu'elles apportent. J'ai évalué la correspondance spatiale des SfN avec l'intensité des aléas climatiques présente et à venir, ainsi qu'avec la capacité des écosystèmes à délivrer des CNP, ceux déjà acquis par les sociétés humaines, ainsi que ceux dont elles nécessitent. Les résultats montrent une faible corrélation, indiquant que les conditions climatiques et les CNP ne se sont pas les principaux moteurs à la mise en oeuvre des SfN dans les Alpes.

Pour identifier les principaux freins et leviers à leur mise en place, j'ai réalisé des entretiens semi-directifs en lien avec vingt SfN recensées. Cela m'a permis de définir leur contexte de décision grâce au cadre conceptuel « valeurs-règles-connaissances » et leur niveau de caractéristiques transformatives. L'analyse a révélé trois groupes de contexte de décision, qui sont les transformations locales en quête d'autosuffisance ; les pratiques incrémentales « green deal » basées sur l'évolution de la réglementation et des subventions disponibles ; ainsi que les initiatives impliquant la concertation d'une large diversité d'acteur · ice · s, chercheur · euse · s inclus · e · s. Pris individuellement, ces groupes montrent un potentiel d'adaptation transformative limité, mais considérer leurs interactions permettraient de définir une stratégie régionale d'adaptation intégrée.

Pour déterminer le potentiel de déploiement des SfN dans les Alpes, j'ai identifié les zones à prioriser pour l'adaptation des territoires aux sécheresses par les SfN. L'analyse spatiale cible à la fois les zones déficitaires en eau, nécessitant une gestion intégrée de cette ressource, et celles excédentaires en eau, qu'il est primordial de préserver. L'hétérogénéité spatiale de leur distribution indique une concentration dans les zones de plaines du sud et du nord-est. Quelques zones prioritaires pour l'adaptation coïncident avec celles qui ont un large potentiel pour la conservation de la biodiversité et la séquestration de carbone, mais elles ne sont pas majoritaires. Les zones prioritaires ne sont qu'en partie situées dans les aires protégées, nécessitant de la prise en compte de la diversité de situations pour la mise en place des SfN.

Cette thèse confirme la capacité du concept de SfN à engager les populations locales dans une démarche d'adaptation aux crises climatique et de la biodiversité. Certaines de ces NbS ont la capacité de décroïsonner les secteurs en silos pour l'adaptation. Intégrer les SfN plus largement dans ces réflexions permettrait d'initier le changement de paradigme transformant la vision antagoniste de l'aménagement des territoires, où la préservation de la biodiversité est en conflit avec le développement local et la prévention des risques, vers une approche symbiotique. Cependant, de nombreux défis persistent pour déployer les SfN, comme le temps nécessaire pour qu'elles deviennent efficaces, l'existence d'autres enjeux, la prise en compte des incertitudes des conditions futures, ainsi que le manque de sources de financement. Échanger les pratiques existantes, de réussites mais aussi d'échecs, reconnaître le rôle des SfN pour l'aménagement intégré des territoires, et définir de nouvelles méthodes de recherche transdisciplinaires permettrait de favoriser leur adoption.

Mots clés

Solutions fondées sur la Nature, Contributions de la Nature aux Populations, Changement climatique, Alpes, Adaptation Transformative.

Acknowledgements (expressed after the defense at the audience)

Vous savez comment on mange un éléphant ? C'est comme une thèse, petit bout par petit bout, on en vient à bout.

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“Nous devons aujourd’hui comprendre
que la terre fournit assez pour tous et pour
l’évolution de tous. L’extinction ne semble
inévitable que si l’on cède à l’avidité, à
l’orgueil et à une approche mécanique et
militariste à des fins de conquête.”
— Vandana Shiva, *1%*, 2019

“Not everything that is faced can be
changed, but nothing can be changed until
it is faced.”
— James Baldwin

“We think we are smarter than nature,
but we are not. Our human intellect is
amazing, but we must be humble and
recognize that there is an even greater
intelligence in nature.”
— Jane Goodall, *Seeds of Hope*, 2015

“Actuellement l’homme mène une guerre
avec la nature. S’il gagne, il est perdu.”
— Hubert Reeves

Chapter I

Introduction



Alpine mountains contribute to people's good quality of life in various ways. For example, forests rooted in steep slopes provide protection to downstream inhabitants and infrastructures by mitigating landslides and rockfalls. In the Krimml region of Austria, the forests are conserved to restore their natural dynamics and improve their adaptability to climate change. Path trails have been established to inform hikers about the potential roles of these protected forests. Source: the author.

1. Straight into a wall: navigating the biodiversity and climate crises

1.1. Major issues and societal challenges

1.1.1. The sources of the catastrophes

Even since human societies developed agriculture, they have modified their environment in order to satisfy their livelihood needs (Foley et al., 2005). Some of the resulting benefits include an increase in food production, health improvement, and social relations support (MEA, 2005). This good quality of life, i.e. the “achievement of a fulfilled human life” increased almost worldwide due to the complete transformation of livelihoods in recent history (Brondizio et al., 2019; MEA, 2005). The latest turning point of societal transformation occurred two centuries ago, with the mainstreaming use of fossil fuels, providing energy access like never before (IPCC, 2023a). The development of human societies based on economic growth has made substantial technological progress, benefiting a large part of the global population and contributing to the increasing life expectancy, periods of peace, and access to food and culture in Western societies (Brondizio et al., 2019; MEA, 2005).

However, these induced changes are impacting global ecological processes and posing threats to all living beings (Steffen et al., 2015a, 2015b). The increase in greenhouse gas emissions from various industries, energy, and transport sectors is a paramount driver of climate change, which threatens the habitability of the Earth (IPCC, 2023a; Pörtner et al., 2022). Additionally, societal restructuring has increased land-use changes, including sealing and deforestation, the over-exploitation of resources from land and sea, the globalisation of markets, the homogenisation of products, the pollution from various sources, and the expansion of invasive species (Brondizio et al., 2019; MEA, 2005). This global transformation poses a major threat to biodiversity and its components, which include all species, their genetic diversity, habitats, and the interactions that occur both between and within species, all of which constitute ecosystems (CBD, 2000; Steffen et al., 2015b). Although the exact number of species remains uncertain, the global extinction rate of species has been surging in the last decades to levels ranging from ten to hundreds of times higher than on average. This extinction rate is mostly considered in the literature to be indicative of massive life extinctions (Brondizio et al., 2019; MEA, 2005).

In addition to the loss of numerous species, the synergetic crises of climate and biodiversity affect human quality of life, in various ways (Pörtner et al., 2021). Among other consequences, climate change is expected to increase the frequency of natural disasters that are already affecting people worldwide (Pörtner et al., 2022). Heavier rainfall is expected, leading to higher occurrences of floods, with considerable impact on people and infrastructures. Similarly, more severe landslides and mudslides are likely to occur. Less rainfall is expected in drier regions, where water scarcity is already an issue, potentially leading to population migration and conflicts, such as water wars (Kåresdotter et al., 2023; Pörtner et al., 2022). Heatwaves are projected to become more intense and frequent, with consequences similar to those of the pan-European 2003 heatwave, which resulted in thousands of fatalities and dramatic losses for agriculture and forestry. This type of event is expected to occur approximately every two years by the end of the century (Hari et al., 2020; Samaniego et al., 2018). The more frequent and intense droughts will put pressure on water use, bringing sectors such as agriculture and forestry into conflict for water (Pörtner et al., 2022, 2021). Additionally, the non-material contributions, that include aesthetic landscape enjoyment and inspiration for art and technologies, are also affected by the combined impact of climate change and biodiversity loss (Brondizio et al., 2019; MEA, 2005).

1.1.2. International science and policy to address major issues

The anthropogenic causes of this global crisis have been increasingly recognized over the past few decades by a growing body of research, and rely on demographic, sociocultural, economic, technological, institutional, governance, conflict and epidemic drivers (Brondizio et al., 2019; Calvin et al., 2023; MEA, 2005). However, these causes were slow to emerge in public debates (Boykoff and Roberts, 2007; Lüth and Schaffer, 2022). Consequently, strategies have recently emerged in response to these issues. Some believe that technological innovation alone will enable the maintenance of the current overdeveloped Western lifestyles while remaining within planetary boundaries (Bamberg et al., 2021). Others turn to individualism as a way to thrive within an overshoot world (Parkkinen, 2021). Last, communities worldwide have united in a shared dedication to sustainable development, aiming at pursuing a high quality of life over time and for all, i.e. “that meets the needs of the present while safeguarding Earth’s life-support system, on which the welfare of current and future generations depends” (Brundtland, 1987). Closely related to the concept of resilience, sustainability shares principles including diversity, equity, fairness, respect, proactiveness, and emphasizes the major role of education to tackle global changes (Fischer et al., 2015; Leach et al., 2018; Wu, 2013). The advocates of sustainability discourage individualism, disconnection from nature and market capitalisation (Ives et al., 2018; McPhearson et al., 2021; Muradian and Gómez-Baggethun, 2021). The Sustainable Development Goals (SDG), endorsed by the United Nations, aim for individual fulfilment through responsible consumption, peace, access to food and clean energy, good health and education, as well as life preservation on land and sea (United Nations, 2015). In order to guide their decisions, governments initiated, with the support of international organisations (including UNEP, FAO, IUCN, UNFCCC) and NGOs (including WWF, Conservation International), two international science-policy platforms, namely IPCC (Intergovernmental Panel on Climate Change), estab-

lished in 1988, and the IPBES (Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services), established in 2012.

These organisations regularly argue, through their literature syntheses, for the immediate reduction of greenhouse gas emissions, coupled with efforts aiming at carbon sequestration, to mitigate the worst effects of climate change (IPCC, 2023a). Moreover, the trend of biodiversity loss must be reversed to limit the degradation of people’s quality of life (Brondizio et al., 2019). However, it became evident that adaptation to future climate conditions is mandatory to achieve the SDG (Pörtner et al., 2022; Roy et al., 2022; United Nations, 2015). Although adaptation was initially envisaged in the 1970s, policies adopted to date have prioritised mitigation strategies over adaptation options (Bassett and Fogelman, 2013). Thus far, adaptation efforts have mainly consisted of sporadic initiatives emerging from local communities once the initial conditions became unsuitable. Consequently, the adaptation gap has widened, resulting in a substantial increase in the efforts required to mitigate impacts (Berrang-Ford et al., 2021; Pörtner et al., 2022; UNEP, 2022).

1.1.3. The emergence of synergetic responses

The relationships between society and nature have also evolved, and the diversity of human values for nature is increasingly recognized worldwide (Anderson et al., 2022). To counteract the environmental degradation that has occurred since the mid-twentieth century, protected areas emerged as institutional instruments to achieve conservation goals (Mace, 2014). Then, conservationists emphasized the benefits that nature provides to societies for preserving biodiversity even outside protected areas. The resulting ecosystem services concept paves the way for nature commodification and its abuses (Gómez-Baggethun and Ruiz-Pérez, 2011; Kallis et al., 2013; Schröter et al., 2014). In response to this, research on social-ecological systems emerged in the 2010s to account for relational values and interdependence between nature and society (Binder et al., 2013; Ostrom, 2009). More recently, the separation of these two components has been questioned, shifting humans’ place from the system centre (Ives et al., 2018; West et al., 2020).

The coexistence of diverse values of nature has led to adaptation initiatives across various sectors (Bennett et al., 2016; Berahmani et al., 2012; Brillinger et al., 2021; Palomo et al., 2021). While grey infrastructures, such as dikes, have traditionally dominated in natural disaster risk reduction field, emerging technologies including ecological engineering, green infrastructure or ecosystem restoration are being recognised to address both adaptation and biodiversity conservation (Munang et al., 2013; Sahani et al., 2019).

Over the past two decades, various ecosystem-based approaches have emerged one after the other, and they have been recently merged under the umbrella concept of Nature-based Solutions (CBD, 2009; Cohen-Shacham et al., 2016). Although NbS have been recently framed (Eggermont et al., 2015; Seddon et al., 2019), the exponential increase of NbS-related publications in the last three years demonstrates the strong attention given to these promising solutions

(Figure 1). My PhD project aims to explore NbS for climate change adaptation in the European Alps. To frame this research, it is essential to delve into the underlying concepts, including climate change risk and adaptation; Nature’s Contributions to People supply, use and demand; the delineation of NbS concept; the decision-making context in social-ecological systems; and spatial planning role for NbS implementation.

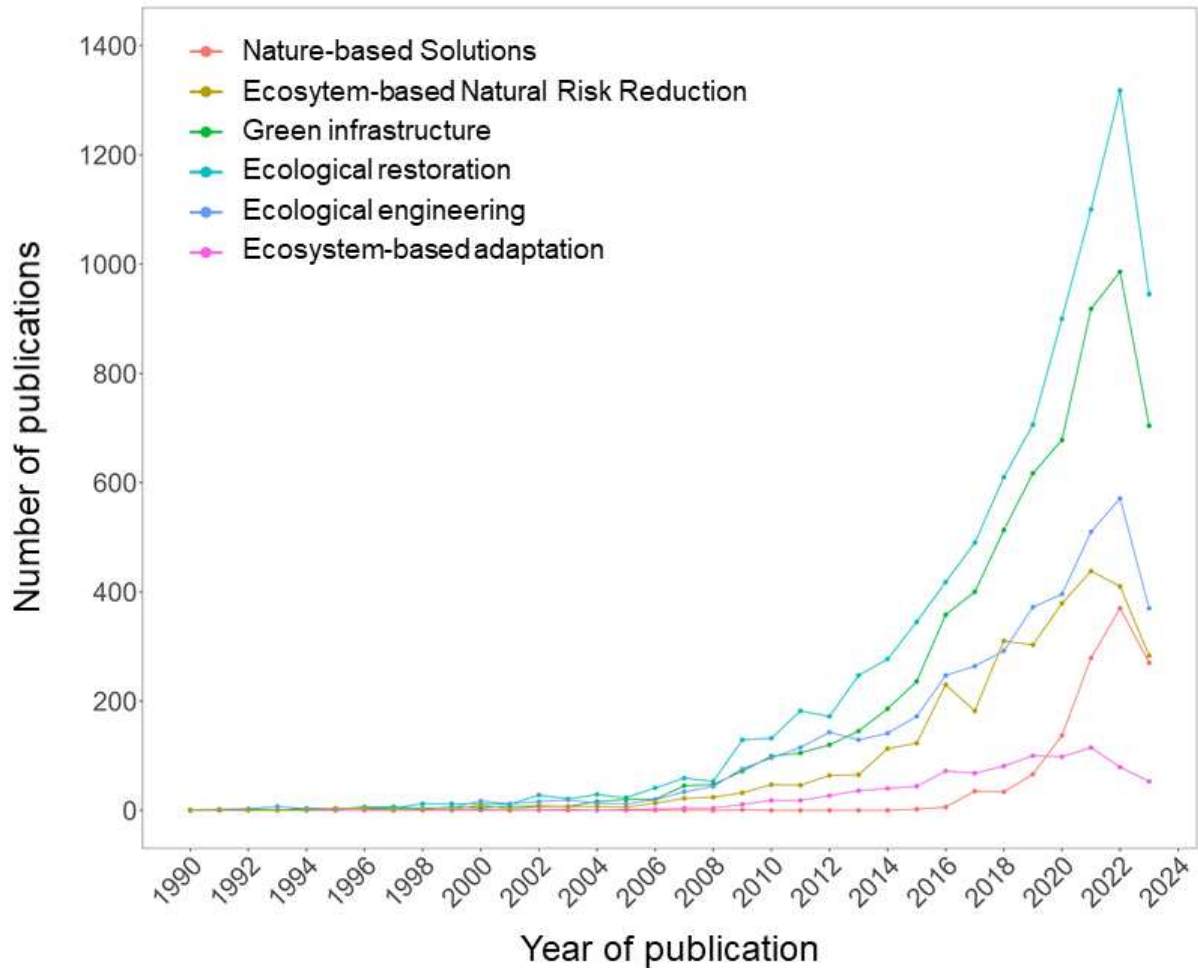


Fig. 1. Trends in the number of research papers mentioning different types of Nature-based Solutions in the topic (title, abstract or keyword) (1990-2023), updated from the initial version (Cohen-Shacham et al., 2016). Source of data: Web of Science (records collected on October 10, 2023, for each term in the figure’s legend).

1.2. Climate change risk and adaptation

1.2.1. The dimensions of adaptation

In its assessment reports published every six years, the IPCC provides an updated synthesis of the existing knowledge on climate change based on three working groups. While the first group reports the consequences of climate change from the perspective of possible socio-economic pathways, the third group evaluates the existing mitigation options, including the significant potential of forests in sequestering atmospheric carbon (IPCC, 2023b, 2023a). The second group (WGII) explores the impact of climate change on ecological and human systems, their vulnerability and their adaptation. Adaptation encompasses ecological and human dimensions. Unless otherwise specified, I use the term ‘adaptation’ in accordance with the human dimension, which refers to the processes aimed at adjusting human systems “to actual or expected climate and its effects in order to moderate harm or exploit beneficial opportunities” (Pörtner et al., 2022). The ecological dimension of adaptation includes “autonomous adjustments through ecological and evolutionary processes” such as species migration in response to the spatial shift of their evolution niche, changing behaviour and variation in selective force driving change in ecological communities (Pörtner et al., 2022).

1.2.2. The IPCC risk framework

In the context of adaptation, risk is defined as “the potential for adverse consequences for human or ecological systems” and as “the result from dynamic interactions between climate-related hazards with the exposure and vulnerability of the affected human or ecological system” (Figure 2).

Hazard refers to “the potential occurrence of a natural or human-induced physical event or trend” that may affect exposed assets. Hazards include biophysical events such as floods, droughts, heatwaves, storms, wildfires, landslides and avalanches, as well as biological incidents such as pest attacks, and the expansion of invasive species. Although the occurrence of these hazards varies across regions, global trends show an increase in intensity and frequency of extreme events, also referred to as natural disasters (Pörtner et al., 2022).

Exposure refers to “the presence of people; livelihoods; species or ecosystems; environmental functions, services, and resources; infrastructure; or economic, social, or cultural assets in places and settings that could be adversely affected”.

Vulnerability is “the propensity or predisposition to be adversely affected” and “encompasses a variety of concepts and elements, including sensitivity or susceptibility to harm and lack of capacity to cope and adapt”.

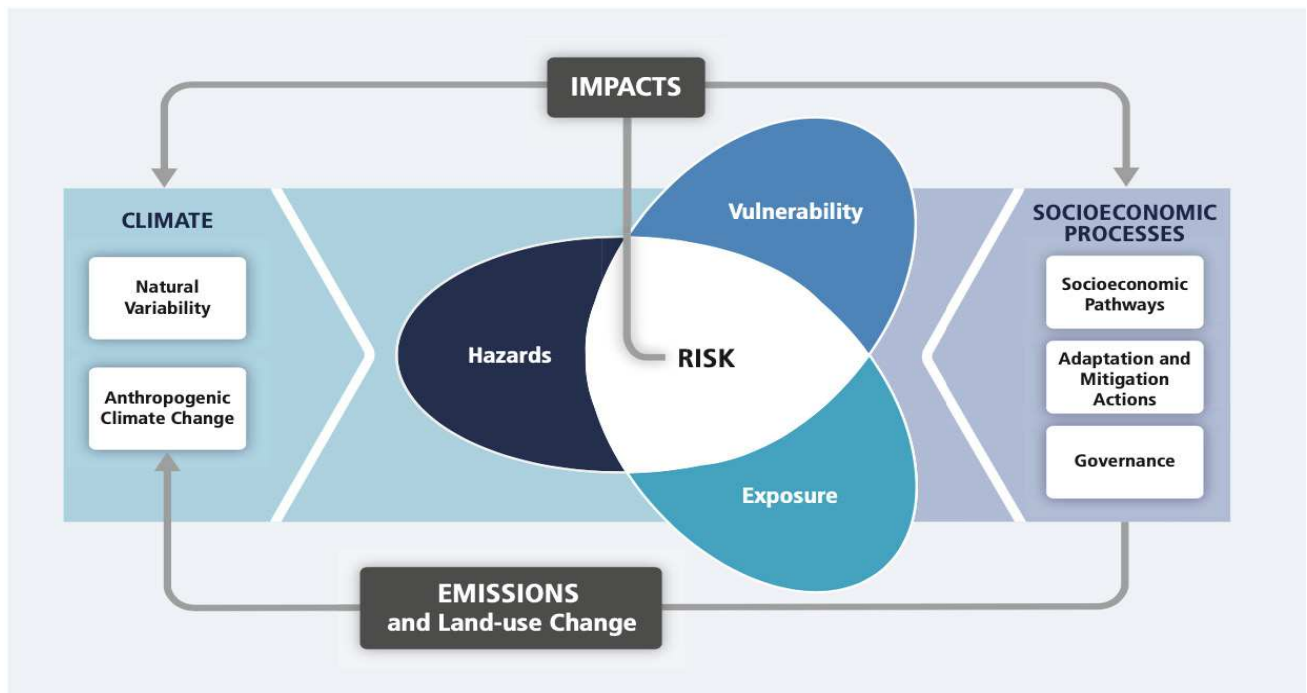


Fig. 2. Illustration of the core concepts of the WGII AR5. Risk of climate-related impacts results from the interaction of climate-related hazards (including hazardous events and trends) with the vulnerability and exposure of human and natural systems. Changes in both the climate system (left) and socioeconomic processes including adaptation and mitigation (right) are drivers of hazards, exposure, and vulnerability. Source: Lavell et al. (2012)

1.2.3. The adaptation typologies

Risk framing is inherently connected to solutions, such as risk management strategies, aiming at aiding human systems to adapt (Ou et al., 2022; Pörtner et al., 2022). Given that most hazards depend on global climate adaptation processes have focused on reducing the probability of assets being affected, on mitigating the propensity (also referred to as ‘predisposition’) to be affected, and on increasing the adaptive capacity of the system (Lavell et al., 2012). Given the increasing number of adaptation initiatives, they have been classified according to the magnitude of changes. First of all, coping strategies are often implemented in response to the impact on the affected systems. They are short-term measures for tackling hazards, such as applying fertilizers or water-

ing plants (Fedele et al., 2019), and are likely to be maladaptive in the long term (Barnett and O’Neill, 2010). Second of all, we have incremental adaptation, understood as actions that aim at doing slightly more, meaning engaging in a step-by-step process towards adaptation (Kates et al., 2012). This strategy, which includes, for instance, the improvement of water use efficiency for irrigation, is increasingly recognised as insufficient in the face of the magnitude of climate change (Fedele et al., 2019; Kates et al., 2012). Third of all, transformative adaptation refers to actions aimed at fundamentally altering the entire system’s properties and functions, in order to address the root cause of vulnerabilities (Feola, 2015; Kates et al., 2012). This approach implies shifts in most of the processes of the system, including governance, knowledge production, power dynamics, relationships with nature, and decision-making processes (Fedele et al., 2019; Patterson et al., 2017; Wise et al., 2014). Although transformative adaptation holds the potential to achieve sustainability that justifies the required effort, real-world cases of transformation are limited (Fedele et al., 2020; Goodwin et al., 2023), and the defining features of transformative adaptation differ across the literature (Fedele et al., 2019; Feola, 2015; O’Brien and Sygna, 2013).

Climate change risk and adaptation can be addressed across time, space, sectors and options (Brondizio et al., 2019; Pörtner et al., 2022; Wise et al., 2014), amplifying their inherent complexity which encompasses feedback loops (e.g. local climate relies on vegetation which depends on the local climate (Zemp et al., 2017)), cascades (e.g. the decrease of one population in a trophic network affect ecosystem stability (Hautier et al., 2015)), non-linear behaviour (e.g. idiosyncratic spatial shifts of species due to climate change (Gibson-Reinemer and Rahel, 2015)) and infinite source of uncertainties (e.g. ranging from biophysical (Kotlarski et al., 2022) to moral uncertainties (Ciullo et al., 2021)). In line with this, this work is not intended to provide the absolute truths but rather to offer reflections on methodology, support existing literature, and lend legitimacy to emerging approaches.

The latest IPCC WGII report introduced a new risk framework that strengthens the relationship between ecological, human and climate systems (Pörtner et al., 2022). However, because my research was designed before the release of this assessment, the risk framework used here refers to the previous framework published in the IPCC Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation (Lavell et al., 2012) and used within the 5th IPCC assessment report (Field and Barros, 2014).

In the following, I introduce key concepts on which I built the framing for my thesis research. Their implementation and corresponding methodological advances are then presented in subsequent chapters, along with their implementation for my situated work in the Alpine context.

1.3. Supply, use and demand of Nature's Contributions to People

1.3.1. The emergence of Nature's Contributions to People to go beyond ecosystem services

Conservation researchers and stakeholders are seeking ways to stop environmental degradation and species extinction that has taken place since the onset of the industrial revolution. The concept of ecosystem services gained prominence at the beginning of the new millennium to emphasise the need to preserve ecosystems given the benefits they provide to humans (Berkes and Folke, 2002; MEA, 2005). Ecosystem services were defined as “the direct and indirect contributions of nature to human wellbeing” and have been incorporated into many public policies (Pramova et al., 2012; Saarikoski et al., 2018). However, scholars have criticised ecosystem services for their limited ability to capture a diversity of worldviews, knowledge systems and stakeholder perspectives (Hill et al., 2021; Kadykalo et al., 2019). Additionally, ecosystem services have the propensity to consider culture in isolation, and to poorly consider the negative effects of ecosystems on people (Kadykalo et al., 2019). These limitations have resulted in limited engagement of social sciences in ecosystem services research (Kadykalo et al., 2019). Consequently, the IPBES has recently introduced the Nature's Contributions to People (NCP) defined as “all the contributions, both positive and negative, of living nature (i.e. biodiversity of organisms, ecosystems, and their associated ecological and evolutionary processes) to quality of life for people” (Díaz et al., 2018, 2015). Nature's Contributions to People embrace ecosystem services but aim to be more inclusive of the diversity of relationships between humans and nature (Díaz et al., 2015; Kadykalo et al., 2021). They have been grouped into eighteen categories within three broad groups: material NCP including the provision of food, feed and materials such as timber; regulating NCP including water filtration, air cooling, pollination, as well as pest control; non-material NCP including inspiration, e.g. for art, physical and psychological experiences, e.g. for outdoor recreation activities, and supporting identities, e.g. traditional celebrations centered on a natural feature (Díaz et al., 2018).

The concept of bundles of NCP recognises that similar ecosystems provide a set of simultaneous NCP, commonly assessed using LULC (Land-use and Land-Cover) categories (Lavorel et al., 2017; Raudsepp-Hearne et al., 2010). For instance, areas covered by forests are expected to provide NCP related to carbon sequestration, soil erosion control, protection against landslides and rockfalls, and habitat for endemic species (Felipe-Lucia et al., 2018; Mina et al., 2017; Pang et al., 2017). In contrast, wetlands mitigate floods, filter water from nitrogen inputs, and sequester carbon (Tomscha et al., 2021; Zedler and Kercher, 2005).

The supply of multiple NCP is based on the functional properties of ecological communities (Cardinale et al., 2012). For instance, agriculture is highly dependent on soil fertility, which in turn, relies on the functions of soil organisms that play a significant role in decomposition and nutrient cycling processes (Blouin et al., 2013; Trap et al., 2016). Any change in soil species di-

versity or abundance, or biophysical conditions can, therefore, reduce the amount of soil organic matter, the flow of nutrients and the water retention capacity, which are indivisible factors for plant health and growth (Hautier et al., 2015; Kopittke et al., 2019). Conventional agriculture is known for decreasing regulating NCP such as soil erosion control, water infiltration and retention (Lal, 2013; Palm et al., 2014).

1.3.2. The supply, flow and demand framework

In this thesis, I applied the supply-flow-demand framework (Baró et al., 2016; Burkhard and Maes, 2017) to NCP. In this framework, the NCP supply is the potential amount of NCP that the ecosystems can provide to societies, e.g. the total amount of freshwater in a watershed; the NCP flow is the amount of NCP that society actually enjoys or benefits from, e.g. the amount of water that is used by public service in a watershed; the NCP demand is the amount of NCP that society needs to maintain their lifestyle, e.g. the amount of water needs to fulfil the actual consumption of the population in a watershed. NCP supply is not always used or needed by people in the same location (Palomo et al., 2013; Schirpke et al., 2019b). For instance, mountain ecosystems regulate and filtrate rainwater and meltwater. This resource mainly serves the demands of lowland communities, including requirements for agriculture, power plants, industries and potable water networks (Huber et al., 2021; Klug et al., 2012).

1.3.3. Global trends in Nature's Contributions to People

The IPBES framework includes direct interactions of NCP with Nature (referring to, from the Western perspective, biodiversity and ecosystems), people's quality of life, anthropogenic assets (including among others infrastructures and knowledge) and indirect drivers of change, i.e. elements issued from societies' organisation. The IPBES has assessed the past and current trends of NCP, as well as their future evolution according to plausible scenarios (Harrison et al., 2019; Pereira et al., 2020). The global assessment report showed a global decrease in all the NCP categories except for material NCP such as food and feed, energy and materials that vary across regions (Figure 3; Brondizio et al., 2019). Even more disturbing, the previously observed degradation trend has not been reversed (Brondizio et al., 2019) and the international Aichi targets for biodiversity conservation upon sustainability have not been met (Brondizio et al., 2019; CBD, 2020). The most impactful direct drivers of the loss in NCP on terrestrial land were attributed, in order of importance, to land use change, overexploitation of resources, climate change, pollution and invasive alien species. However, the indirect causes of these changes are rooted in societal factors, including demographic, sociocultural, economic, and technological factors, and are exacerbated by institutions, governance, conflicts and epidemics (Brondizio et al., 2019; MEA, 2005).

1.3.4. The interlinked impacts of climate and biodiversity crises

The WGII of the IPCC dedicated a section of their report to the NCP and published a joint report with the IPBES to address the relationships between climate and biodiversity issues (Pörtner et al., 2022, 2021). The most recent evidence indicates that the attribution of climate change to the loss of NCP is expected to increase in the future if the current trend is not reversed (Pörtner et al., 2021; Runting et al., 2017). For instance, the increasing occurrences of droughts and pest attacks attributed to climate change also negatively impact crops and forests' functions (Mina et al., 2017; Rosenzweig et al., 2014). The snow cover reduction due to the increase in temperature in mountains poses a threat to the viability of winter tourism activities (Morin et al., 2021; Palomo, 2017). These impacts mean that social adaptation will be required. The concept of Nature's Contributions to Adaptation (NCA) was introduced to refer to the benefits provided by ecosystems that specifically address climate change adaptation (Colloff et al., 2016; Lavorel et al., 2015). NCA include the current supply that may be increasingly used in the future, e.g. freshwater that is expected to be under more pressure due to climate change, the persistence of the ecosystems under future conditions, e.g. due to the phenotypic plasticity of organisms, the ecosystem properties that currently exist but that may appear to be beneficial under future conditions, and the potential novel NCA delivered through the transformation of ecosystems in responses to new conditions, e.g. due to glacier retreat (Colloff et al., 2020).

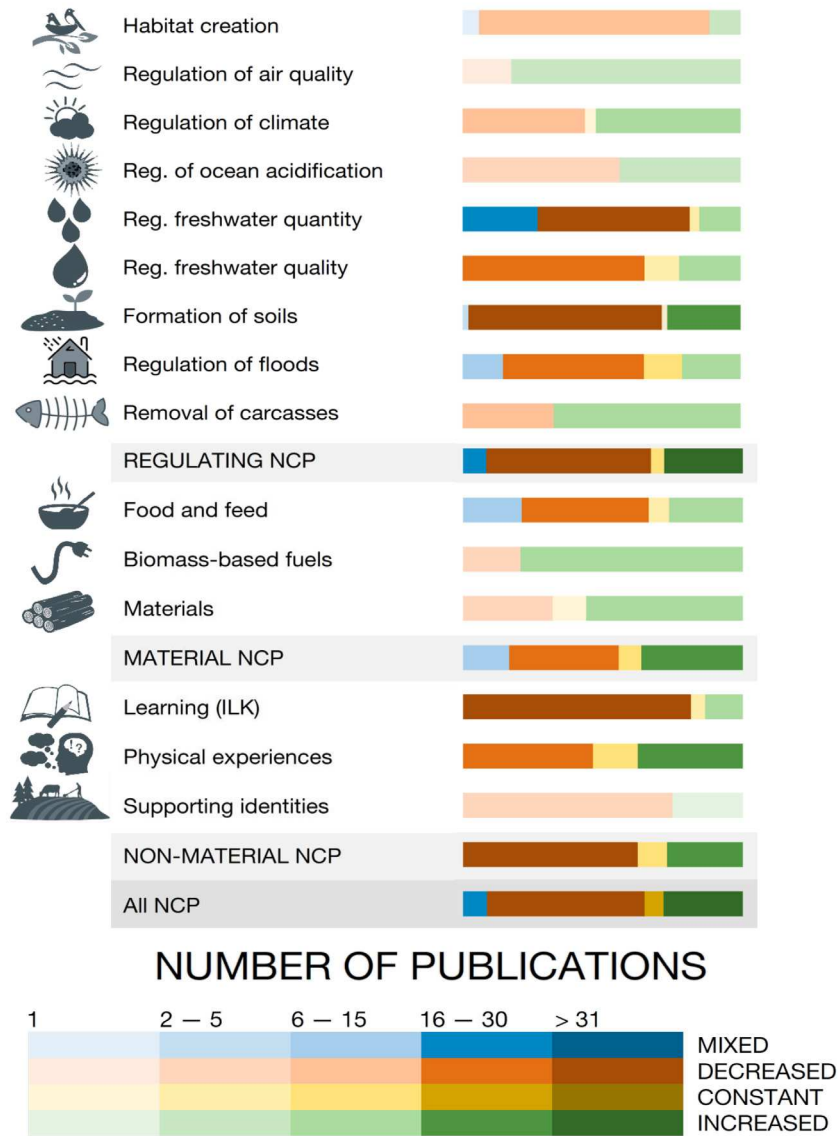


Fig. 3. Assessment of each of the 15 categories of Nature's Contributions to People analysed, from 1970 to the present, by the number of studies, for Europe and Central Asia, adapted from IPBES European and Central Asia regional assessment (Rounsevell et al., 2018). The bar indicates the proportion of papers that provide evidence of decreasing, constant, increasing or mixed trends for each contribution, representing the level of agreement. The intensity of the colour represents the total number of publications identified and used in this assessment (i.e., solid colours indicate many papers, whereas faded colours indicate few, and blank space indicates zero studies), thus, representing the quantity of evidence

1.4. The concept of Nature-based Solutions (NbS)

1.4.1. Nature-based Solutions emerged as an umbrella concept

From its first use in the late 2000's, the Nature-based Solutions (NbS) concept was intended to address simultaneously biodiversity conservation and other societal challenges, which were, in these pioneer cases, climate change adaptation and mitigation (Eggermont et al., 2015). The NbS concept rapidly gained in popularity in the following years, after the IUCN (International Union for Conservation of Nature) first mentioned it concerning climate change. The promising benefits of NbS for the economy offer opportunities to uptake them into policies, especially from the European Union has funded many research projects on NbS since 2015 (Al Sayah et al., 2022; Davies et al., 2021). The IUCN officially framed NbS in 2016 as an umbrella concept that considers all similar approaches belonging to the NbS family and that was related to wordings such as “power of nature”, “potential of ecosystems” or “enhancing resilience” (Dudley, 2010; IUCN, 2012, 2009). NbS are defined as “actions to protect, sustainably manage and restore natural or modified ecosystems that address societal challenges effectively and adaptively, simultaneously providing human well-being and biodiversity benefits” (Figure 4, Cohen-Shacham et al., 2016). As understood by the IUCN, the defined principles delineate NbS as actions that embrace nature conservation norms, produce benefits fairly and equitably, maintain biological and cultural diversity, recognise and address the existing trade-offs, belong to an overall adaptation strategy and can be implemented alone or in conjunction with other solutions - e.g. through hybrid infrastructure (Cohen-Shacham et al., 2016).

NbS are thus been introduced recently, yet the idea of managing ecosystems to provide societal benefits is not new. NbS draw upon previous approaches known as ecosystem-based natural disaster mitigation (Eco-DRR), ecosystem-based adaptations and NCP management (Figure 1; Ruangpan et al., 2020). For example, the French Mountain Landscape Restoration programme (RTM, Restoration des Terrains de Montagne, in French) was initiated in the mid-19th century to restore and manage mountain forests to enhance their capacity to reduce landslides and rockfalls (Buisson et al., 2018). For sustainable agriculture that balances the reduction of crop yields due to climate change, farmers implement agroecological practices such as hedges plantations, banned ploughing, crop rotation, and diversification of products through a holistic approach (Altieri et al., 2015). Such practices, that combine agronomic and ecological processes enhance the capacity of the agroecosystem to face harsher situations, through higher pest control, soil fertility and water retention capacity (Aguilera et al., 2020). In Europe, these practices are considered, in some way, as updated versions of abandoned traditional practices to current socioeconomic conditions (Cayre et al., 2018). Others argue that current knowledge of ecological processes can help to optimize agriculture through sustainable intensification (Barot et al., 2017; Cayre et al., 2018; Garnett et al., 2013).

1.4.2. Nature-based Solutions for climate change adaptation

NbS to adapt to climate change gained in popularity for their implementation within multiple ecosystems, including mangroves where ecosystem restoration aimed at mitigating the more frequent coastal flooding, river floodplains where management of riparian forests decreased flood risks, agricultural systems where agroecological practices mitigate hazards such as drought, soil erosion and pest attacks, forests where sustainable management increase resilience to climate hazards (CBD, 2009; Cohen-Shacham et al., 2016). Subsequently, initiatives emerged in other ecosystems, as evidenced by the high number of projects related to NbS that have been funded by the European Union (Faivre et al., 2017). They concern various sectors, including agriculture, forestry, urban planning, and water bodies management, among others. Despite the diversity of interventions, NbS share a common principle: the dynamic essence of the ecosystems allows them to adapt to changing conditions, and to become more effective over time in addressing societal challenges. In contrast, grey infrastructures deliver immediate benefits but deteriorate over time and do not provide a range of co-benefits (Anderson et al., 2021; Daigneault et al., 2016; Seddon et al., 2020). Criticism has been raised regarding the NbS concept, seen by some as a novel marketing notion that fails to address the root cause of vulnerability, and maintains the system on the same trajectory, without considering the diverse values of nature (Eggermont et al., 2015; Melanidis and Hagerman, 2022). Others argue that NbS gather under a common purpose all the alternative options that sometimes have not even had a voice, and argue for the use of international standards for their operationalization (Eggermont et al., 2015; IUCN, 2020).

1.4.3. Implementation stage of Nature-based Solutions

NbS can be implemented by public institutions, e.g. adaptive management of forests on steep slopes to enhance protection against landslides using drought-tolerant mixed species (Lingua et al., 2020). They can be implemented by municipalities in urban areas to increase runoff regulation through river restoration or to mitigate heatwaves by increasing tree cover (Kabisch et al., 2017; Ramírez-Agudelo et al., 2020). Private actors are also involved in NbS implementation, e.g. farmers adopting agroforestry or agroecological practices (Aguilera et al., 2020; Vermeulen et al., 2018). Programs have emerged to disseminate NbS initiatives worldwide, and share experiences and good practices, such as PANORAMA, Climate-Adapt, Nature-based Solutions Initiative, and Oppla (Table S1).

NbS have demonstrated their effectiveness in addressing various challenges, such as mitigating floods and drought, enhancing biodiversity conservation and providing space for outdoor recreation (Buckwell et al., 2020; Chausson et al., 2020; Huang et al., 2021; Sahani et al., 2019; Seidl et al., 2011; Tomscha et al., 2021; Vojinovic et al., 2021). However, NbS effectiveness appears to be context-dependent, and some scholars have proposed guidelines aimed at designing NbS to maximize their effectiveness potential, e.g. by including local values and mitigating trade-offs between beneficiaries (Albert et al., 2021; Cohen-Shacham et al., 2019). However, additional to still lagging evidence on NbS effectiveness, other knowledge gaps remain, especial-

ly concerning the nature of NbS that are already implemented, their current local implementation rate and location, particularly in mountains (Doswald et al., 2014), and the driving forces behind their implementation, including the obstacles and motivations with their adoption (Albert et al., 2021; Mastrángelo et al., 2019; Ruangpan et al., 2020). These are the gaps this thesis focuses on.



Fig. 4. Nature-based Solutions are rooted in the relationships between biodiversity, ecosystem functioning and their contributions to human well-being. They are “actions to protect, sustainably manage and restore natural or modified ecosystems that address societal challenges effectively and adaptively, simultaneously providing human well-being and biodiversity benefits” (Cohen-Shacham et al., 2016). Source: Cohen-Shacham et al. (2016)

1.5. Decision-making context and enabling conditions

1.5.1. The values-rules-knowledge framework

NbS, as an adaptation option, are implemented after consideration of plausible options, that should include site-specific characteristics and considerations of people's beliefs and habits. The decision-making context comprises this set of elements that together lead individuals or groups in making decisions (Moser and Ekstrom, 2010). Environmental scholars have identified the decision-making context as a result of interactions between human values, formal and informal rules and knowledge (Gorrdard et al., 2016). Values represent a “set of ethical precepts that determine the way people select actions and evaluate events” and include, among others, universalism and power (Schwartz, 2012). In the IPBES values assessment report, broad values are described as “general moral guiding principles”, while the specific values of nature are considered the “judgements regarding nature's importance in particular situations” (IPBES, 2022). The specific values of nature encompass instrumental values when biodiversity and ecosystems are perceived as a source of provision, relational values, i.e. described by an intrinsic interlinkage between individuals and nature, such as place attachment, and intrinsic values, i.e. when nature is considered as a conservation target for itself or, in other words, disinterested (Chan et al., 2016; Jax et al., 2018; Pascual et al., 2017). Multiple broad and specific values may be involved in a decision, and their weight in a choice can vary from one decision to the other.

The legal and regulatory policy instruments applied to a certain region, i.e. formal rules; have a large potential to impact a decision, e.g. through binding legislation or incentives (Dopfer and Potts, 2009). The habits and norms, i.e. the informal rules, also wield powerful influence over the direction of choices (Ostrom, 2011). Lastly, although information alone does not drive decisions to take action, the mix of technical, scientific evidence-based and experiential knowledge contributes to evaluating the available options (Kadykalo et al., 2021; Stoutenborough and Vedlitz, 2014; Toomey, 2023; Vogel et al., 2007).

1.5.2. The levers and barriers to adaptation

The values, rules and knowledge framework (vrk) was previously used to detect the levers and barriers that play a role in the decision-making context of adaptation initiatives (Figure 5, Gorrdard et al., 2016; Lavorel et al., 2019; Topp et al., 2021). However, the main components of decision-making contexts that drive NbS implementation are still unclear. Previous studies identified specific pivotal levers that had played a role in decision-making, including change in access to funds, collaboration processes (Moreau et al., 2022), governance (Egusquiza et al., 2019), regulations (Chan et al., 2020), knowledge system (Kumar et al., 2020), societal values (Abson et al., 2017; Boon-Falleur et al., 2022). A better understanding of the decision-making context leading to NbS implementation would identify the key enabling conditions for NbS implementation.

Importantly, the identified leverage points for adaptation relate to the indirect drivers of climate and biodiversity crises (Brondizio et al., 2019; Chan et al., 2020). Previous scholars have identified the levers to activate to amplify adaptation initiatives in social-ecological systems, hereafter referred to as scaling (Lam et al., 2020; Moore et al., 2015). Scaling refers to the multiplication of initiatives (scaling-out), that can be fostered by raising awareness and shifting values (scaling-deep) (Lavorel et al., 2019; Pascual et al., 2023), and through new policies enabling NbS implementation (scaling-up) such as binding regulations or incentives (Schröter et al., 2022; Toxopeus and Polzin, 2021).

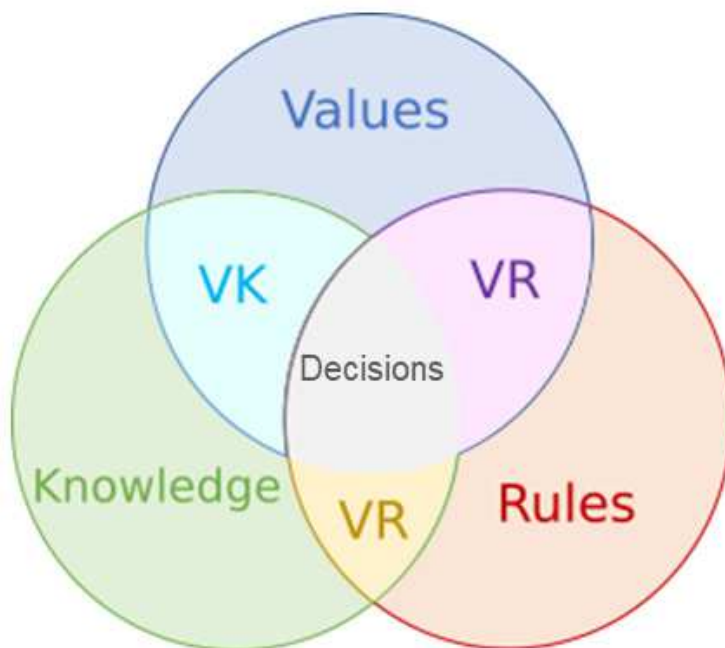


Fig. 5. The vrk (values-rules-knowledge) framework describes the decision-making context in social-ecological systems. Adapted from Gorddard et al. (2016).

1.6. Spatial prioritisation of Nature-based Solutions

Spatial planning is a promising instrument to foster NbS by incorporating decision-making into landscape management interventions (Albert et al., 2014a, 2020). Spatial planning policies have increasingly incorporated biodiversity, NCP or climate change adaptation (Longato et al., 2021; Perosa et al., 2021) and spatial planning and prioritization around NbS is thus a key element for their future scaling.

1.6.1. Spatial prioritization for conservation

Given the limited amount of human and financial resources to implement on-ground interventions, prioritisation is crucial to optimize these resources (Sinclair et al., 2018). Due to the spatial heterogeneity of biophysical and socio-economic conditions in a given region, mapping variables of interest is useful to support decision-makers and planners (Albert et al., 2014b, 2014a). Indeed, opportunities and constraints can be identified. For example, in conservation research, tools have been developed to identify priority areas to preserve biodiversity, although this objective is often considered in contrast to the local economy or development (Bigard et al., 2020; DeFries et al., 2004; Gonzalez-Redin et al., 2016). The methods commonly used for this purpose are the identification of biodiversity hotspots based for example on species richness (Moilanen et al., 2011; Ramel et al., 2020), or an approach based on endangered species, such as the identification of their habitat suitability (Chen et al., 2019; Huang et al., 2020). These mapping works were used to support the creation of protected areas (Jung et al., 2021; Kukkala et al., 2016), or to contribute to habitat connectivity through ecological corridors (Garibaldi et al., 2021; Huang et al., 2020).

The emergence of ecosystem services in research and policy has driven a substantial body of studies with a focus on ecosystem services assessment and mapping to provide guidance for optimising biodiversity conservation and human activities (Bateman et al., 2013; Burkhard and Maes, 2017; Evers et al., 2018; Kremen and Merenlender, 2018; Naidoo et al., 2008). Various tools have been developed to this purpose, mainly based on biophysical variables and LULC data (Maes et al., 2012; Schirpke et al., 2019a). However, mismatch can arise between priority areas for NCP and for other interests, such as biodiversity (O'Connor et al., 2021), and between NCP categories (Birol et al., 2009; Crouzat et al., 2015). These studies mostly concentrate on identifying hotspots of specific variables of interest, e.g. biodiversity or NCP, to guide decision-making towards their preservation in the face of human activities (Dunford et al., 2015; Gonzalez-Redin et al., 2016). However, spatial prioritisation for conservation is criticised for not considering the actual benefits of this action compared to the scenario without preservation (Tallis et al., 2021), or for not considering local context (Wyborn and Evans, 2021).

1.6.2. Spatial prioritization for interventions

Another expanding body of literature focuses on areas where the variables of interest have experienced the most significant declines, emphasizing the need for restoration (Bullock et al., 2011; Mappin et al., 2019). Consistent with conservation research, restoration prioritisation tools have emerged for biodiversity (Mappin et al., 2019), ecosystem services (Comín et al., 2018), and both (Egoh et al., 2014; Yin et al., 2022). The methods are mainly based on the prediction of values derived from restoration projects, and comparisons with the initial state to evaluate the effectiveness of the measure (Bastin et al., 2019; Strassburg et al., 2020). The areas to prioritize are, therefore, those with the highest positive outcomes.

More recently, prioritisation studies have focused on various types of NbS, such as agroforestry practices (de Mendonça et al., 2022; Fagerholm et al., 2016), wetland reconstruction (Odgaard et al., 2017), urban green infrastructure (Ou et al., 2022), and protective forests against landslides and rockfalls (Kato and Huang, 2021). However, studies focusing on spatial prioritisation often fall short in considering social aspects and equity (see some exceptions (Langemeyer et al., 2018; Ruangpan et al., 2021)) (Albert et al., 2020; Sandbrook et al., 2023).

1.6.3. Spatial prioritization for climate change adaptation

A limited number of prioritization studies have addressed climate change adaptation (Longato et al., 2021), although methods to incorporate climate change in spatial prioritisation have been developed for decades (Dessai et al., 2005; Vos et al., 2008). Climate risk assessments are often spatial-explicit to guide decision-making in identifying areas where the most vulnerable and exposed communities are facing climate hazards (Villani et al., 2022). Several methods have been developed for this purpose, with risk commonly assessed by the multiplication of its three components (Dilawar et al., 2022; Liu and Chen, 2021). However, exposed assets to climate hazards are rarely linked to NCP, as well as to vulnerability indicators (Hagenlocher et al., 2019). Some frameworks have emerged to spatially prioritize NbS, in different contexts such as deltaic socio-ecological systems (Depietri, 2020; Hagenlocher et al., 2018), river basins (Mubeen et al., 2021) and agriculture landscapes (Shah et al., 2020). However, they addressed separately ecological and social dimensions of exposure and vulnerability, missing opportunities to consider NCP (exception in urban areas (Balzan et al., 2021; Longato et al., 2023)) (Lazzari et al., 2021; Thiault et al., 2018). Local context and relevant variables need to be considered for spatial prioritisation of NbS interventions, and to deal with the uncertainty of the model predictions.

2. Study area – the European Alps

2.1. History and extent of the Alps

The European Alps, hereafter the ‘Alps’, constitute a mountain range that spans 1,200 km long and 250 km wide, covering a total of 190,000 km². The highest peak of the Alps is Mont Blanc, which stands at an elevation of 4,808 m asl (Gazzelloni et al., 2015).

Humans (*Homo sapiens*) have inhabited the Alps since around 4 000 BC. During this time, agriculture has flourished and natural Alpine grasslands have been used for livestock breeding – a practice that persists nowadays during summer (von Scheffer et al., 2019). The traditional practices of the inhabitants are recognized as cultural heritage (EEA, 2010; Marsoner et al., 2018) and several local handmade products are certified as preserving the tradition (European Commission et al., 2013; Lamarque and Lambin, 2015). The demography in the Alpine arc has increased over time, reaching 13 million inhabitants to date, spread across eight countries: Austria, Italy, France, Germany, Liechtenstein, Monaco, Slovenia and Switzerland (Gazzelloni et al., 2015).

Two administrative boundaries delineated the spatial extent of the Alps (Figure 6). The Alpine Convention, ratified by the eight Alpine countries in 1991, and the Alpine Space, defined by EUSALP (European Union Strategy for the Alps), a structure established by the European Union to support a macro-regional strategy addressing common challenges at the Alpine scale. The Alpine Convention area covers the Alpine arc, without the surrounding lowlands. Within it, the two major cities are Grenoble (France) with 600,000 inhabitants in its urban area, and Innsbruck (Austria) with 150,000 inhabitants (Gazzelloni et al., 2015). The Alpine Space covers the Alpine Convention area and the surrounding lowlands, including some areas of the Mediterranean coasts, as well as major urban centres such as Lyon (France), Munich (Germany), Milan (Italy) and Wien (Austria), Zurich (Switzerland) and Ljubljana (Slovenia).

2.2. The threatened biodiversity and Nature’s Contributions to People

The Alps are a biodiversity hotspot due to the unique habitats they comprise, housing rich arrays of species, some of which such as the Alpine ibex (*Capra ibex*), the Alpine marmot (*Marmota marmota*), the European blueberry (*Vaccinium myrtillus*) and the edelweiss (*Leontopodium nivale*) have a symbolic value (Rüdisser et al., 2019). The unique character of these habitats and the fact that the increasing amount of pressure from human activities is however lower in their case compared to the lowlands made possible the creation of protected areas all over the Alps (Bender et al., 2017).

The Alps, considered as the water tower of Europe, are renowned for the precious NCP they provide. In addition to the immense amount of freshwater that benefits both the Alpine Space and areas beyond, the Alps also attract tourists in the millions all around the year with outdoor recreation activities (Gazzelloni et al., 2015; Schirpke et al., 2019b). Moreover, the natural Alpine grasslands are home to a rich cultural heritage and famous agricultural products such as cheeses and honey (EEA, 2010; European Commission et al., 2013). The Alps have been recently referred to as sentinels of climate change due to the fact that environmental changes are more visible in their societies and ecosystems (Gobiet and Kotlarski, 2020; Pepin et al., 2015). For instance, Alpine temperatures have increased by 1.8°C since the preindustrial period, a rate twice the global one, and are expected to rise by 4°C by the end of the century, according to the strongest emissions scenarios of the IPCC (Gobiet and Kotlarski, 2020). Moreover, the changes in precipitation seasonal distribution are likely to continue, with lower expected precipitation levels in the summer, and higher ones in the winter. However, these changes are not evenly distributed across the Alps, with greater effects observed in the southern part and at higher elevations (Kotlarski et al., 2022).

Consequently, ecological niches of Alpine species are shifting upwards, but the species already living at the summits are critically threatened (Brambilla et al., 2018). Although vegetation productivity is increasing, forests and grasslands are undergoing an expansion of pests, e.g. die-back attacks on oak and spruce forests, worsened by more frequent water scarcity (De Boeck et al., 2016; Sire et al., 2022). Agriculture and forests are affected by drought and wildfires, leading to a reduction in food production and the protective function of forests against landslides and avalanches (De Boeck et al., 2016; Dupire et al., 2020; Stephan et al., 2023; Vacchiano et al., 2018). Permafrost thawing causes an increase in rockfall events, exposing many communities to higher occurrences of floods (Ragettli et al., 2021; Schlögl et al., 2021; Wilhelm et al., 2022).

2.3. Adaptation responses in the Alps

Adaptation responses have emerged across all sectors in the Alps (Bergeret and Lavorel, 2022; Cattivelli, 2021), and include, among others, local initiatives such as wetland conservation options, changing agricultural and forestry practices, and snow-making technology (Vij et al., 2021). Outdoor recreation activities, upon which a large part of the Alpine economy relies, are also disrupted by climate change (Beaumet et al., 2021). For example, ski tourism is particularly vulnerable to snow cover reduction, while summer activities such as hiking are becoming more attractive due to the cool temperature of the mountains. Nevertheless, these activities increase pressure on already sensitive ecosystems (Morin et al., 2021; Pröbstl-Haider et al., 2015). Moreover, although a limited number of governance and policy responses has been reported (Elkin et al., 2015; Vij et al., 2021), some emerged to mitigate climate impacts such as land use regulations, policy recommendations, incentives for adaptation measures implementation, and raising awareness activities (Cattivelli, 2021; Nordbeck et al., 2019; Thieken et al., 2016). The implementation gap is still deepening, requiring unprecedented efforts to limit losses and damages (Cattivelli, 2021; McDowell et al., 2021).

3. Research context

My PhD thesis is part of the PORTAL project (Pathways of Transformation in the Alps), funded by the French National Research Agency's Programme d'Investissements d'Avenir - Make Our Planet Great Again (2019-2025) and led by Ignacio Palomo (IRD-IGE, Grenoble) and Sandra Lavorel (CNRS-LECA, Grenoble). The project aims to identify and characterize initiatives seeking transformative adaptation to climate change in the Alps. Its objectives include the identification of NbS in the Alps, the assessment of NbS outcomes, their characterization in relation to transformative change and the co-construction and dissemination of related knowledge.

My PhD thesis, which started at the beginning of PORTAL, contributes to the development of the objectives of the project. Within the PORTAL project, I participated in the supervision of six interns who have contributed to the progress of the project's objectives. Through regular meetings, some of the members of the project have contributed to the achievement of this work, namely Bruno Locatelli (CIRAD & CIFOR, background in Environmental Sciences), Emilie Crouzat (INRAE, background in ecology), Enora Bruley (University of Geneva, background in Environmental Science), Alberto González-García (IGE, background in Geography), and Nicolas Dendoncker (University of Namur, background in Geography).

During my PhD thesis, I undertook a research stay at the Technical University of Munich for three months, spanning from October to December 2022. I was hosted by the Chair for Strategic Landscape Planning and Management, under the leadership of Pr. Stephan Pauleit, and I collaborated with Aude Zingraff-Hamed and her team. I had the opportunity to benefit from the experiences and insights of researchers involved in a European-funded project, PHUSICOS, which aimed at assessing the NbS effectiveness in mitigating hydrological hazards (Solheim et al., 2021), and discerning the key governance models associated with the various stages of the NbS implementation (Zingraff-Hamed et al., 2021). This collaboration significantly contributed to the achievement of my research, offering not only insights specific to my work, but also a broader understanding of NbS through interactions with researchers working on NbS in sub-Saharan and South American contexts, as well as in urban areas.

4. Research questions and objectives

My PhD thesis aims to understand the current implementation of NbS in the Alps to guide their future scaling.

To address this challenge, I focused my work on three research questions along with their specific objectives (Figure 6):

1) What NbS have been implemented in the Alps and where?

The main aim of Chapter II is to identify and characterise the already implemented NbS in the Alps. The specific objectives are: i) to describe the portfolio of existing NbS; ii) to identify the interlinkages between the NCP they aimed to provide and the hazards they aimed to address; and iii) to characterize the location of NbS regarding socio-ecological and climate conditions.

2) Which factors drive NbS' implementation? What conditions may facilitate their future scaling?

The main aim of Chapter III is to understand the decision-making contexts around the NbS implemented in the Alps. The specific objectives are: i) to identify the main values, rules and knowledge involved in the implementation process; ii) to evaluate the transformative potential of these NbS; and iii) to assess the relationships between the levers and the transformative potential.

3) Where to scale NbS implementation in priority areas for adaptation?

The main aim of Chapter IV is to identify the priority areas to implement NbS for adaptation to droughts. The specific objectives are: i) to develop a method to determine priority areas for nature-based adaptation considering hazards and NCA; ii) to evaluate the potential synergies and trade-offs of these priority areas regarding climate adaptation, mitigation and biodiversity conservation; and iii) to characterise the enabling conditions to implement NbS in the identified priority areas.

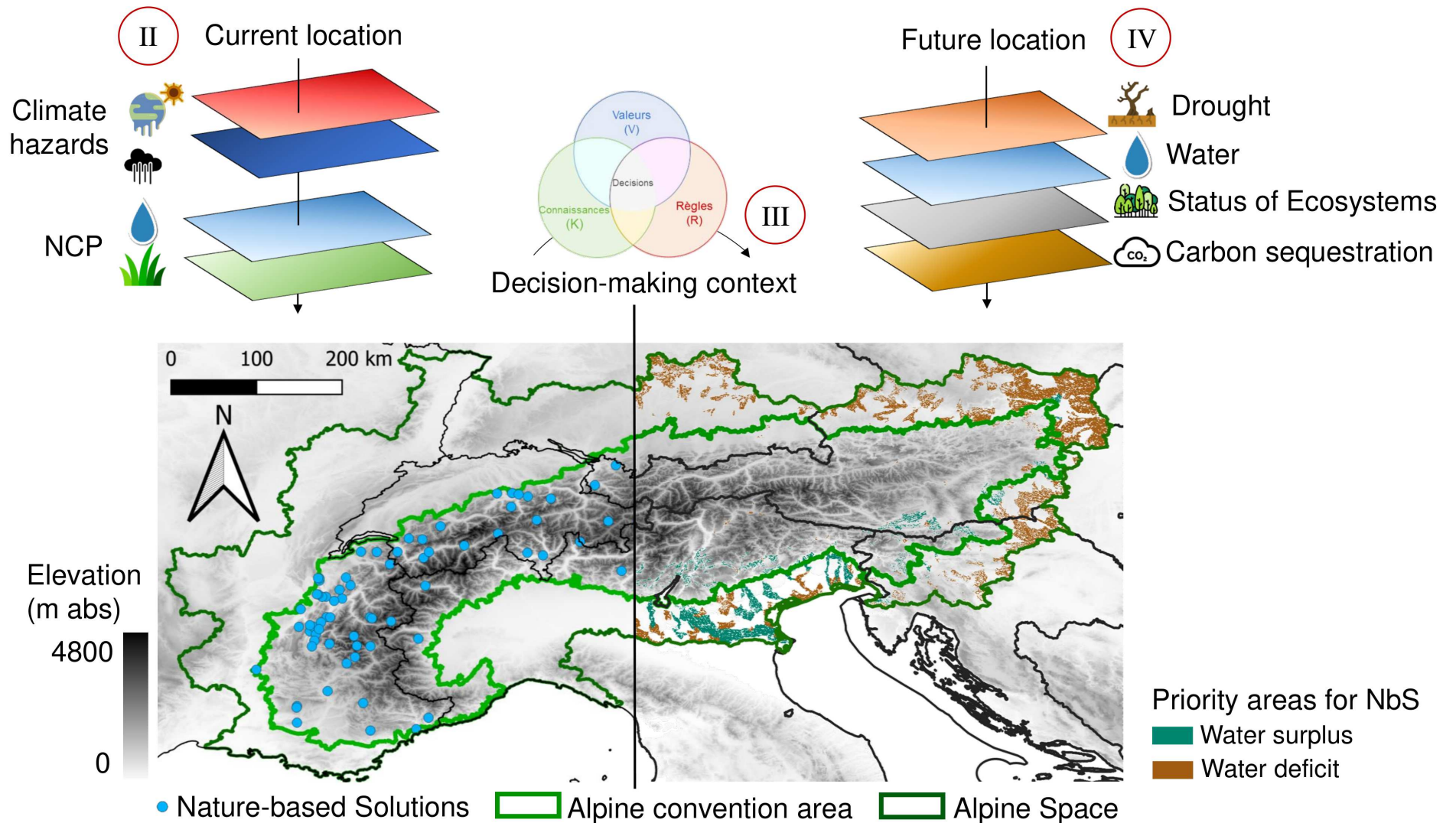


Fig. 6. Graphical summary of the methodologies used for the three chapters of the PhD thesis. Source: the author. Elevation data is publicly available for academic use by Worldclim (<https://worldclim.org/>). Country borders and the perimeter of the Alpine Convention Space are publicly available for academic use by the Permanent Secretariat of the Alpine Convention (<https://www.atlas.alpconv.org>).

5. General methodology

5.1. Description and method to build the PORTAL database

To address these research questions, I initially reviewed the NbS already implemented in the Alps that were published on available online databases gathering adaptation initiatives. I collected all the initiatives that I could identify in the Alps, aligning with the IUCN definition of NbS. I limited the search to the initiatives implemented within the Alpine Convention to remain specific to mountain areas. Although many NbS have already been studied in the surrounding lowlands, particularly in cities such as Milan or Munich, my objective was to contribute to reducing the knowledge gap for mountain regions with only a limited number of identified initiatives.

The inclusion criteria were designed to collect initiatives that aim to address at least one climate-related hazard, to maintain or provide NCP, to deliver benefits for biodiversity, and to provide social or economic outcomes. I collected most of the available information regarding these initiatives, including basic information regarding their names, descriptions, references, countries, and locations. I also included addressed hazards, additional objectives, and the NCP they aimed to maintain or provide. The current stage of implementation and durations, the leading organisations and the collaborative ones, were also filled in. The last included element is the type of interventions, that was categorised following the classification proposed by Donatti et al. (2020): (i) on-ground NbS which includes restoration, protection, sustainable management and creation of ecosystems; (ii) enabling NbS which include knowledge production, awareness-raising activities, the implementation of new policies or plans about NbS; and (iii) mixed NbS which comprise both on ground and enabling activities. An additional section of the database allowed for the inclusion of supplementary elements related to the initiatives, such as funding and cost data, although this information was not accessible for the majority of the NbS.

Among the few databases dedicated to NbS, most of the initiatives are located in the southern countries (such as EquatorInitiative¹). Other databases gather a lot of adaptation initiatives worldwide. However, most of these initiatives do not meet the NbS inclusion criteria, e.g. grey infrastructure implementation for natural disaster reduction. Some NbS were made available through research projects, particularly those recently funded by the EU Horizon 2020 programme² (Al Sayah et al., 2022; Davies et al., 2021), and by the EU Interreg Alpine Space

1 The EquatorInitiative database collected NbS to recognize and communicate on local sustainable development initiative. More information available online (last visit on September 30, 2023): <https://www.equatorinitiative.org/knowledge-center/nature-based-solutions-database/>

2 The Horizon 2020 was the EU's research and innovation funding programme from 2014-2020. More information available online (last visit on September 30, 2023): https://research-and-innovation.ec.europa.eu/funding/funding-opportunities/funding-programmes-and-open-calls/horizon-2020_en

programme³. Additionally, national and transboundary programs have funded research-action projects related to NbS, such as the Swiss National Climate Change Adaptation pilot programme⁴, the 4 per 1000 initiatives⁵ to implement NbS for carbon sequestration in soils, and the Bundesamt für Naturschutz⁶ which provided examples of NbS in Bavaria (Germany).

Considering the limited number of NbS identified within these databases and projects (the full list is available in the Appendix of this chapter), I applied an additional research protocol to seek local initiatives from grey literature. I extended the collection to the websites of the governmental agencies related to biodiversity conservation, protected areas, agriculture, forestry and water bodies management, for each of the six main Alpine countries. Through this method, I found some NbS led by local stakeholders, and I contacted some of them to request further information regarding their initiative, when needed. These individuals not only provided me invaluable insights regarding their work but also broader information, including details about other NbS they knew. This snowballing method has proven its ability to collect more NbS, e.g. the ones that were not publicly shared online.

I mapped the boundaries of each NbS using QGIS (version 3.16.5) based on the initiative's online description or by contacting one person who was involved in the initiative and who had sufficient knowledge of it. The quality of the database was improved through the contributions of three master students who worked on identifying and mapping some NbS. A large part of online NbS records did not include their spatial boundaries, and due to unresponsive NbS implementers to our requests, we were only able to map and include almost one hundred NbS. To foster the dissemination of NbS, I published online⁷, with the great help of two students and my supervisors, the description of a quarter of the NbS of the database.

Rather than aiming to be exhaustive, the PORTAL database seeks to represent the diversity of existing solutions to address similar issues across different contexts. Importantly, the database is flexible and may be complemented over time with additional NbS. The database was not only used for this PhD thesis, but has also been used by colleagues working within the PORTAL project, and external partners. The database's flexibility enables external people to use it, e.g. by selecting NbS related to specific interventions, such as addressing water scarcity, or reforestation, and to improve it, e.g. by mapping more precisely the spatial boundaries of the initiatives.

3 The Interreg Alpine Space programme finances transboundary projects involving research institutions, companies, NGO and associations to tackle common societal challenges in the Alpine Space. More information available online (last visit on September 30, 2023): <https://interreg.eu/programme/alpine-space/>

4 The Swiss Pilot programme Adaptation to climate change of the NCCS (National Centre for Climate Services) supports innovative projects aimed at adapting Swiss regions or cities to climate change. More information available online (last visit on September 30, 2023): <https://www.nccs.admin.ch/nccs/en/home/measures/pak.html>

5 The “4 per 1000” initiative aims to collect initiatives aiming at addressing food security and carbon sequestration. More information available online (last visit on September 30, 2023): <https://4p1000.org>

6 The Bundesamt für Naturschutz is the German Federal Agency for Nature Conservation, aimed at collecting NbS in Germany. More information available online (last visit on September 30, 2023): <https://www.bfn.de/en>

7 The PORTAL website presents the description and the location of some of the NbS of the database, that are made available online: <https://portal.osug.fr/-EXPLORE-THE-INITIATIVES->

5.2. Ecological and climate services

The increasing considerations of climate and ecological issues have led institutions from countries and the European Union to fund regional assessments and mappings of ecological and climate conditions, as well as their trends. The European Environment Agency (EEA) and Copernicus have, therefore, significantly contributed to providing climate projections, including temperature, precipitation and hazards on a pan-European scale. They have also assessed and mapped the status of habitats for biodiversity conservation, the land-use and land-cover at very high resolution, the amount of carbon sequestered in ecosystems and their carbon saturation. However, some of the EEA layers I used do not cover Switzerland. The main challenge was to find other datasets and to harmonize data.

The database on NCP assessed and mapped at the Alpine scale by the AlpES project⁸ was a core element to address the hypotheses of this PhD thesis. To evaluate whether the NbS implemented in the Alps correlated with higher or lower values of NCP or climatic data, I extracted the values of the variables of each NbS location and I computed Wilcoxon tests to compare the values in NbS location with values in average in the Alpine Convention. Due to the heterogeneity of NbS size, and in order to deal with the spatial autocorrelation of the data, I performed statistical tests on thousands of permutations with random values within each NbS. To evaluate whether the location NbS relies on the combination of climatic and NCP variables, I computed heatmaps of the number of NbS per interval of both climate and NCP variables. The main constraint was to define the accurate number of intervals, and the cutting rules, to detect distribution differences.

5.3. Interviews and on-ground fieldwork

To identify the main reasons driving individuals or groups to implement the identified NbS, I contacted the implementers to request interviews. I decided to conduct semi-structured interviews because the decision-making context encompasses various elements that may not be adequately addressed by a questionnaire or a written description. These elements often relate to personal feelings, experiences, or worldviews, which are difficult to access without relevant initial and follow-up questions. In order to capture similar challenges as well as diversity, I selected the NbS that aimed to address the three most frequently addressed hazards of the database, namely droughts, floods and landslides. After having contacted, for each NbS, one person with enough knowledge of its implementation, twenty people answered positively to my request for conducting the interview.

⁸ The AlpES project (Alpine Ecosystem Services – mapping, maintenance and management) is a research project funded by the Interreg Alpine Space programme and that spanned from 2014 to 2020. The project assessed and mapped eight NCP supply, flow and demand at the municipality level in the Alpine Space. More information available online (last visit on September 30, 2023): <https://www.alpine-space.eu/project/alpes/>

Given that most of the case studies involved on-ground interventions, I decided to conduct in-person interviews and visit the interventions in the field every time it was possible. Firstly, I conducted interviews close to Grenoble, France, to test the interview guidelines with significant support from a master's student. Subsequently, in order to represent all the Alpine countries in this study, I organised a one-month field trip to conduct interviews with the individuals I contacted from the five other main Alpine countries, namely Switzerland, Germany, Austria, Slovenia and Italy. Unfortunately, I was not able to visit all the NbS sites, due to adverse weather conditions or to the large distance between the interviewee's office and the intervention sites. However, most of the interviewees had pictures of the intervention, which supported the follow-up discussions during the interviews. The analyses, presented in detail in Chapter III, comprise a textual analysis to code the mentioned levers and barriers. Then, a clustering analysis was performed to identify the different decision-making contexts. The transformative adaptation potentials were assessed using six criteria and correlated to the decision-making contexts.

During the field trip, I also visited the NbS interventions of the database for which I did not plan an interview. These visits allowed me to validate the information obtained from their online description, and in most of the cases, I collected additional information on the interventions. Lastly, I also discovered new NbS interventions that were not previously found. I have consequently included them in the PORTAL database for future purposes.

5.4. Roles of stakeholders in the thesis and roles of researchers in society

Stakeholders, practitioners and citizens played a significant role in designing the objectives of this PhD thesis. In addition to the NbS implementers I contacted to improve the database, many individuals I encountered contributed to shaping the direction of this research.

The PORTAL project organised a kick-off event during which local stakeholders related to biodiversity conservation or climate change adaptation were invited. The participants mentioned their perceptions of the rapid changes in ecosystems. They expressed awareness regarding the NbS concept but noted a lack of feedback regarding the existing initiatives. They mentioned some of the barriers they encountered to implement NbS but did not identify levers to overcome them.

During my PhD thesis, I had also the opportunity to collaborate with colleagues working on the PORTAL project. I participated in a stakeholders workshop focused on NbS for climate change adaptation in the Alps organised by Enora Bruley (Bruley et al. in prep.). The discussions held during the workshop were closely aligned with the topic of my PhD thesis, and, therefore, provided elements for guiding methods and interpreting the results.

In sustainability science, researchers are often in a position that is far from neutral (Crouzat et al., 2018). While maintaining rigorous and ethical methods remains crucial, the addressed

questions are rooted in societal issues (Donner, 2014). Some researchers prioritize active engagement in science-policy interfaces such as the IPBES or the IPCC, aiming to provide evidence-based recommendations to policymakers. In some cases, scientists, who can be the same, become activists to inform the public and urge policymakers to consider evidence-based knowledge for a sustainable future (Gardner et al., 2021). In this context, certain researchers argue for knowledge co-production, a collaborative approach to conduct research involving – often local – stakeholders aiming at providing solution-oriented outcomes that address concrete issues experienced by communities (Norström et al., 2020). Although my research does not strictly comply with the co-production framework, I aimed to evaluate the main barriers and needs of the stakeholders I met, including farmers, foresters, urban planners, hydrologists, conservationists, engineers, entrepreneurs, municipal and regional officers. I was conscientious when making recommendations, e.g. for policymakers, to ensure I did not misrepresent the visions and the values of these individuals. Preserving the trust-based relationship between the academic and on-ground worlds is essential to mitigate trade-offs towards a sustainable world (Chambers et al., 2021; Norström et al., 2020).

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Appendix

S1. Table: List of databases of initiatives reviewed for collecting Nature-based Solutions in the Alps

Database of initiatives	Website
Naturvation	https://naturvation.eu/
Oppla	https://oppla.eu/
BISE	https://biodiversity.europa.eu/
Nature4Cities	https://implementation-models.nature4cities-platform.eu/
ThinkNature	https://www.think-nature.eu
UrbanEurope	https://jpi-urbaneurope.eu/
Nature-based Solutions Initiative	https://www.naturebasedsolutionsinitiative.org/
Pegasus	http://pegasus.ieep.eu
ClimateADAPT	https://climate-adapt.eea.europa.eu/
PANORAMA	https://panorama.solutions/fr
Reconnect	http://www.reconnect.eu/
GEF	https://www.thegef.org/
WeADAPT	https://www.weadapt.org/
PreventionWeb	https://www.preventionweb.net
Operantum	https://www.operandum-project.eu/oals/
PreventionWeb	https://www.preventionweb.net/
4per1000	https://www.4p1000.org/
Adelphi	https://www.adelphi.de/en/

Ecologic	https://www.ecologic.eu/
Phusicos	https://www.phusicos.eu/
Interreg Alpine Space Programm	https://www.alpine-space.eu/
AQUACROSS	https://aquacross.eu/
ROBUST	http://rural-urban.eu/
UNFCCC	https://www4.unfccc.int/
Bfn	https://www.bfn.de/en
TRANSIT	https://www.transit-h2020.eu
Nature4cities	https://www.nature4cities.eu/
EquatorInitiative	https://www.equatorinitiative.org/
GANadapt	https://www.unep.org/gan/fr
EKLIPSE	https://eklipse.eu/
Nature4Climate	https://nature4climate.org/
Connect4Climate	https://www.connect4climate.org/
GoldStandard	https://registry.goldstandard.org/
Wbcsd	https://www.wbcsd.org/
Green cities	https://www.thegreencity.eu/
Regreen	https://www.regreen-project.eu/
Enable	http://projectenable.eu/
DReAMS	https://iclei-europe.org/
ConnectingNature	https://connectingnature.eu

ICLEI	https://iclei.org/en
Nature-based Solutions	https://www.nature-basedsolutions.com/
IWMI	https://www.iwmi.cgiar.org/
GrowGreen	http://growgreenproject.eu/
IKI	https://www.international-climate-initiative.com/
IUCN	https://www.iucn.org/
UN DecadeOnRestoration	https://www.decadeonrestoration.org/
NCCS	https://www.nccs.admin.ch/
CARE	https://careclimatechange.org/
CRiSTAL	https://www.iisd.org/
WaterRessource	www.waterandnature.org
UNGlobalCompact	https://www.unglobalcompact.org/take-action/events/climate-action-summit-2019/nature-based-solutions
Greensurge	https://greensurge.eu
Openness	http://www.openness-project.eu
AdaptationLearning	https://www.adaptationlearning.net/
CleverCities	https://clevercities.eu/
Progireg	https://progireg.eu
PEDRR	https://pedrr.org/
GCA	https://gca.org/global-commission-on-adaptation
Bluesolutions	https://bluesolutions.info/
Mountain Wilderness	https://www.changerdapproche.org

Chapter II

Nature-based Solutions for climate change adaptation are not located where they are most needed across the Alps



Mountain lakes are crucial ecosystems that provide a large range of contributions to people and constitute a habitat for Alpine biodiversity. They are increasingly impacted by global changes, highlighting the need for protection. At the Hintersee Lake, located in the Austrian Hohe Tauern National Park, human activities are limited to conserve the habitat, which has been declared as a natural monument. Source: the author.

Nature-based Solutions for climate change adaptation are not located where they are most needed across the Alps

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Abstract

Climate change impacts mountains socio-ecosystems by increasing certain natural disasters and changing Nature's Contributions to People (NCP). Nature-based Solutions (NbS) are increasingly implemented to help local communities adapt to climatic hazards. However, the relevance of their location in relation to those hazards and local NCP has hardly been addressed. In the PORTAL project (Pathways of Transformation in the Alps), we identified and mapped a portfolio of 97 NbS for climate change adaptation in the European Alps. Most NbS addressed drought or soil instability, and aimed to provide multiple NCP simultaneously such as wood production and protective function against landslides. We analysed whether NbS are located where they are the most needed, according to both current and future intensity of the hazards they aim to address and to supply-flow-demand indicators of the NCP they aim to provide. We found that the location of NbS is overall not related to current supply-flow-demand indicators of most NCP, nor to intensity of hazards. Nevertheless, NbS addressing droughts and floods are located in areas where these hazards are more intense, but do not match higher values for NCP indicators. Conversely, NbS aiming to produce wood and to provide protective function against landslides are located in areas with greater levels of these NCP, regardless of the intensity of hazards. These results suggest that hazards and NCP indicators are not the main drivers of NbS implementation. We argue that integrating local climate conditions and current NCP flows is needed to underpin a macro-regional strategy for planning NbS implementation.

Keywords

Nature-based Solutions, Climate Change Adaptation, Nature's Contributions to People, European Alps, Spatial analysis.

1. Introduction

Considered as one of the greatest challenges humanity faces, climate change threatens human good quality of life and ecosystems, especially in high-elevation areas, where temperature has been rising faster than in lowlands (Pepin et al. 2022). With this accelerating change, mountain communities already experience more frequent and intense natural hazard events, and these are expected to increase in the future whatever the carbon emission scenario (Gobiet and Kotlarski 2020). In the European Alps, climate scenarios suggest that the frequency and the intensity of extreme climatic hazards and climate-induced disasters – such as heatwaves, erratic rainfall, floods, wildfires, landslides, rockfalls and avalanches – will increase significantly during the 21st century (Gobiet et al. 2014; Einhorn et al. 2015; Beniston and Stoffel 2016; Gariano and Guzzetti 2016; Huss et al. 2017). The magnitude of these hazards will be elevation-dependent, with higher altitudes expected to experience a greater relative increase in temperature, and a lower relative decrease in snow cover duration (Gobiet and Kotlarski 2020). Precipitation projections are more uncertain especially in terms of potential changes in their geographic distribution; overall precipitation is likely to increase in winter, and decrease in summer, with significant geographic variation along a north-south axis (Gobiet and Kotlarski 2020). This, together with glacier retreat, will lead to more intense and frequent droughts, especially in summer (Gobiet et al. 2014; Laurent et al. 2020). Snow cover decrease will continue, in terms of quantity and duration (Gobiet and Kotlarski 2020; Morin et al. 2021).

This climate change threatens mountain biodiversity. Increasing temperatures in all seasons drive the upward shift of plant species, resulting in ecosystem composition change (Lamprecht et al. 2018), extinction risk for cold-adapted plant and animal species isolated to summits that may have nowhere to go (Pauli and Halloy 2019) and new suitable climatic conditions for invasive species (Carboni et al. 2018). This suggests the future loss of major parts of the habitat for up to half of endemic Alpine plants (Engler et al. 2011; Dullinger et al. 2012), and the high extinction risk of animal populations such as some Alpine ungulates (Lovari et al. 2020) and birds (Dirnböck et al. 2011; Ferrarini et al. 2017; Brambilla et al. 2018) in the absence of adapted conservation planning (Chamberlain et al. 2016). These effects on biodiversity and ecosystems, added to the increasing natural hazards and declining cryosphere, affect ecosystem functioning and consequently the diverse Nature’s Contributions to People (NCP) in mountain regions, including freshwater supply, wood and fodder production, forest protective function against landslides, pest control, outdoor recreation activities and global climate regulation among others, which benefit local communities, tourists and people living in lowlands (Palomo 2017; Schirpke et al. 2019a, b; Grêt-Regamey and Weibel 2020). For example, freshwater supply is highly sensitive to climate change in mountains, and millions of users upstream and downstream will be put at risk (Immerzeel et al. 2020; Mastrotheodoros et al. 2020). Heatwaves and drought hazards resulting from increasing temperature and the reduction of freshwater supply will have large social and economic consequences (Zappa and Kan 2007), with human health impacts in urban areas (Villanueva et al. 2015), perturbations of grassland and forest carbon sequestration ability (Mina et al. 2017; Ingrisich et al. 2018), pest expansion (Huss et al., 201), reduction of forest protective function against landslides due to increasing tree mortality (Allen et al. 2010; Sass 2014), and economic losses of farms with dairy cows submitted to more severe heat stress (Boni et al. 2014).

In the face of these unprecedented changes, adaptation options are being put in place in Alpine socio-ecological systems (Terzi et al. 2019; Vij et al. 2021). Among them, Nature-based Solutions (NbS) have recently gained attention in global research and practice as climate adaptation strategies (Seddon et al. 2020). NbS are actions to protect, sustainably manage and restore natural or modified ecosystems that address societal challenges effectively and adaptively, simultaneously providing human well-being and biodiversity benefits (Cohen-Shacham et al. 2016). Some examples are grassland conservation methods within ski resorts to reduce soil erosion (Casagrande Bacchiocchi et al. 2019); forest management practices and mixed tree species options to increase forest resilience (Elkin et al. 2015; Irauschek et al. 2017); adapted grassland management practices for mountain livestock production (Lamarque et al. 2013; Nettiier et al. 2017); and green infrastructure to reduce heatwave intensity in urban areas (Kabisch et al. 2017).

NbS for climate change adaptation are claimed to have the potential to maintain or enhance multiple NCP that help society adapt to climate change (Jones et al. 2012; Colloff et al. 2020). These NbS can apply on the ground measures to conserve or improve NCP that protect people from climate change (e.g., reforesting a landslide-prone area to improve NCP such as soil conservation or landslide reduction). They can also act on NCP drivers, such as land-use policies or incentives for good management (e.g., forest harvesting regulations or payments for ecosystem services), and address the vulnerability of NCP to climate change (e.g., by reforesting with species that will be adapted to future climate).

To our knowledge no study has evaluated the location of NbS regarding NCP or the hazards they aim to address. We assume that the need for NbS is higher where society is more likely to be affected, i.e. where climatic hazards are more intense or frequent; NCP are less supplied; and/or NCP are more used or demanded by society. We hence explicitly consider for the first time for assessing NbS the three NCP dimensions: supply, the amount of NCP coproduced by ecosystems and people (Schröter et al. 2012); flow, the part of the supply benefiting society; and demand, the amount of NCP society needs (Burkhard and Maes 2017). Our analysis considered those socio-economic factors included in NCP indicators (such as population density, presence of infrastructure or livestock) but not other factors often used in risk assessments, such as education levels, wealth, or governance (e.g. Gerlitz et al. 2017; Birkmann et al. 2022). We restricted our analysis to hazards and NCP indicators because of the subjectivity of selecting and combining socio-economic factors that may not be relevant to local society needs (Beccari 2016; Il Choi 2019). Following the IPCC framework (Field and Barros 2014), we define a hazard as “the potential occurrence of a natural or human-induced physical event or trend that may cause loss of life, injury, or other health impacts, as well as damage and loss to property, infrastructure, livelihoods, service provision, ecosystems and environmental resources”.

Here, we define needs for NbS in terms of climatic hazards combined with NCP, for example erratic rainfall (hazard) with forest protective function against landslides (NCP). We assume that the need for NbS is high where the NCP surplus is low, i.e. where the amount of NCP sup-

plied is closer to the amount of NCP used or demanded by society. In our example, this would regard areas with limited protective function from current forest against landslides. Similarly, we also assume that the needs for NbS are high where the NCP demand-supply is high, i.e. where any decrease in NCP supply risks to leave demand unmet. This would regard the same areas with currently low protective function of forest against landslides but also high demand from population and infrastructure for protective function against landslides. Similarly, we also assume that the need for NbS is high where the NCP demand-supply is high, i.e. where any decrease in NCP supply risks to leave demand unmet. This would regard the same areas with currently low protective function against landslides but also important protective function demand from the population and infrastructures against landslides. This consideration also applies to locations with a low demand-supply ratio in cases where currently low demand is expected to increase due to increasing hazards and current NCP supply may not sufficiently cover future demand. However, we note that this approach does not address cases of mismatch between supply and demand locations (Schirpke et al. 2019b).

To understand how NbS are distributed, we explore the spatial distribution of NbS in the Alps in relation to current and future climate change hazards and to NCP indicators separately, and in relation to their combinations. We first identified and mapped the location of implemented NbS in the Alps into a novel database. Secondly, we computed a spatial analysis to compare NbS locations to i) a series of current and future climate change hazards; ii) the NCP indicators including NCP supply, flow, demand as well as flow-supply and demand-supply ratios; iii) common combinations of hazards and NCP indicators.

2. Materials & Methods

2.1. Nature-based Solutions grey literature review

We identified NbS for climate change adaptation within the Alpine Convention space area, referred to as the Alps henceforth, which covers 190 717 km² within Austria, Italy, France, Switzerland, Germany, Slovenia, Liechtenstein and Monaco. We searched existing NbS and adaptation initiative databases, including ClimateADAPT, Oppla and PHUSICOS. Then, we explored the websites of environmental public agencies related to the forest, agriculture, fresh-water provision, biodiversity conservation and protected area sectors, for all countries of the Alps. We complemented this search with data from websites of partner organisations involved in the implementation of these NbS. Our main inclusion criteria targeted NbS aiming to address at least one climate change impact or at least one impact that is known to be enhanced by climate change. These initiatives had to address also the loss of habitat for biodiversity to be included.

We grouped NbS into three categories following the classification from Donatti et al. (2020): i) On the ground NbS, including the restoration, protection, creation of ecosystems and ecosystem sustainable management ; ii) Enabling NbS, which focus on the creation of new knowledge, awareness-raising activities and the implementation of new policies or plans in relation to nature-based adaptation; iii) Mixed NbS, which implement both on the ground and enabling activities.

We coded the climatic hazards addressed by each NbS as well as the NCP they address. For NCP we used the classification from Diaz et al. (2018) and adapted it to specific NCP addressed by NbS in mountain regions. We created subcategories resulting into 22 NCP listed in Supplementary file 1. For example, the extreme events regulation NCP from IPBES classification has been divided in eight sub-categories such as flood regulation or heatwave regulation. We then computed a Sankey diagram to illustrate the links between hazards addressed by NbS and the NCP they aim to provide. Finally, we mapped the boundaries of each NbS (QGIS software version 3.16.5) based on the initiative's description online or by contacting the person in charge.

2.2. Climatic hazards and Nature's Contributions to People

To assess current and future climatic hazards, we used data from the Climate Data Store, hosted on the Copernicus platform, between 1970 and 2000 for the reference period, and between 2050 and 2060 for the future. We selected the following variables: temperature, precipitation, snow cover, heatwaves intensity, flood hazard and wildfire hazard. Because we aimed to compare relative rather than absolute values between locations we selected the climatic scenario that had been used for each climate model (RCP 8.5 for most variables, and RCP 4.5 when RCP 8.5 was not available). For all variables, we computed the relative change from current to future values for each pixel. Details on each specific variable are in the Supplementary Files 2 and 3.

We used the indicators of NCP supply, flow and demand for seven NCP assessed and mapped at the municipality level by the AlpES project (Alpine Ecosystem Services - mapping, maintenance, management) based on biophysical and socio-economic variables (Schirpke et al. 2019a): freshwater; fodder; fuel wood; forest protective function against landslides; CO₂ sequestration; outdoor recreation; and symbolic biodiversity (for details, see Supplementary File 4). As the flood and heatwave regulation NCP were not mapped by the AlpES project, we did not include them in our analysis.

Adapted from the surplus-balance-deficit indicator developed by (Li et al. 2016), we computed the demand-supply ratio and the flow-supply ratio for each NCP, except for symbolic biodiversity for which we computed only the flow-supply ratio given demand for this NCP can be considered as global and was therefore not mapped by AlpES. As most NbS identified have been implemented after the data acquisition to map NCP indicators (e.g. 2012 for land use and land cover maps), we assumed that the NbS identified have not influenced NCP values (Schirpke et al. 2019a; Meisch et al. 2019; Jäger et al. 2020). Moreover, because most on-the-ground NbS cover a small surface relatively to the municipality's surface, we considered that they have a low influence on NCP supply at the municipality scale.

2.3. Data analysis

To deal with the different sets of units across studied climatic and NCP variables, we rescaled their values using a min-max normalisation (Peng et al. 2016), both for positive and negative values, calculated as (1):

$$X_s = \frac{X_i - X_{min+}}{X_{max+} - X_{min+}} \text{ if } X_i > 0 ; X_s = \frac{X_i - X_{max-}}{X_{min-} - X_{max-}} \text{ if } X_i < 0 \quad (1)$$

Where X_s is the rescaled value, X_i is the initial value, X_{min+} the lowest value of the subset of positive value, X_{max+} the highest value of the subset of positive value, X_{min-} the lowest value of the subset of negative value, X_{max-} the highest value of the subset of negative value.

We assigned the values of hazards and NCP layers spatially overlapping each NbS, and we performed Wilcoxon tests in order to detect whether values of hazards and NCP within NbS addressing them are significantly higher or lower than across the entire Alps (for details, see Supplementary File 2).

To detect whether the presence of NbS in the Alps reflects the combination of the intensity of the targeted climatic hazard and of the NCP known to help adapt to, or impacted by this hazard, we first created subsets of NbS targeting a specific combination of hazards and NCP known to address the impact. Given available data these were: drought hazards addressed by

NbS aiming to provide freshwater; drought hazards addressed by NbS aiming to provide grassland fodder; drought hazards addressed by NbS aiming to produce wood; heatwave hazards addressed by NbS aiming to produce wood. For each of them, we then computed two heatmaps of value distributions across the gradients of climatic hazard and NCP values, one for NbS locations and one for the entire Alps. We then subtracted the heatmaps of the Alps from the NbS heatmaps and used a Khi2 test to detect whether the NbS distribution is different from the distribution across the Alps.

3. Results

3.1. The multifunctionality of Nature-based Solutions in the Alps

We identified 97 NbS in the Alps (Fig. 1, for details in Supplementary File 5), addressing in total 22 different hazards in relation to climate change, and aiming to provide 22 different NCP. A quarter of NbS implement activities on the ground only (n=23), a quarter of NbS are enabling activities (n=23), and around half of the NbS are mixed (n=51), implementing simultaneously enabling activities and activities on the ground.

Overall, NbS across the Alps address a diversity of hazards. Half of NbS documented in our database aim to address at least two hazards simultaneously (51%). NbS addressing three (9%) or four hazards simultaneously (5%) are enabling activities that aim to counteract several hazards or target several sectors, such as research projects or local adaptation plans designed with stakeholders from multiple sectors (Supplementary File 5). Each NbS often aims to provide more than one NCP, which highlights the multifunctionality potential of NbS in terms of NCP they aim to deliver (Fig. 2). Hazards related to temperature changes are those most commonly addressed by NbS, including drought (32% of NbS), heatwaves (11%) and increasing temperature (6%). Among these, drought is associated with the highest diversity of NCP. Overall, NbS targeting drought aim to address 19 different NCP, including material NCP (mainly food), regulating NCP (mainly freshwater supply and soil quality) and non-material NCP (providing outdoor recreation activities) (Fig. 2). NbS also commonly address hazards related to soil stability, specifically landslides (11%), rock falls (7%), soil erosion (10%), avalanches (7%), and mudslides events (2%). Among these, NbS addressing landslides and rockfalls co-occur with 14 different NCP in total, mainly those related to the protective function against landslides. NbS addressing vector and water-borne diseases (32% of NbS – related to pests) co-occur with 14 different NCP in total, mainly the material NCP of wood production and the pest control regulating NCP (Fig. 2).

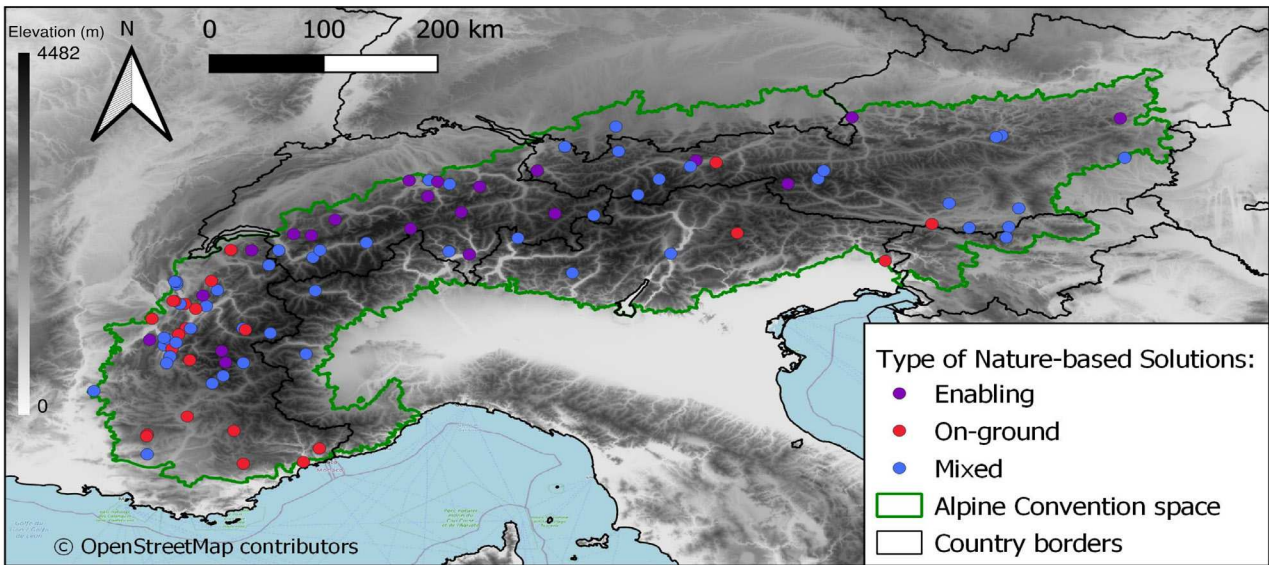


Fig. 1. Map of the 97 Nature-based Solutions identified within the Alps.

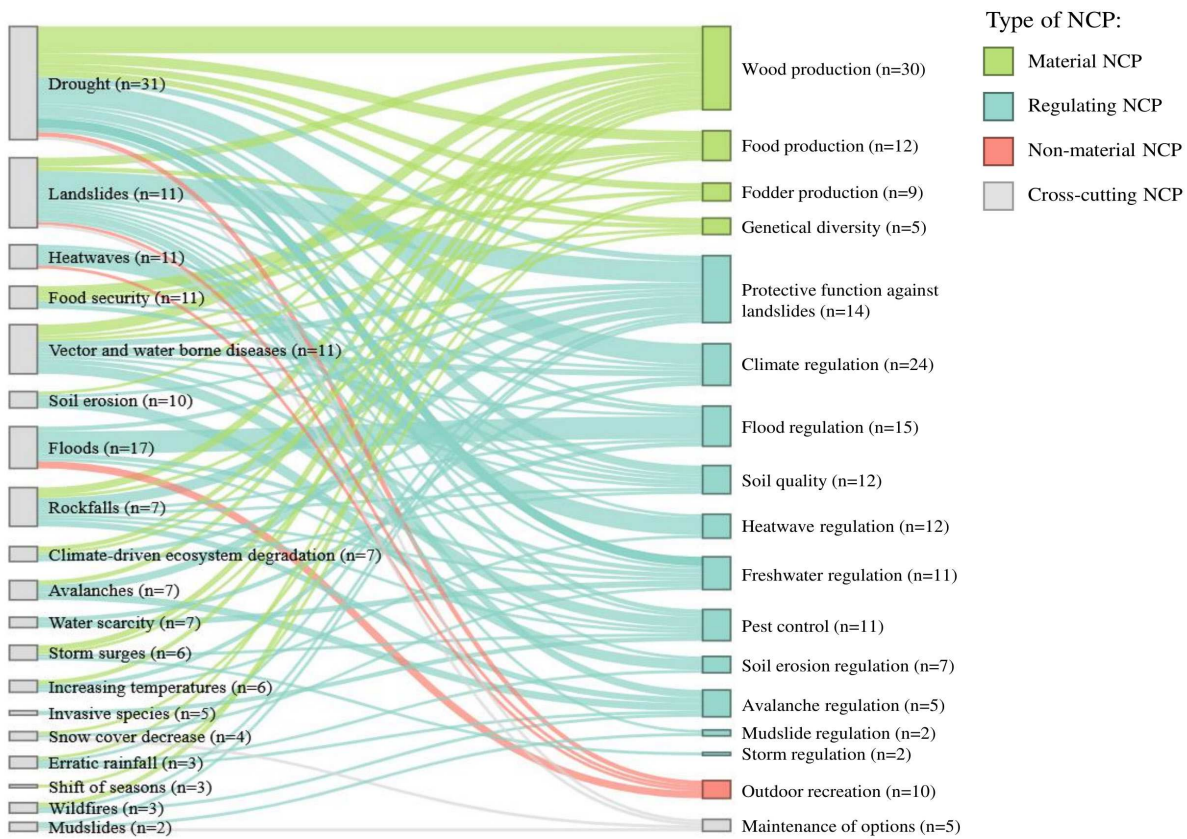


Fig. 2. Systematic map of the climatic hazards addressed by Nature-based Solutions (NbS) – on the left – and the Nature's Contributions to People (NCP) targeted by NbS – on the right. The links involving only one NbS are not represented. The number in each row indicates the number of NbS in each category.

When considering NCP, NbS mainly aim to provide materials, mainly wood production (31%), and address a total of at least 17 different hazards (mainly landslides and vector and water-borne diseases) (Fig. 2). A large number of NbS (29%) aim to provide food production NCP, and they address mostly food insecurity and drought hazards. A significant number of NbS aims to provide regulating NCP particularly the regulation of floods (15%), the protective function against landslides (14%) and the regulation of heatwaves (12%). Importantly, we reported many cases of NCP co-occurrence. For example, among initiatives aiming to provide protective function against landslides, some reforestation initiatives simultaneously target avalanche prevention. This explains why most NbS (50/97) aim to provide at least two NCP simultaneously, and seven NbS aim to provide more than five NCP simultaneously.

3.2. Location of Nature-based Solutions according to climatic hazards

For most hazards, NbS are not located in areas of highest hazards within the Alps, for the historical period, the future, or for the relative change of this hazard between the two periods, except for a few exceptions (Table 1). NbS addressing drought are located in areas that are not currently submitted to higher hazards than across the Alps. However, they do target areas that are projected to experience more intense drought, with greater changes in the drought index. On the contrary, NbS addressing heatwaves are located in areas that have experienced lower occurrence in the historical period than the Alps overall and that are likely to experience lower heatwaves in the future. Similarly, NbS addressing snow cover reduction are located where the snow cover will be less reduced during summer than across the Alps, with a lower reduction in summer snow cover from the historical to the future period. NbS addressing floods are located where the flood index is higher in the historical period than across the Alps. However, we found future flood hazards to be lower within NbS than across the Alps. Distributions of hazard values for each NbS are illustrated in the Supplementary File 6.

Table 1. Wilcoxon tests results comparing climatic variable values within Nature-based Solutions (NbS) and across the Alps.
 Significance level: (*): p-value <0.1 ; (**): p-value <0.05 ; (***): p-value <0.01; NS: not-significant.
 n: number of NbS.

Addressed-hazard	Seasonality	Historical	Future	Relative change
Temperature change (n=6)	Annual	NS	NS	NS
Heatwaves (n=11)	Annual	NbS < Alps (***)	NbS < Alps (*)	NbS < Alps (*)
Drought (n=38)	Annual	NS	NbS > Alps (***)	NbS > Alps (***)
Wildfires (n=3)	Annual	NS	NS	NS
Floods (n=17)	Annual	NbS > Alps (***)	NbS < Alps (***)	NbS > Alps (***)
Precipitation change (n=9)	Annual	NS	NS	NS
	Winter	NS	NS	NS
	Spring	NS	NS	NS
	Summer	NS	NS	NS
	Autumn	NS	NS	NS
Snow cover reduction (n=4)	Winter	NS	NS	NS
	Spring	NS	NS	NS
	Summer	NS	NbS < Alps (***)	NbS < Alps (***)
	Autumn	NS	NS	NS

3.3. Location of Nature-based Solutions according to Nature's Contributions to People

NbS follow different spatial patterns in relation to the distribution of NCP supply, flow, demand and their ratios. NbS targeting fodder production and outdoor recreation NCP are generally not located where their supply or demand differ from the Alps (Table 2). In contrast, NbS targeting freshwater supply are located where its flow value, namely water use, is higher than across the Alps. Similarly, NbS targeting protective function against landslides are located in hotspots of its flow-supply ratio, mostly reflecting the higher value of the flow. This indicates that these NbS are implemented where the NCP is highly used, independently of the supply and demand. NbS targeting wood production are located in areas where they are least needed as they are located where fuel wood demand is lower and supply is higher compared to the Alps. NbS targeting CO₂ sequestration are located in areas where supply is higher than across the Alps, yet where demand is also higher. Finally, regarding symbolic biodiversity all NbS are located in areas with lower values of both supply and flow than across the Alps. Distributions of NCP values for each NbS are illustrated in the Supplementary File 7.

Table 2. Wilcoxon tests results comparing Nature's Contributions to People (NCP) values within Nature-based Solutions (NbS) and across the Alps. D-S ratio means NCP demand-supply ratio. F-S ratio means NCP flow-supply ratio. D-S/F ratio is used when the supply and the flow are equivalent. Significance level: (): p-value <0.1 ;(**): p-value <0.05 ; (***): p-value <0.01; NS: Not-significant. The number on each row indicates the number of NbS targeting the specific NCP*

NCP	Demand	D-S ratio	Supply	F-S ratio	Flow
Freshwater (n=11)	NS	NS	NS	NS	NbS > Alps (***)
Fodder (n=9)	NS	NS	NS	NS	NS
Fuel wood (n=30)	NbS < Alps (**)	NS	NbS > Alps (*)	NS	NS
Protective function against landslides (n=14)	NS	NS	NS	NbS > Alps (*)	NbS > Alps (*)
Outdoor recreation (n=10)	NS	NS	NS	NS	NS
Symbolic biodiversity (n=97)	NA	NA	NbS < Alps (**)	NS	NbS < Alps (*)
NCP	Demand	D-S/F ratio	Supply/Flow		
CO ₂ sequestration (n=24)	NbS > Alps (**)	NS	NbS > Alps (***)		

3.4. Location of Nature-based Solutions according to the combination of climatic hazards and Nature’s Contributions to People

Consistent with our findings for climatic hazards and NCP supply, flow and demand, overall NbS are not located in combined hotspots of relative change in hazards and NCP flow-supply ratio, nor in combination with the NCP demand-supply ratio. In the following we focus in particular on the distribution of values within the most numerous NbS addressing drought hazards in combination with NCP of freshwater, fodder or wood production, and NbS addressing heat-waves in combination with wood production (Fig. 3). Our analyses show that values within NbS are similar to those across the Alps regarding the future relative change in drought index and NCP flow-supply and demand-supply ratios. However, NbS addressing drought appear to be concentrated in the upper values of relative change in the drought index, whatever the targeted NCP, in comparison with Alps values (Fig. 3). Nevertheless, the distributions of values within NbS addressing drought differ across targeted NCP. NbS targeting fodder and wood production match upper values of their flow-supply ratio, while the NbS addressing the freshwater NCP are uniformly distributed along the drought change gradient.

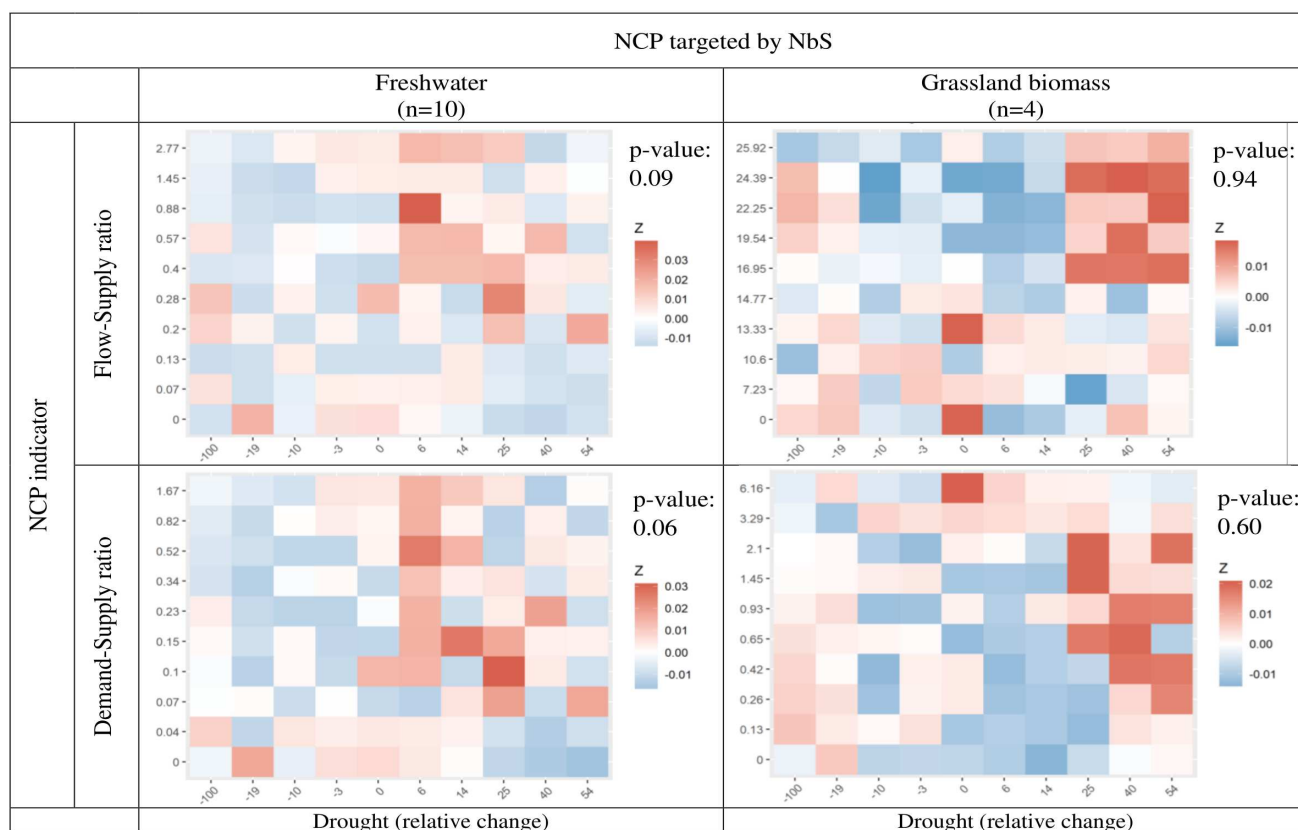


Fig. 3. Heatmaps displaying the associations between one climate-related hazard (horizontal axis) and one Nature’s Contributions to People (NCP) indicator (vertical axis). The values correspond to the difference between the number of values within Nature-based Solutions (NbS) addressing the hazard as well as the NCP and the values within the entire Alps distributed along the gradient of the hazard and the NCP. The number (n) associated to each NCP corresponds to the number of NbS addressing both hazard and NCP for each heatmap.

We also assessed the combination of relative change in fire hazard and wood production NCP. While the distribution of values within NbS is not statistically different to those across the Alps, our analyses show an absolute greater occurrence of NbS at the higher end of the hazard gradient in conjunction with the medium-to-high range of the wood production flow-supply ratio (Supplementary File 8), suggesting further analysis of this potential correlation.

4. Discussion

This study explores climate change adaptation within a large region, and questions the spatial location of NbS in relation to societal needs, by focusing on hazards and NCP. We identified 97 NbS in the Alps illustrating the diverse potential actions in various type of habitat. This portfolio confirms NbS practical implementation including the creation of knowledge for nature-based climate change adaptation on the ground (Debele et al. 2019; Vij et al. 2021) as well as enabling initiatives (Donatti et al. 2020). However, we found that in general NbS are not located in areas of higher current and future climatic hazards, nor of greater NCP supply- flow-demand indicators. We discuss in the following sections what drives implementation of adaptation initiatives such as NbS, and first explore the barriers of implementation that can explain why NbS did not match the greatest climatic hazards and NCP levels. Secondly, we explore the further consideration of socio-ecological and climatic conditions for optimal NbS location. Lastly, we address recommendations to overcome the limited knowledge on NbS effectiveness for climate change adaptation (Seddon et al. 2019; Donatti et al. 2020), through a macro-regional programme supporting adaptation of areas experiencing the most intense hazards and higher impacts on NCP.

4.1. Diversity and multifunctionality of Nature-based Solutions for climate change adaptation

Consistent with previous syntheses, we found that NbS in the Alps have the potential to address multiple hazards (Chausson et al. 2020; Palomo et al. 2021). Some hazards are addressed jointly because of their similar nature and biophysical mechanisms, for example NbS addressing several natural hazards such as landslides and avalanches through forest protection, management and restoration. But co-occurring hazards of different natures are also addressed jointly by NbS, such as wildfires and natural pests through sustainable forest management (Felipe-Lucia et al. 2018; Stritih et al. 2021). Drought and floods are also addressed jointly by wetland restoration, which is known to be effective when well designed (Erwin 2009).

As highlighted in previous reviews, most of the NbS we identified aim to maintain a NCP threatened by climate change hazards, and to provide multiple NCP co-benefits (Brink et al. 2016; Osaka et al. 2021). While a large proportion of NbS target material NCP, such as wood, fodder and food production, the NbS which we documented across the Alps involved a large diversity of ecosystems, such as forests, pastures, wetlands, bare rock and urban areas. They are not predominantly located within a given ecosystem, such as previous study on European NbS (Vij et al. 2021), but in contrast with global review identifying NbS mostly in forests (Chausson et al. 2020).

4.2. Nature-based Solutions are distributed across a range of climate change hazard levels

Although NbS in the Alps are overall not located in hotspots of the current and future hazards they target, we found a few significant trends for NbS addressing specific hazards. For example, NbS addressing drought are located in areas where drought will be more severe in the future than across the Alps. While NbS locations are not associated with current droughts, this result is consistent with a previous study illustrating that local adaptation initiatives in Mediterranean agriculture are implemented where farmers experience higher temperatures and more intense water scarcity (Harmanny and Malek 2019). NbS addressing floods are located within hotspots of current hazard, but not in areas of higher future hazard. This focus on current rather than future hazard can be explained by the future decrease of flood risk in lowlands due to change in precipitation patterns in future climate scenarios for the Alps (Beniston and Stoffel 2016; Wilhelm et al. 2022). For example, NbS addressing floods are mostly located to protect downstream cities such as Innsbruck (Austria) or Vizille (France) from current flood events. Although here we did not consider impacted populations and their adaptive capacity, a previous study reported a mismatch between nature-based adaptation initiatives for flood regulation and where they are the most needed (Houghton and Castillo-Salgado 2020).

A large part of the NbS from our database addresses droughts and floods. It can be explained by the fact that these two hazards impact NCP supply from various sectors, like agriculture (Tello-García et al. 2020), forestry (Elkin et al. 2013), and natural disaster risk reduction (Mina et al. 2017), with severe economic impacts (Fraser et al. 2013; Andres and Badoux 2019; Brèteau-Amores et al. 2019). Moreover, the assessment and adaptation of these two hazards are hot topics in the literature (Aguiar et al. 2018; Mubeen et al. 2021), especially in mountain areas (Deléglise et al. 2019; Zingraff-Hamed et al. 2021a) and this can contribute to the large number of adaptation actions (Cook et al. 2012; Street et al. 2019).

Contrary to drought and floods, NbS addressing heatwaves are located in areas with lower hazard occurrence than across the Alps. While we have not explored the fine-resolution land cover of areas where NbS are implemented, in our database NbS that address heatwaves are green infrastructure within urban areas, where vulnerability to heatwaves is higher (Jagarnath et al. 2020). However, the heatwave index used in this study is based on predicted temperatures, which increase most in higher-altitude areas, therefore not fully relevant to these NbS. Future analyses would need to include urban heat islands as a hazard that urban NbS are addressing by controlling temperature with trees (Schwaab et al. 2021).

The paucity of NbS addressing snow cover reduction and wildfires can explain the non-significant results regarding these, for which further studies are needed. Nevertheless, we found that NbS addressing snow cover reduction are located where changes will be lower in summer than across the Alps. This is because they refer to three enabling NbS that focus on ski resorts at higher altitudes that are less affected by snow cover change during winter but with higher change during summer (Beaumet et al. 2021). While our database is not exhaustive, the rela-

tively small number of initiatives identified for ski resorts adaptation is consistent with previous syntheses showing limited nature-based interventions from the skiing sector, which still mainly invests in snowmaking solutions (Berard-Chenu et al. 2021). Concerning wildfires, although climate change is expected to increase their frequency in the Alps (Stritih et al. 2021), impacts are not severe or intense enough yet as a single threat to mountain forests (Kulakowski et al. 2017), especially outside of the southern Alps (Bebi et al. 2017). Our results are thus in line with this current low risk perception, with the three NbS addressing wildfires targeting multiple co-benefits of adaptation to landslides, storms or drought.

The location of NbS addressing increasing temperature or precipitation appeared independent of the geographic distribution of these two climatic variables. Although they are leading indicators of climate change in the literature (Field and Barros 2014), we identified relatively few NbS addressing these drivers directly. This may be because, except for their direct impacts on shifts in species niches or changes in plant phenology, their socio-ecological impacts are indirect through increased intensity of hazards like floods or avalanches (Gobiet and Kotlarski 2020).

4.3. Nature-based Solutions location according to NCP demand, supply and flow

Overall, we found that NbS location was in general poorly related to hotspots of NCP demand, supply or flow. Nevertheless, our analyses showed that many NbS are located in areas needing protective function against landslides according to the flow of this NCP. A visual analysis confirmed that they tend to be situated in probable release areas above settlements that need protection, such as railways, roads or infrastructure (see Supplementary File 5). This suggests accurate perceptions of risks and NCP by managers, in spite of contentions this may not be the case (Stritih et al. 2021). In contrast, NbS targeting the freshwater NCP are located where freshwater flow (indicating the water use by inhabitants) is highest across the Alps, but not in hotspots of freshwater supply (indicating water availability). In the Alps, as happens in many mountain massifs, hotspots of freshwater supply (upstream) and flow (in lowlands) are disjoint (Meisch et al. 2019). Thus, NbS appeared to focus on areas where freshwater is used rather than on supplying areas which are often located at high altitude areas which also have lower population density (Meisch et al. 2019).

Symbolic biodiversity and climate mitigation CO₂ sequestration are two NCP for which demand is global, but supply is local or regional. While biodiversity conservation is a priority goal of NbS (Cohen-Shacham et al. 2016), we found that locations of NbS for climate change adaptation are unrelated to symbolic biodiversity, which is mainly located within protected areas (Schirpke et al. 2018). In-depth analyses would need to investigate whether NbS implemented outside protected areas are located where the value of symbolic biodiversity is higher or lower than within non-protected Alpine areas. Furthermore, only few NbS identified in the Alps mention a symbolic species; they rather target species with a key functional role like *Pinus heldreichii* to test new tree varieties or *Carex nigra* to characterise the wetland restoration success. The

case of symbolic biodiversity contrasts with climate mitigation. Although not directly motivated by climate change mitigation, many NbS identified for climate change adaptation across the Alps are located within low- to mid-elevation forests with higher, even if not maximum values of both demand and supply for the CO₂ sequestration NCP (Schirpke et al. 2019a).

4.4. Combination of climatic hazards and NCP for Nature-based Solutions implementation

While climatic hazards and socio-ecological variables have been used to prioritise areas for implementing NbS for climate change adaptation (Bourne et al. 2016), the location of NbS in this study does not generally coincide with climatic hazards or NCP, neither with their combinations. Of all the combinations of hazards and NCP assessed, our results suggest that only NbS targeting the resilience of freshwater supply to drought are located where drought threatens this NCP's flow. Indeed agricultural practices and especially irrigation are emerging as responses to drought impacts in mountain areas (Grüneis et al. 2018; Bergeret and Lavorel 2022), as in other regions (Harmanny and Malek 2019). Although the results were not significant, NbS targeting the resilience of fodder production to drought appeared to be located in the areas most exposed to drought and with a higher fodder flow, namely high mountain pastures, whose forage production is known to be vulnerable to climate change (Schirpke et al. 2017; Deléglise et al. 2022) and where adaptation of practices is essential (Nettier et al. 2017). Nevertheless, hazards perceived by stakeholders, and therefore adaptation behaviours, are not always associated with the most sensitive conditions, as previously observed in the French Alps (Bruley et al. 2021b).

4.5. Limitations of the study

Our analyses had four main limitations. First, we acknowledge that the database of NbS we compiled is not exhaustive, and therefore, further studies that include a larger number of NbS are needed, particularly for targeted hazards for which the number of NbS we identified was lower, such as for temperature change, wildfires, snow cover or precipitation changes. Reviewing grey literature is a practical way to identify NbS and adaptation initiatives (Zingraff-Hamed et al. 2021b). Although we identified almost one hundred initiatives, our database is limited as identifying and georeferencing all NbS implemented in the Alps is impossible. As our analysis is mainly based on project documentation, we were limited in understanding reports published in other languages than English and French. This also explains why we identified more initiatives in France, but when analysing NbS addressing a specific hazard or NCP, the limited number of NbS for each Alpine country reduced this bias *de facto*.

Secondly, our analyses were further constrained by the coarse spatial resolution for climatic hazards (5 km² for the flood index) that might also be a source of mismatch, where some pixels covering up to a 1000 m elevation range may not provide an accurate flood hazard value for NbS implemented in valleys, nor capture change in future hazards for small catchments (Wilhelm et al. 2022). As the on-the-ground NbS usually had a small extent, a more precise estimation of the hazard value could yield different results for some specific NbS. Moreover, other socio-economic factors may better capture societal needs for NbS through aspects of exposure or vulnerability to hazards (Pörtner et al. 2022). However, these were included in several NCP indicators. For example, demand for freshwater and outdoor recreation activities were assessed through population density and tourism statistics. As another example, the quantification of the demand for the protective function of forest against landslides is based on the presence of infrastructure at risk (Schirpke et al. 2019a; Meisch et al. 2019). Thirdly, the overall mismatch between NbS and NCP needs to be considered cautiously given we used NCP values mapped at municipality level (Schirpke et al. 2019a), while some NbS are smaller than the municipality in which they are implemented. This may conceal local social needs or biophysical details, especially land use at finer resolution. For example, the protective forest against landslides implemented in Engadin (Switzerland) covers 45 ha, while the municipality in which it implemented is 20 000 ha, with 20% covered by forest. As a result, the municipal data indicates a low level of wood supply, while the NbS is well located to protect downstream settlements. Likewise, our approach did not allow us to assess the spatial location of NbS in relation to certain vulnerable social groups, as for example for heatwaves impacting elderly people and children in urban areas (Kabisch et al. 2017).

Fourthly, our spatial analysis explored the combination between current or future climatic conditions and NCP supply-flow-demand representing socio-ecological conditions. However, as we focused solely on initiatives that aim to adapt to climate change, we did not consider multiple other anthropogenic pressures on ecosystems that must be examined in future analyses of NbS optimal locations (Egarter Vigl et al. 2021). Furthermore, we only analysed climatic hazards

rather than their potential impacts on future NCP supply, which is likely to be reshaped due to combined climate and land-use changes (Dunford et al. 2015; Mouchet et al. 2017; Schirpke et al. 2017). We did not consider climate-driven ecosystem transformation, which with the exception of glacier retreat is unlikely at higher altitudes in the short term (Schirpke et al. 2020).

4.6. Recommendations for outscaling Nature-based Solutions

To implement NbS for climate change adaptation, integrating current and future climate conditions and NCP indicators into spatial planning tools is essential for avoiding maladaptation (Lavorel et al. 2015; Pártl et al. 2017; Hurlimann et al. 2021). Moreover, they need to be combined with local decision contexts to offer effective solutions (Kruse and Pütz 2014). Spatial planning is still poorly addressed for NbS (Bourne et al. 2016), especially in Europe (Geneletti and Zardo 2016), and the establishment of appropriate processes is critical (Albert et al. 2021). Spatial planning of NbS has mostly been limited to urban areas (Brink et al. 2016; Kooy et al. 2020; Simperler et al. 2020), coastal ecosystems (Jones et al. 2020; Sutrisno et al. 2021), or locally tailored initiatives (Turconi et al. 2020; Zaimes et al. 2020). To support the future scaling of NbS and their spatial planning, future research needs to determine the personal, institutional and economic drivers of NbS implementation, such as previous experiences of climate change impacts (Demski et al. 2017; Harmanny and Malek 2019), stakeholder visions for adaptation (Lupp et al. 2021; Bergeret and Lavorel 2022), governance processes (Zingraff-Hamed et al. 2021a) and funding (Jones et al. 2017; Bruley et al. 2021a). Improving knowledge on NbS effectiveness and their cost-benefit balance compared to other types of solutions is also essential to support decision-maker choices and avoid maladaptation (Seddon et al. 2020; Seddon 2022).

Broad scale planning and active adaptation can also provide positive outcomes for climate change adaptation. Macro-regional strategies have shown their positive outcomes at national level for NbS implementation for climate change mitigation (Bradfer-Lawrence et al. 2021), at the European scale for climate change adaptation (Wende et al. 2012; Lung et al. 2013) and ecosystem restoration (Egoh et al. 2014; Schulp et al. 2016), and at the Alps to conserve biodiversity through ecological networks (Plassmann et al. 2016). Macro-regional strategies need to be strengthened for future NbS outscaling (Bennett et al. 2016; Juschten et al. 2021), so that NbS better target climatic hazards and NCP.

Conclusion

Climate change is already threatening mountain ecosystems and the NCP they provide to local and distant communities. We found that NbS are implemented in the Alps to tackle the diverse impacts of climate change and to increase or maintain the supply of several NCP. While few NbS are located within hotspots of climate change hazards, such as for droughts and current floods, NbS are generally not located within the hotspots of the current or future hazards they claim to address, neither within NCP hotspots, nor where they coincide. This reveals the need to explore the NbS decision-making context with an interdisciplinary approach including in particular institutional and economic aspects, personal values and knowledge. Our findings also suggest the need to integrate local climatic projections and NCP quantification into future planning of NbS. A macro-regional strategy in combination with local stakeholder engagement has the potential to meet this challenge.

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Appendices

S1. Table. List of Nature's Contributions to People (NCP) adapted from IPBES classification (Díaz et al., 2018) to correspond to the NCP associated to Nature-based Solutions for climate change adaptation identified in the PORTAL project.

IPBES classification	IPBES shortened definition	PORTAL classification	Remark
Habitat creation and maintenance	The formation and continued production, by ecosystems or organisms within them, of ecological conditions necessary or favorable for living beings of direct or indirect importance to humans. E.g. growing sites for plants, nesting, feeding, and mating sites for animals, resting and overwintering areas for migratory mammals, birds and butterflies, roosting places for agricultural pests and disease vectors, nurseries for juvenile stages of fish, habitat creation at different soil depths by invertebrates	/	We have not take in account Habitat NCP as the preservation of habitat for biodiversity was a criteria of inclusion in the database
Pollination and dispersal of seeds and other propagules	Facilitation by animals of movement of pollen among flowers, and dispersal of seeds, larvae or spores of organisms beneficial or harmful to humans	/	No identified NbS aim to provide pollination NCP
Regulation of air quality	Regulation (by impediment or facilitation) by ecosystems, of CO ₂ /O ₂ balance, O ₃ , sulphur oxide, nitrogen oxides (NO _x), volatile organic compounds (VOC), particulates, aerosols, allergens	/	No identified NbS aim to provide air quality NCP
Regulation of climate	Climate regulation by ecosystems (including regulation of global warming)	Climate regulation	

Regulation of ocean acidification	Regulation, by photosynthetic organisms (on land or in water), of atmospheric CO ₂ concentrations and so seawater pH, which affects associated calcification processes by many marine organisms important to humans (such as corals)	/	No identified NbS aim to address ocean acidification
Regulation of freshwater quantity, location and timing	Regulation, by ecosystems, of the quantity, location and timing of the flow of surface and groundwater used for drinking, irrigation, transport, hydro-power, and as the support of non-material contributions. Regulation of flow to water-dependent natural habitats that in turn positively or negatively affect people downstream, including via flooding (wetlands including ponds, rivers, lakes, swamps). Modification of groundwater levels, which can ameliorate dryland salinization in unirrigated landscapes	Freshwater supply	
Regulation of freshwater and coastal water quality	Regulation – through filtration of particles, pathogens, excess nutrients, and other chemicals – by ecosystems or particular organisms, of the quality of water used directly (e.g. drinking, swimming) or indirectly (e.g. aquatic foods, irrigated food and fiber crops, freshwater and coastal habitats of heritage value)	Water quality	

Formation, protection and decontamination of soils and sediments	Formation and long-term maintenance of soil structure and processes by plants and soil organisms. Includes: physical protection of soil and sediments from erosion, and supply of organic matter and nutrients by vegetation; processes that underlie the continued fertility of soils important to humans (e.g. decomposition and nutrient cycling) ; filtration, fixation, attenuation or storage of chemical and biological pollutants (pathogens, toxics, excess nutrients) in soils and sediments.	Soil quality	
Regulation of detrimental organisms and biological processes	Regulation, by organisms, of pests, pathogens, predators or competitors that affect humans (materially and nonmaterially), or plants or animals of importance for humans. Also the direct detrimental effect of organisms on humans or their plants, animals or infrastructure.	Pest control	
Energy		Energy	
Food and feed	Production of food from wild, managed, or domesticated organisms, such as fish, bushmeat and edible invertebrates, beef, poultry, game, dairy products, edible crops, wild plants, mushrooms, honey. Production of feed (forage and fodder) for domesticated animals (e.g. livestock, work and support animals, pets) or for aquaculture, from the same sources.	Food from grasslands	The production of fodder within grasslands have been separated to match with the NCP maps corresponding to the grassland production
		Food	This NCP corresponds to the food production that do not come from grasslands
Materials, companionship and labor	Production of materials derived from organisms in cultivated or wild ecosystems, for construction, clothing, printing, ornamental purposes (e.g. wood, peat, fibers, waxes, paper, resins, dyes, pearls, shells, coral branches).	Materials	This NCP mainly correspond to wood production

Medicinal, biochemical and genetic resources	Production of materials derived from organisms (plants, animals, fungi, microbes) used for medicinal, veterinary and pharmacological (e.g. poisonous, psychoactive) purposes. Production of genes and genetic information used for plant and animal breeding and biotechnology.	Genetical	No identified NbS aim to provide medicinal or biochemical NCP, we therefore only kept genetical NCP
Learning and inspiration	Provision, by landscapes, seascapes, habitats or organisms, of opportunities for the development of the capabilities that allow humans to prosper through education, acquisition of knowledge and development of skills for well-being, information, and inspiration for art and technological design (e.g. biomimicry)	/	Because some NbS aim to provide new knowledge, we have classified the NCP according to the NCP that the new knowledge aim or help to provide.
Physical and psychological experiences	Provision, by landscapes, seascapes, habitats or organisms, of opportunities for physically and psychologically beneficial activities, healing, relaxation, recreation, leisure, tourism and aesthetic enjoyment based on the close contact with nature (e.g. hiking, recreational hunting and fishing, birdwatching, snorkeling, diving, gardening)	Experiences	
Supporting identities	Landscapes, seascapes, habitats or organisms being the basis for religious, spiritual, and social-cohesion experiences.		No identified NbS aim to support identities.
Maintenance of options	Capacity of ecosystems, habitats, species or genotypes to keep options open in order to support a good quality of life.	Maintenance of options	

Regulation of hazards and extreme events	Amelioration, by ecosystems, of the impacts on humans or their infrastructure caused by e.g. floods, wind, storms, hurricanes, heat waves, tsunamis, high noise levels, fires, seawater intrusion, tidal waves. Reduction or increase, by ecosystems or particular organisms, of hazards like landslides, avalanches.	Floods regulation	Because identified NbS addressing different type of natural disasters, we decided to create sub-categories of extreme events regulation NCP to correspond to the different events addressed by NbS.
		Heatwaves regulation	
		Avalanches regulation	
		Fires regulation	
		Soil erosion regulation	
		Mudslides regulation	
		Food from grasslands	
		Storm regulation	
		Protective function against landslides	

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Climatic hazards:

1. Temperature and heatwaves

We used the annual temperature mean data computed by the CLIM4ENERGY project using the bias-adjusted EURO-CORDEX model for 2 metre air temperature, averaged for an ensemble of models using 4 Regional Climate Models (RCMs) and 4 General Circulation Model (GCM) (Jacob et al. 2014). The values are averaged on a 30-year period.

We used the number of heatwaves from the same dataset, considered as a period of at least three consecutive days on which the maximal daily temperature exceeds the 99th percentile of the maximal daily temperature of the May to September season (Jacob et al. 2014).

2. Precipitation, soil moisture and floods

We used the annual precipitation mean, the seasonal precipitation mean, the snow cover during the winter season and the autumn season computed by the EDgE project, using an ensemble of models combining RCPs, GCMs and hydrological models. These take into account the water falling as rain, snow, sleet or hail (Samaniego et al. 2019). The values are averaged on a 30-year period.

Within the same dataset, we used a specific indicator computed to calculate the drought index based on a soil moisture model, considered as the volume of water within the unsaturated zone of the soil profile. Another indicator evaluates the flood hazard based on a river discharge model (Samaniego et al. 2019).

3. Wildfires

To assess wildfire hazard, we used the Fire Weather Index dataset computed within the framework of C3S European Tourism project. This meteorologically based index considers the soil moisture at different soil depths, air temperature, relative humidity, wind speed and 24-h accumulated precipitation. The values are averaged on a 5-year period.

Data analysis:

We computed all plots and statistical tests, including Wilcoxon tests, Heatmaps and Khi2 tests, with R software (version 4.0.5).

1. Wilcoxon tests

In order to reduce spatial autocorrelation, we created a subset of values with a sample of 1% of the values inside and outside Nature-based Solutions (NbS) respectively (i.e. with at least one pixel by NbS initiative). For each climatic hazard (current, future, relative change), we ran 1000 Wilcoxon tests to compare the median of the values outside and inside NbS, for NbS that aimed to address the related impact. For each NCP variable (demand, supply and demand-supply ratio), we ran 1000 Wilcoxon tests to compare the median of the values outside and inside NbS,

for NbS that aimed to address the related NCP. For all the tests, we extracted the p-value, and we calculated the 99% confidence interval of the p-values for each variable.

2. Heatmaps

To evaluate the distribution of NbS along the gradient of relative change of climatic hazards they addressed and the gradient of the NCP demand-supply and flow-supply ratio they targeted, we created subsets of data including NbS that targeted a specific combination of hazards and NCP known to address the impact: drought hazard with drinking water; drought with grassland fodder; drought with fuel wood; heatwaves with fuel wood.

We then computed one contingency table of the number of NbS included in each decile of the variable distributions for each of the two gradients, and one contingency table of the number of pixels outside NbS included in each decile of the variable distributions for each of the two gradients. To get comparable values in each pair of contingency tables, the values of each table were transformed to proportion by dividing values by the sum of the respective table. We then computed the khi2 test to evaluate whether the anomalies are distributed equally along the two gradients.

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S3. Table. List of climatic hazard data used in the analysis.

Climate aspect	Variable	Historical period	Future period	Unit	Spatial resolution	Model
Temperature	Annual mean air temperature	1971-2000	2050 (RCP8.5)	°C	0.11° x 0.11°	IPSL-CDFT22
Heatwaves	Number of heatwaves days	1971-2000	2050 (RCP8.5)	days	0.11° x 0.11°	IPSL-CDFT22
Precipitation	Annual mean precipitation per unit area	1970-2000	2050 (RCP8.5)	mm/day	1.875° x 3.75°	IPSL-CM5A LR (climate), NOAH-MP (hydrological)
Precipitation	Winter mean precipitation per unit area	1970-2001	2050 (RCP8.5)	mm/day	1.875° x 3.75°	IPSL-CM5A LR (climate), NOAH-MP (hydrological)
Precipitation	Spring mean precipitation per unit area	1970-2004	2050 (RCP8.5)	mm/day	1.875° x 3.75°	IPSL-CM5A LR (climate), NOAH-MP (hydrological)
Precipitation	Summer mean precipitation per unit area	1970-2007	2050 (RCP8.5)	mm/day	1.875° x 3.75°	IPSL-CM5A LR (climate), NOAH-MP (hydrological)
Precipitation	Autumn mean precipitation per unit area	1970-2010	2050 (RCP8.5)	mm/day	1.875° x 3.75°	IPSL-CM5A LR (climate), NOAH-MP (hydrological)
Drought index	Soil moisture-based drought period duration index per year	1970-2010	2050 (RCP8.5)	months	1.875° x 3.75°	IPSL-CM5A LR (climate), NOAH-MP (hydrological)
Floods index	River discharge-based floods index	1970-2010	2050 (RCP8.5)	m ³ /s	1.875° x 3.75°	IPSL-CM5A LR (climate), NOAH-MP (hydrological)
Snow cover	Daily average snow water equivalent during winter	1970-2010	2050 (RCP8.5)	mm/day	1.875° x 3.75°	IPSL-CM5A LR (climate), NOAH-MP (hydrological)
Snow cover	Daily average snow water equivalent during spring	1970-2010	2050 (RCP8.5)	mm/day	1.875° x 3.75°	IPSL-CM5A LR (climate), NOAH-MP (hydrological)
Snow cover	Daily average snow water equivalent during summer	1970-2010	2050 (RCP8.5)	mm/day	1.875° x 3.75°	IPSL-CM5A LR (climate), NOAH-MP (hydrological)
Snow cover	Daily average snow water equivalent during autumn	1970-2010	2050 (RCP8.5)	mm/day	1.875° x 3.75°	IPSL-CM5A LR (climate), NOAH-MP (hydrological)
Wildfires	Daily average Fire weather index	1980-2005	2046-2055 (RCP4.5)	non-dimensional	0.11° x 0.11°	IPSL-IPSL-CM5A-MR/RCA4

S4. Table. List of NCP indicators mapped and assessed by the AlpES project (Schirpke et al., 2019)

NCP	Demand	Supply	Flow
Drinking water with minor or no treatment	Water abstraction: the total annual abstraction of water for the public supply system ($\text{m}^3 \text{ha}^{-1} \text{y}^{-1}$)	Water availability: the annual average available water runoff with drinking-water quality ($\text{m}^3 \text{ha}^{-1} \text{y}^{-1}$)	Water use: the annual amount of water that is withdrawn from the public water supply system ($\text{m}^3 \text{ha}^{-1} \text{y}^{-1}$)
Fodder	Livestock feed energy requirements (energy demanded by cattle, horses, and other forage feeding animals for their nourishment and for the production of desired animal products, such as milk) ($\text{MJ NEL ha}^{-1} \text{y}^{-1}$)	Gross fodder production ($\text{t DM ha}^{-1} \text{y}^{-1}$)	Net fodder energy content: the fraction of the local yield that is utilized, expressed by its energy content ($\text{MJ NEL ha}^{-1} \text{y}^{-1}$)
Fuel wood	Potential fuel wood requirements ($\text{m}^3 \text{ha}^{-1} \text{y}^{-1}$)	Net annual increment of wood biomass in the Alpine forests ($\text{m}^3 \text{ha}^{-1} \text{y}^{-1}$)	Wood removals ($\text{m}^3 \text{y}^{-1}$)
Protective function against landslides and avalanches	Infrastructure at risk: the need for protection from natural hazards by showing the percentage of human infrastructure in potential danger zones (index)	Site-protecting forest: amount of forests with a potential protective function (index)	Object-protecting forest: the share of object-protecting forests only (index)
Outdoor recreation	Potential beneficiaries: proportional to the number of potential beneficiaries, i.e. residents and tourists (Resident equivalent (index))	Recreational offer (outdoor recreation potential index)	Visitation rate (relying on metadata linked to photographs uploaded on social media) (index)
Symbolic species	Desired symbolic species and landscapes	Habitats of symbolic species: the range of selected species that have a symbolic value in the Alpine Space (index)	Occurrence in hotel names (Number of hotels)
Carbon sequestration	CO_2 emission ($\text{t CO}_2 \text{ha}^{-1}$ in 2010)	CO_2 sequestration ($\text{t CO}_2 \text{ha}^{-1} \text{y}^{-1}$ in alpine forests)	

Schirpke, U., Candiago, S., Egarter Vigl, L., Jäger, H., Labadini, A., Marsoner, T., Meisch, C., Tasser, E., Tappeiner, U., 2019. Integrating supply, flow and demand to enhance the understanding of interactions among multiple ecosystem services. *Science of The Total Environment* 651, 928–941. <https://doi.org/10.1016/j.scitotenv.2018.09.235>

S5. Table. List of all the Nature-based Solutions identified in the Alps, the country where they are implemented, the climatic hazard addressed and the targeted Nature's Contributions to People (NCP)

Code	Initiative	Country	Adressed hazards	Targeted NCP
AFPar	Restoration of the natural growing processes of trees within the Partias Natural Reserve to increase forest resilience	France	Loss of Biodiversity; Increasing temperatures; Soil erosion	Wood supply; Habitat; Supporting identities; Climate regulation; Soil erosion regulation
AILOS	Reduction of heat islands by developing green space adapted to climate change	France	Heatwaves; Increasing temperatures	Heatwave regulation; Habitat
ANHoh	Development of new practices for protecting biodiversity in the Hohe Tauern National Park	Austria	Loss of Biodiversity	Habitat
ANJoh	Johnsbach river restoration to reduce the impact of floods	Austria	Floods; Loss of Biodiversity	Flood regulation; Habitat
ANNeo	Development of measures to control the invasion of neophytes potentially increased by climate change	Austria	Invasive species	Pest control
ATEco	Implementation of an agroforestry field for and by student	France	Food security; Loss of Biodiversity	Food; Habitat; Pest control; Soil quality
AuADA	Adaptation of cities to reduce the impact of heatwaves thanks to green infrastructure	Austria	Heatwaves	Heatwave regulation
BFTEA	Sustainable land-use management plan to prevent floods, heavy rain and drought impacts	Austria	Floods	Flood regulation
BIDyn	Conservation of the natural dynamics of the Lech river system and surrounding riparian landscapes	Austria	Loss of Biodiversity; Floods	Habitat; Flood regulation
CBGEB	Alpine meadows restoration with local seeds to prevent soil erosion	France	Loss of Biodiversity; Soil erosion	Habitat; Soil erosion regulation
CERes	Chautagne swamp restoration while maintaining appropriate uses such as agriculture and tourism	France	Invasive species; Loss of Biodiversity; Water scarcity	Habitat
ChAgr	Implementation an agroforestry field in Chautagne swamp area	France	Loss of Biodiversity; Climate-driven ecosystem degradation	Water quality; Food; Wood supply; Habitat

CiRes	Restoration of two wetlands around Chambéry	France	Water scarcity; Floods	Habitat; Flood regulation; Freshwater supply
CIAll	Conservation of moor landscapes in the Allgäu region to reduce climate change impact and conserve NCP	Germany	Loss of Biodiversity	Habitat; Climate regulation
CIRoc	Preservation and management of protection forests against rockfalls	Switzerland	Avalanches; Rockfalls; Landslides; Erratic rainfall; Wildfires	Soil quality; Wood supply; Protective function against landslides; Avalanche regulation
CIsec	Management of forests to secure future water supply	Austria	Water scarcity; Storms; Landslides; Rockfalls; Vector and water borne diseases	Freshwater supply; Wood supply; Protective function against landslides; Pest control; Genetic resources; Flood regulation
EcObe	Sustainably management of forests to maintain the CO ₂ sequestration	Switzerland	Climate-driven ecosystem degradation	Wood supply; Climate regulation
EuGre	Development of ecosystem-based risk governance concepts with respect to natural hazards and climate impacts	Austria; Italy; France; Slovenia; Germany	Avalanches; Rockfalls; Landslides; Wildfires; Floods	Protective function against landslides; Avalanche regulation; Wood supply
EUIMP	Innovative management of grasslands with farmers for sustainable water use	Austria; Switzerland; Slovenia	Soil erosion; Climate-driven ecosystem degradation; Water scarcity	Habitat; Soil quality
HAMOU	Adaptation of grassland management towards ecological intensification practices to conserve NCP	France	Drought; Shift of seasons	Fodder; Food
InRe1	Wetland restoration to control invasive species in the face of climate change	France	Invasive species	Habitat; Fodder; Climate regulation; Freshwater supply; Outdoor recreation
InRe2	Cover crop sowing in a vineyard	France	Loss of Biodiversity; Vector and water borne diseases	Habitat; Pest control
InRe4	Wetland restoration to reduce flood and drought risks	France	Floods; Water scarcity	Habitat; Flood regulation

IRAlp	Communication and knowledge co-production to adapt Alpine pasture management to the climate change	France	Shift of seasons; Drought	Fodder
IRRef	Experimental set up to adapt to global change in Alpine mountains	France	Glacial retreat; Loss of Biodiversity	Habitat; Outdoor recreation
ITHel	Adaptation of agricultural practices to sustainable conservation practices in the context of climate change	Italy	Food security; Loss of Biodiversity; Drought	Food; Habitat; Soil quality; Climate regulation
ITRet	Creation an ecological belt for better agriculture and to adapt to climate change	Italy	Climate-driven ecosystem degradation; Food security	Habitat; Food; Climate regulation
IUGen	River restoration in mountains to fight against soil erosion and landslides	France	Soil erosion; Loss of Biodiversity; Floods	Habitat; Protective function against landslides
IUIse	Isère river restoration to reduce the impact of floods	France	Floods; Loss of Biodiversity	Flood regulation; Habitat; Outdoor recreation
IURom	Romanche river restoration to reduce the impact of floods	France	Floods	Flood regulation; Habitat; Outdoor recreation
IUUp	Restoration of the Saint-Ruph-Glière-Eau Morte upper catchment to reduce the impact of floods	France	Floods; Loss of Biodiversity	Flood regulation; Habitat
KIALP	Innovative re-use water method in the network of agricultural ditches to improve the ecosystem health of the Rotaliana river-floodplain system	France; Italy; Austria; Slovenia; Switzerland	Water scarcity; Loss of Biodiversity	Heatwave regulation; Freshwater supply
KLHar	Development of a strategic plan to adapt agriculture and forestry to climate change	Austria	Heatwaves; Drought	Soil quality; Wood supply; Heatwave regulation; Outdoor recreation
KLIn1	Raising people awareness in the Walgau about adaptation measures to climate change in relation to heatwaves	Austria	Heatwaves	Heatwave regulation
KLIn2	Development of a pilot site in the Walgau on sustainable management of forest to control soil erosion	Austria	Soil erosion	Soil erosion regulation

KIKli	Development of management practices for mixed forests adapted to climate change and sharing with forest owners	Austria	Climate-driven ecosystem degradation; Drought; Increasing temperatures	Maintenance of options; Wood supply; Pest control
KLRos1	Reforestation to reduce impacts of heatwaves in Rosental cities	Austria	Heatwaves; Increasing temperatures	Heatwave regulation
KLRos2	Development of climate change adaptation measures in Rosental for agriculture and forestry	Austria	Erratic rainfall; Soil erosion	Wood supply; Soil erosion regulation
KLTer	Adaptation to climate change in forestry and agriculture to face pests impacts through Terra Future programme	Austria	Drought; Vector and water borne diseases	Food; Wood supply; Pest control; Soil quality
KLTie	Raising people awareness about adaptation measures for agriculture, such as permaculture, and forestry, such as climate-smart forests, in Tiebeltal and Wimitzerberge	Austria	Storms; Food security; Drought; Wildfires	Storms regulation; Fires regulation; Food; Wood supply
KLVor	Development of a new strategic plan to adapt forests to climate change in the Vorderwald-Egg region, with measures such as forest rejuvenation	Austria	Climate-driven ecosystem degradation; Vector and water borne diseases; Drought	Protective function against landslides; Climate regulation; Wood supply; Genetic resources
LINat	Development of a methodology to assess the vulnerability to climate change of protected areas; production of an adaptation strategy for management practices to better conserve biodiversity - LIFE Natur'Adapt project	France	Loss of Biodiversity; Snow cover decrease; Glacial retreat	Habitat
MiGes	Development of an alternative rainwater management system in the Ouagadougou urban park, Grenoble, to limit the water use for the park, create recreation opportunities and restore a wetland to reduce the impact of floods and heatwaves	France	Heatwaves; Floods	Flood regulation; Heatwave regulation; Outdoor recreation; Habitat
N4Gru	Development of methods to study benefits of green spaces for the urban climate and ecology - GrunOase project	Austria	Heatwaves	Heatwave regulation
NCAME	Restoration of the diversity in an Alpine pond threatened by climate change - Acclamé project	Switzerland	Loss of Biodiversity	Habitat

NCFre	Adaptation of the hydraulic flow to preserve biodiversity through water scarcity maps	Switzerland	Glacial retreat; Drought	Habitat; Freshwater supply
NChea	Raising people awareness by implementing green spaces to reduce the intensity of heatwaves in schools	Switzerland	Heatwaves	Heatwave regulation
NCION	Promotion of water and vegetation in cities to reduce the impact of heatwaves within the Acclimatisation project	Switzerland	Heatwaves	Heatwave regulation
NCMai	Development of a method to identify the water need of the basin and the area where interventions are needed to limit the drying-out of the wetland	Switzerland	Drought; Loss of Biodiversity	Habitat; Freshwater supply
NCMRP	Development of measures for reducing the expansion of the proliferative renal disease accelerated by climate change and threatening fish populations	Switzerland	Vector and water borne diseases	Pest control
NCPeo	Raising awareness of public institutions to disaster risk reduction to adapt their practices to climate change	Switzerland	Landslides; Mudslides; Floods	Maintenance of options; Protective function against landslides; Mudslides regulation
NCPre	Assessment of the presence of <i>Alianthus altissima</i> and development of environmental-friendly and efficient strategies to limit its expansion	Switzerland	Invasive species	Pest control
NCPPro	Identification of the best tree species to prevent railways from landslides	Switzerland	Avalanches; Rockfalls; Landslides; Drought	Protective function against landslides; Avalanche regulation; Wood supply; Genetic resources
NCSoi	Adaptation of agricultural practices through soil moisture mapping	Switzerland	Drought; Food security	Food; Soil quality; Genetic resources
NCStr	Development of a multi-actor strategy to reduce landslides risk in the context of climate change while maintaining livestock production in forests	Switzerland	Landslides; Mudslides	Mudslides regulation; Protective function against landslides; Soil erosion regulation; Maintenance of options
NCTig	Assessment and mapping of the risk of expansion of the tiger mosquito (<i>Aedes albopictus</i>) for control	Switzerland	Vector and water borne diseases	Pest control

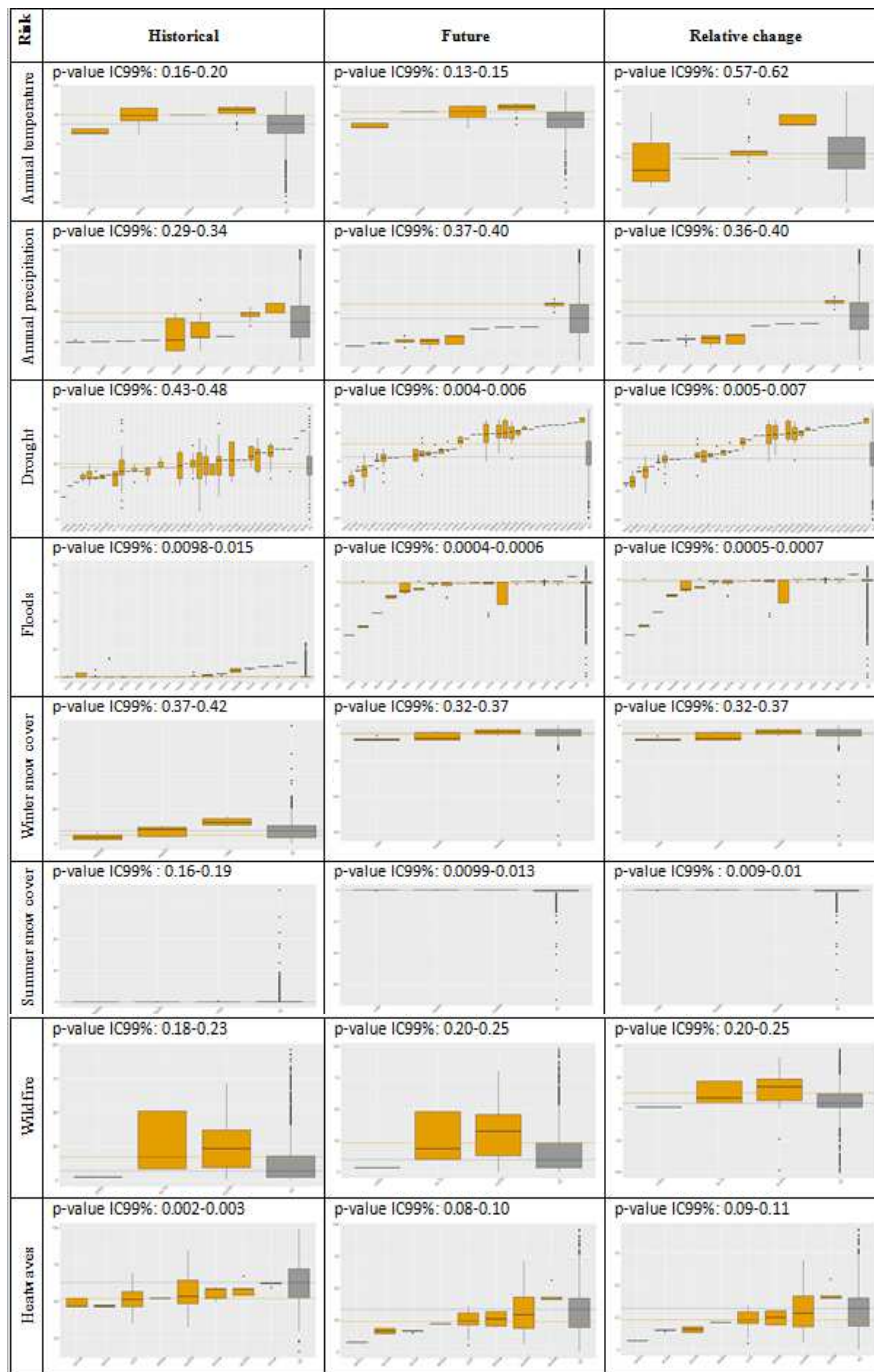
NCUrb	Management of urban trees to reduce the impact of heatwaves	Switzerland	Heatwaves	Climate regulation; Heatwave regulation
NCWat	Development of adaptation measures to limit the impact of drought in agriculture	Switzerland	Drought; Food security	Habitat; Freshwater supply
NCWin	Production of knowledge of the windmill palm (<i>Trachycarpus fortunei</i>) ecology and produce support to limit its expansion	Switzerland	Invasive species	Pest control
ONFRE	Development of free-evolution forests to preserve biodiversity in the context of climate change	France	Loss of Biodiversity	Habitat; Wood supply
ONMET	Development of tree species better adapted to climate change - METIS project	France	Drought; Vector and water borne diseases; Storms	Wood supply; Pest control
ONRes	Adaptation of forest management by planting new varieties of fir adapted to drought and shifting seasons	France	Drought; Increasing temperatures; Shift of seasons	Habitat; Wood supply; Climate regulation; Genetic resources
ONRTM	Restoration of mountain areas to support the protection services by forests against natural disasters	France	Avalanches; Rockfalls; Landslides	Protective function against landslides; Avalanche regulation
OpAgr	Development of field and market values for agro-forestry - PEGASUS project	Slovenia	Food security	Fodder from grasslands
OpOAL	NbS implementation to prevent the impact of landslides - Operandum project	Austria	Landslides	Protective function against landslides
PCPCE	Adaptation of agriculture to climate change in the Gresivaudan valley	France	Increasing temperatures; Drought; Food security	Food
PeAT3	Preservation of the benefits of mountain forests in the Pinzgau region	Austria	Avalanches; Landslides; Erratic rainfall; Soil erosion	Habitat; Outdoor recreation; Protective function against landslides; Avalanche regulation; Soil erosion regulation
PhKau	Development of an altitude-adapted seed mixture to stabilize slopes in the Kaunertal Valley - PHUSICOS project	Austria	Glacial retreat; Soil erosion	Habitat; Soil quality

PNAR1	Assessment of the vulnerability of the Haut Chablais region to climate change and suggestions of adaptation measures to add to local development - ARTACLIM project	France	Snow cover decrease; Drought; Avalanches; Rockfalls; Landslides; Floods; Vector and water borne diseases	Freshwater supply; Outdoor recreation; Pest control; Flood regulation; Protective function against landslides
PNAR2	Assessment of the vulnerability of the Bauges regional park to climate change and suggestions of adaptation measures for the park's strategy - ARTACLIM project	France	Snow cover decrease; Drought; Vector and water borne diseases	Food; Fodder; Wood supply; Freshwater supply; Climate regulation; Maintenance of options; Energy
PNLi1	Development of agricultural practices to reduce soil erosion in vineyards on steep slopes, within the Links4Soils project	Italy	Soil erosion; Storms	Soil quality; Supporting identities; Food
PNLi3	Development of guidelines for better forest management practices, within the Links4Soils project	Austria	Drought; Loss of Biodiversity; Vector and water borne diseases; Avalanches; Rockfalls	Wood supply; Soil quality; Protective function against landslides; Climate regulation; Water quality
PNLub	Adaptation of grassland management practices to adapt the Lubéron regional park to climate change	France	Loss of Biodiversity; Food security	Habitat; Fodder
PNTr1	Understanding of collective adaptation pathways to implement NbS for facing drought - Trajectories project	France	Drought; Food security	Maintenance of options; Fodder; Supporting identities
PNTr2	Understanding collective adaptation pathways to implement NbS for facing snow cover reduction - Trajectories project	France	Snow cover decrease; Glacier retreat	Maintenance of options; Fodder; Supporting identities
PNWet	Wetland protection in Vanoise national park	France	Climate-driven ecosystem degradation; Water scarcity	Habitat; Freshwater supply; Outdoor recreation
ReBur	Forest restoration and sustainable management in Burdignin	France	Drought; Loss of Biodiversity	Wood supply; Habitat; Climate regulation
ReCan	Forest restoration in Verdon with tree species to adapted extreme weather events	France	Storms	Wood supply; Habitat; Climate regulation
ReCha	Forest restoration and sustainable management in Chautagne	France	Drought; Loss of Biodiversity	Wood supply; Habitat; Climate regulation

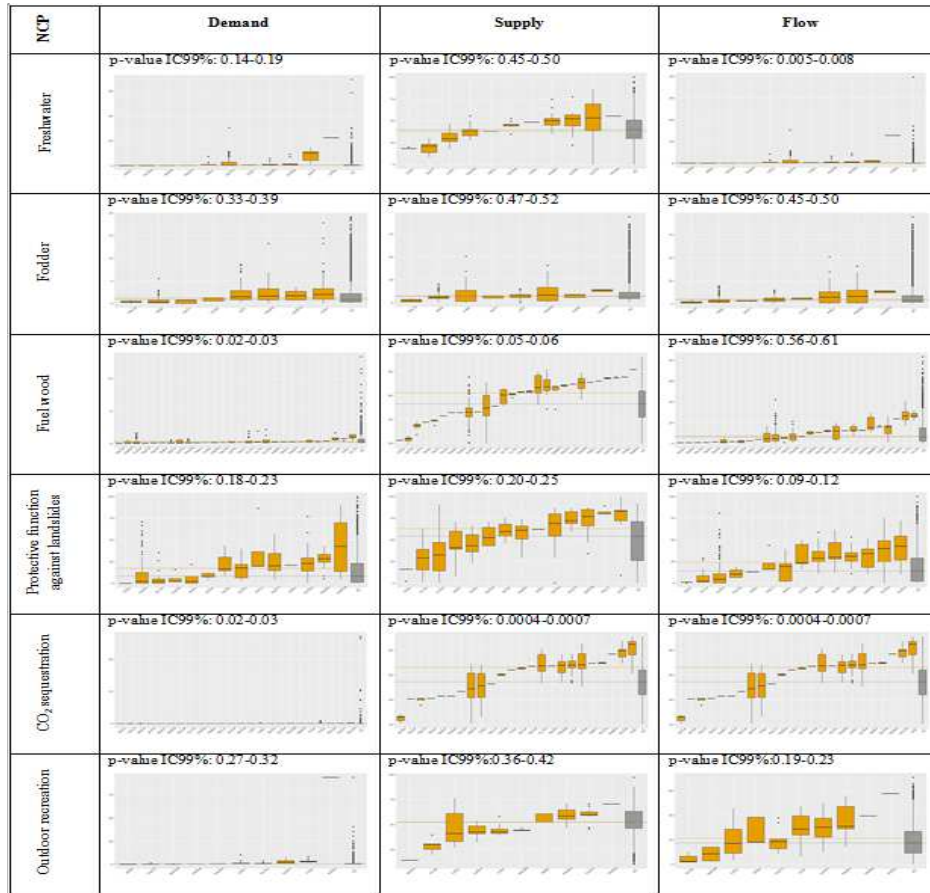
ReChi	Forest restoration and sustainable management in Chirens	France	Drought; Loss of Biodiversity	Wood supply; Habitat; Climate regulation
ReInn	Restoration of the Inn river basin to reduce the impact of floods and landslides	Austria	Floods; Landslides	Flood regulation; Protective function against landslides
ReIss	Forest restoration and sustainable management in Issole	France	Drought; Loss of Biodiversity	Wood supply; Habitat; Climate regulation
ReLa	Implementation of an agroforestry field in La-Bégude-de-Mazenc	France	Loss of Biodiversity; Food security	Habitat; Food
ReLuc	Forest restoration and sustainable management in Lucéram	France	Drought; Loss of Biodiversity	Wood supply; Habitat; Climate regulation
ReMen	Forest restoration and sustainable management in Menthon-Saint-Bernard	France	Drought; Loss of Biodiversity	Wood supply; Habitat; Climate regulation
ReSa1	Forest restoration and sustainable management in Saint-Christol	France	Drought; Loss of Biodiversity	Wood supply; Habitat; Climate regulation
ReSa2	Forest restoration and sustainable management in Saint-Christol	France	Loss of Biodiversity	Wood supply; Habitat; Climate regulation
ReSem	Alpine grasslands restoration with local plant species to reduce soil erosion - Sem'Les Alpes project	France	Soil erosion; Climate-driven ecosystem degradation; Loss of Biodiversity	Soil quality; Soil erosion regulation
ReVal	Forest restoration and sustainable management in Valernes	France	Drought; Loss of Biodiversity	Wood supply; Habitat; Climate regulation
ReVar	Restoration of the Var river basin to reduce the impact of floods, conserve ecological dynamics and stimulate socio-economic development - RECONNECT project	France	Floods	Flood regulation; Habitat
ReVe1	Forest restoration and sustainable management in Verthemex	France	Drought; Loss of Biodiversity	Wood supply; Habitat; Climate regulation
ReVe2	Forest restoration and sustainable management in Verthemex	France	Vector and water borne diseases	Wood supply; Habitat; Climate regulation

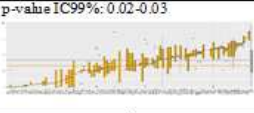

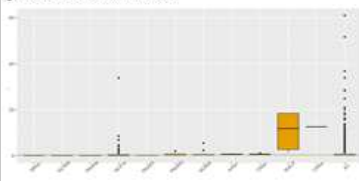
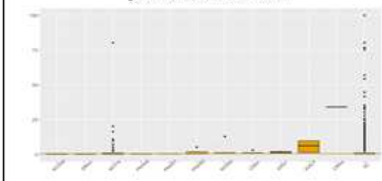
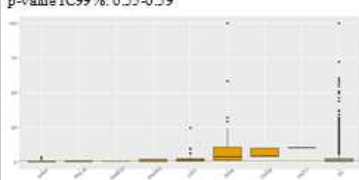
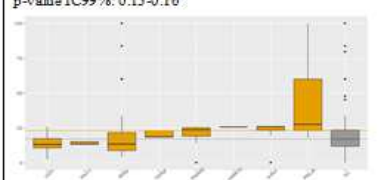

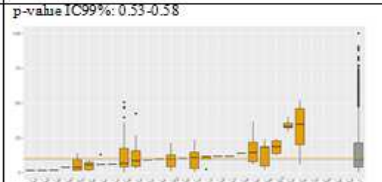
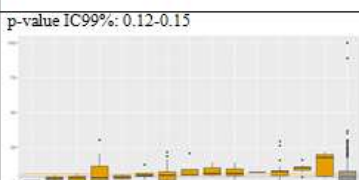

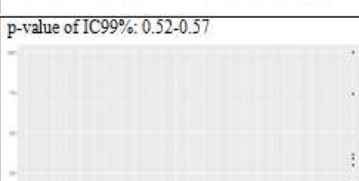
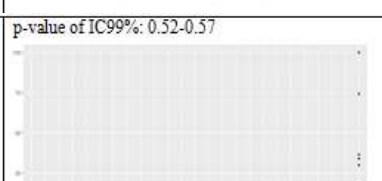
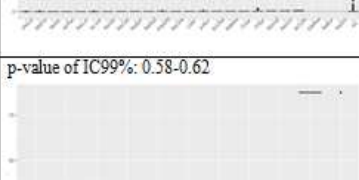
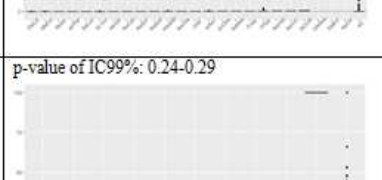

RNFor	Forêts Sentinelles network to observe and monitor the impact of climate change for adapting forest management practices	France	Loss of Biodiversity; Increasing temperatures	Habitat; Wood supply; Climate regulation
SfNec	Restore Necuidet wetlands to reduce water scarcity in summer period	France	Drought; Land and Forest degradation	Habitat; Freshwater supply
UICli	Identification of management options that increase the resilience of the socio-ecological system to extreme heat - ClimLUC project	Austria	Drought; Heatwaves	Soil quality; Fodder; Heatwave regulation
UrGre	Management of urban storm water for facilitating robust, synergistic and multi-functional green infrastructures - Green Blue Cities project	Austria	Floods	Flood regulation
WaHyM	Restoration of rivers to be adapted to climate change - HyMoCARES project	Austria	Drought; Floods	Flood regulation; Outdoor recreation
WOWOW	Restoration of protection forests with tree species well-adapted to storms - WOWalps project	Italy	Storms	Storms regulation; Habitat

S6. Figure. Boxplots of values of climatic hazards for each Nature-based Solutions (NbS) addressing this hazard (in orange, with each code identifying a NbS), and for the values of the entire Alps at the same elevation range than the subset of NbS (in grey, coded AC), for the historical period, the future projections and the relative change between these two periods. p-value IC99% indicate the confident interval at 99% of the p-values collected from the Wilcoxon tests of the 1000 permutations

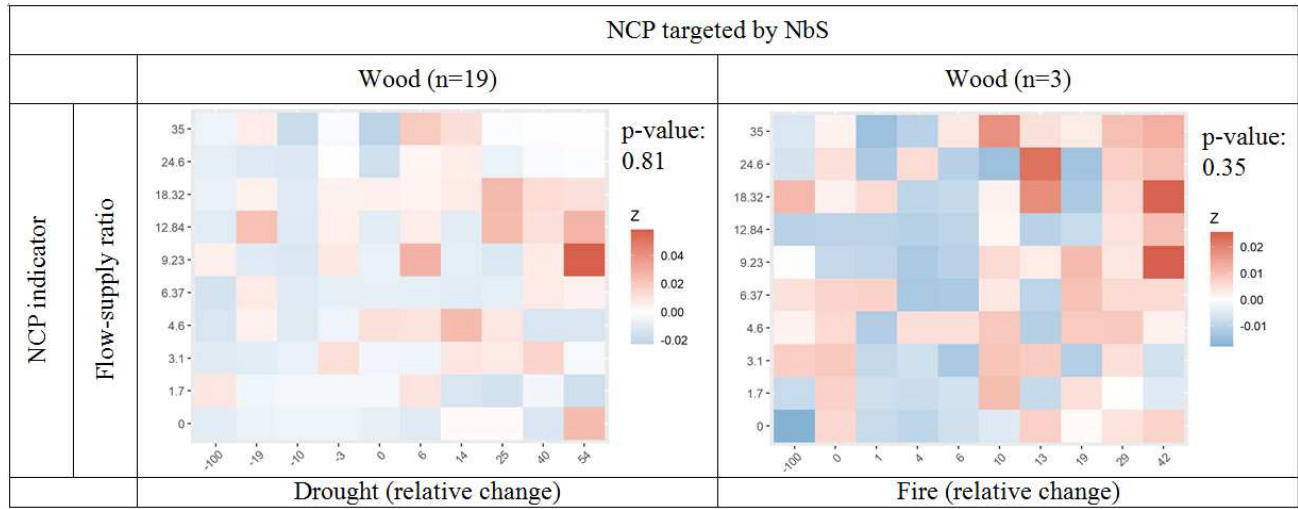


S7. Figure. Boxplots of values of Nature's Contributions to People (NCP) demand, supply, flow, demand-supply ratio and flow-supply ratio for each Nature-based Solutions (NbS) targeting this NCP (in orange, with each code identifying a NbS), and for the values of the entire Alps at the same elevation range than the subset of NbS (in grey, coded AC). NA: no data. p-value IC99% indicate the confident interval at 99% of the p-values collected from the Wilcoxon tests of the 1000 permutations



Symbolic biodiversity	NA	p-value IC99%: 0.02-0.03 	p-value IC99%: 0.06-0.08 
NCP	Demand-supply ratio		Flow-supply ratio
Freshwater	p-value IC99%: 0.37-0.42 		p-value IC99%: 0.12-0.15 
Fodder	p-value IC99%: 0.55-0.59 		p-value IC99%: 0.13-0.16 
Fuel wood	p-value IC99%: 0.23-0.28 		p-value IC99%: 0.53-0.58 
Landslides protection	p-value IC99%: 0.12-0.15 		p-value of IC99%: 0.20-0.25 
CO ₂ sequestration	p-value of IC99%: 0.52-0.57 		p-value of IC99%: 0.52-0.57 
Outdoor recreation	p-value of IC99%: 0.58-0.62 		p-value of IC99%: 0.24-0.29 
Symbolic biodiversity	NA		p-value of IC99%: 0.19-0.24 

S8. Figure. Heatmaps displaying the associations between one climate-related hazard (horizontal axis) and one Nature's Contributions to People (NCP) indicator (vertical axis). The values correspond to the difference between the number of values within NbS addressing hazard as well as NCP and the values within the entire Alps distributed along the gradient of the hazard and the NCP. The number (n) associated to each NCP corresponds to the number of NbS addressing both hazard and NCP for each heatmaps.



Chapter III

Levers for transformative nature-based adaptation initiatives in the Alps



In addition to housing endemic species, wetlands are recognized for providing opportunities for outdoor recreation and for their role in mitigating water-related extreme events such as floods and droughts. The Rothenthurm peatland in Switzerland played a pivotal role in the creation of the Swiss wetland protection law, through the engagement of the local communities. Source: the author.

Levers for transformative nature-based adaptation initiatives in the Alps

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Abstract

Transformative adaptation is essential to face the unprecedented biodiversity and climate change crises and the resulting loss in Nature's Contribution to People (NCP). Nature-based Solutions (NbS) can accelerate this transformation of social-ecological systems. Understanding the drivers of the decision-making context that support NbS implementation is crucial to address potential bottlenecks and barriers for such a transformative adaptation. Here, semi-structured interviews were conducted with managers of twenty NbS implemented in the Alps. Their decision-making contexts were investigated using the values-rules-knowledge framework and their transformative characteristics. A clustering analysis revealed three types of NbS characterized by specific groups of levers and barriers. Firstly, *Local transformation* NbS are self-sufficient initiatives motivated by relational values to nature. They are supported by informal governance and share experiential knowledge to support the adaptive capacity of nature. Secondly, *Green deal* NbS employ a gradual change in practices and are supported by funding opportunities or regulations to experiment with new approaches fostering instrumental values of nature. Thirdly, *Multi-scale co-production* NbS benefit larger areas and communities. Their social acceptance rest on extensive participatory processes involving local practitioners and diverse values of nature. This last group is designed to persist even when challenged by the instability of funding opportunities. These findings suggest that in order to accelerate the implementation of transformative NbS, future policies need to: i) foster NbS implementation by local communities facing economic constraints when implementing new NbS-related practices; ii) support transdisciplinary programmes to create an inclusive network around NbS practices; and iii) adapt incentives to enable transformative adaptation through NbS. A macro-regional strategy may have the potential to address these challenges.

Key-words

Nature-based Solutions; Transformative adaptation; Climate change adaptation drivers; Social-ecological systems; European Alps

1. Introduction

The interlinked climate and biodiversity crises urge societies to adapt to whatever the emissions scenarios [1–3]. However, incremental adaptation actions are likely to maintain the system’s current trajectory and prove insufficient in addressing new climate conditions [4]. Sustainable responses of social-ecological systems need transformative adaptation, i.e. fundamentally altering the entire system’s properties and function to reduce the root cause of vulnerabilities [4–6]. Transformative adaptation encompasses a holistic approach that entails new governance systems, knowledge production, power relations, and a shift in values, assumptions, and policies [7–9]. Despite the growing interest in transformative adaptation within sustainability science and policy [1,3,10], empirical evidences of transformative responses to climate change remains limited [11,12]. This implementation gap is mainly due to the inherent complexity involved in that transformation process that entails various elements such as governance, stakeholders’ diversity, value systems, and habits [8]. Previous studies have proposed a set of characteristics for transformative adaptation such as, but not limited to, innovation, restructuration, shift to an alternative direction, and long-term impacts at large scale and across scales to measure transformative adaptation [8]. While some empirical studies have identified promising examples of transformative adaptation, many report incremental responses [12,14]. Therefore, further research needs to evaluate different adaptation strategies and their relationships to transformative adaptation processes.

There is a growing interest in Nature-based Solutions (NbS) as adaptation options with the potential for transformative adaptation to address the intertwined climate change and biodiversity loss [13,15–17]. NbS are “actions to protect, sustainably manage and restore natural or modified ecosystems that address societal challenges effectively and adaptively, simultaneously providing human well-being and biodiversity benefits” [18]. On-the-ground NbS for climate change adaptations are, for example, small-scale greening projects in urban areas co-created with local communities to reduce heatwaves impact [19]; wetland restoration with the introduction of silvopastoral systems in the mountains to adapt to reduced water provision [20]; agroecology practices to reduce drought impacts, increase soil biodiversity, and secure food production [21,22]. NbS are also understood as incentive measures to enhance farmers to safeguard Nature’s Contribution to People (NCP) [23], co-producing knowledge networks to adapt management practices [24], and creating a biosphere reserve to reduce deforestation trends [13]. While some NbS may be maladaptive, e.g. protecting ecosystems without considering the negative effects on displaced local communities, other NbS may demonstrate some other transformative adaptation characteristics, e.g. by implementing innovative practices for restoration; by co-producing solutions across several sectors. Only NbS demonstrating a high level of transformative features, hereafter referred to as transformative NbS, contribute to transformative adaptation [13].

To achieve transformative adaptation, amplification is needed. We refer to amplification rather than scaling to avoid confusion with the scale of initiatives. Amplification includes: disseminating the initiatives in similar contexts, mainstreaming them into public action, and changing values and relation to nature [25]. To foster the NbS amplification, it is necessary to increase the understanding of the main levers and barriers associated with existing NbS in relation to their transformative characteristics.

Despite the growing evidence of the abilities of NbS in addressing a wide range of issues and simultaneously providing diverse NCP co-benefits [26–28], they are not widely implemented [8,22,29], particularly in the areas where NbS are most needed [27,30]. Technical or biophysical elements are often not the main barriers; instead, the NbS implementation is influenced by diverse social-ecological elements and the decision-making context [31–33]. Commonly identified barriers to NbS implementation are i) the lack of funds and financial instruments for implementing NbS [34]; ii) the path dependency in practices, leading to resistance to change among stakeholders and institutions [31,35]; iii) the limited participation of local stakeholders [36]; iv) the limited coordination between stakeholders from different sectors [37]; and v) the knowledge gap regarding the multiple co-benefits of NbS [37,38]. Several levers have been highlighted to overcome the barriers, including the promotion and assessment of NbS co-benefits [39,40], the collaboration and the co-construction of solutions between stakeholders [40,41], the polycentric governance [37], the incentives and environmental law [7], the social innovation [31,42] and overcoming path dependency [31,43]. Most of these levers are identified and listed in the literature as general recommendations, with limited considerations of local contexts and the synergies or trade-offs between them [7,19]. However, multiple levers and barriers to adaptation co-occur within decision-making contexts, such as place attachment and resistance to innovation [43]; subsidies for conservation action and the willingness (or unwillingness) of local actors to act [44]; the conservation of traditional practices and the need to adapt them to new conditions [44]; and the valuation of landscape aesthetics associated with the lack of instrumental benefits it provides [45]. While these findings improve the understanding of the decision-making process, it remains unclear how levers are activated jointly to achieve NbS implementation successfully and to what extent co-occurring levers contribute to transformative adaptation. This knowledge gap prompts the following research questions: What levers are activated jointly within the decision-making context of NbS? Which barriers have been overcome through levers co-occurrence? Do NbS from different decision-making contexts contribute equally to transformative adaptation? What factors enable or constrain the future implementation of transformative NbS?

To answer these questions, the decision-making context and the transformative characteristics of twenty NbS initiatives implemented in the European Alps were analyzed to i) understand which levers and barriers co-occur in the implementation of NbS; ii) identify which NbS are implemented under different decision-making contexts; iii) determine which factors should be fostered to amplify transformative NbS.

2. Materials and Methods

2.1. Geographical context

Previous studies identified mountain areas as sentinels of climate change due to their high vulnerability regarding the rapid temperature increase in elevated areas [46,47]. The European Alps, where fourteen million inhabitants live in eight countries [48], are submitted to this rapid warming [49]. The worst emissions scenarios project a 4°C increase in annual mean temperature for the end of the century compared to the preindustrial period in high-altitude areas [49]. The annual precipitation distribution is expected to change whatever the emissions scenarios in the Alps. However, this change is uneven across latitudes, with a greater decrease in summer precipitation in the southern than in the north-eastern Alps [49]. Increased climatic hazards such as drought, floods, and landslides are also expected [49,50]. The resulting impacts threaten the unique habitats the Alps provide for biodiversity and the substantial NCP that benefit local communities and those living in lowlands [51–55]. To address these challenges, various adaptation initiatives have been implemented [56–58], among which NbS have emerged as a viable option [27,31,59].

2.2. Theoretical background

In order to identify the levers and barriers to NbS implementation and to relate these to their potential for transformative adaptation, we combined two frameworks (Fig 1).

2.2.1. The values-rules-knowledge framework

The vrk (values-rules-knowledge) framework analyses the decision-making context [60] with proven relevance to situations of uncertain environmental change [44,45,61]. This framework analyses decision-making for NbS design, funding, and realization, a step-by-step process which we hereafter refer to as ‘implementation,’ as interconnected systems of values, rules, and knowledge. Values refer to “a set of ethical precepts that determine the way people select actions, evaluate events” [62]. In the context of human-nature relationships, values commonly refer to the intrinsic value of species and ecosystems, the instrumental values, and the relational values [63]. Rules include informal norms, practices, taboos, habits, heuristics, and formal regulations, legislation, treaties, and ordinances [64,65]. Knowledge combines evidence-based (scientific and technical) knowledge, experiential, meanings-based knowledge [66,67], or indigenous knowledge [33,68]. Identifying values, rules, and knowledge, and their interactions involved within the decision-making context of NbS implementation enables to discern a set of levers and barriers required for transformative adaptation [5,43,60]. The vrk framework has previously been employed to identify constraints and opportunities [43,44], conflicting values and economic trade-offs [69] in adaptation within various social-ecological systems, as well as the types of decision-making contexts involved in ecosystem management [45] and their temporal changes [61].

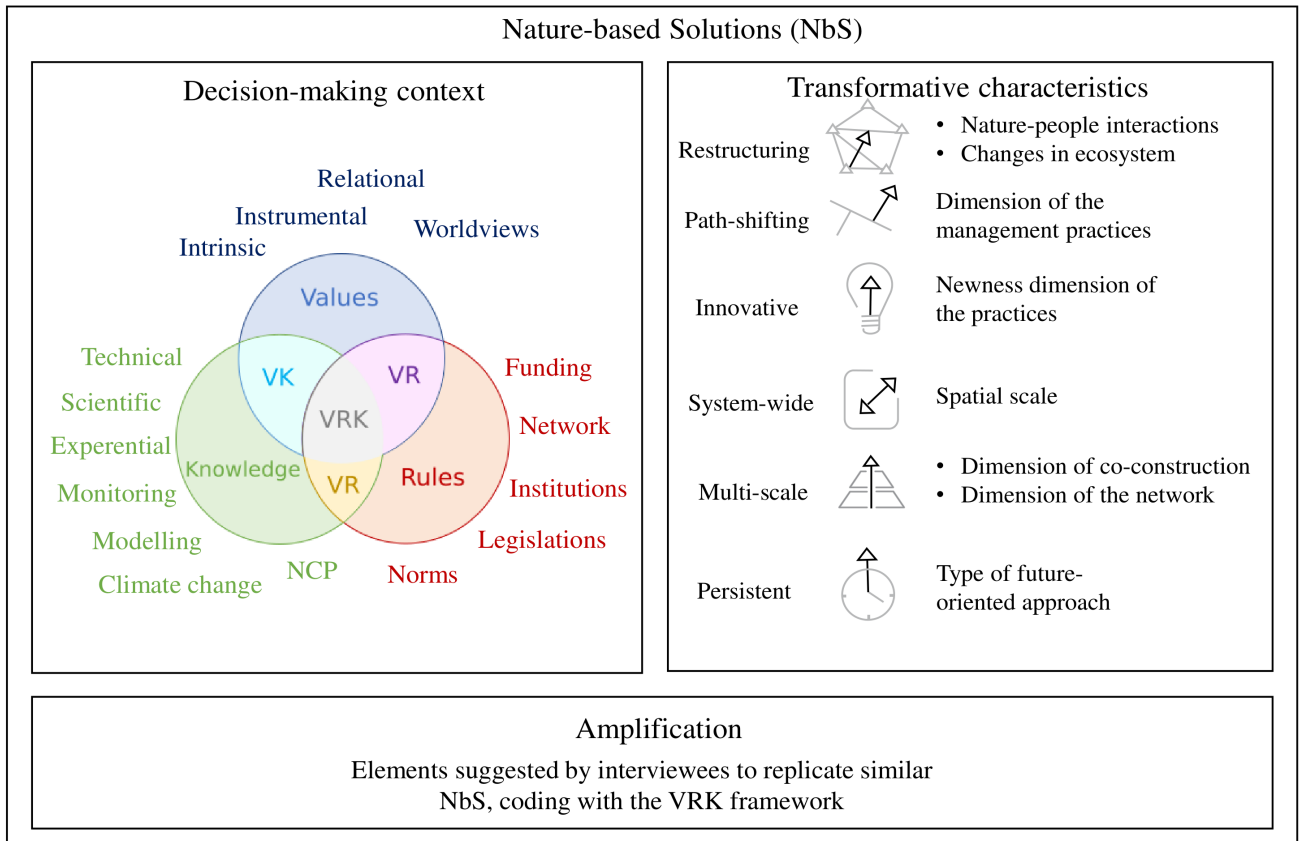


Fig. 1. The two conceptual frameworks used for the analysis of Nature-based Solutions (NbS): (1) The values-rules-knowledge framework that defines the decision-context, and (2) the transformative characteristics of the implemented NbS. The variables used to code the interviews are also displayed. Adapted from [8,60].

2.2.2. The transformative adaptation characteristics

Transformative adaptation extends beyond coping and incremental adaptation and encompasses various forms that have not been sufficiently assessed [4,70]. To address this gap, Fedele et al. [8] developed a framework comprising six characteristics to qualify transformative adaptation based on a literature review of transformative adaptation [8]. These characteristics examine whether an initiative is restructuring, i.e. involves major shifts in fundamental properties, functions, or interactions; path-shifting, i.e. alters the systems' current trajectory towards an alternative direction; innovative, i.e. changes in the system to new states that have not previously existed; multi-scale, i.e. impacts the system across multiple scales (e.g., trophic, spatial, jurisdictional, or sectoral scales); system-wide, i.e. occurs at large scale (e.g., regions, ecosystems, landscapes, or communities); persistent, i.e. with long-term impacts although not necessarily irreversible [8].

2.2.3. Semi-structured interviews with Nature-based Solutions managers

The NbS implemented in the Alps were identified using the PORTAL database of initiatives (<https://portal.osug.fr/-EXPLORE-THE-INITIATIVES->). This database collects around one hundred initiatives that aim to adapt to climate change or to mitigate increasing natural hazards by safeguarding or enhancing benefits related to NCP and biodiversity [27]. To create a comparable subset of NbS, the three climatic hazards most addressed through the PORTAL database were identified: droughts, floods, and soil erosion [27]. The NbS targeting these hazards were selected. They encompass a range of interventions, including reforestation of plots by planting trees to reduce droughts' impact, to safeguard the protective function of forests against natural hazards, or to protect crops from heatwaves. Others involve the natural regeneration of degraded forests to increase their resilience to natural disturbances, the restoration of rivers to reduce the impacts of floods as well as the restoration of grasslands to reduce landslides. Some identified NbS established a transdisciplinary network to co-produce and share knowledge on adaptation to climate change in forestry, agricultural, or natural disaster management sectors. Each of the selected NbS explicitly mentions their potential benefits for biodiversity.

Then, twenty semi-structured interviews were performed during spring 2022 with the managers of the selected NbS who possessed in-depth knowledge of the implementation process (see S1 Table). Semi-structured interviews are a suitable method for qualitative research as they allow for open-ended questions within a flexible network [71,72]. The interview protocol was designed to characterise the decision-making context of each NbS implementation, based on previously identified components of decision-making and NbS planning [31,39,45,60,73] (see S2 Table). The questions addressed eight topics: i) the reasons and the context behind the implementation of the NbS; ii) whether the NbS primarily targeted climate change adaptation, biodiversity loss, or socio-economic issues; iii) whether alternative solutions were considered and how the chosen solution was determined, especially whether an initial diagnosis was made; iv) how the NbS was implemented; v) how it was funded; vi) whether there were collaborations or conflicts with other entities or individuals and how the relationships were framed; vii) how the future of the NbS was perceived in case the NbS was long-lasting; and viii) what have been the outcomes of the NbS in case they were monitored. Subsequently, questions focused on the barriers encountered during the implementation and the levers activated to overcome them. The interviews concluded by questioning the managers' expectations regarding factors that could foster or constrain the amplification of similar NbS. Interviews lasted from 55 to 120 minutes, with a median duration of around 90 minutes. We obtained the written consent of participants to record and transcribe the interviews for coding and analyses. The sites where the studied NbS were implemented were mapped using QGIS software (version 3.16.5) (Fig 2).

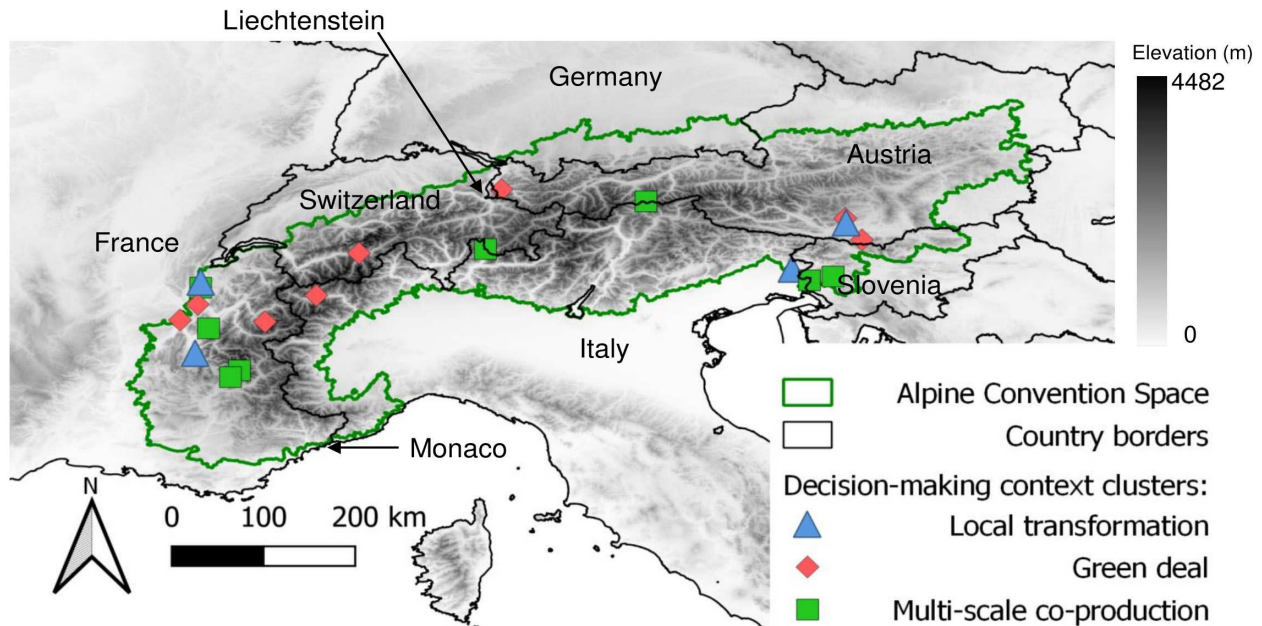


Fig. 2. Map of the twenty studied Nature-based Solutions (NbS), coloured according to the clustering analysis based on the levers and barriers mentioned by the NbS managers during semi-structured interviews and the transformative characteristics of the NbS. Elevation data is publicly available for academic use by Worldclim (<https://worldclim.org/>). Country borders and the perimeter of the Alpine Convention Space are publicly available for academic use by the Permanent Secretariat of the Alpine Convention (<https://www.atlas.alpconv.org>).

2.3. Data processing

The interviews were coded using Qualcoder software (version 3.1) enabling systematic textual analysis. First, the contextual information of each case study was extracted: the role of the interviewee in the NbS implementation, the organisation(s) leading the implementation, funding sources, the ecosystem or land-use in which the NbS was implemented, the type(s) of interventions, and the climatic hazards targeted by the NbS.

Next, a combination of inductive and deductive approaches was used to code the levers and barriers mentioned by the interviewees about the implemented NbS based on the levers and barriers identified by a preliminary literature review (Table 1, Fig 1). For example, the intrinsic, instrumental and relational values involved in the implementation of NbS were identified, based on criteria found in the literature [63,74]. This classification was adapted regarding the context of the NbS, e.g., whether the involved values refer to the landscape’s aesthetics, the willingness not to harm the surrounding environment or the biodiversity for itself. New variables not identified in the literature were also assessed if mentioned by multiple interviewees. For example, the labour value that two interviewees considered as a lever to the NbS implementation was coded, although the identified literature does not cover it. Each resulting variable was coded as a value (hereafter v), a rule (hereafter r), a knowledge (hereafter k), or an interaction of two or

three components of the vrk framework (hereafter, rk for rules-knowledge interactions, vr for values-rules interactions, vk for values-knowledge interactions and vrk for values-rules-knowledge interactions).

A matrix (S3 Table) was created to describe each NbS, indicating whether each variable mentioned by interviewees as a lever (coded '1'), a barrier (coded '-1') or whether it was not mentioned (coded as '0'). Some variables were coded as a semi-quantitative factor, such as funding (e.g., no funding, partial funding, full funding). The levers and barriers to NbS amplification were coded according to the same process for each interview (S5 Table). The matrix (S1 Table) also included the contextual information of each NbS.

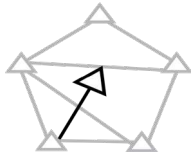
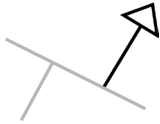


Finally, the transformative characteristics were coded using both an inductive approach based on the responses provided by the interviewees and a deductive approach based on indicators reviewed from published studies. For each transformative characteristic, the modalities of the indicators identified in the literature were adapted according to the response from the interviews (Table 2, Fig 1). For example, the innovative characteristic was assessed in the existing literature by considering the introduction of new elements (species, practices, technologies, policies, behaviours, awareness or financial instruments) or from various perspectives (new to the region, sector, or world) [20]. Since the interview responses received did not cover all identified indicators, only those mentioned were selected. For example, the innovative characteristic was described by the type of practices, including conventional practices (not innovative), non-usual practices in the region but known elsewhere, non-conventional practices but known alternative way of doing (partially innovative), practices from known experiments but never applied, and practices never seen elsewhere (highly innovative). Some modalities of transformative characteristics cannot be ranked, e.g., to characterise the persistence of NbS; if one initiative developed new methods for successful NbS and another initiative has built a strong partnership between local actors, these two initiatives would be coded differently using non-ordered modalities. Each transformative characteristic was coded with a single variable, except the multi-scale and restructuring characteristics, which were coded using two types of indicators to capture the multiple elements they encompassed. For the multi-scale characteristic, the type of collaboration (e.g., peer-to-peer or within a collaboration between public and private institutions) and the type of network (e.g., single-sector or cross-sectoral network) were used. For the restructuring characteristic, the type of nature-people relationships (e.g., with instrumental values only or combined with relational or intrinsic values) and the type of ecological changes (in species, species richness, landscape connectivity, land-cover, or NCP) were used. The coded information is summarized in Fig 1 and detailed in S6 Table.

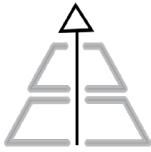
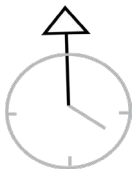
Table 1. Definition of each element of the decision-making context from the values-rules-knowledge framework, their related indicators based on the literature, and the elements used to code the interviews.

Element	Definition	Indicators	Coded variables
Values (v)	“Values refer to a set of ethical precepts that determine the way people select actions and evaluate events“ [60]	Personal worldviews, beliefs [75,76]	Cultural heritage; inclusiveness; valuing work; willingness to invest time and energy; worthiness of collective intelligence; quest for self-sufficiency; wish to deliver products of high quality
	Human-nature relationships include the multiple ways of considering ecosystems and biodiversity, from intrinsic value considering conservation of nature for itself; instrumental value considering utilitarian vision of nature for people; relational value considering conservation of nature for the specific relationship established with it [63,74]	Intrinsic values; instrumental values; relational values [63,74]	Landscape aesthetics; motivation to protect nature; intrinsic value of biodiversity; utilitarian value of nature
Values-Rules (vr)	“The favouring of particular sets of values that may be built into the way that rules are interpreted by decision-makers or can be imposed upon the decision process” [60]	Example from the literature: cost-benefit framing; legal liability excluding amenity and ecological values; public deliberation about policy options [60]	Co-production processes (consultation, concertation); local hero involvement; involvement of external actors; political interest in the initiative; cultural values of external actors; institutions with horizontal decision-making; shift in societal norms; previous collaboration; business-as-usual practices
Rules (r)	“Rules-in-use”	Norms, practices, taboos, habits, heuristics [60]	Multi-use landscape; conventional way of doing in the region; institutional expertise; informal sharing or trading
	“Rules-in-form”	Regulations, legislation, treaties and ordinances [60]	Legislation; funding opportunities; incentives; bureaucracy; owner’s approval requirement

Rules-Knowledge (rk)	The favouring of particular knowledge that may be built into the way that rules play in the source of knowledge involved [60]	Example from the literature: standardized assessment; mandated hazard assessment; public consultation on knowledge base of adaptation options [60]	External knowledge involvement; Lack of discipline-specific expertise; Sharing experiential knowledge with peers; matching practices with institutional strategy or current policies; social inertia of adaptation; favourable conditions in the local social-ecological context; data accessibility; lack of policy support
Knowledge (k)	“The mix of evidence-based (scientific and technical) knowledge and experiential, meanings-based knowledge that forms part of constructed knowledge systems in the decision-making process” [60]	Scientific, technical and experiential evidence regarding: i) ecological functions and ecosystem state; ii) material, regulating and non-material NCP; iii) current and future climate change impacts, adaptation options; local knowledge regarding social-ecological system; knowledge gaps [45,77,78]	Local social-ecological knowledge; Time lag before getting benefits; previously acquired technical knowledge; feasibility of measurements; technical knowledge gap; NPC co-benefits; material NCP; regulating NCP; scientific ecological knowledge (food web, ecosystem resilience, biological regulation); adapted species; cumulative climate change impacts; uncertainties of future climate conditions
Values-Knowledge (vk)	The favouring of particular knowledge that may be built without considering multiple values [60]	Example from the literature: Focus on direct property scale impacts; decisions made on spatial planning without values; assessment of private property damage excluding primarily valued public assets [60]	Personal experience of climate change; interest in external perception of climate change; personal interest in scientific knowledge; willingness to apply eco-friendly practices; willingness to support the adaptive capacity of nature; willingness to learn by doing including failing; identification of required grey solutions; identification of grey solutions to be abandoned
vrk	“The vrk interactions described above determine which values, knowledge and rules influence decisions and which are excluded” [60]		Willingness to take economic risk; inspiration from traditional practices; Transdisciplinary approach; emergence of the initiative from external actor; social acceptance; Networking activities; path dependency of habits; personal mindset change; other priorities considered before climate adaptation; practices based on existing initiatives; applied outcomes; dialogue between peers; lack of structured sector

Table 2. Definition of each transformative characteristic and their relative indicators identified in the literature, the variable, and its modalities. Some modalities are ranked by a less-than sign “<” according to increasing levels of transformative adaptation. The ones that cannot be ranked are separated by semicolons. The plus sign “+” indicates that the higher level of transformative adaptation cumulates the modalities of the lower level and the one mentioned after the plus sign.

Transformative characteristics	Definition from Fedele et al. [8]	Indicators from the literature [13,20,79–85]	Variable	Modalities
Restructuring (R) 	“It is ‘restructuring’ in that it involves major shifts in fundamental properties, functions, or interactions within the social, ecological, or social-ecological system”	Indicators of re-structured elements (flow of information, materials; management of ecosystem; system organisation and functions; system governance, power relations, values, land cover)	Type of people-nature values promoted (RPN) Level of change in ecosystem (RES)	no mentioned value < + instrumental < + relational < + intrinsic Change in species < change in species richness < change in landscape connectivity < change in land-cover < change in NCP
Path-shifting (PS) 	“It is ‘path-shifting’ in that it alters the systems’ current trajectory by pushing it towards an alternative direction”	Change in social-ecological systems, from silos or monoculture to governance reforms, new financial mechanisms or resilient mix of species	Level of change in management	Business-as-usual < gradual change in practices < radical change in practices < change in social relationships < integrated/holistic vision of the system
Innovative (I) 	“It is ‘innovative’ because it often changes systems to new states that have not previously existed in that area thanks to new knowledge, policies, or technologies”	Existing or new species, knowledge, practices, technologies, policies, behaviours, partnerships	Level of newness in practices	conventional < unusual in the region but known elsewhere < new species < non-conventional practices but known alternative way of doing < known experiments < novel
System-wide (SW) 	“It is ‘system-wide’ in that it occurs at large-scale and leads to systemic changes across whole regions, ecosystems, landscapes, or communities”	Spatial scale; number of beneficiaries	Spatial scale	Pilot site; small, i.e. at local scale < municipality scale < region; interregional

<p>Multi-scale (MS)</p> 	<p>“It is ‘multi-scale’ in that it has impacts across multiple scales (e.g., trophic, spatial, jurisdictional, or sectoral scales)”</p>	<p>Number of trophic levels, sectors and governance level</p>	<p>Scale of co-production (MSC)</p>	<p>No collaboration < fostering collaboration < peer-to-peer < partnership within private sector < partnership between public and private sector < co-design</p>
			<p>Scale of network (MSN)</p>	<p>No network < single disciplinary network < Fostering interdisciplinarity < interdisciplinary network or transdisciplinary network (ITD)</p>
<p>Persistent (P)</p> 	<p>“It is a ‘persistent’ shift with long-term impacts, although not necessarily irreversible”</p>	<p>Time of impact and institutional anchoring</p>	<p>Type of future-oriented approach</p>	<p>Aborted < Methods < funding-dependent longevity; policy-dependent longevity; planned to persist < adaptable initiative < anchored rules in-form or in-use</p>

2.4. Data analysis

The data analysis was performed using the FactoMineR package (version 2.4) in the R software (version 4.1.0). A Multiple Correspondence Analysis (MCA) was first performed with the involved levers and barriers in the NbS implementation as well as with the transformative characteristics of NbS to identify their simultaneous occurrences in each NbS initiative, named hereafter co-occurrence. The levers and barriers with the highest representation along the first three dimensions of the MCA were identified. As a second step, hierarchical clustering of the performed MCA was performed to identify decision-making context clusters, named hereafter NbS clusters. The main elements defining each cluster were extracted and plotted in the MCA based on the elements of the vrk framework and according to the level of the transformative characteristics highlighted by the clustering analysis. Then, the amplification levers and barriers were projected as supplementary variables within the MCA space to identify their correlation with the decision-making context clusters. Finally, the most commonly mentioned levers and barriers to NbS implementation and their amplification were identified. Chi-squared tests were performed to examine the associations between the most frequently mentioned levers and barriers to implementation and amplification and the NbS clusters.

3. Results

3.1. Shared levers and barriers in decision-making contexts

The analysis of twenty interviews (case studies mapped in Fig 2) identified a total of 47 levers and twelve barriers. Depending on the interviewee, ten additional elements were mentioned as barriers or as levers. On average, each interviewee mentioned twenty elements to characterise the decision-making context of the NbS implementation.

The levers most frequently mentioned were associated with formal rules, with funding opportunities mentioned by sixteen of the twenty interviewees, legislation mentioned by nine interviewees, and incentives mentioned eight times (Fig 3). Rules were also mentioned to explain the success of the NbS in interaction with other elements. Firstly, rules interacted with values, such as the network strength, especially for the eleven interviewees who indicated the relevance of previous collaboration and for the eleven interviewees engaging in networking activities. Secondly, rules interacted with knowledge, with eleven cases emphasizing experiential knowledge sharing and implementing practices aligned with current policy or planning documents (seven cases). Lastly, rules interacted with knowledge and values, e.g. regarding social acceptance of the initiatives (ten cases). Regarding knowledge, understanding ecological dynamics and the regulating NCP have positively influenced decision-making processes for eleven and thirteen interviewees, respectively. More than seven interviewees recognized knowledge related to adapted species, NCP co-benefits and the cumulative impacts of climate change to help implement NbS. Moreover, knowledge was also perceived as a lever in interaction with values, with ten interviewees expressing their motivation to benefit from academic knowledge in designing NbS.

Uncertainty about the cost-efficiency of the measures was the most frequently mentioned barrier. This uncertainty was identified by five interviewees as a risk to be undertaken to embrace adaptation. The next most mentioned barriers were associated with knowledge: the technical knowledge gap (mentioned in seven cases) and the time lag of NbS to deliver benefits (mentioned in six cases).

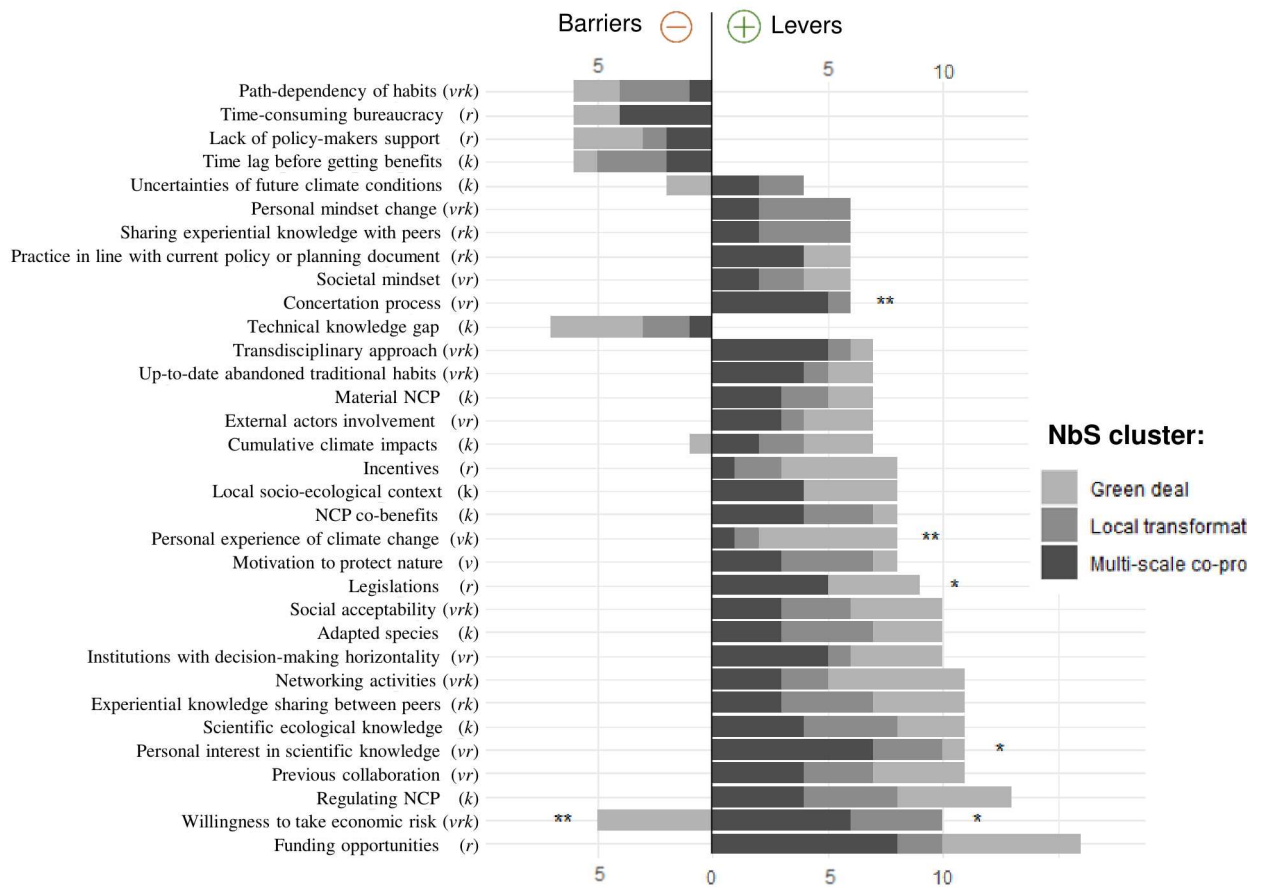


Fig. 3. Barplot of the number of interviewees during which the levers and barriers to implementing their Nature-based Solutions were mentioned, plotted according to the decision-making context cluster, and for the subset of the levers and barriers mentioned by more than five interviewees. Significance level of the difference of occurrence between clusters for each lever or barrier: * p -value < 0.1; ** p -value < 0.05; *** p -value < 0.01

3.2. Transformative adaptation characteristics

The twenty NbS varied in their levels for transformative adaptation characteristics (Fig 4). The multi-scale network characteristic was the most commonly met transformation characteristic across NbS initiatives. Still, many NbS did not involve any collaboration, and two NbS had only a single disciplinary network. The system-wide characteristic showed a similar pattern, with six NbS as pilots and six NbS with interregional implementation. All NbS addressed the multi-scale co-construction and the innovation characteristics, with most NbS presenting a high level for both. Conversely, people-nature restructuring was rare, as only two NbS integrated multiple values of nature, and two NbS involved instrumental and relational values. The path-shifting, persistence, and ecosystem restructuring characteristics did not differentiate across NbS.

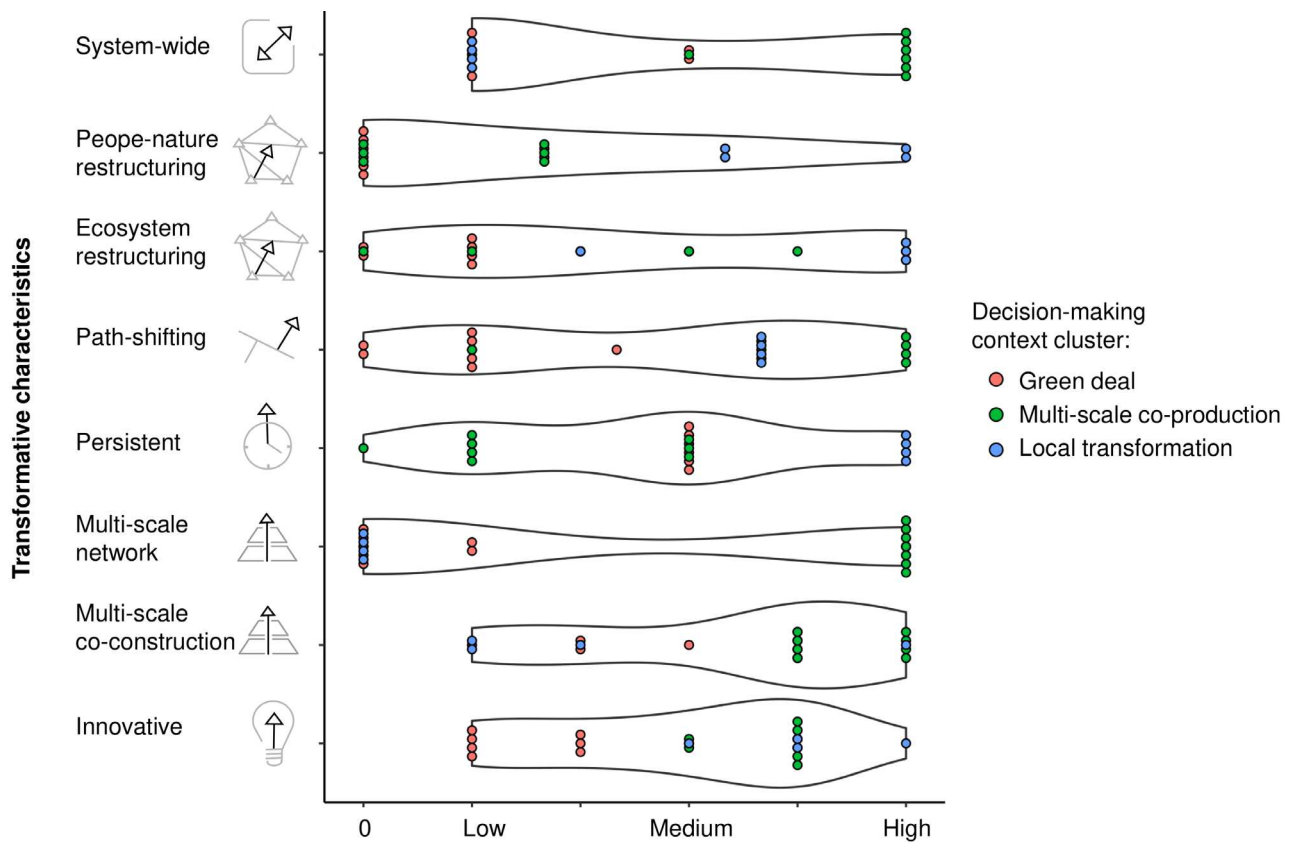


Fig. 4. Violin boxplot of the level of the transformative characteristics of each Nature-based Solutions (NbS). Within each transformative characteristic, the dots represent individual NbS, coloured according to the decision-making context cluster they belong to.

3.3. Co-occurrence of levers and barriers to Nature-based Solutions implementation

The correlation patterns across decision-making context indicators and transformative characteristics of the analyzed NbS formed three clusters of decision-making contexts (Fig 5). These three clusters were labeled *Local transformation*, *Green deal*, and *Multi-scale co-production*, based on their main associated elements represented along the first two axes of the MCA (Fig 6).

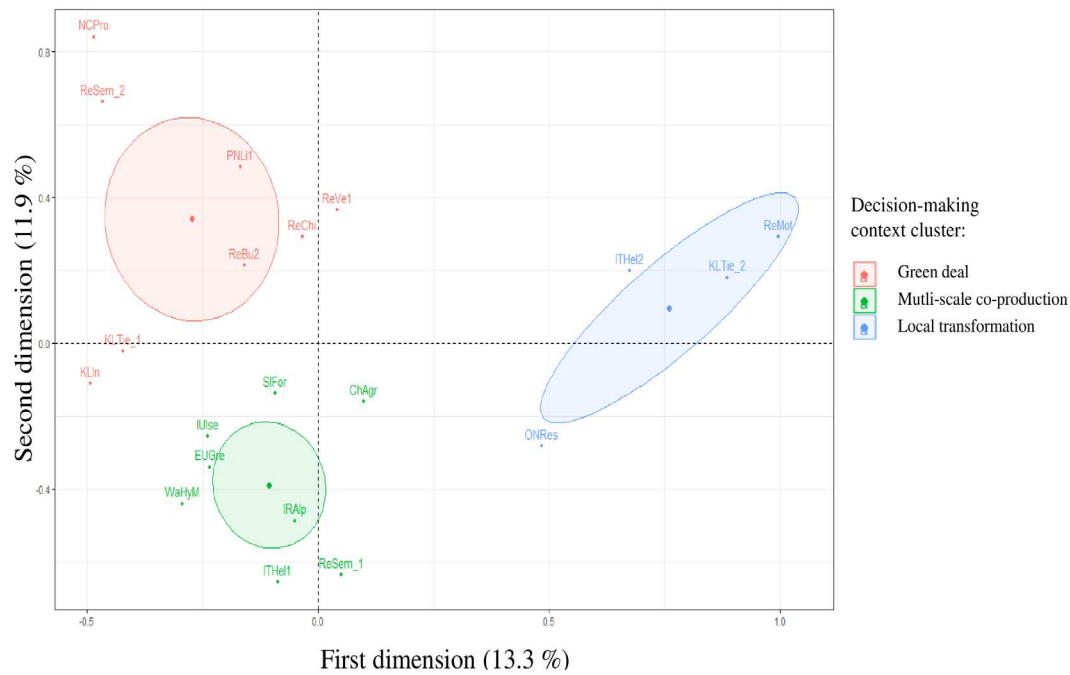


Fig. 5. Clustering analysis of the levers and barriers identified in decision-making contexts for Nature-based Solutions (NbS) implementation. They show the clusters displayed on the first and the second axes of the Multiple Correspondence Analysis (MCA) used to compute the clustering algorithm. For each axis, the percentage of variance explained by each dimension of the MCA is indicated. Each NbS code corresponds to the ID in Table S1 in the supplementary information).

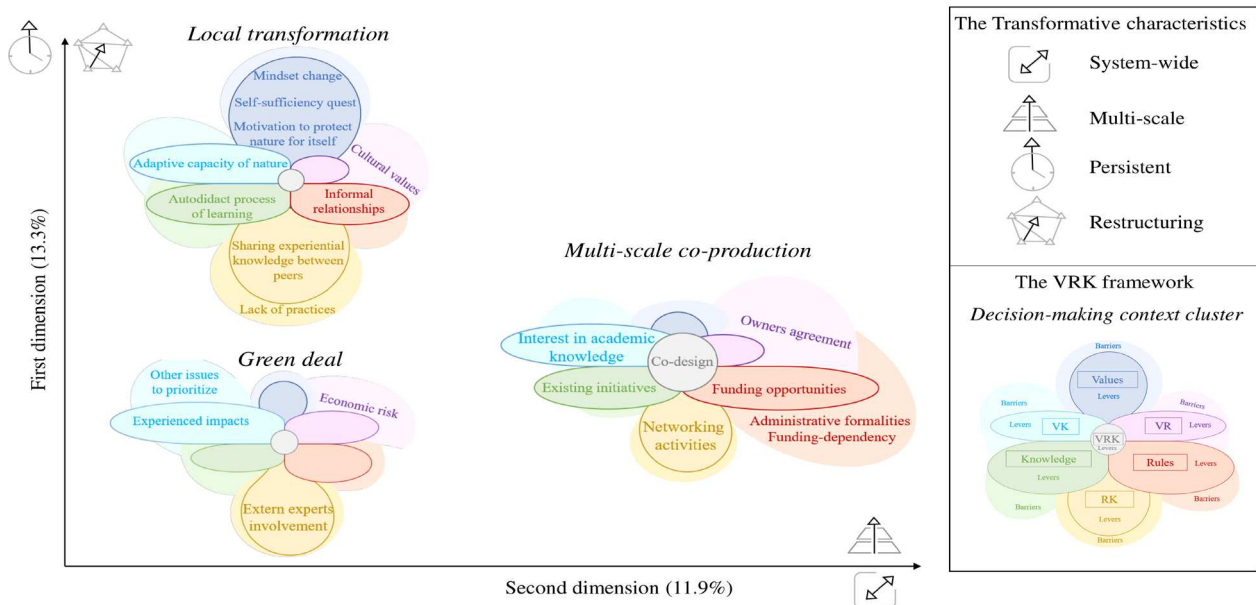


Fig. 6. The decision-making context clusters of the implemented Nature-based Solutions shown through vrk (values-rules-knowledge) flowers, plotted according to the Multiple Correspondence Analysis (MCA) of their levers (inside the related petals), their barriers (around the related petals) and their transformative characteristics. Indicated levers and barriers are those that contributed the most to the clustering analysis and that are well represented in the MCA. Numbers indicate the percentage variance explained by each axis of the MCA. Symbols transformative characteristics associated with each axis, with increasing levels for these characteristics for clusters with higher scores the axis.

3.3.1. Local transformation

The *Local transformation* cluster (four cases) was mainly discriminated by the first axis of the MCA. One representative case of this cluster is the implementation of agroforestry practices in an organic vineyard to reduce the impact of drought on wine production. The cluster is associated with a large role in sharing experiential knowledge with external stakeholders and peers to guide NbS implementation (rk). Stakeholders assessed from their experiences the adaptability of these NbS to evolving environmental conditions and expressed a willingness to protect nature for itself (v) (quote n°1, translated from French, original quote in the supplementary file, S4 Table).

Quote n°1: “As a result, we have biodiversity support since we have fungi, birds and entomofauna that is compatible with this type of fir. That is also why we chose fir: better social acceptance; it fits better with French biodiversity.”

This cluster leverages nature to adapt to climatic hazards (vk). The analysis revealed the significant role of personal values in the decision-making process, including a shift in personal mindset and the mention of relational values to nature. Interviewees mentioned a strong willingness to adapt their activity towards self-sufficiency (v). They were determined to learn through self-directed learning, compensating for their lack of technical knowledge. Three of the four cases mentioned open-access platforms such as YouTube as sources for acquiring new technical knowledge. Furthermore, a shift in personal mindset (v), driven by relational values to biodiversity and by personal experience of climate change (vk), appeared to overcome the profound cultural barriers within the social context (vr) (quote n°2, translated from French, original quote in the supplementary file, S4 Table).

Quote n°2: “[the bramble] comes, it comes at a gallop, so afterward it questions what is going to be the management of the bramble, how are we going to manage it, how can we live with it, how can we live with the look of the people who are going to say [...] there are brambles everywhere in these vineyards.”

NbS within this cluster have a high level for the restructuring transformative adaptation characteristic reflecting informal rules based on friendships, strong relationships built with neighbours and peers rather than formal rules, and the lack of institutional support (r). This dynamic underpins the limited levels for multi-scale and system-wide characteristics. Nevertheless, this cluster supports innovative practices and new relationships to nature, e.g., by promoting NCP co-benefits or alternative socio-economic systems, such as introducing non-monetary trade (quote n°3, original).

Quote n°3: “We have neighbours and friends who come to help us when we have a lot of work. Then we make something to eat and drink, and we give them products from the farm.”

3.3.2. Green deal

The *Green deal* cluster (eight cases) is positioned at the opposite end of the *Local transformation* cluster along the first axis of the MCA. One representative case of this type is the restoration of Alpine grasslands using local seeds to reduce soil erosion and promote biodiversity in degraded ski slopes. This cluster involves technical knowledge on how to adapt to climatic hazards from requested experts (rk). However, one of the most mentioned barriers is the uncertainty of the cost-efficiency of the measures (vr). While climate change adaptation was not perceived as a primary issue, and despite managers’ awareness of the lack of a one-fits-all solution due to evolving environmental conditions, implementation decisions were urged by recent experiences or previous exposure to local climate impacts (vk). Constraints associated with the multifunctional use of the same resource, such as land for two cases, also drove NbS implementation (vk) (quote n°4, translated from French, original quote in the supplementary file, S4 Table).

Quote n°4: “Afterwards, an action was needed [on this mountain pasture], and we were very keen that there should be a wider action that could serve the whole agricultural sector [of the area].”

Funding programmes and incentives were opportunities for five cases of this cluster to experiment with new practices in collaboration with experts from the specific sector (e.g., forestry technicians or academics for reforestation projects). This collaboration helped to overcome economic barriers (vr). Consequently, this cluster has low to medium level of multi-scale characteristics. While this cluster encompasses, on average, larger areas or a higher number of beneficiaries when compared to the *Local transformation* cluster, the NbS remained limited to one institution or to a small number of beneficiaries in municipalities, resulting in a low score for the system-wide characteristic. In three cases, the decision to adopt NbS instead of grey solutions was strongly driven by the relational values to nature of one or a few people occupying influential positions or highly connected to local networks (quote n°5, translated from French, original quote in the supplementary file, S4 Table).

Quote n°5: “Me, I do this for passion. I do this for passion, I was five years old, I was going in the woods with my father.”

Still, interviewees of this cluster mentioned mainly instrumental values rather than intrinsic or relational values to nature. The resulting NbS were primarily based on their ability to provide material or regulating NCP (knowledge) (Quote n°6, translated from French, original quote in the supplementary file, S4 Table). In line with this, path-shifting or restructuring characteristics of these decision-making contexts are limited. Instead, they tended to support gradual changes of practices rather than radical shifts to alternative approaches.

Quote n°6: “And we can demonstrate that when I plant, I planted six hectares, I do not know how much it corresponds to, but I will capture carbon for 60 years, more maybe, for 100 years, if I build a house.”

3.3.3. Multi-scale co-production

The *Multi-scale co-production* cluster (eight cases) is discriminated along the second axis of the MCA. One representative initiative is a river restoration to reduce floods, increase ecological connectivity and create space for outdoor recreation. This NbS was implemented by unions of municipalities using a participatory process involving local stakeholders and civil society for decision-making (vrk). NbS in this cluster co-produced knowledge with local stakeholders and academics (vrk). Interviewees perceived the inclusiveness of values and knowledge as a key lever for successful implementation, fostering social acceptance and sharing experiences from research and local initiatives (vrk). They involved experts and academics from various disciplines, from natural to social sciences, as well as from public and private sectors. This, therefore, explains this cluster’s medium to high multi-scale characteristics. Additionally, this multi-stakeholder engagement contributed to the large area or the high number of beneficiaries associated with the resulting NbS, i.e. a high system-wide characteristic. Nevertheless, according to four of eight interviewees, existing local initiatives and pilot sites were essential for developing novel practices at this scale (k), particularly for three of eight cases operating in an emergent or non-existent sector, explaining the lack of qualified experts (rk) (quote n°7, translated from French, original quote in the supplementary file, S4 Table). In line with this, the cluster promotes a favourable social context for implementing existing practices through networking activities (vr) and participatory processes (vrk).

Quote n°7: “So the big idea was on the cards, but there were not so many, at least in France, projects of this scale which allowed us to go and find an example.”

The implementation of these NbS was contingent upon funding (r), and for four of eight cases the interviewees perceived intense bureaucracy as a barrier (r) (quote n°8, original). Consequently, the cluster presents a low to medium restructuring level, associated with the uncertainty of the persistence of these NbS due to their funding-dependency. The funding insecurity and the changes in institutional support were explained by the frequent turnover of policymakers (r). Two of eight cases have overcome these barriers by leveraging the long-lasting

reputation of the organisation from the effectiveness of their NbS (vr), and five of eight cases established strong collaboration between participants to ensure the viability of the NbS (vr).

Quote n°8: “And for me as the lead partner, but also I think many other partners had to fight with it, was the administration, the high level of administration.”

3.4. Levers for Nature-based Solutions amplification

Among the suggestions provided by the interviewees to amplify NbS, a total of 25 levers and 23 barriers were identified. Additionally, three elements were identified either as a lever or a barrier, depending on the interviewees. Nine elements, including four levers and five barriers, were mentioned by more than five interviewees (Fig 7). Most of these levers and barriers were not specifically associated with any particular decision-making context cluster. For instance, in each cluster, at least one case mentioned “policymakers’ awareness-raising” as a lever to amplify NbS (rk) (six cases). However, interviewees from *Multi-scale co-production* initiatives were the only ones who argued for “writing guidelines for stakeholders” to amplify NbS (r) (five cases). Similarly, initiatives within *Local transformation* cluster scarcely mentioned levers that involve rules, either in interaction with knowledge through “raising local stakeholders’ awareness” (rk) (nine cases) or in interaction with values through “co-designing NbS” (vrk) (eight cases) and “enhancing the institution’s reputation” (vr) (six cases).

Formal rules were the most frequently mentioned amplification barrier (seven cases). Indeed, interviewees from all three clusters referred to the lack of “existing or adapted incentives” to amplify NbS (r). Other mentioned barriers primarily related to knowledge, such as the “time lag for NbS to deliver benefits” (six cases), and in interaction with rules, such as the “limited capacity of NbS to reduce climate impacts” (rk) (six cases) and the inadequacy of “one-fits-all solution” due to dependency of effectiveness on the social-ecological context (rk) (5 cases). Some interviewees (four cases) from the *Multi-scale co-production* and *Green deal* clusters wished for more pilot sites and experiments to bridge the technical knowledge gap regarding the implementation of effective NbS (rk).

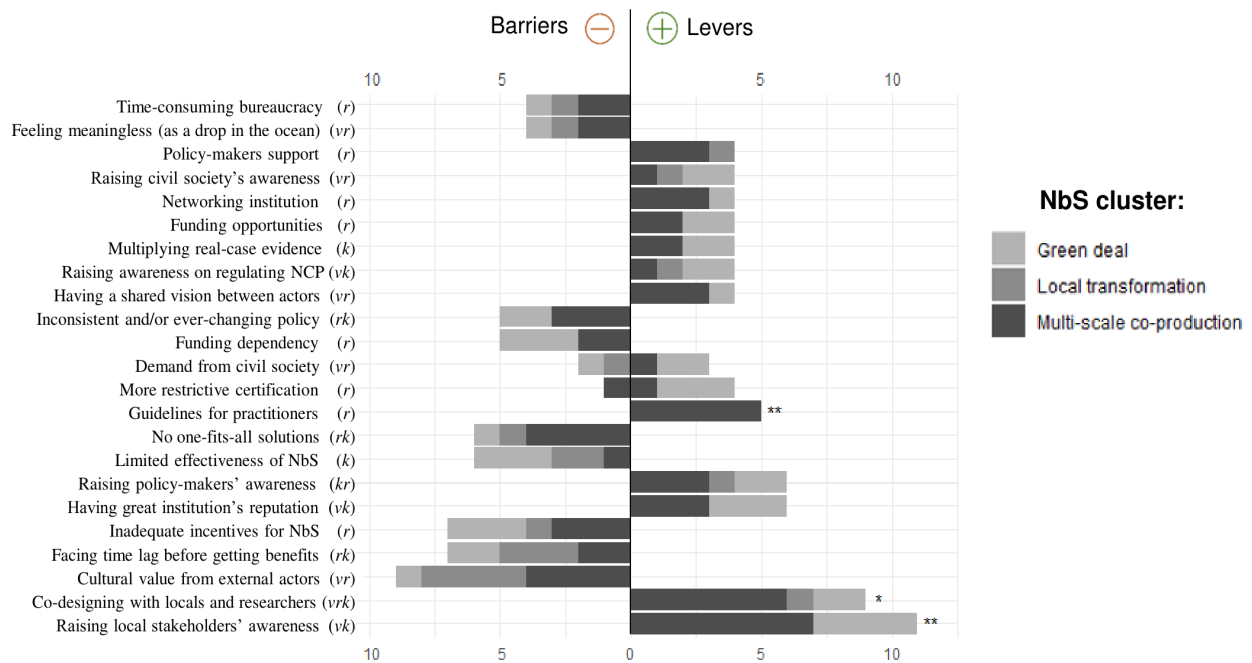


Fig. 7. Barplot of the number of interviews during which the levers and barriers to future amplification of similar Nature-based Solutions were mentioned, plotted according to the decision-making context clusters, and for the subset of levers and barriers mentioned by more than four interviewees. Significance level of the difference of occurrence between clusters for each lever or barrier: * p -value < 0.1; ** p -value < 0.05; *** p -value < 0.01

Two interviewees identified “civil society expectations” (vr) as a potential barrier, referring to the risk of low social acceptability of the NbS. In contrast, three others perceived the shift in “societal values” (vr) as an opportunity to promote NbS, e.g., through additional and more accessible funding. Similarly, while a few interviewees wished for more restrictive “access to incentives” to ensure biodiversity conservation and prevent greenwashing (r), one interviewee cautioned against current overly incentive requirements that might discourage stakeholders from embracing NbS implementation (r).

4. Discussion

4.1. Levers and barriers identified with values-rules-knowledge and transformative adaptation characteristics

This analysis integrated the vrk framework and the assessment of transformative adaptation characteristics to identify levers and barriers to NbS implementation in the Alps. The findings confirm the suitability of the vrk framework in identifying the key elements influencing adaptation initiatives [43,86,87]. The study reveals that formal rules, robust project coordination, positive cultural values within local communities, knowledge sharing through informal exchanges, collaborative planning, and academic support are currently the primary levers for NbS imple-

mentation. These insights align with the levers for NbS implementation identified in the literature's [31,45,83,88,89]. However, the findings show that not all levers mentioned in the literature co-occur within the same initiatives. For example, the levers involving values such as a “mindset change” and “willingness to self-sufficiency” appeared simultaneously with “experiential knowledge sharing”, but they did not coincide with institutional levers such as governance processes and funding opportunities, which have been identified in the literature as priorities to amplify NbS [31,90–92]. Additionally, the findings highlight the inherent uncertainty in the ability of NbS to deliver benefits as a prominent barrier to preferring NbS as an option over grey infrastructures [93,94]. While grey solutions benefit from widespread societal acceptance [95,96] due to their one-size-fits-all designs and short-term outcomes, NbS, in contrast, are site-specific, and their effectiveness is relatively less understood [26,97].

Here, the clustering analysis of the co-occurrence of levers and barriers across the selected case studies identified three types of NbS decision-making contexts and their transformative adaptation characteristics. The *Local transformation* type corresponds with previously recognized alternative practices observed in various regions (e.g., Vermeulen et al. [83] for adaptation initiatives of agriculture worldwide). These initiatives are considered bottom-up approaches implemented by local stakeholders, independently from institutional support [83,98]. They involve experiential knowledge, relational values, and informal rules [45]. The *Green deal* type aligns with the current European *Green Deal* policy strategy [99]. These initiatives are fostered by evolving environmental regulations and available incentives, resulting in a gradual change of practices toward sustainability through awareness-raising activities [99]. This type shares similarities with previous typologies involving technical knowledge and instrumental values [45]. Lastly, the *Multi-scale co-production* type encompasses changes in interactions across sectors and within the research-policy-action sphere, as illustrated in inclusive social-ecological decision-making and transdisciplinary demonstrators [36,45]. While the findings align with previously identified typologies [36,45,100], the three types do not discriminate decision-making contexts based on whether they are led by bottom-up or top-down approaches. Indeed, most of the analyzed initiatives involve a combination of personal decisions to involve institutions or are driven by existing collaborations between the public and private sectors, consistent with previous stakeholder mapping studies for NbS [101]. Therefore, this typology provides a more detailed understanding than the binary differentiation between bottom-up and top-down approaches and offers a solution-oriented typology to assist projects in overcoming barriers. Indeed, given that NbS are site-specific, an approach focusing on the decision-making context rather than on specific interventions may facilitate NbS amplification.

The vrk framework highlights that transformative adaptation is supported by specific interactions between values, rules, and knowledge [60]. In this study, the vrk framework was combined with transformative adaptation characteristics rather than focusing on the coping-incremental-transformative trichotomy since real-life cases often combine these facets of adaptation [4,102,103]. The approach covers the multiple aspects of transformative adaptation and provides a more detailed overview of the elements in place in transformative adaptation processes as well as their outcomes. According to the selected indicators, the findings confirm that greater interactions of values, rules, and knowledge in a decision-making context are expected to im-

plement initiatives with more significant transformative adaptation potential. The results also reveal that transformative adaptation characteristics vary within individual decision-making contexts. For example, in the *Local transformation* type, NbS that were co-designed had more multi-scale co-construction than NbS that benefitted from peer-to-peer exchanges. Moreover, within the *Green deal* type, NbS that were initially designed for long-term persistence, whatever the evolving social-ecological conditions, have a higher level of persistence than NbS that depends on future funding opportunities. The analysis highlights the transformative adaptation characteristics each decision-making context can support and those for which high levels are less likely. Considering that each type of decision-making context falls short of achieving high levels of at least two transformative adaptation characteristics, the results emphasise the limited use of transformative adaptation in current initiatives [12,14]. While assessing the contribution of individual initiatives to transformative adaptation remains challenging, the findings validate the potential of NbS to support transformative adaptation, aligning with other studies that have synthesized datasets of NbS elsewhere [13,15,104]. Moreover, there is a need for transformative NbS, namely in governance and policies supporting the adaptive capacity of nature, financial compensation for transition, co-creation of knowledge and solutions, monitoring systems, and disseminating knowledge [7,31,56,83,105].

These three types of NbS are new insights that complement previous classifications of NbS. While some scholars have categorized NbS based on factors such as climatic hazards, NCP co-benefits [26,27] or types of interventions [18,97], our results demonstrate that similar decision-making contexts can underpin the implementation of different interventions (e.g. ecological restoration and sustainable management), or address various climatic hazards (e.g. floods and drought). This suggests, in line with NbS global standards [106], that NbS interventions should focus on enabling the decision-making context expected to implement the most appropriate NbS for transformative adaptation rather than only focusing on what type of NbS should address a given climatic hazard. These findings align with the latest interdisciplinary studies reporting the plurality of stakeholders and governance models involved in NbS implementation [37,101,107,108]. The NbS types identified from the study cases do not discriminate governance models because the interview guide did not target this aspect. However, the NbS with high levels for the system-wide and multi-scale co-construction characteristics were co-designed with a large range of stakeholders and were coordinated by one of them without necessarily holding more power [109,110].

Furthermore, the assessment of transformative adaptation characteristics reveals the specific aspects of transformation that each NbS type is likely to support. This provides valuable insights for policymakers into levers that can foster transformative NbS [73]. The following two sub-sections develop how interactions, first with values and second with rules, can enhance transformative NbS. The interactions of knowledge for transformative NbS are not addressed in a separate sub-section, as knowledge is involved in its interactions with values and rules.

4.2. Interactions with values to enhance transformative Nature-based Solutions

The analysis highlights the valuable role of values within NbS decision-making contexts. Values have been identified as crucial determinants of transformation [111–113]. However, the transformative adaptation characteristics of the NbS depended on the type of values involved in their implementation. For example, relational values to nature were involved in innovative practices that restructured relationships between nature and people, aligning with local ecological knowledge studies [33,45]. The willingness to include the diverse range of values into NbS design, e.g. through participatory approaches, resulted in initiatives with a high level of multi-scale co-production and networking and the potential to benefit large communities and regions [37].

The direct experience of climate impacts was not a primary driver of the identified NbS [114]. However, the effects of climate change played a role in most of the analyzed decision-making contexts. The majority of the NbS reacted to impacts rather than being designed to prevent future impacts. This confirms that adaptation usually arises when the social-ecological system is forced to adapt to new conditions [83,115,116]. Within the *Green deal* type, NbS emerged in response to the experience of climate impacts or natural disasters. Similarly, within the *Local transformation* type, some NbS emerged due to economic viability being threatened by climate change, requiring adaptation measures. These drivers of change led to initiatives with different transformative adaptation characteristics, but without being anticipated by stakeholders, except in the NbS of the *Multi-scale co-production* type where future conditions were expected through methods such as climate models analysis. The uncertainty of future conditions and consequently of the efficiency of implemented solutions, predicted or not, is one of the most mentioned barriers elsewhere in the literature [83,94]. However, the results indicate that each decision-making type of context delivers one option to face this uncertainty in implementing NbS. *Local transformations* NbS aim to support ecosystem resilience and adaptability to face unpredictable conditions through a learning-by-doing process [5,83,117], including failure. *Green deal* NbS gradually change their practices to maintain the ability to shift from one method to another one, despite the limited evidence regarding the effectiveness of this option [4,118,119]. *Multi-scale co-production* NbS aim to build a robust social network through new governance models to foster collective support, thereby increasing resilience to future conditions [37,83,120,121].

The *Multi-scale co-production* type encompasses existing innovative initiatives and highly aware local stakeholders. These initiatives identified raising awareness of local stakeholders as a primary lever to amplify NbS. However, one of the most difficult barriers to overcome for adaptation is associated with the need of a shift in values [87,111]. Particularly, overcoming path dependency by including intrinsic and relational values that are not commonly shared or of non-material NCP remains challenging [45,122]. Social acceptance of the NbS within the *Multi-scale co-production* type overcomes this barrier [95].

Cultural values of the local social-ecological system, and the path dependency of practices, were perceived as barriers to *Local transformation* and *Green deal* initiatives. These barriers have been overcome through different approaches. *Green deal* NbS employ participatory processes, while *Local transformation* NbS align with different cultural values than the constraining one, such as the values of labour or landscape aesthetics. This highlights the trade-offs that occur within decision-making contexts [123,124].

4.3. Interactions with rules to foster transformative Nature-based Solutions

The findings revealed that institutional support plays a crucial role in NbS implementation, although the intensity and the nature of its contribution varies across decision-making contexts. Funding opportunities provided by governmental institutions are essential for the *Multi-scale co-production* of NbS for which the implementation might not have been possible without such financial support, aligning with previous insights [83]. These highly transformative NbS benefited mostly from transdisciplinary research projects, with public funding from national or European programmes or incentives, and involved public administrations related to biodiversity conservation, protected areas, agriculture, forest, and water management [16,83]. However, these initiatives encountered significant bureaucratic burdens imposed by funders, challenging their implementation.

Interviewees from *Local transformation* and *Green deal* NbS argued for context-specific incentives to support implementers in overcoming economic uncertainties associated with the implementation of new practices. Participants from *Local transformation* NbS expressed the need for incentives, particularly in addressing the time lag before obtaining the benefits of the implementation and the initial required expenses, e.g., acquiring specialized equipment for innovative practices. In the case of *Green deal* NbS, interviewees recognized incentives as effective instruments for mainstreaming biodiversity conservation [83]. Additionally, a large proportion of the interviewees emphasized the crucial role of departmental or regional administrations in facilitating the interactions between policy-makers and practitioners [83]. For example, the involvement of public institutions and research organisations has been identified as crucial for co-designing adaptation initiatives through transdisciplinary research programmes [125,126], or regional adaptation plans [98,127]. Still, local stakeholders emphasized the significant impact of sharing experiences with peers to enhance their willingness to adopt and implement new practices [128,129]. Future research should further investigate the pivotal role of peer-to-peer governance in promoting NbS [45,100].

The absence of a well-structured sector was also identified as a barrier to NbS implementation, such as the absence of local seeds markets for Alpine grasslands restoration [130] or the absence of a value chain for new agricultural products [131]. While *Local transformation* NbS manage to diversify their marketing strategies [132], e.g., by developing direct marketing to local communities, the institutions involved in *Multi-scale co-production* NbS aim to develop emerging value chains for their products in collaboration with stakeholders [130]. However, this

institutional involvement in enabling-NbS activities is limited due to cultural barriers [32,132] and the time that stakeholders involvement consumes [133]. Only intense involvement related to personal values enables the implementation of *Multi-scale co-production* NbS [134].

Many interviewees stressed the need for NbS implementation guidelines and standards to support NbS amplification in the future, as previously identified [19,39,73,135]. However, they also highlighted the uniqueness of each NbS to indicate the challenges associated with replicating similar initiatives, confirming that NbS are not one-size-fits-all solutions [108,123,136]. Moreover, operationalizing NbS guidelines may prove ineffective or even counterproductive if actors' interpretations of the NbS concept remain unclear [104,137,138]. Finally, institutional support is needed to facilitate monitoring NbS outcomes using standardized methods [139].

4.4. Study limitations

The study focused on a limited number of existing NbS in the Alps. However, this sample encompassed the diversity of activities identified to address drought, floods, and soil erosion in this region [27,59]. The insights can support NbS amplification in other regions, as identified levers and barriers align with studies from other social-ecological systems worldwide [83,140].

The interviews were conducted with only one manager involved in the implementation process for each NbS. Although the perception of the NbS can depend on the interviewee [134,141], the perception bias was reduced by employing structured questions specifically related to the implementation process. Moreover, in four cases, two interviewees were involved in the same network despite not being involved in the same NbS, and their responses were consistent.

This study did not assess the adaptation pathways of the NbS, i.e. the long-term adaptation process, shifting from one decision-making context to one favourable to NbS implementation [87]. However, the NbS were implemented to address an emerging issue within specific contexts, and the interviewees' perceptions regarding the future of the NbS were captured. This combination of knowledge enables the identification of the elements from the *vrk* that influence the system trajectory towards adaptation and that might contribute to building pathways [43,86]. Furthermore, potential levers and barriers towards NbS amplification were identified, considering stakeholders' vision and experiences in determining actions toward desired adaptation pathways [31].

This study did not directly assess the effectiveness of NbS. However, the interviewee's perception of the initiative's outcomes was captured through specific questions, indicating to what extent the addressed issues have been or are being resolved [142]. Moreover, although the investigated NbS were at different stages of implementation, the analysis did not segregate initiatives according to implementation stages. This aligns with the NbS implementation process, known to follow diverse pathways [83,108,143].

The analysis did not consider power relationships that are known to be crucial for sustainable development considering equity and justice [112,144,145]. However, they were considered when interviewees mentioned these aspects in the decision-making process. For example, the participatory methods such as consultation, concertation, and co-design approaches that aim to benefit equally within local communities were captured in the data processing. Given the regional context, the identified NbS did not integrate indigenous local knowledge that is known to be crucial for sustainable development [104,146]. However, the interviewees highlighted the role of experiential knowledge and the relational value to nature in NbS implementation.

4.5. Perspectives and recommendations for policymakers: There is no one-fits-all lever

NbS have the potential to foster transformative adaptation to climate change, and their amplification is crucial to mitigate future impacts on ecosystems and human well-being. However, transformative practices remain limited in NbS implementation [12,14], and most of the local stakeholders we interviewed preferred incremental actions [98,147]. This reluctance can be attributed to the complexity of aspects to consider in transformative NbS, such as climate change impacts, ecosystem functioning, NCP co-benefits, long-term economic and social benefits, along with associated trade-offs [112,121,148].

The analysis conducted in this study identified the levers and barriers suggested by NbS managers to amplify similar initiatives. Aligning with previous research that identified different enabling contexts leading to NbS implementation [149], the study reveals that certain combinations of levers allow to overcome certain barriers and facilitate the implementation of a specific type of NbS. Based on the findings, three recommendations for policymakers to amplify NbS can be proposed. Firstly, creating opportunities for non-governmental stakeholders (private sector, NGO, and civil society) who are already aiming to implement transformative NbS but who are facing economic or technical issues. Opportunities include, among others, funding programmes, networking events, and support in monitoring activities. Secondly, shifting public administration strategies towards prioritizing transformative NbS for public action, e.g., natural disaster risk reduction, managing public land, and common goods. Lastly, encouraging non-governmental stakeholders unwilling to implement transformative NbS, e.g., through strong incentives and establishing binding measures through legislation when required.

According to the findings of this study, the levers to be activated must be tailored to the local decision-making context and the transformative potential of the NbS they might support. For example, in the context of disaster risk reduction, supporting a transdisciplinary approach can enhance NbS co-design involving local communities and developing a network of stakeholders willing to collaborate. However, this approach could fail if local stakeholders focus only on adapting their own practices and do not want to be involved in new projects. A preliminary analysis of the decision-making context is, therefore, critical. Moreover, multiplying *Local transformations* NbS initiatives by non-governmental stakeholders is a powerful strategy to foster

initiatives at a broader scale when complemented by the promotion of sharing networks and monitoring activities [36,150]. Introducing new financial incentives or environmental regulations can support NbS amplification to stakeholders who are already willing to implement NbS, particularly those with economic or technical constraints. However, these instruments must be framed considering principles for effective NbS, namely economic viability, inclusive governance, equity, sustainability, and mainstreaming [106]. This approach may not support stakeholders unwilling to implement NbS, e.g. due to cultural barriers. Additional facilitating levers are required in such cases. For example, introducing new policies can be accompanied by activities aiming to raise stakeholders' awareness about the potential of NbS to mitigate climate impacts and to provide NCP co-benefits [35].

In order to enhance knowledge co-production, further sustainability research needs to bridge the gap between the *Local transformations* NbS that design their implementation based on experiential knowledge and the *Multi-scale co-production* NbS that involve academic knowledge [109,151]. Therefore, transdisciplinary approaches are crucial to bridge institutions and communities to produce relevant and applicable knowledge to local contexts [152]. This would foster the dissemination by public institutions of academic knowledge in an actionable way for stakeholders, e.g., through knowledge hubs or living labs [153]. Knowledge hubs are also essential for multiplying local initiatives and sharing experiences without being considered non-standard cases, pilot projects, or on the margins [36].

Societal mindsets and worldviews were found to be strong motivations for NbS implementation. Therefore, raising awareness among local communities about the crucial role of ecosystems in adaptation can significantly increase social acceptance. Similarly, raising policymakers' awareness about NbS benefits can accelerate their amplification [154]. Lastly, as demonstrated within *Green deal* NbS, greater institutional support can contribute to amplifying NbS with high levels of innovation, persistence, and cross-scaling, e.g., when an agriculture chamber or a research program fosters the inclusion of stakeholders into already existing dynamics such as legislations and available incentives, or knowledge, by creating spaces for dialogue to share experiential lessons [83].

These points highlight the importance of strengthening international cooperation for NbS implementation in large interconnected regions, such as the Alps. The Alpine spatial continuum with cross-regional similarities is an opportunity to benefit from experiential lessons and multiple levels of governance [56,155]. Cross-regional institutions such as the Alpine Convention or EUSALP (European Union Strategy for the ALPine region) have demonstrated their potential to engage macro-regional governance in biodiversity conservation or energy transition [156,157]. However, the heterogeneity of formal rules, such as different legislative frameworks or available incentives, and informal rules, such as habits, are barriers cross-regional interactions should overcome. Enabling activities, including networking and transdisciplinary projects, can help overcome this barrier and promote cooperation for NbS amplification [158,159].

Conclusion

To effectively address the concurrent crises of biodiversity loss and climate change and ensure a transformative adaptation towards a sustainable future, the implementation of NbS must be urgently accelerated. Accordingly, the levers to transformative NbS implementation are being increasingly studied. However, prevalent levers and barriers are often assessed in relation to different NbS types, and scarce attention has been given to the local decision-making context, which ultimately influences levers and barriers. Based on the analysis of twenty NbS implemented in the Alps, this study illustrates the influence of values, rules, and knowledge in the transformative adaptation potential of NbS and reveals three decision-making contexts that can foster transformative NbS in different ways. These three NbS types of co-occurring levers and barriers are: Firstly, *Local transformation* NbS are self-sufficient initiatives motivated by relational values to nature. They are supported by informal governance, and they share experiential knowledge to support the adaptive capacity of nature. They incorporate the deep cultural value of their environment by creating an alternative system of practices. Secondly, *Green deal* NbS employ gradual changes in practices and are supported by funding opportunities or regulations to experiment with new approaches. They prioritise instrumental values to foster NbS benefits and to overcome path dependency in current practices but poorly contribute to transformative adaptation. Thirdly, *Multi-scale co-production* NbS benefit large areas and communities. Their social acceptance results from extensive participatory processes involving local practitioners and diverse values of nature. These initiatives are designed to persist even when challenged by the instability of funding opportunities.

In order to amplify transformative NbS, future implementation will require better integration of values, rules, knowledge, and their interactions. This can be achieved through i) the creation of multiple levels of governance; ii) the creation of new incentives and regulations to foster transformative NbS; iii) the greater support from public institutions to local initiatives; iv) the increasing awareness of NbS benefits among policymakers; v) the creation of long-lasting spaces for dialogue. Given its social-ecological consistency and its climate impact similarities, the Alpine scale has the potential to address these issues, thanks to its pivotal position for strategic macro-regional governance. Future research on transformative NbS for climate change adaptation is needed to explore how to engage local communities with active peer-to-peer dialogues and the stakeholders who benefit from scientific knowledge on NbS effectiveness to address their shared challenges effectively.

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Appendices

S1. Table. Information of each Nature-based Solution analyzed to define the decision-making context and their transformative characteristics

Code	Initiative	Description	Activities	Addressed issues	Ecosystem or land-use	Interviewee	Interview	Cluster of decision-making context
ReSem2	Restoration of ski slopes with seeds of local species	Shift in the mindset of the company to reduce environmental degradation of the ski resort activities, led by the latest change of the company direction. Applied restoration practices with a small proportion of endemic species in the mixture usually based on allochthone species. Economic trade-offs limit the use of high proportion of endemic species in a large surface. Concertation with local stakeholders, and expert-based knowledge involvement	grassland restoration; knowledge co-production	Snow cover reduction; soil erosion	Alpine grasslands; ski slopes	Ski resort manager	Remotely	Green deal
IUIse	River restoration to reduce flood risk	Paradigm shift from grey to green solutions to reduce flood risk, as a pioneer project for such a large scale (large valley of nineteen municipalities). Concertation process to increase social acceptance, and creation of a coordination council involving scientists, decision-makers and local communities. New compensatory measures in case of crop loss due to floods.	River restoration; compensation rules	Floods	Rivers; floodplain with croplands	Public water-related management officer	Face-to-face	Mutli-scale co-production

ReMot	Agroforestry practice in a vineyard submitted to drought	Change from organic monoculture to agroforestry, and let nature evolve by itself to support biological pest regulation through trophic network understanding. The farming area will decrease because new practices involved higher workforce on a same surface. Developed alternative trade systems to reach aware costumers on their practices, and value co-product of the trees through non-monetary exchanges.	Sustainable management; Food production	Drought; soil erosion; pest attack	Vineyard	Vineyard owner	Face-to-face	Local transformation
ReBu2	Reforestation of a private mixed forest with drought-tolerant species	Change of management practice in one forest, from one species to three drought-tolerant species planted in mixed forests, thanks to incentives from carbon market. Networking with local foresters through cooperative structure to gather material and knowledge.	Reforestation; sustainable management	Drought; pest attack	Forest	Forest owner	Remotely	Green deal
ONRes	Assisted migration of exotic drought-tolerant species in Alpine forests	Choice of alternative pathway to adaptation by planting exotic species seedlings, that looks like to local ones to support biodiversity and increase social acceptance. Concertation between motivated decision-makers. Belong to overall adaptation strategy involving different options.	Reforestation; sustainable management	Drought	Forest	Public forest officer	Face-to-face	Local transformation
ReSem1	Trandisciplinary network to restore Alpine grasslands with seeds of local species	Developed experiments and network to use local species for Alpine grassland restoration instead of allochthone ones usually used. Transdisciplinary project developing new network to develop local economic sector, by increasing technical knowledge and involving companies. New project is going to improve the evidence of the practices	grassland restoration; knowledge co-production; networking	Increasing temperature; soil erosion control	Alpine pastures; grasslands	Public biodiversity conservation officer	Face-to-face	Mutli-scale co-production

ChAgr	Agroforestry practices in a wetland	Paradigm shift from one land for one use thought to multi-use of the land with agroforestry practices, still conflictual with current biodiversity conservation practices that claim for avoiding economic activities. Funding opportunity to experiment with local stakeholders, the project failed in benefiting positively to practitioners. New project is going to use abandoned land to deliver positive outcomes	Sustainable management; Food production	Increasing temperature; land pressure	Wetland with crops and forest	Public agricultural officer	Face-to-face	Mutli-scale co-production
IRAlp	Trandisciplinary network to develop a shared knowledge and vision of Alpine grassland	Gradual changes led by sharing experiences and practices of Alpine grassland management between peers and with scientists, through transdisciplinary research programmes, but constraint by the need of understanding future impacts. Deep shift in the way of connecting science-policy-actions from local to transregional scale	Networking; Knowledge co-production	Drought; increasing temperature; tradition heritage	Alpine pastures	Researcher; project coordinator	Face-to-face	Mutli-scale co-production
ReVel	Reforestation of a private forest	Exploration of reforestation options, unusual in the region, with expert's knowledge and foresters networking through association of local foresters to gather material and knowledge.	Reforestation; sustainable management	Species shift; Drought; storms; pest attack; deer invasion	Forest	Forest owner	Face-to-face	Green deal
ReChi	Natural regeneration of a private forest	Shift from current planted forest to natural regeneration, targeting long-term benefits instead of maximising short-term profit. Implemented in one owned forest thanks to regional administration support and incentives opportunity. Networking with other practitioners through association of local stakeholders.	Sustainable management; Timber production	Pest attack; disease; drought; long-term impacts	Forest	Public forest advisor	Remotely	Green deal

ITHel1	Trandisciplinary network to enhance conservative agriculture	Raising awareness and spread expert knowledge on conservative agriculture practices to tackle soil erosion, inputs and drought in cropland, with positive economic outcomes. Transdisciplinary project co-designed with existing demonstrative farms to convince local farmers. Network is maintained after the project ended	Networking; Knowledge co-production	Drought; soil erosion; soil fertility; pollution from fertiliser	Cropland	Two public agricultural officers	Remotely	Mutli-scale co-production
ITHel2	Conservative agriculture practices and high-tech equipment	Paradigm shift from traditional practices to competitive conservative agriculture thanks to high-tech equipment, pioneer farm that share with other pioneers, networking with regional administration and schools of agronomy to show positive outcomes	Sustainable management; Food production	Drought; floods; precipitation change; soil fertility; animal welfare	Cropland	Farmer	Face-to-face	Local transformation
NCPPro	Adapting protective forest managed by a railway company	Opportunity from national funding programmes to collaborate to experiment and increasing awareness on the need to adapt forest management of a valley to drought but waiting for strong recommendations before changing practices, without connections with local communities, and no future plans for now	Sustainable management; knowledge production	Drought; glacier retreat; landslides; rockfalls	Forest over railway	Risk reduction manager of railway company	Face-to-face	Green deal
WaHyM	Transdisciplinary project to increase NCP through river management	Raising awareness and spreading local initiatives to river managers to enhance NCP through NbS thanks to already known processes poorly applied on ground. Concertation process to solve conflicts but still difficult. No more connections after the project ended.	Raising awareness; knowledge co-production	River connectivity; energy production	Rivers	Civil protection officer; NGO employee	Remotely	Mutli-scale co-production
KLTie2	Agroecology practice and alternative exchange network	Shift from traditional agricultural practices to agroecology practices in a farm, promoting biodiversity and biological regulation, unusual in the region. Developed a direct market to local costumers, thanks to pedagogic activities and social medias, valuing balder instead of money, and network with local farmers and municipality.	Sustainable management; alternative market system	Drought; pest attack; food quality	Cropland; grasslands	Farmer	Face-to-face	Local transformation

KLIn	Municipalities involvement in supporting local NbS with stakeholders	Municipalities' actions to support NbS through raising awareness activities and experiments of existing adaptative practices with local stakeholders from different sectors but some difficulties to involve them despite bottom-up approach and consultation. Project coordination role led by one person hired by municipalities. The project was born from new national funding programmes, and is likely continue with additional funding.	Raising awareness; pilot site for experiments	Drought; erratic rainfall; pest; floods; heatwaves	Landscape of municipalities	Municipality officer, project coordinator	Face-to-face	Green deal
EUGre	Transdisciplinary research project to enhance forest-based protection management	Transdisciplinary research project following a previous project, to develop models and decision-making tools with local foresters and decision-makers for ecosystem-based natural risk reduction of forests. Transborder project with small pilot areas. Project coordination role took from one practitioner. Used research impact framework. Network of actors should be maintained.	Networking; Knowledge co-production	Global disturbances to forest; landslides; rockfalls	Forest and sites to protect	Researcher; project coordinator	Face-to-face	Mutli-scale co-production
PNLi1	Reducing soil erosion with grass cover management in vineyard	Experiments and spreading practices to reduce soil erosion in Alpine vineyard thanks to cover grasses and organic market. Involved in transdisciplinary research project, but difficulties to involve local stakeholders and supported mainly by the one person at local scale.	Sustainable management; Food production; pilot site for experiments	Erratic rainfall; soil erosion; soil fertility	Pilot vineyard	Researcher	Face-to-face	Green deal

KLTe1	Municipalities involvement in supporting local NbS from stakeholders	Municipalities' actions to support NbS through raising awareness activities and experiments of existing adaptative practices with local stakeholders from different sectors but some difficulties to involve them despite bottom-up approach and consultation. Project coordination role led by one person hired by municipalities. The project was born from new national funding programmes, and is likely continue with additional funding.	Raising awareness; pilot site for experiments	Erratic rainfall; floods; drought; water quality	Landscape of municipalities	Municipality officer, project coordinator	Face-to-face	Green deal
SIFor	Adapting close-to-nature forest management for climate change adaptation and mitigation	Transdisciplinary approaches to evaluate, test and recommend the best management practices of forests and the most adapted tree species to address climate change adaptation and mitigation. The activities are funded by national and European funding programmes	Raising awareness; guidelines for stakeholders; knowledge co-production	Drought; storms	Forest	Forester, project coordinator		

S2. Table. Guidelines used to conduct semi-structured interviews with managers of implemented Nature-based Solutions to climate change adaptation

Main topic	Question	Follow-up questions
Reasons of the project	Could you tell us how came the idea of implementing the project?	Could you please describe in few words the area where the project is implemented?
		What are the reasons that led to the decision to implement the project?
		How have you become aware of this/these issue(s) / problem(s)?
		Have you also the objective to address: i) a problem led or enhanced by climate change; ii) biodiversity loss; iii) a local economic or social issue?
Diagnostic	Is the project based on a diagnostic or a state of the art, done before or by yourself?	If yes, what was this diagnostic?
		What have you learned from it?
Choice of the solution	Was there other possibility in alternative to address this problem?	If yes, which ones?
		How have you chosen this method? (based on which criteria)
Relationships and collaboration	How are the relationships with your partners?	Is it easy to cooperate?
		How the decisions are made and by who?
		Is there any conflict: i) with your partners; ii) with the population? If yes, how have you deal with them?
Funding	How the project was fund?	How have you obtained these funds?
		Have you encountered difficulties to obtain them?
Main barriers and levers	Is there something that has been particularly easy to do in this project?	Is there a specific element that enable to move forward the project?
	What have been the most difficult for you in the implementation of the project?	How have you deal with this difficulty?

Sustainability	What statement of the project could you make today?	Have you monitored effectiveness indicators?
		How do you see the project in a mid-term future (2030)?
Scaling potential	Do you think that this project can be replicate in other sites?	If yes, what would be the conditions?
		What could facilitate the replication of your project?
	In which circumstances have you talk about your project?	Do you have feedback on what your project inspired elsewhere?

Quest for self-sufficiency	1		1	1																
Willingness to invest time and energy	1	1											1	1				1		
Identification of required grey solutions			1		-1					-1	1									
Identification of grey solutions to be abandoned	1						1													
Willingness to learn by doing including failing	1			1	1	1														
Willingness to support the adaptive capacity of nature	1	1		1		1												1		
Personal interest in scientific knowledge	1	1	1		1		1								1	1	1	1	1	1
Interest in external perception of climate change						1				1	1			1	1					
Personal experience of climate change	1					1	1		1	1		1	1							1
Uncertainties of future climate conditions	1	1								-1	-1				1					1
Cumulative climate impacts	1		1					1		-1	1		1	1						1
Increasing non-climatic disturbances	1					-1		-1			1									1
Adapted species	1	1	1	1		1		1	1								1	1		1
Autodidact process of learning	1		1	1		1						1								
Scientific ecological knowledge	1	1	1	1	1	1		1			1				1				1	1

Incentives	Few	No	Few	No	Few	Few	Few	Few	Fully	Few	No	Fully	No	No	No	No	No	No	No	No	
Owners' approval requirement					-1											-1		-1	-1		-1
Bureaucracy						Few		Few							Hard	Hard			Hard	Hard	
Willingness to take economic risk	1	1	1	1	1		-1	-1		-1	-1	-1			1	1		1	1	1	
Inspiration from traditional practices				1	1		1			1						1			1		1
Transdisciplinary approach		1								1						1	1		1	1	1
Emergence of the initiative from external actor								1		1	1							0,5			
Social acceptability		1	1	1	1					1	1	1	1					1		1	
Lack of external awareness							-1		-1				-1				-1				
Path-dependency of habits	-1	-1		-1			-1					-1								-1	
Personal mindset change	1	1	1	1											1			1			
Designing from existing initiatives															1		1	1	1		
Dialogue between peers															1	1			1		
Lack of built sector															-1		-1		-1		

S4. Table. Original quotes from semi-structured interviews conducted with managers of implemented Nature-based Solutions to climate change adaptation in the European Alps, cited in the main text.

Quote n°1	« Du coup on a un support de biodiversité puisqu'on a une fonge, une avifaune, une entomofaune qui est compatible avec ce type-là de sapin. C'est pour ça aussi qu'on a choisi du sapin : meilleure acceptabilité sociale, ça collait mieux à la biodiversité française. »
Quote n°2	« [la ronce] arrive, elle arrive à grand galop, donc après c'est : quelle va être la gestion de la ronce, comment on va la gérer, comment on peut vivre avec, comment on peut vivre avec le regard des gens qui vont dire [...] y a des ronces partout dans ces vignes »
Quote n°3	“We have neighbours and friends who come to help us when we have a lot of work. Then we make something to eat and drink, and we give them products from the farm.”
Quote n°4	« Après il fallait une action [sur cet alpage], et on tenait beaucoup à ce qu'il y ait une action plus large qui puisse servir à tout le secteur agricole [du secteur] »
Quote n°5	« Moi je fais ça par passion hein. Je fais ça par passion, j'avais cinq ans, j'allais dans les bois avec mon père »
Quote n°6	« Et nous on peut quand-même démontrer que, moi quand je plante, j'ai planté six hectares, je ne sais pas à combien ça correspond, mais je vais capter du carbone pendant 60 ans, plus peut-être, pendant 100 ans, si je fais un bâtiment »
Quote n°7	« Donc [...] la grande idée était dans les cartons, mais il n'y avait pas tellement, en tout cas en France, de projet de cette ampleur qui nous permettait d'aller chercher un exemple quoi »
Quote n°8	“And for me as the lead partner, but also I think many other partners had to fight with it, was the administration, the high level of administration”

S5. Table. Matrix of the elements suggested by the interviewees involved in Nature-based Solutions implementation to amplify similar initiatives. The code “1” indicates that the element is expected to enhance the amplification of NbS. The code “-1” indicates that the element is expected to constrain the amplification of NbS. The blank cell indicates that the element is not mentioned by the interviewee. Each column corresponds to one NbS as follows: a: ReMot; b: ONRes; c: ITHel2; d: KLTie_2; e: ChAgr; f: ReVe1; g: PNLi1; h: ReChi; i: ReBu2; j: ReSem_2; k: NCPPro; l: KLTie_1; m: KLIIn; n: ITHel1; o: IRAlp; p: WaHyM; q: IUise; r: ReSem_1; s: EUGre; t: SIFor

Nature-based Solutions																				
Levers and barriers	a	b	c	d	e	f	g	h	i	j	k	l	m	n	o	p	q	r	s	t
Giving more power to local administration																	1			1
Having a shared vision between actors									1						1			1		1
Required long-term investments						-1														
Demand from civil society		-1				-1	1			1								1		
Great institution’s reputation						1		1	1						1		1	1		
Being in a bubble with only aware people								-1				-1	-1							
Vision gap between locals						-1		-1												
Required intense personal investment						-1														
Expliciting personal vision															1					
Fear of changes									-1											
Sharing initiatives	1						1			1										
Raising awareness on regulating NCP	1				1	1				1										
Getting inspired by traditional practices					1															
High adaptation occurs when no choice	-1				1										1					

S6. Table. Matrix of the transformative adaptation characteristics of the Nature-based Solutions identified in the Alps.

Transformative adaptation characteristics								
Nature-based Solutions	Restructuring People-Nature (RPN)	Restructuring ecosystem (RES)	Path-shifting (PS)	System-wide (SW)	Innovative (I)	Multi-scale network (MSN)	Multi-scale co-production (MSC)	Persistency (P)
ReMot	Intrinsic values	Change in NCP	Change in social relationships	Small	Known experiments	Single disciplinary	Peer-to-peer	Adaptable
ONRes	Relational values	Change in species richness	Change in social relationships	Pilot site	Never seen before	Single disciplinary	Co-design	Adaptable
ITHel2	Relational values	Change in NCP	Change in social relationships	Small	Unusual in the region but known elsewhere	Single disciplinary	Peer-to-peer	Adaptable
KLTie_2	Intrinsic values	Change in NCP	Change in social relationships	Small	Known alternative	Single disciplinary	Fostering collaboration	Adaptable
ChAgr	Instrumental values	Change in land-cover	Gradual change in practices	Small	Known alternative	ITD	Co-design	Aborted
ReVe1	No mentioned value	Change of species	Gradual change in practices	Small	New species	Single disciplinary	Peer-to-peer	Policy-dependent
PNLi1	No mentioned value	Change in species richness	Gradual change in practices	Pilot site	Unusual in the region but known elsewhere	Single disciplinary	Fostering collaboration	Methods
ReChi	Instrumental values	Change in landscape connectivity	Radical change in practices	Pilot site	Known alternative	Single disciplinary	Fostering collaboration	Policy-dependent
ReBu2	Instrumental values	Change of species	Gradual change in practices	Small	New species	Single disciplinary	Public-private partnership	Planned to persist

ReSem_2	No mentioned value	Change of species	Business-as-usual	Pilot site	New species	ITD	Public-private partnership	Planned to persist
NCPPro	No mentioned value	Change of species	Business-as-usual	Small	New species	Single disciplinary	Private-private partnership	Methods
KL Tie_1	No mentioned value	No change	Gradual change in practices	Municipalities	Unusual in the region but known elsewhere	Fostering inter-disciplinarity	Public-private partnership	Funding-dependent
KLIn	No mentioned value	No change	Gradual change in practices	Municipalities	Unusual in the region but known elsewhere	Fostering inter-disciplinarity	Public-private partnership	Funding-dependent
ITHel1	Instrumental values	Change in NCP	Change in social relationships	Interregional	Known alternative	Single disciplinary	Public-private partnership	Methods
IRAlp	No mentioned value	No change	Change in social relationships	Interregional	Known experiments	ITD	Public-private partnership	Methods
WaHyM	Instrumental values	Change in NCP	Integrated vision of the system	Interregional	Known experiments	ITD	Co-design	Methods
IUIse	Relational values	Change in landscape connectivity	Integrated vision of the system	Municipalities	Known experiments	ITD	Co-design	Planned to persist
ReSem_1	Relational values	Change in species richness	Change in social relationships	Interregional	Known experiments	ITD	Public-private partnership	Funding-dependent
EUGre	No mentioned value	Change in NCP	Integrated vision of the system	Interregional	Known experiments	ITD	Co-design	Methods
SIFor	No mentioned value	Change in species	Integrated vision of the system	Interregional	Known experiments	ITD	Public-private partnership	Policy-dependent

Chapter IV

Priority areas for nature-based adaptation to climate change in the Alps



Conservative Agriculture aims to enhance soil fertility, biodiversity and climate change adaptation through no-tillage practices, cover crops, and crop rotation. This Italian farm is engaged in the Life-HelpSoil project, which focuses on the experimentation and the dissemination of conservative agriculture practices in Udine region. The vehicle injects manure into the soil, without compacting it, fostering species diversity of grasslands.

Source: the author.

Priority areas for nature-based adaptation to climate change in the Alps

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Abstract

Nature-based Solutions (NbS) are promising initiatives for climate change adaptation, aiming to protect, restore or sustainably manage ecosystems for mitigating climate hazards. In conjunction with their role as Nature's Contribution to Adaptation (NCA), NbS can deliver multiple co-benefits, including carbon sequestration and the provision of habitats for biodiversity. However, the implementation of NbS remains limited, exacerbating the adaptation gap alongside the accumulation of global carbon emissions in the atmosphere. Given the finite human and financial resources for NbS implementation, prioritising areas is urgent. Existing literature on climate risk assessment in social-ecological systems faces challenges in accounting for the NCA supplied by ecosystems in the face of future climate conditions. Moreover, the overlaps of priority areas for NCA with areas providing co-benefits for climate change mitigation and biodiversity conservation are still unclear. Here, we considered future soil moisture and groundwater as indicators of NCA. They allowed the identification of priority areas for the implementation of NbS for adaptation to drought in the European Alps. Our analyses reveal that co-benefits for carbon sequestration and biodiversity conservation do not overlap with these priorities for drought adaptation. Moreover, our results illustrate the high potential of NbS in croplands and wetlands located within protected areas to enhance NCA. In contrast, participatory approaches involving local communities are required to implement NbS within priority forests and grasslands that face significant pressures from outdoor recreation activities. Future NbS initiatives must consider specific landscape contexts within priority areas to identify beneficiaries from their outcomes.

Key-words

Nature-based Solutions; Climate change adaptation; Biodiversity conservation; Carbon sequestration; Spatial prioritisation

1. Introduction

The transition towards a sustainable future is urgent to tackle climate and biodiversity crises. (Brondizio et al., 2019; Pörtner et al., 2023, 2022). Nature-based Solutions are increasingly recognised as suitable options for climate change mitigation and adaptation from and for biodiversity (Chausson et al., 2020; Cohen-Shacham et al., 2016; Girardin et al., 2021; Torralba et al., 2016). NbS also maintain or enhance multiple Nature Contributions to People (NCP) (Manes et al., 2022; Torralba et al., 2016).

Research on NbS is still in its infancy (Seddon, 2022), but these promising actions that protect, restore or sustainably manage ecosystems are already integrated into adaptation policies aimed at addressing the impacts of climate and biodiversity crises. Notably, the Nature Restoration Law recently passed by the EU (European Union) incorporates objectives for NbS implementation, consistently with the Kunming-Montréal Convention for Biodiversity Framework (CBD, 2022; European Commission, 2022, 2021). Following these commitments, the policy aims to restore “at least 20% of the EU’s land and sea areas by 2030 and all ecosystems in need of restoration by 2050”, and to ensure “that there is no deterioration in conservation trends or in the status of protected habitats and species” (European Commission, 2022). The Alpine Convention developed a Climate Action Plan in 2021 that based most of its actions on NbS (Alpine Convention, 2021).

Despite these promising policies, a substantial NbS implementation gap persists in Europe, particularly in the Alps (Lückge and Simon, 2022; McDowell et al., 2021). Therefore, given the finite human and financial resources for NbS implementation, identifying priority areas is required (European Commission, 2022), especially as current NbS are not always implemented where they are the most needed (Dubo et al., 2022; Houghton and Castillo-Salgado, 2020). Although the European Alps are under multiple legislation from eight countries, they constitute a coherent biophysical continuum with a common cultural heritage (Alpine Convention, 2016; Gazzelloni et al., 2015). Consequently, the prioritisation of adaptation efforts must be reasoned at the entire Alpine scale, and not only at the country level.

Most of the previously identified NbS in the Alps primarily targeted adaptation to drought (Dubo et al., 2022). Drought events are expected to become more intense and more frequent in the future whatever the climate change scenario (Gobiet and Kotlarski, 2020; Kotlarski et al., 2022), exacerbating impacts on crop yields, forest health, wetlands functioning, and fodder production in Alpine meadows, among others (Elkin et al., 2015; Seidl et al., 2017; Stephan et al., 2023). Moreover, droughts also threaten Alpine biodiversity and the valuable NCP it provides (Egarter Vigl et al., 2021; Elkin et al., 2013; Stritih et al., 2021). NbS have proven their effectiveness in drought adaptation of forestry and water bodies management in the Alps (Elkin et al., 2015; Pugliese et al., 2020; Seidl et al., 2011) and agriculture elsewhere (Altieri et al., 2015; Torralba et al., 2016). In the Alps, NbS encompass a range of interventions, such as agroforestry to mitigate drought impact on agriculture; silvopastoral practices to safeguard fodder production during extreme drought and reduce heat stress of livestock; natural forest regeneration to

enhance their resilience to drier conditions; and wetland restoration to improve water connectivity within landscapes and, therefore, reduce the water scarcity duration and protect biodiversity (Dubo et al., 2022). In these examples, NbS aim to enhance or maintain the retention of water in ecosystems, an example of the crucial NCP for adaptation that we refer hereafter to as Nature's Contributions to Adaptation (NCA, Colloff et al., 2020). With expected increasing demand in future conditions, the existing NCA, such as groundwater already abstracted for irrigation, may become increasingly used and valued (Elliott et al., 2014; Iglesias et al., 2011). At the same time, NCA can be enhanced, e.g. with practices that enhance soil water retention to face periods of drought when access to irrigation is restricted.

Given the goal of a just and sustainable future, priority areas to implement NbS for adaptation to climate change should be where communities are the most at risk (Allen et al., 2018; Birkmann et al., 2022). The IPCC defined the risk as “the potential for adverse consequences for human or ecological systems”, resulting from a combination of (i) hazards, i.e. “the potential occurrence of a natural or human-induced physical event or trend” that may cause damages, such as droughts; (ii) exposure, i.e. “people, livelihoods, environmental services and resources, infrastructure, or economic, social, or cultural assets in places that could be adversely affected by physical event” including ecosystem services; and (iii) vulnerability, i.e. “the propensity or predisposition” of the exposed element to be adversely affected by a physical event (IPCC, 2014; Lavell et al., 2012). Despite the interdisciplinary nature of the risk assessment literature, only a few studies adapted this framework to social-ecological systems, including the Delta-SES framework (Depietri, 2020), the Global Delta Risk Index (Hagenlocher et al., 2018) and the Vulnerability and Risk Assessment of Social-ecological Systems in NbS (Shah et al., 2020).

In addition, the NCP supply is rarely included in risk assessment (Lecina-Diaz et al., 2021; Stritih et al., 2021; Xu et al., 2016). The commonly used approaches generally separate ecological and social assessments (Hagenlocher et al., 2018; Lazzari et al., 2021; Thiault et al., 2018). This distinction excludes in most cases NCP evaluation, even in NbS studies for climate change adaptation. Rather, the social part of the vulnerability index is assessed from broad indicators, such as health expenditure of the local government and net inflow, that may not reflect the local well-being (Hagenlocher et al., 2019; Shah et al., 2020). The ecological part of vulnerability is assessed with indicators, such as protected areas cover or the presence of arsenic (Hagenlocher et al., 2018; Shah et al., 2020), that may bias the actual impacts of a specific hazard on NCP. Moreover, some indicators that may be relevant for a region or a country, e.g. the corruption index, may be inappropriate elsewhere. Therefore, practitioner-friendly approaches that facilitate the identification of priority areas for adaptation and that include current and future NCA supply are needed (Hagenlocher et al., 2019).

Many spatial prioritisation approaches focus on hotspots of a target variable. For instance, biodiversity richness or the presence of threatened species and habitats are considered in prioritisation approaches for conservation areas (Eitelberg et al., 2016; Huang et al., 2020; O'Connor et al., 2021). Hotspots of sequestered carbon were highlighted to support mitigation efforts (Eitelberg et al., 2016) and were also combined with biodiversity to address synergies in conser-

vation (Jung et al., 2021). Some spatial NbS prioritisation studies consider the multiple NCP to be safeguarded, such as freshwater supply, biomass production, air quality and flood regulation (Cimatti et al., 2022; Li et al., 2021; Mori et al., 2021). Others have also integrated the monetary values of NCP (Pártl et al., 2017).

In contrast, other spatial approaches identified as priority areas the coldspots (i.e. areas with lowest values) of a target variable, assuming those would be the places with the largest potential to increase this value. For instance, priority areas for NbS were identified according to their potential for carbon sequestration (Lugato et al., 2014a; Pan et al., 2023; Zomer et al., 2017), creation of habitat for biodiversity (Bourne et al., 2016) or NCP provision (Comín et al., 2018; Odgaard et al., 2017).

In either hot- or coldspot approaches, some studies combined multiple target variables to identify trade-offs and synergies, for instance between biodiversity and carbon (Strassburg et al., 2020), climate change adaptation and mitigation (Jones et al., 2020; Villarreal-Rosas et al., 2023), or NCP and biodiversity (Felix et al., 2022; Ou et al., 2022; Srivathsa et al., 2023; Thiault et al., 2018). However, these previous assessments do not consider joint areas to maintain and enhance NCP for biodiversity conservation, climate change adaptation and mitigation.

In summary, the identification of priority areas for NbS requires considering on the one hand the need for maintaining NCA and on the other hand the need for enhancing them, alongside their potential co-benefits for climate change mitigation and biodiversity conservation. Furthermore, the characterization of the social-ecological contexts surrounding priority areas informs on conditions for their future implementation (Crouzat et al., 2016, 2015). In this study, we detected where to prioritize NbS in the Alps for adaptation to drought, and whether identified areas overlap with the highest potential to safeguard or enhance carbon sequestration and biodiversity.

Our objectives were: i) to identify and characterize priority areas to implement NbS for adaptation to drought aiming to maintain or enhance water retention; ii) to evaluate the potential co-benefits of these priority areas for carbon sequestration and biodiversity conservation; and iii) to describe the potential of social-ecological contexts that comprise priority areas to implement future NbS.

To address these objectives, we identified priority areas to implement NbS for adaptation to drought across the Alpine Space, ranging from high mountains to surrounding lowlands with common policy cooperation programs, for which we refer hereafter to as the Alps. We identified priority areas in the land-use and land-cover types (LULC) within which NbS are commonly implemented to adapt to drought, namely croplands, grasslands, forests and wetlands. We characterized the location of priority areas in regard to geography and elevation. We assessed the overlaps of priority areas for adaptation with co-benefits for carbon sequestration and biodiversity conservation. We evaluated the distribution of priority areas with respect to protected

areas, in order to assess feasibility. Lastly, we used the supply, flow and demand for eight NCP to describe the potential of social-ecological contexts surrounding priority areas to implement future NbS.

2. Material & Methods

2.1. Conceptual background

We reviewed the indicators used in drought risk assessment literature (Table S1). Drought hazard is often related to soil moisture, i.e. the volume of water within the unsaturated zone of the topsoil. Drought is commonly declared when soil moisture decreases under a threshold (Dilawar et al., 2022; Sekhri et al., 2020). The adaptation options to address drought include watering, e.g. with irrigation systems, and increasing soil water retention, e.g. through agroecological practices (Altieri et al., 2015; Iglesias et al., 2011; Pulido-Velazquez et al., 2011). Here, we defined NCA for drought as the available volume of water contained in both topsoil and aquifers. Watercourses were not considered as they are mainly connected to aquifers (Haas and Birk, 2017).

The volume of water contained in topsoil (hereafter “soil moisture”) and in aquifers (i.e. the percolating water through the unsaturated zone, hereafter “groundwater”) are positively correlated due to their dependence on precipitation, canopy interception, snow accumulation and melting, infiltration, evapotranspiration, and runoff generation (Haas and Birk, 2017; Samaniego et al., 2018). However, groundwater may respond differently to drought compared to soil moisture. Therefore, within areas experiencing the most severe drought, we applied the “bright spots” approach (Cinner et al., 2016) to identify places where the amount of groundwater is substantially higher (bright spots) or lower (dark spots) than expected, i.e. areas presenting a surplus and a deficit of NCA, respectively.

Our approach followed six methodological steps presented in Fig 1. The three first steps describe the process for calculating the priority index, and the next steps describe the location of priority areas (fourth step), the potential co-benefits of implementing NbS in priority areas for climate change mitigation and biodiversity conservation (fifth step), and the social-ecological systems that comprise priority areas (sixth step).

2.2. Data processing

Given a drought event, with a decrease in soil moisture and groundwater, the impacts are different across regions, reflecting site-specific adapted ecosystems across the range of climates in the Alps (Hari et al., 2020; Stephan et al., 2021). To compare values across climates, we applied the bright spots analysis which has proven its ability to identify valuable places for NCP management across regions (Frei et al., 2018). We first downloaded groundwater and soil moisture

data computed by the EDgE project (End-to-end Demonstrator for improved decision-making in the water sector in Europe) for the reference (1970-2000, hereafter referred to as 2000) and future period (2085 and 2115, hereafter referred to as 2100), at the pan-European scale (tab. 1). Previous hydrological research related to NCP or NbS has identified that the subwatershed level is adequate for large scale analysis (Comín et al., 2018; Meisch et al., 2019; Villarreal-Rosas et al., 2023). Therefore, we computed the median values for soil moisture and groundwater at the finest available watershed division provided by the HydroBASIN v1 dataset (Lehner et al., 2008; Lehner and Grill, 2013) (Table 1).

We computed statistical linear models to analyse the relationship between future groundwater and future soil moisture, considering all combinations that include annual and seasonal data, as well as raw and log-transformed data. Because the absolute soil moisture values were not available from the EDgE dataset, we used the derived drought duration indicator as a proxy of it. For each subwatershed, we calculated the distance between the future groundwater values from the EDgE project, and the fitted groundwater values from the model with the highest accuracy, hereafter referred to as groundwater anomalies (Fig 1, step 1). A positive deviation indicates a bright spot of groundwater, i.e. where values are higher than expected from future soil moisture. In contrast, a negative groundwater deviation indicates a dark spot of groundwater, i.e. where values are lower than expected (Fig 1, step 1).

For each subwatershed we computed a priority index by multiplying min-max normalised values for groundwater anomalies and the relative change in drought, which we used as a proxy of the future drought intensity (Langemeyer et al., 2015) (Fig 1, step 2). The priority areas selected based on the priority index are hereafter referred to as “water surplus” for bright spots, and as “water deficit” for dark spots.

2.3. NbS options for drought adaptation in Alpine lands

To determine which NbS options can be implemented for adaptation to drought and where, we reviewed previously implemented NbS that aim to adapt to drought using the PORTAL database (Table 1; Dubo et al., 2022). We selected the most implemented NbS interventions for each of the four main LULC of the database, namely croplands, grasslands, wetlands and forests. These NbS are agroecological practices in croplands, such as agroforestry practices and soil conservation approaches; silvopastoral practices in grasslands; wetland protection or restoration; and sustainable forest management, previously referred to as “close-to-nature-forestry” (Brang et al., 2014), which encompasses the natural regeneration and the promotion of mixed forest featuring coniferous and broadleaf tree species where their assembly is viable (Dubo et al., 2022). Because none of the urban NbS in PORTAL’s database addressed drought, we excluded urban areas from our prioritisation approach. We extracted the areas corresponding to the four selected LULC from the Corine Land-Cover dataset (Table 1).

2.4. Identification of priority areas

We further defined exclusion criteria reflecting the biophysical feasibility of NbS implementation, based on grey and academic literature (Fig 1, step 3). For silvopastoral practices and sustainable forest management, we excluded grasslands and forests that exceed the elevation of the future tree line distribution (Table 1., Mauri et al., 2022). Due to the complexity of planting trees in steep areas, croplands and grasslands that are located where slopes exceed 35° were excluded for implementation of agroecological and silvopastoral practices, respectively (Table 1., De Mendonça et al., 2023). We did not identify exclusion criteria for wetlands, as we considered they can all be either protected or restored depending on their conditions (Odgaard et al., 2017; Zedler and Kercher, 2005).

We applied respective exclusion criteria for every studied LULC and selected, for each, the 10% of the resulting areas with the highest positive priority indices, indicating water surplus, and the 10% of those with the lowest negative priority indices, indicating water deficit (Fig 1, step 4).

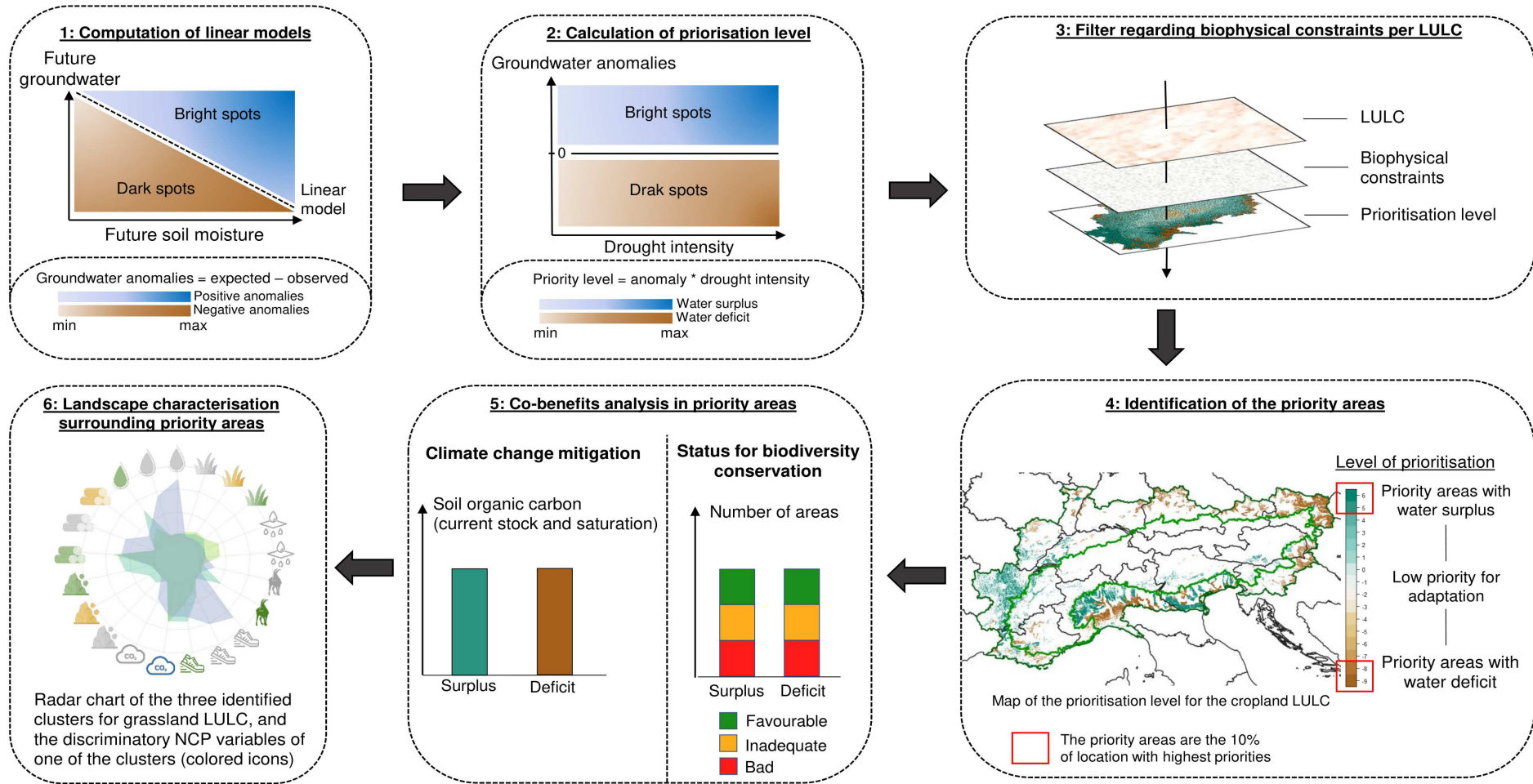


Fig. 1. Methodological steps to identify the priority areas to implement NbS to adapt to drought in the Alps. Steps 1 and 2 describe the computation of the prioritisation level based on soil moisture, groundwater and relative change in drought intensity from 2000 to 2100 (RCP8.5). Step 3 describes the filtering step applied for each LULC considering biophysical constraints for NbS implementation. Step 4 describes the selection of priority areas considering the 10% of the highest level of prioritisation for both bright and dark spots. Step 5 describes the analysis of potential co-benefits within priority areas. Step 6 describes the characterisation of the landscapes surrounding priority areas.

2.5. Potential co-benefits for climate mitigation and biodiversity

To quantify climate mitigation potential, we identified the distribution of the amount of soil organic carbon and soil carbon saturation across priority areas, within each LULC category (Fig 1, step 5). These variables were assessed and mapped at the EU level by the EDSAC (European Soil Data Centre) from samples collected between 2006 and 2010 at the EU level (European Commission et al., 2013; Lugato et al., 2014a, 2014b) (Table 1). Soil carbon saturation was assessed and mapped considering possible alternative management practices, including agroecological practices such as straw incorporation and reduced tillage. Although aboveground biomass in forests contains two to three times the carbon sequestered in their soil, they are highly correlated (Cheng and Niklas, 2007; Liski et al., 2002; Meier and Leuschner, 2010). We therefore used soil carbon content to compare carbon stocks between forests. We conducted an analysis of variance (ANOVA) to detect whether soil organic carbon and soil carbon saturation differ between areas with water deficit and those with water surplus.

Regarding biodiversity potential, the EEA (European Environment Agency) assessed at the EU level the status of ecosystems for biodiversity conservation according to habitat range, structure, functions and population dynamics of its typical species. The EEA categorised ecosystems into three statuses: favourable, unfavourable and bad status for biodiversity conservation (EEA, 2020). We evaluated the proportion of each status within priority areas, and we performed X^2 tests, for each LULC category, to detect whether the distribution of ecosystems' status differs between areas with water deficit and those with water surplus (Fig 1, step 5).

Finally, to detect whether the protection status of ecosystems influences the potential for climate change mitigation within each of the two types of priorities, we computed ANOVA for each LULC. The explanatory variables were the protection status of ecosystems and the types of priority (i.e. water deficit or surplus), and the response variable was first the soil organic carbon, and secondly the carbon saturation.

Because the available datasets at the European scale do not cover Switzerland, the co-benefits analyses were conducted without considering priority areas in Switzerland.

Table 1. Description of data used to identify priority areas for NbS, to analyse the potential co-benefits and to characterize the enabling conditions to implement NbS.

Data	Description	Unit	Spatial coverage	Source and references
Identification of NbS options				
NbS interventions	The different NbS identified in the Alps that aim to adapt to drought	NA	NA	PORTAL database (https://portal.osug.fr/)
Identification of priority areas				
Drought index	The duration during which the soil moisture remains under a threshold in a year	Months	Europe	(Samaniego et al., 2019)
Groundwater recharge	The volume of percolating water through the unsaturated zone to the aquifers	mm/day	Europe	(Samaniego et al., 2019)
Watersheds areas	Delimitations of the areas where all the water falling within gathers in one point	Spatial coordinates	Europe	(Linke et al., 2019)
LULC	Land-use and land-cover	Categories	Europe	European Commission, 2018
Future potential distribution of trees	Future potential distributions of 67 tree species in Europe for 2050	Potential of presence (yes/no) for each species	Europe	EU-Trees4F project (Mauri et al., 2022)
Potential co-benefits				
Soil organic carbon	Amount of organic carbon in the topsoil (0-30 cm depth)	tC.ha-1	Europe	(Lugato et al., 2014b)
Carbon sequestration potential	Amount of atmospheric carbon that can be sequestered with optimized management towards this objective	Mt CO2 eq.	EU	(Lugato et al., 2014a)
Status of ecosystem for biodiversity conservation	Status of a habitat based on natural range, area, structure and functions, and prospects	Aggregated index of status of conservation	EU	(EEA, 2020)

Characterisation of priority areas				
Elevation	The altitude of the surface above the sea level	Meters	Europe	Worldclim v2.0 (Fick and Hijmans, 2017)
Countries borders	/	Spatial coordinates	Europe	Eurogeographics, 2020
Forest types	Categories of forests based on the tree cover density for broadleaves and conifers.	Forest category: broadleaf dominance; coniferous dominance; mixed forests	Europe	Copernicus (2018)
Protected areas	Delimitations of the protected areas; category of protected areas' management defined by the IUCN	Spatial coordinates; IUCN categories	Europe	WDPA (2023)
NCP supply (S), flow (F) and demand (D) assessed and mapped at the municipality scale	Freshwater provision from the ecosystems (S), used by society (F), and abstractions (D)	m ³ .y ⁻¹ ; m ³ .ha ⁻¹ .y ⁻¹ ; m ³ .ha ⁻¹ .y ⁻¹	Alpine Space	AlpES project (Schirpke et al., 2019)
	Fodder production in grasslands (S), harvested and grassed biomass in grasslands (F); fodder needs for livestock	tDM.ha ⁻¹ ; MJ NEL ha ⁻¹ ; MJ NEL ha ⁻¹		
	Net annual increment of biomass in Alpine forests (S), timber removals for fuel wood production (F), required amount of fuelwood (D)	m ³ .ha ⁻¹ .yr ⁻¹		
	Nitrogen removal (S-F); Nitrogen loads (D)	Kg.ha ⁻¹ .y ⁻¹		
	Protective forests against landslides (S); Protected sites (F); Sites requiring protection (D)	Index		
	Annual rate of CO ₂ sequestration by forests (S-F); CO ₂ emissions	tCO ₂ .ha ⁻¹ .y ⁻¹ ; tCO ₂ .ha ⁻¹		
	Outdoor recreational activities offer (S); Visitation rate (F); Beneficiaries (D)	Index		
	Habitats of symbolic species (S); occurrences in hotel names	Index (S); number of hotels (F)		

2.6. Characterization of priority areas

We characterised priority areas by analysing, for each LULC, their distribution across elevation and across countries, based on the Worldclim database (Table 1., Fick and Hijmans, 2017). Moreover, we assessed the proportion of priority areas within and outside protected areas, considering the IUCN categories of protected (Table 1., Vimal et al., 2021).

To characterize the social-ecological systems surrounding priority areas, hereafter “landscapes”, we first extracted the amount of NCP supply, flow and demand assessed and mapped at the municipality scale by the AlpES project for eight NCP: drinkable freshwater, fodder from grasslands, timber from forests, water filtration, protective function of forests against landslides, carbon sequestration, outdoor recreation, habitat for symbolic biodiversity (Schirpke et al., 2019). We selected these material, non-material and regulating NCP because they inform on the social-ecological conditions in landscapes surrounding priority areas. We note that, given the mosaic of LULC within each municipality, they can differ from potential co-benefits of priority areas assessed at the patch level. To characterize the variety of landscapes surrounding priority areas across the Alps, we performed, for each LULC, a clustering analysis based on NCP values of municipalities containing the priority areas, and we extracted the NCP variables that discriminated each cluster. We grouped the clusters from different LULC that share more than half of their discriminating NCP variables, and we validated the group with the observation of the areas from satellite images. We finally assessed the proportion of these clusters within the priority areas to compare the distribution of the clusters in those with a water surplus with those with a water deficit (fig. 2, step 6).

All data analyses were performed with R (version 4.1.0) and QGIS (version 3.16.5).

3. Results

3.1. Linear model and deviation distribution

The linear model using the log-transformed value of groundwater during the summer season as a response variable, and the soil moisture as an explanatory variable, had the highest accuracy among all the models of the relationship between groundwater and soil moisture (Fig 2a, Fig. S2). More watersheds are located in bright spots, i.e. with water surplus (295,141 km², 76% of the Alpine Space extent), than within dark spots, i.e. with water deficit (95,088 km², 24% of the Alpine Space extent). Both positive and negative groundwater anomalies are, on average, greater within watersheds with the highest increase in drought intensity (Fig. 2b) than watersheds with the lowest increase. The distribution of the anomalies is similar between the four LULC (Fig S3).

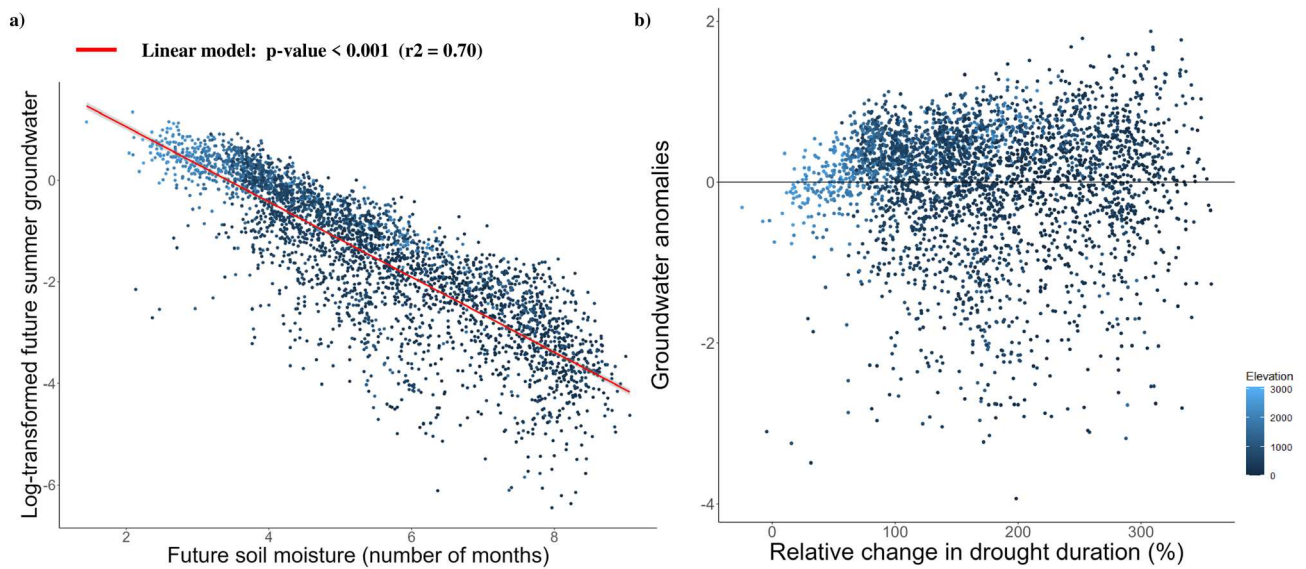


Fig. 2. Scatter plot of the values in each watershed for: a) log-transformed values of future groundwater in the summer season (mm/day) depending on future soil moisture (number of dry months per year); b) groundwater anomalies, i.e. the distance between future groundwater and the fitted groundwater from the linear model plotted in red (in panel a), depending on the relative change in drought duration based on current and future soil moisture (number of dry months per year) between 2000 and 2100. Each dot is coloured by the average elevation of the corresponding watershed.

3.2. Distribution of priority areas across the Alps

Priority areas to implement NbS for adaptation to drought are unevenly distributed across Alpine countries (Fig S4), and along elevation (Fig 3). Regions with water deficit are mainly located in lowlands, close to mountainous areas, in the southwestern Alps (in France and Italy) and in the northeastern Alps (in Austria). Regions with water surplus are in two main locations: the western Alps (in France and Switzerland) and southern hillsides (in Italy) (Fig S4).

Priority areas in croplands and forests are located consistently with the elevation distribution that corresponds to their respective LULC, i.e. croplands are located in lowland valleys, and forests are found at mid-elevation (Fig 3). Priority areas within grasslands and wetlands are evenly distributed along elevation, with areas of water deficit at lower elevations than those of water surplus. The number of priority wetlands in the Alps is limited compared to priority areas in other LULC (1% of all priority areas) and concentrated in two main zones. Firstly, priority wetlands with water surplus are mostly located in the western Alps, corresponding to the Dombes region (France). Secondly, priority wetlands with water deficit are mostly located in the eastern Alps, corresponding to the Neusiedl Lake region (Austria).

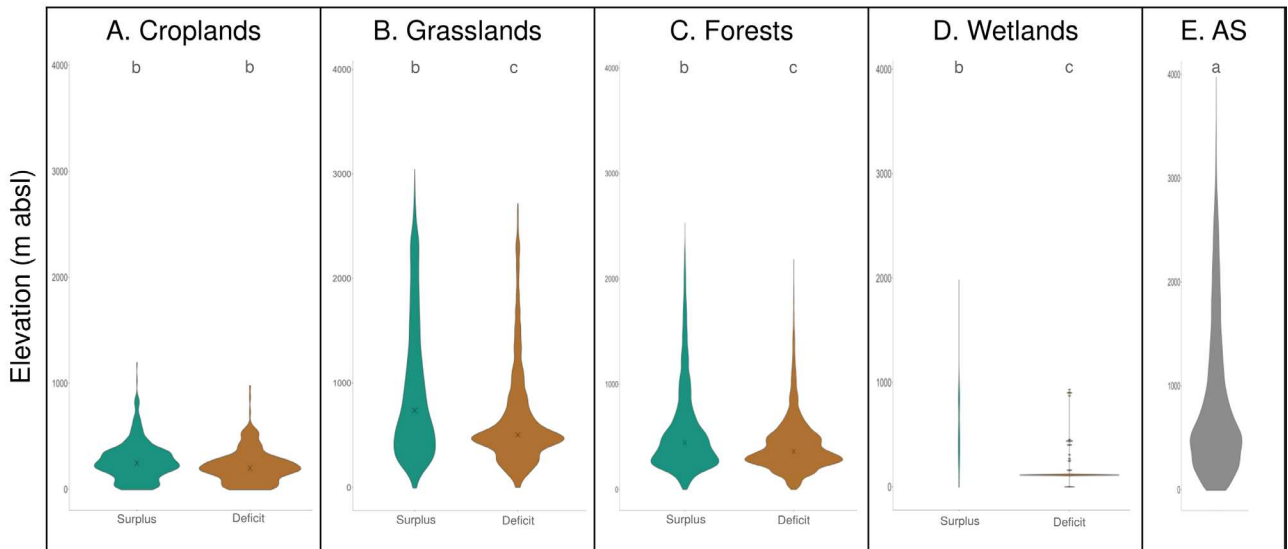


Fig. 3. Distribution of elevation of the priority areas to implement NbS for adaptation to drought in the Alps, considering bright (in blue) and dark (in brown) spots of groundwater for four LULC: croplands (A), grasslands (B), forests (C), and wetlands (D). AS indicates all the values within the Alpine Space (E). The letters indicate whether the distribution of bright and dark spots is significantly different (p -value < 0.05), for each LULC. The distribution with the letter “a” indicates that it has a similar distribution than across the Alpine Space. The distribution between LULC is not compared here.

3.3. Co-benefits of priority areas

3.3.1. Carbon sequestration

- **Soil organic carbon in priority areas**

Priority wetlands with water deficit currently store higher soil organic carbon than those located in watersheds with water surplus, suggesting that priority wetlands for maintaining groundwater do not overlap with hotspots of soil organic carbon. No differences were found in current soil organic carbon between priority areas of the other LULC (Fig 4).

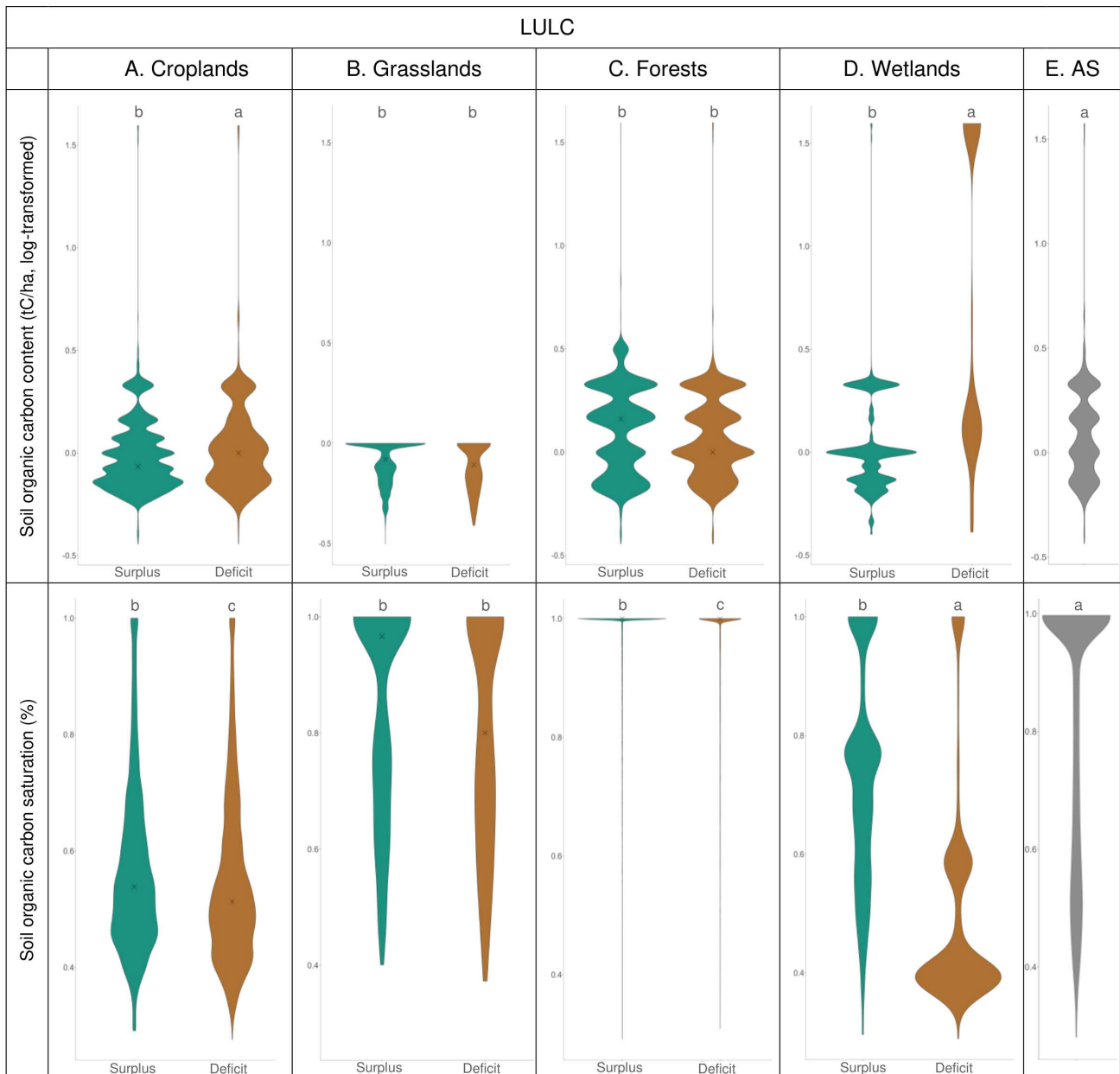


Fig. 4. Distribution of soil carbon content (tC/ha, log-transformed) (top row) and soil carbon saturation (from 0 to 1) (bottom row) in priority areas to implement NbS for adaptation to drought, considering bright and dark spots of groundwater for four LULC: croplands (A), grasslands (B), forests (C), and wetlands (D). AS indicates all the values within the Alpine Space (E). The letters indicate whether the distribution of bright and dark spots is significantly different (p -value < 0.05), for each LULC. The distribution with the letter “a” indicates that it has a similar distribution as across the Alpine Space. The distribution between LULC is not compared here.

- **Soil carbon saturation in priority areas**

Soils in priority forests are highly saturated in carbon (significantly more than across the Alpine Space), in both priority areas with water deficit and surplus, indicating that their soils have already reached maximum carbon sequestration capacity (Fig 4). The level of soil carbon saturation in priority croplands varies from low to medium, both in areas with water deficit and surplus. Most of their soil has carbon saturation below 50%, offering the capacity of these areas to sequester at least twice the amount of current carbon with appropriate management like straw incorporation and reduced tillage. For priority wetlands and grasslands, soil carbon saturation is higher in areas with water surplus than with water deficit. Soil carbon saturation of these priority areas with water surplus is around 80%, suggesting that NbS in these wetlands and grasslands would be optimal for maintaining abundant groundwater and carbon. Complementary to these, priority wetlands and grasslands with water deficit appear as optimal locations for NbS like wetlands surroundings of the Neusiedl Lake (Austria) or grasslands surrounding the Cian gorges (southern French Alps) that would simultaneously foster water retention to address drought and sequestering carbon (Fig 4).

3.3.2. Habitat conservation status for biodiversity

Overall, most of the priority areas fall within ecosystems without a favourable status for biodiversity conservation (96%), representing a higher proportion than across the entire Alps (83%) whatever the LULC (Fig 5). We found that the majority of priority croplands, forests, and wetlands with water deficit are located within ecosystems that do not have a favourable status for biodiversity conservation, in contrast to the areas with water surplus. Grasslands with water surplus have a worse status for biodiversity conservation than those with water deficit, likely reflecting more intensive use and the degraded status of many wet grasslands, e.g. in the Dombes region.

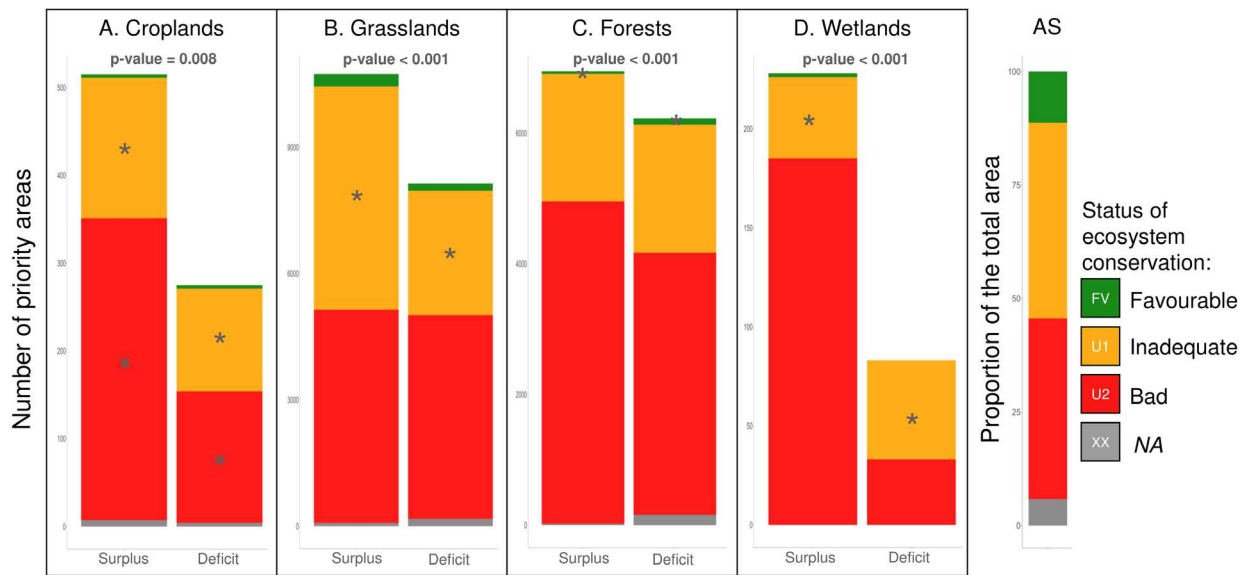


Fig. 5. Barplots of the number of priority areas to implement NbS for adaptation to drought depending on the status of the ecosystems for biodiversity conservation, considering bright (Surplus) and dark (Deficit) spots of groundwater for four LULC: croplands (A), grasslands (B), forests (C), and wetlands (D). AS indicates all the values within the Alpine Space. The bar at the right side displays the distribution of the status of the ecosystems for biodiversity conservation across the Alpine Space (AS). The stars indicate the IUCN category for which the distribution significantly differs between bright and dark spots of the same LULC.

3.3.3. Co-occurrence of benefits for climate mitigation and biodiversity conservation

- **Associations between current soil organic carbon and biodiversity**

Soils of priority croplands with a favourable status for biodiversity conservation currently store more organic carbon than priority croplands with inadequate or bad status (Fig S5). This suggests that NbS aimed at maintaining groundwater in these croplands overlap with high priorities to simultaneously prevent biodiversity and soil carbon from future deterioration.

Soils of priority grasslands with a bad status for biodiversity currently store more organic carbon than soils of grasslands with a favourable or inadequate status for biodiversity, highlighting trade-offs between these areas.

The results are more contrasting for forests. Among priority forests with water deficit, those with a bad status for biodiversity conservation store more soil organic carbon than those with a favourable or inadequate status. Among priority forests with water surplus, those with an inadequate status for biodiversity conservation store more soil organic carbon than forests with a bad status. A closer examination of their distribution does not reveal an association of these

combinations for biodiversity and soil organic carbon with specific forest types. Similarly, soils store more organic carbon in priority wetlands with inadequate status than in others (with favourable or bad status).

- **Associations between potential carbon sequestration and biodiversity**

In priority grasslands, the soils the more saturated in carbon are associated with favourable status of the habitat for biodiversity conservation (Fig S5). In contrast, we found that the soils of priority croplands with inadequate status are more saturated in carbon than those in other croplands. Implementing NbS in these croplands is therefore expected to benefit biodiversity conservation but not to increase carbon sequestration. The soils of forests with a bad status are less saturated in carbon than those in other forests, indicating that implementing NbS in these areas is expected to jointly increase carbon sequestration and the provision of habitat for biodiversity.

The results are more contrasting for priority wetlands. Although the soils of wetlands with inadequate status for biodiversity conservation are, on average, less saturated with carbon than other wetlands, we found that the saturation rate varies with the status of biodiversity conservation and type of priority areas. Indeed, the soils of wetlands with inadequate status are less saturated in areas with water deficit than those with water surplus, offering an opportunity for NbS to simultaneously address water scarcity, provide habitat for biodiversity and sequester carbon. Moreover, the soil carbon saturation of priority wetlands with a bad status and water deficit areas is equivalent to the saturation in wetlands in areas with water surplus and an inadequate status for biodiversity conservation. The wetlands with water surplus and a favourable or bad status are the ones with the highest soil carbon saturation, indicating expected synergies of NbS implementation in these areas.

To summarize, our analyses revealed many mismatches and few synergies of NbS implementation between adaptation and the potential co-benefits regarding biodiversity conservation and carbon sequestration. Bright spots for adaptation do not consistently coincide with a large amount of carbon (coupled with a low potential for increasing sequestration) or favourable status for biodiversity. Similarly, the dark spots coincide partially with ecosystems with a bad status and a substantial potential for increasing carbon sequestration, offering optimal locations to benefit from the multiple promises of NbS implementation.

Landscapes comprising priority areas

3.4.1. Bundles of Nature's Contribution to People

The clustering analysis identified three clusters for priority areas in each LULC. We then grouped the clusters that were characterized by the same variables across LULC, resulting in a total of six landscapes, each corresponding to one social-ecological system surrounding the priority areas (Fig. 6).

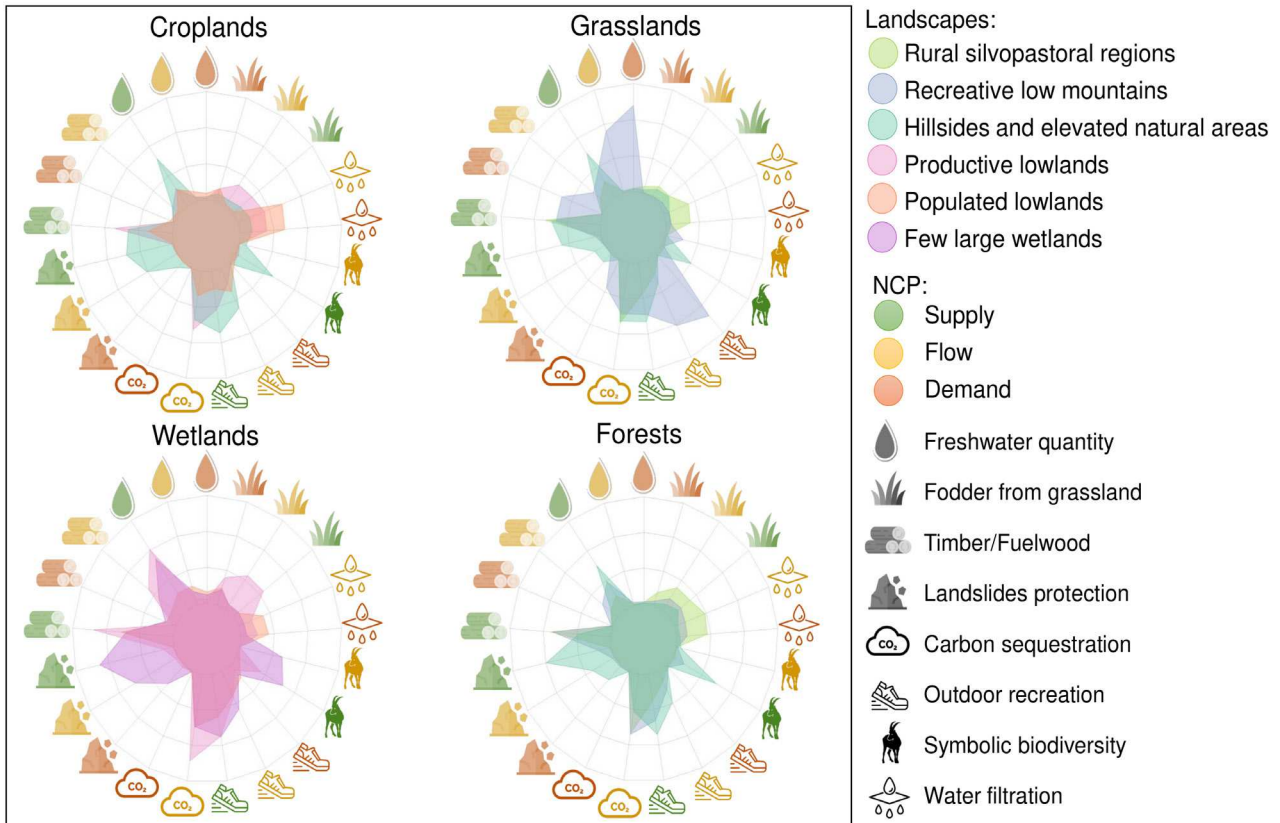


Fig. 6. Radar chart of the mean values of NCP supply (green), flow (yellow) and demand (red) for each cluster identified by aggregating the NCP values of the municipalities within which priority areas to implement NbS for adaptation to drought were identified, for the four studied LULC. The clustering analysis identified three groups in each LULC, resulting in a total of six categories when clusters of different LULC are grouped by similarities in main characteristics.

Some priority forests, croplands and grasslands are located within hillsides and elevated natural areas. This landscape provides a large amount of non-market NCP, including freshwater from ecosystems, forest protection against landslides, and areas for outdoor recreation and biodiversity. These areas correspond, among others, to French and Italian National parks. When comparing the distribution of this landscape across priority areas, we found that this landscape is more frequent in regions with water surplus than those with water deficit, for each LULC (Fig S6). This landscape comprises a high proportion of priority grasslands (63%) and forests (25%), but only 2% of priority croplands.

The productive lowlands landscape corresponds to areas with significant marketable production, such as fodder and wood production, and outdoor recreation. This landscape comprises a quarter of priority croplands (25%), similarly for areas with water deficit or surplus. In contrast, this landscape comprises a quarter of priority wetlands with water surplus (25%), but a limited part of priority wetlands with water deficit (2%).

The populated lowlands landscape corresponds to areas with higher flow and demand for freshwater and timber. This landscape also supplies significant outdoor recreation opportunities. This landscape comprises priority croplands, similar for areas with water deficit (69%) and those with water surplus (68%). In contrast, almost all the priority wetlands with water deficit are located within the populated lowlands, although this landscape comprises a significant but lower proportion of priority wetlands with water surplus (64%) (Fig S6).

The rural silvopastoral regions are characterised by substantial water filtration capacity and timber production, as well as high fodder production, flow and demand. This landscape comprises most of the priority forests (80% and 70% for forests with water deficit and surplus, respectively) located among others in the eastern Alps close to Neusiedler Lake Austria, and in a large western Alps region around Lyon (France). In contrast, a limited proportion of grasslands (27% and 14% for grasslands with water deficit and surplus, respectively) belongs to rural silvopastoral regions, including within regions such as Augsburg's surroundings (Germany), and the same region around Lyon (France).

The recreative low mountains are characterised by the large provision, flow and demand for freshwater and outdoor recreation, as well as the wood flow (and its demand) and symbolic biodiversity. This landscape mostly comprises priority areas within grasslands, with similar proportions for areas with water deficit (19%) and those with water surplus (14%). These areas include, among others, grasslands within the Jura massif (France), and Ardèche mountains (France). A limited number of priority forests (2%) belong to this landscape, and only within areas with water surplus.

The last landscape comprises the few large wetlands that are located in landscapes with water surplus and discriminated by their significant forest protection against landslides and high provision, flow and demand for water filtration, in line with the flow and the demand for this NCP.

3.4.2. Distribution within or without protected areas

Overall, 40% of priority areas to implement NbS for adaptation to drought are located within protected areas, which is a higher proportion than for protected areas located across the Alps (29%, Fig 7). However, the distribution differs across LULC. Almost all priority croplands and wetlands with water deficit are located in protected areas (84% and 94%, respectively), similar to most croplands and wetlands with water surplus (60% and 74%, respectively) (Fig 7). In contrast, a majority of priority grasslands and forests are located outside protected areas, for

both areas with water deficit (52% and 62%, respectively) and those with water surplus (66% and 69%, respectively, Fig 7).

Only a few priority areas are located in protected areas with a high protection level (1% are in protected areas of categories I-III, similar to the corresponding proportion found across the Alps) when considering all the LULC, although it accounts for 56% of the priority wetlands with water deficit (Fig 7).

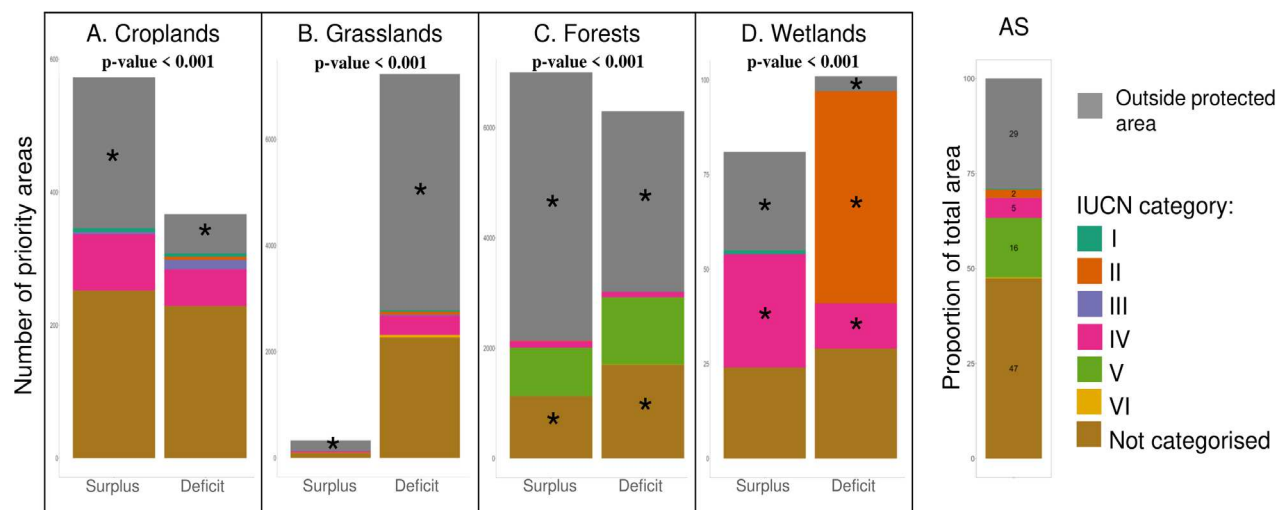


Fig. 7. Barplots of the number of priority areas to implement NbS for adaptation to drought located outside protected areas, within specific IUCN category, or within protected areas without a specific category (Not categorised), considering both bright (Surplus) and dark (Deficit) spots for groundwater, for four LULC: croplands (A), grasslands (B), forests (C), and wetlands (D). AS indicates all the values within the Alpine Space. The bar on the right side displays the same distribution across the Alpine Space (AS). The stars indicate the IUCN category for which the distribution significantly differs between bright and dark spots of the same LULC.

4. Discussion

4.1. Priority areas for adaptation to drought (biophysical conditions)

This study identified priority areas for adaptation to future drought based on groundwater and relative change in drought intensity between 2000 and 2100. The model with the highest accuracy involves the amount of groundwater during the summer season, corresponding to the most sensitive period for agriculture production to the absence of precipitation (Haslinger and Blöschl, 2017a; Stephan et al., 2021).

The groundwater dark spots are found in similar locations to areas previously identified as being sensitive to drought in the Alps, mostly located in south-western Europe and at lower elevations (Gobiet et al., 2014; Gobiet and Kotlarski, 2020; Kotlarski et al., 2022). These loca-

tions are already experiencing increased annual mean temperature and a change in precipitation distribution, with an increase in rainfall during the winter season and a decrease during the summer season. The low groundwater values are not surprising in the Mediterranean region which has a low infiltration rate (Martinsen et al., 2022). In contrast, groundwater bright spots, such as the western part of the Alps (in France) and the southern hillsides (in Italy), do not correspond to regions highlighted by previous drought assessments (Haslinger and Blöschl, 2017b; Tramblay et al., 2020). Indeed, despite the greater drought intensity, these downstream areas benefit from the large groundwater accumulated downstream of mountain catchments (Meisch et al., 2019).

Due to the location of most priority areas at low elevations, Alpine meadows were not selected as priority grasslands for adaptation to drought. However, this crucial fodder production provided in these areas is recognized as being increasingly vulnerable to climate change (Deléglise et al., 2022, 2019). Few priority grasslands are located in the Southern Alps, including the Luberon Regional Park as one of the most impacted areas, and in Lissinia (Italy) corresponding to areas with high-temperature increase but which benefit from plentiful groundwater provided downstream of mountain catchments (Gobiet and Kotlarski, 2020; Kotlarski et al., 2022).

4.2. Multiple co-benefits potential of priority areas for NbS

Although NbS are considered as adaptation options to address simultaneously several challenges (Chausson et al., 2020), there is a limited number of studies addressing spatial overlap between priority areas to maintain or enhance NCA, carbon sequestration and biodiversity. We found that for wetlands, forests and croplands, priority areas with water surplus overlap with ecosystems with a good status for biodiversity conservation. In contrast, priority areas with water deficit overlap with ecosystems without a favourable status. Consistent with previous spatial assessments, the implementation of NbS should be prioritised in these areas to maximise their potential to maintain or enhance simultaneously NCA and habitat biodiversity with a limited number of interventions (Ou et al., 2022). Nevertheless, when considering NCP without integrating climate change, trade-offs can arise between priority areas for maintaining NCP and those focused on biodiversity conservation (Ramel et al., 2020). Further spatial planning research should, therefore, consider other anthropogenic pressures, especially to prevent areas less sensitive to climate change from future degradation (Egarter Vigl et al., 2021; Gonzalez-Redin et al., 2016).

We found that priority areas to implement NbS for adaptation to drought do not consistently overlap with priority areas for carbon sequestration, whatever the LULC. These findings contrast with previous studies that identified the substantial potential of NbS to address simultaneously mitigation and adaptation targets (Villarreal-Rosas et al., 2023), or to conserve both carbon, water and threatened species (Jung et al., 2021) in a given place.

Although it was not the main aim of this study, we found that substantial soil organic carbon overlaps with ecosystems with a favourable status for biodiversity conservation. Moreover, areas with a high potential for carbon sequestration (low saturation) overlap with ecosystems with a bad status. Previous global studies demonstrated that restoration prioritisation can nearly achieve the maximum benefits for both biodiversity conservation and climate mitigation (Strassburg et al., 2020). Future research may explore whether in the Alps the implementation of NbS in these areas may effectively address both challenges.

4.3. Levers and barriers to implement NbS

The levers and barriers to the implementation of NbS depend on social-ecological systems (Topp et al., 2021, Dubo et al., 2023) and stakeholders' visions (Lavorel et al., 2019; Locatelli et al., 2022). On the one hand, the easiest interventions can be prioritised to rapidly get the benefits from NbS (Girardin et al., 2021). NbS that aim at enhancing NCA by changing practices, e.g. from monoculture to agroforestry, or enhancing tree species richness in forests, are easier to implement within protected areas with enough resources (Dudley, 2010; Palomo et al., 2014; Watson et al., 2014). As previously highlighted, protected areas offer legal and governance clarity and capacity, that would help to define NbS initiatives through participatory approaches with local stakeholders (Bruley et al., 2021; Palomo et al., 2011). Moreover, protected areas are already engaged in concrete measures for biodiversity conservation (Watson et al., 2014). Integrating an additional measure such as NbS in their current or future biodiversity conservation plan would be more feasible. We found that priority wetlands and croplands with water deficit are mostly located in protected areas. This can be explained by the strong representation of wetlands as conservation targets for provisioning biodiversity habitat and regulating NCP (Kingsford et al., 2021; Tomscha et al., 2021). Future decision-makers should consider the category of protected areas in prioritizing NbS because the pressure of human activities on ecosystems can differ across IUCN categories (Egarter Vigl et al., 2021).

On the other hand, addressing strong barriers, such as societal values, should also be prioritised to get the benefits sooner than if they are addressed last, or in reaction to natural disasters such as dramatic droughts (Ossola and Lin, 2021). Moreover, activating these deep levers needs to be prioritised because they are also the most impactful on the decision-making process (Abson et al., 2017). In the identified productive lowlands, stakeholders from working landscapes (Kremen and Merenlender, 2018) may express strong resistance due to the inherent uncertainties in changing practices (Nicholls and Altieri, 2018). In contrast, priority croplands in populated lowlands offer opportunities to implement new practices (e.g. to shift to a recreation-based economy) than the ones in productive lowlands, due to the demand for environmentally friendly products and recreation from the urban population (Stubelj Ars and Bohanec, 2010).

Grasslands and forests are often considered in management plans of protected areas, due to their habitat value for a large number of endemic species (Kingsford et al., 2021; Selvi et al.,

2023). However, we found less than half of the priority grasslands and forests within protected areas. Substantial effort in communication and awareness raising will therefore be needed to implement NbS outside protected areas where their acceptance remains limited (Comín et al., 2018; Dai et al., 2021). This effort can be achieved within recreative low mountain areas due to the already existing communication network built for tourism activities (Stubelj Ars and Bohanec, 2010). However, co-production with local stakeholders is required to implement NbS in grasslands and forests within rural silvopastoral regions, especially within groundwater bright spots. Indeed, most of the identified adaptation initiatives are reactive and not proactive (Harmanny and Malek, 2019; van Loon-Steensma and Goldsworthy, 2022, Dubo et al., 2023). Protecting the crucial resources for the future such as freshwater needs participatory approaches to consider and balance local needs. This can be achieved when enhancing stewardship of local communities for the environment, or by financial instruments such as Payments for Ecosystem Services (Jax et al., 2018; Zandersen et al., 2021).

4.4. Current political trends for NbS and recommendations

NbS are increasingly integrated into spatial planning policies, but their implementation remains limited (Faivre et al., 2017; Nordbeck et al., 2019; Reckien et al., 2014). Three pathways to scale NbS were identified: helping stakeholders who are strongly committed to implement NbS from personal value or technical needs; shifting public policy to select NbS as primary options; convincing reluctant stakeholders to implement NbS, through awareness raising or new financial instruments (Martin et al., 2021; Nicholls and Altieri, 2018; Vermeulen et al., 2018). These three ways are unequally fostered in the adaptation policies. For example, local producers with a strong willingness are not supported and are instead marginalized by public policies (Vermeulen et al., 2018; Dubo et al., 2023)

The allocation rules to implement NbS need to be discussed with local stakeholders. The priorities would not be the same in productive lowlands and recreative low mountains, and stakeholders' engagement helps define local needs (Ruangpan et al., 2021). Nevertheless, from a landscape ecology perspective, the diversification of landscapes and subsequent NCP increases simultaneously local adaptive capacity (Simelton et al., 2021; Wamsler et al., 2014) and biodiversity when ecological corridors are connected to climate refugia (Heller and Zavaleta, 2009; Vos et al., 2008).

4.5. Limitations and perspectives

We applied the bright spot approach to determine the priority areas to implement NbS with two biophysical variables. In contrast with previous risk assessments, we did not include social data in our assessment, such as income, age and gender. However, this top-down perspective to spatially assess the social component of vulnerability may distort results due to the limited representativeness of local context in these indicators (Preston et al., 2011). In addition, we did not integrate into the spatial prioritisation quantitative assets that are expected to be impacted,

such as crop or timber production. Instead, we identified areas where the impact of drought is expected to be higher whatever the number of affected assets. Due to the inherent people-dependent nature of what vulnerability encompasses (Farbotko et al., 2023; Stephan et al., 2023), participatory approaches are best suited to define prioritisation rules considering local contexts and visions (Bruley et al., 2021; Langemeyer et al., 2018; Ruangpan et al., 2021).

The analyses of co-benefits were conducted without considering priority areas located in Switzerland due to the absence of homogenous data regarding carbon saturation and biodiversity status at the Alpine Space level. However, our findings indicate that less than 5% of priority areas are situated in Switzerland, which suggests a limited bias in our results.

Lastly, this study focuses on the drought hazard, whereas the Alps experience other impacts from heatwaves, floods and landslides. Therefore, we suggest that future multi-hazard adaptation studies apply our methodology to each hazard independently. For example, had we considered flood intensity in addition to drought intensity, some areas that are likely to experience intense drought in the future might not have been identified, because these two hazards are not spatially overlapping. Similarly, NbS options that can simultaneously mitigate heatwaves and drought hazards can be prioritised in areas with either a surplus or a deficit of the NCA to these hazards (Yin et al., 2023).

Conclusion

The combined crises of climate change and biodiversity loss urge the need to prioritize adaptation. NbS are promising options to foster the adaptation of Alpine social-ecological systems to drought by enhancing soil water retention and increasing rainwater infiltration into groundwater. Our proposed methodology for identifying priority areas to implement NbS for adaptation to drought relies on two NCA indicators: soil moisture and groundwater. This approach highlights areas of water deficit that should be prioritized for NCA enhancement and areas of water surplus where safeguarding this resource is crucial to address increasing drought intensity. Our analyses revealed the consistent spatial distribution of priority areas across the different LULC. The southeastern and northeastern lowlands were identified as priority areas with water deficit. In contrast, the southern hillsides and the western Alps emerged as priority areas with water surplus. We identified potential synergies to address priorities for adaptation to drought and biodiversity conservation. In contrast, there are limited synergies with priority areas for carbon sequestration, suggesting that the location for future NbS to mitigate and adapt to climate change should be carefully evaluated. Implementing NbS in most priority croplands and wetlands can be supported by protected areas institutions. However, for other priority areas located in productive, densely populated or tourist regions where multiple pressures may deepen the adaptation gap, concertation processes between local stakeholders are required to develop a regional adaptation strategy. Future research needs to explore strategies to foster NbS implementation in these regions, understand the potential outcomes of NbS implementation in priority areas, while accounting for other existing hazards, and evaluate the distribution of benefits among beneficiaries.

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Appendices

S1. Table. List of indicators reviewed from socio-ecological risk assessment literature.

Indicators	Context	References
Hazards		
SPEI (standardized precipitation evapotranspiration index)	Global assesement; European Alps	(Liu & Chen, 2021; Deléglise et al., 2022)
SPI-3 (Standardized Precipitation Index on 3 months)	Coastal and deltaic regions ; crop-lands in Morocco	(Hagenlocher et al., 2018; Cotti et al., 2022)
PDSI (Palmer Drought Severity Index)	Pakistan	(Dilawar et al., 2022)
Comprehensive meteorological drought index	China	(Wu et al., 2019)
Changes and fluctuations and frequency of extreme events of annual temperature	Tibetan Plateau ; Himalaya	(Wang et al., 2021; Sekhri et al., 2020)
Changes and fluctuations and frequency of extreme events of precipitation	Tibetan Plateau ; Himalaya	(Wang et al., 2021; Sekhri et al., 2020)
Changes and fluctuations and frequency of extreme events of wind speed	Tibetan Plateau	(Wang et al., 2021)
Deviation to the ratio between actual evapotranspiration (AET) and potential (PET) evapotranspiration of crops in the crop growing season	Rain-fed croplands	(Meza et al., 2021)
Annual difference between the water resource available for irrigation and irrigation water requirement.	Irrigated croplands	(Meza et al., 2021)
Change in glacier melt water content	Peruvian Andes	(Motschmann et al., 2020)
Change in precipitation runoff	Peruvian Andes	(Motschmann et al., 2020)
Vegetation Health Index	Zimbabwe	(Frischen et al., 2020)
Moisture Index	Himalaya	(Sekhri et al., 2020)
Unirrigated cropped area	Himalaya	(Sekhri et al., 2020)
Drought Prone Area	Himalaya	(Sekhri et al., 2020)

Declared number of drought	Himalaya	(Sekhri et al., 2020)
Exposure		
Population density (persons per surface unit)	Global assesement; Tibetan Plateau; Coastal and deltaic regions; Peruvian Andes; Pakistan	(Liu & Chen, 2021; Wang et al., 2021; Hagenlocher et al., 2018; Chen et al., 2019; Motschmann et al., 2020; Dilawar et al., 2022)
GDP (purchasing power parity in \$)	Global assesement; Pakistan	(Liu & Chen, 2021; Dilawar et al., 2022)
Economic losses from severe drought	China	(Wu et al., 2019)
Area or presence of rain-fed farmlands	Morocco; South Africa	(Cotti et al. 2022; Meza et al., 2021)
Area or presence of Irrigated farmlands	Morocco; South Africa; Peruvian Andes	(Cotti et al. 2022; Meza et al., 2021; Motschmann et al., 2020)
Area or presence of croplands	China	(Chen et al., 2019)
Topography (slopes)	European Alps	(Deléglise et al., 2022)
Presence of forage production	European Alps	(Deléglise et al., 2022)
Presence of water extraction infrastructure	Peruvian Andes	(Motschmann et al., 2020)
Presence of irrigation channels	Peruvian Andes	(Motschmann et al., 2020)
Vulnerability		
Ecosystem susceptibility		
Freshwater scarcity	Coastal and deltaic regions	(Hagenlocher et al., 2018)
Wetland loss	Coastal and deltaic regions	(Hagenlocher et al., 2018)
Percentage of deforested area	Coastal and deltaic regions	(Hagenlocher et al., 2018)
River connectivity	Coastal and deltaic regions	(Hagenlocher et al., 2018)
Percentage of government expenditure on environmental protection	Coastal and deltaic regions	(Hagenlocher et al., 2018)

Agricultural area under certified production schemes	Coastal and deltaic regions	(Hagenlocher et al., 2018)
Participation in international conservation Treaties	Coastal and deltaic regions	(Hagenlocher et al., 2018)
Ecosystem Functionality Index	Coastal and deltaic regions	(Hagenlocher et al., 2018)
Soil erodibility	Morocco	(Cotti et al., 2022)
Farm land ratio	South Africa	(Meza et al., 2021)
Land Degradation Index (LADA)	South Africa	(Meza et al., 2021)
Clay content (0-2 micro meter) at depth 0-5 cm (%)	South Africa	(Meza et al., 2021)
Maximum fertilizer application rate kg/h	South Africa	(Meza et al., 2021)
Ecosystem robustness		
Percentage of protected areas	Coastal and deltaic regions	(Hagenlocher et al., 2018)
Percentage of area covered by Wetlands of International Importance (Ramsar Sites)	Coastal and deltaic regions	(Hagenlocher et al., 2018)
Policies supporting biodiversity conservation	Coastal and deltaic regions	(Hagenlocher et al., 2018)
Average shallow soil (0–5 cm) organic carbon content	Morocco	(Cotti et al., 2022)
Social susceptibility		
Gender parity	Coastal and deltaic regions : South Africa : Zimbabwe	(Hagenlocher et al., 2018; Meza et al., 2021; Frischen et al., 2020)
Access to road and cities	Coastal and deltaic regions ; Morocco ; South Africa ; Zimbabwe	(Hagenlocher et al., 2018; Cotti et al., 2022; Meza et al., 2021; Frischen et al., 2020)
Percentage of the population with disabilities (%)	Coastal and deltaic regions ; Morocco	(Hagenlocher et al., 2018; Cotti et al., 2022; Meza et al., 2021)
Percentage of population below national poverty line (%)	Coastal and deltaic regions	(Hagenlocher et al., 2018)
Food poverty prevalence (%)	Zimbabwe	(Frischen et al., 2020)

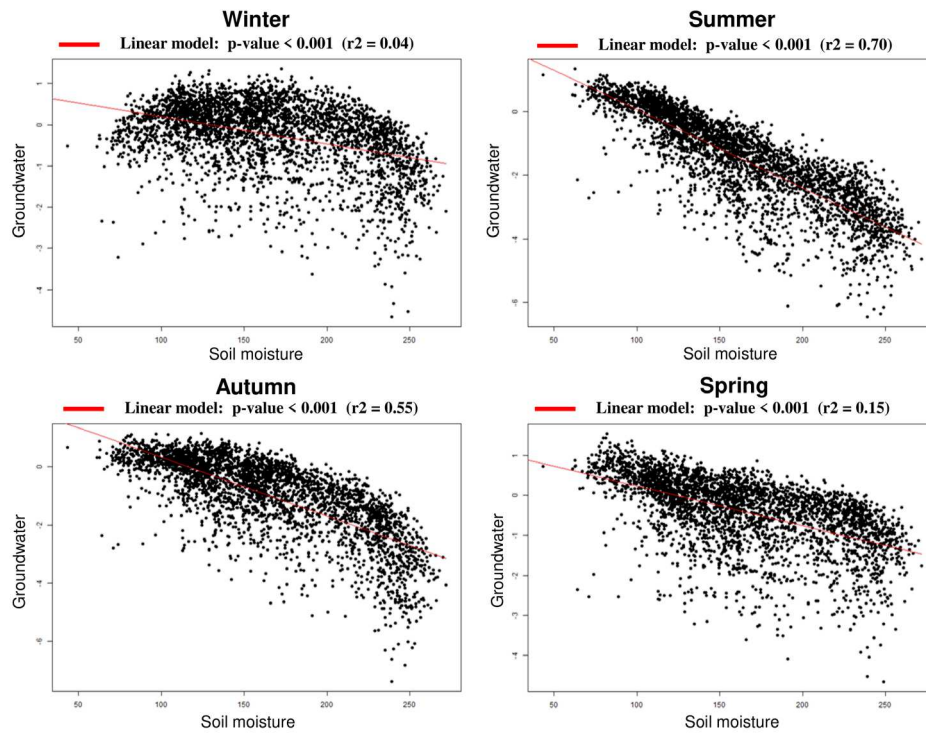
Rural population (%)	Zimbabwe	(Frischen et al., 2020)
Dependency ratio (%)	Coastal and deltaic regions; Morocco : South Africa : European cities	(Hagenlocher et al., 2018; Cotti et al., 2022; Meza et al., 2021; Tapia et al., 2017)
Percentage of contribution of agriculture/forestry/fisheries to GDP (%)	Coastal and deltaic regions ; Morocco : South Africa	(Hagenlocher et al., 2018; Cotti et al., 2022; Meza et al., 2021)
Percentage of population without access to clean water (%)	Coastal and deltaic regions ; Zimbabwe	(Hagenlocher et al., 2018; Frischen et al., 2020)
Unemployment rate (%)	South Africa : Zimbabwe ; European cities	(Meza et al., 2021; Frischen et al., 2020; Tapia et al., 2017)
Population with environmental awareness by district	South Africa	(Meza et al., 2021)
Population that have experienced violence and crime	South Africa : Zimbabwe	(Meza et al., 2021; Frischen et al., 2020)
Debtors by municipality (%)	South Africa	(Meza et al., 2021)
Density of health facilities	Zimbabwe	(Frischen et al., 2020)
Access to electricity (%)	Zimbabwe	(Frischen et al., 2020)
Maternal and infant mortality	Zimbabwe	(Frischen et al., 2020)
Proportion of households that are lone-parent households	European cities	(Tapia et al., 2017)
Total use of water (m3 per capita per year)	European cities	(Tapia et al., 2017)
Price of a m3 of domestic water (Euro)	European cities	(Tapia et al., 2017)
Population density	European cities	(Tapia et al., 2017)
Adaptative capacity		
Access to information or communication	Coastal and deltaic regions ; Morocco ; Himalaya	(Hagenlocher et al., 2018; Cotti et al., 2022; Sekhri et al., 2020)

Existence of early warning systems	Coastal and deltaic regions ; Morocco	(Hagenlocher et al., 2018; Cotti et al., 2022)
Density of schools per 100,000	Coastal and deltaic regions	(Hagenlocher et al., 2018)
Percentage of households without access to waste/water treatment (%)	Coastal and deltaic regions	(Hagenlocher et al., 2018)
Density of health facilities	Coastal and deltaic regions ; Morocco ; Himalaya	(Hagenlocher et al., 2018; Cotti et al., 2022; Sekhri et al., 2020)
Number of hospital beds per 1000	Coastal and deltaic regions	(Hagenlocher et al., 2018)
Volume of water storage in a safe reservoir/container (m3)	Coastal and deltaic regions	(Hagenlocher et al., 2018)
Lacking availability of food reserves	Coastal and deltaic regions	(Hagenlocher et al., 2018)
Percentage of population without a health insurance (%)	Coastal and deltaic regions ; Morocco	(Hagenlocher et al., 2018; Cotti et al., 2022)
Public health expenditure (% of GDP)	Coastal and deltaic regions	(Hagenlocher et al., 2018)
Lending interest rate (%)	Coastal and deltaic regions	(Hagenlocher et al., 2018)
Microinsurance penetration (%)	Coastal and deltaic regions	(Hagenlocher et al., 2018)
Net inflow in US\$ (% of GDP)	Coastal and deltaic regions	(Hagenlocher et al., 2018)
Density of adaptation projects (governance, DRM) in the past 10 years	Coastal and deltaic regions	(Hagenlocher et al., 2018)
Percentage of GDP spent on innovation and research (%)	Coastal and deltaic regions	(Hagenlocher et al., 2018)
Total dam storage capacity in million cubic meters	South Africa : Zimbabwe	(Meza et al., 2021; Frischen et al., 2020)
Borrowed money from total municipality liability	South Africa	(Meza et al., 2021)
People that receive social grants	South Africa	(Meza et al., 2021)
Road density (m/km2)	South Africa; Himalaya	(Meza et al., 2021; Sekhri et al., 2020)
Proportion of area equipped for irrigation expressed	South Africa	(Meza et al., 2021)

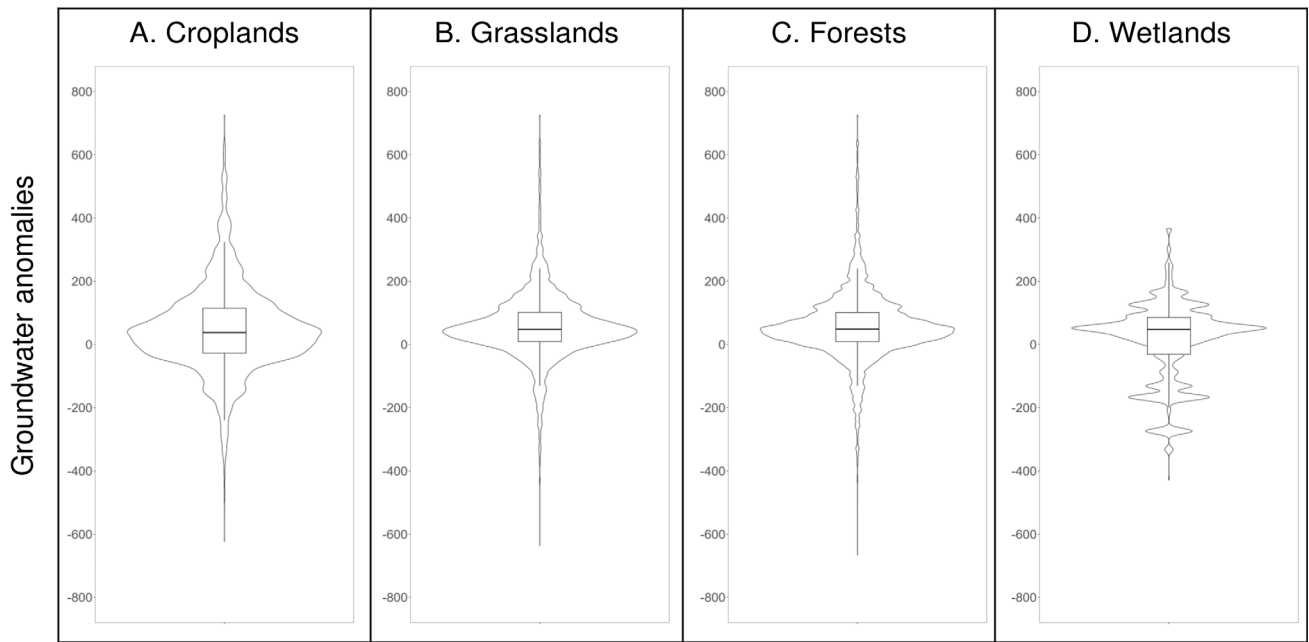
Land or livestock ownership	Zimbabwe	(Frischen et al., 2020)
Access to credit	Zimbabwe	(Frischen et al., 2020)
Median and mean disposable annual household income - Euro	European cities	(Tapia et al., 2017)
Most people can be trusted (synthetic index 0–100)	European cities	(Tapia et al., 2017)
City committed to fight against climate change (synthetic index 0–100)	European cities	(Tapia et al., 2017)
General Indices		
GDP per capital (PPP \$)	Global assesement	(Liu & Chen, 2021)
People suffering financial poverty	Morocco	(Cotti et al., 2022)
fraction of cropland (%)	Global assesement	(Liu & Chen, 2021)
total water withdrawal per capital/total renewable water ressources per capita (dimensionless)	Global assesement	(Liu & Chen, 2021)
Proportion of the children in the total population (%)	Tibetan Plateau	(Ji et al., 2021)
Proportion of the elderly in the total population (%)	Tibetan Plateau	(Ji et al., 2021)
Proportion of the non-agricultural population in the total population (%)	Tibetan Plateau; Morocco	(Ji et al., 2021; Cotti et al., 2022)
Average years of education (yrs)	Tibetan Plateau	(Ji et al., 2021)
People with secondary education (%)	Morocco	(Cotti et al., 2022)
Percentage of farms smaller than 5ha	Morocco	(Cotti et al., 2022)
Number of crops exceeding 1% of cultivated surface	Morocco	(Cotti et al., 2022)
Surface cultivated with barley (drought-resistant crop)	Morocco	(Cotti et al., 2022)
Surface irrigated (%)	Morocco	(Cotti et al., 2022)
Available water (supply) to satisfy long-term average requirements (demand)	Peruvian Andes	(Motschmann et al., 2020)

Inefficient water supply systems	Peruvian Andes	(Motschmann et al., 2020)
Mistrust in national water institutions	Peruvian Andes	(Motschmann et al., 2020)
Missing opportunities for water storage	Peruvian Andes	(Motschmann et al., 2020)
NDVI	Pakistan	(Dilawar et al., 2022)
Distance to water bodies	Pakistan	(Dilawar et al., 2022)
Night light time imageries (NLT)	Pakistan	(Dilawar et al., 2022)
Land Surface Temperature (LST)	Pakistan	(Dilawar et al., 2022)
Risk		
$R=H*E*V$	Global assesement; Pakistan	(Liu & Chen, 2021; Dilawar et al., 2022)
Drought Risk Index = HazardExposure * Vulnerability Index	Zimbabwe	(Frischen et al., 2020)
Drought Management Index: joint measure of probability of Resilience and Vulnerability	Indian catchment	(Maity et al., 2013)

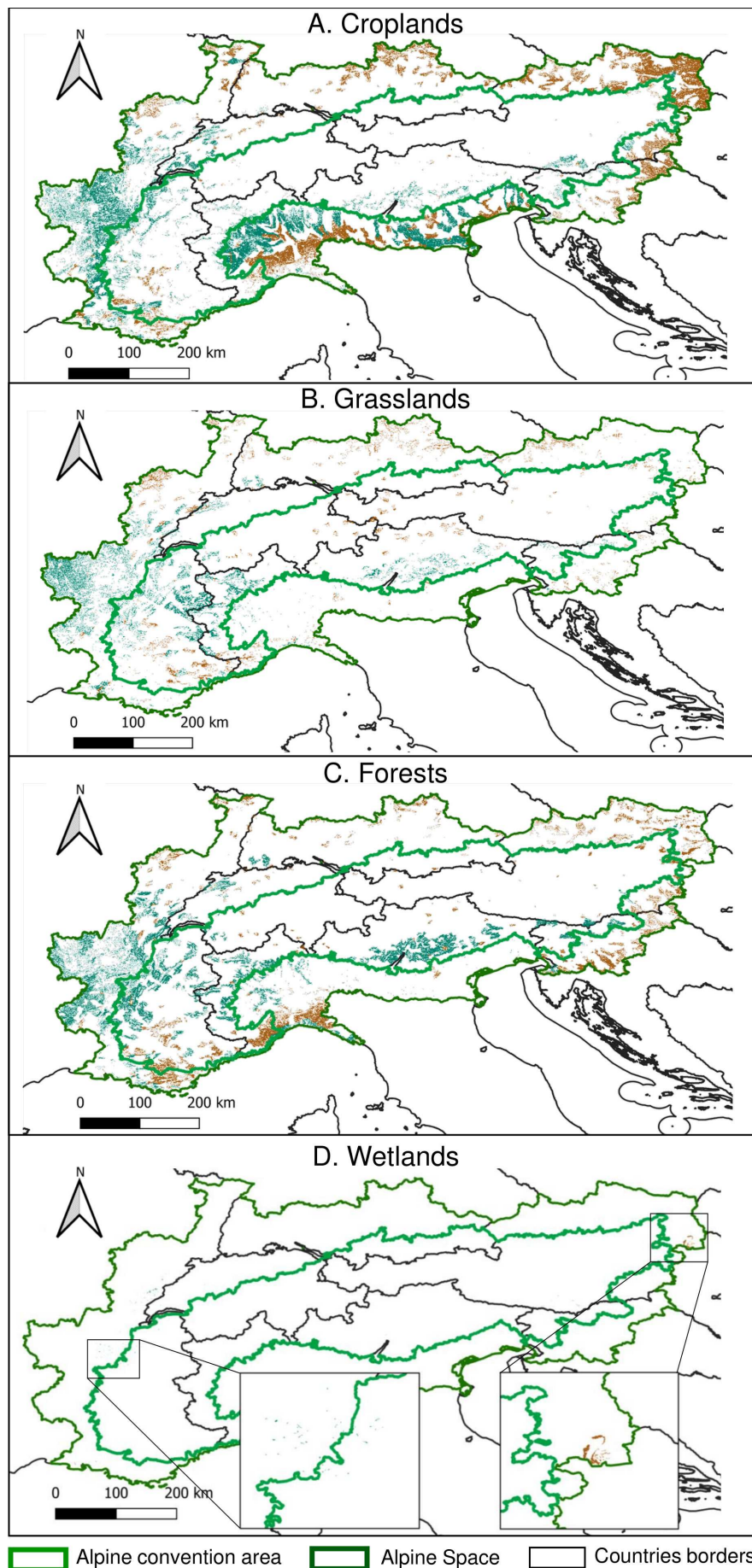
S2. Fig. Scatter plot of the log-transformed values of future groundwater for each season depending on future soil moisture (number of dry months over 30 years) in the dataset of watersheds, and the associated computed linear models (red line).



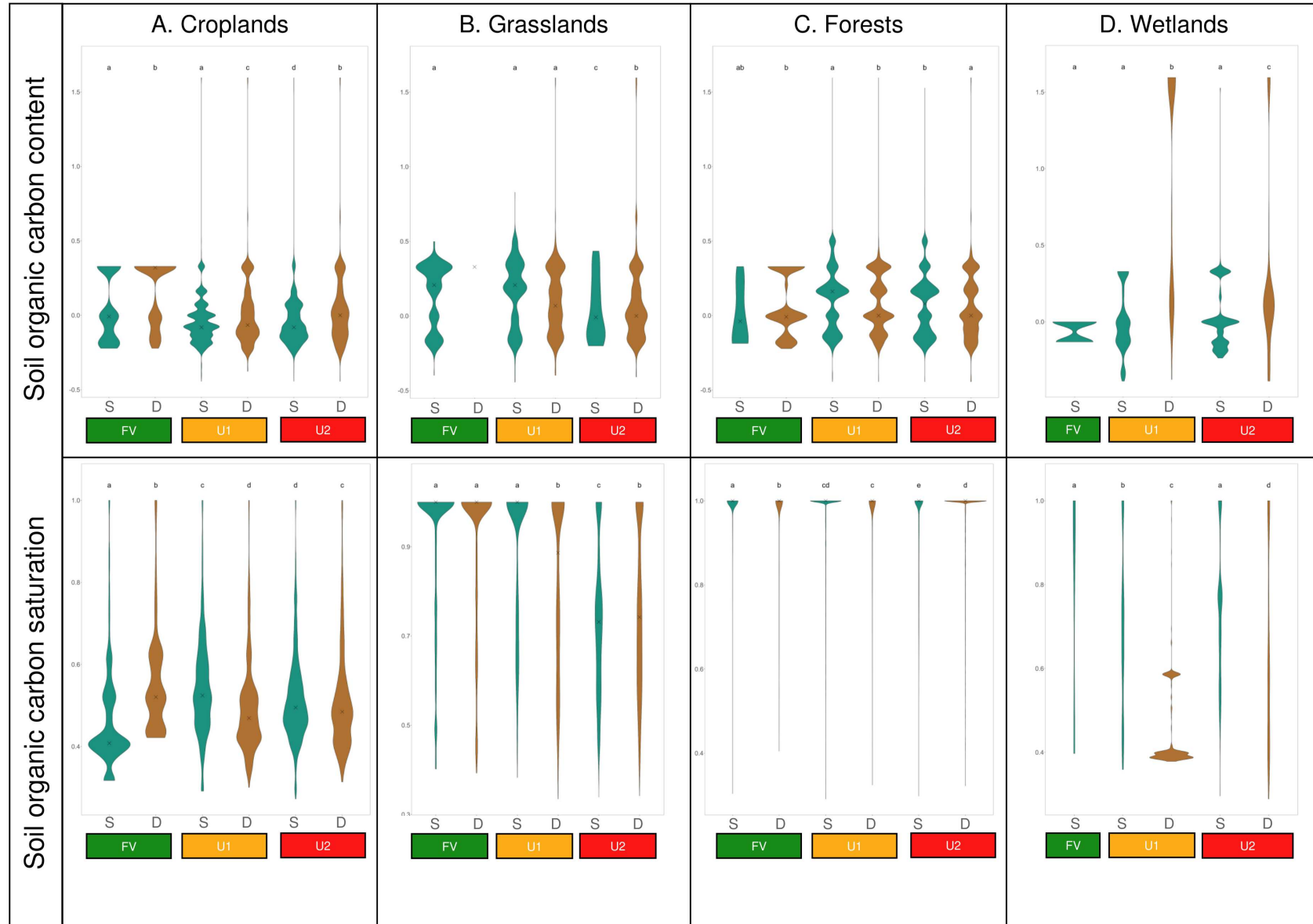
S3. Fig. Distribution of the anomalies of the linear model for each LULC



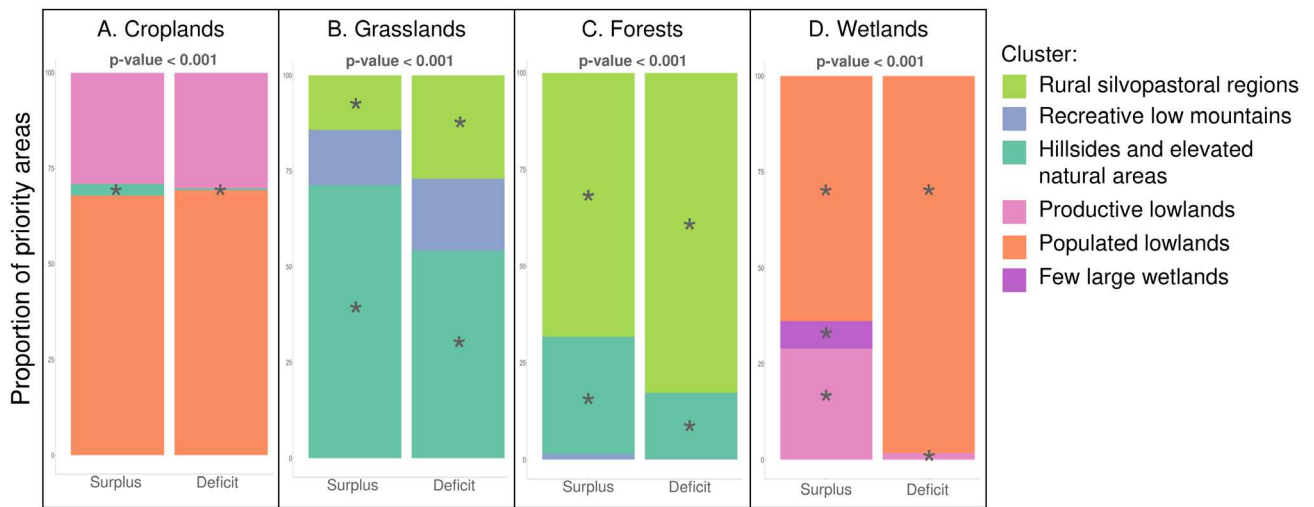
S4. Fig. Location of the priority areas for NbS to adapt to drought in the Alps, considering both areas with an expected surplus and a deficit of groundwater considering the relative change in drought duration between 2000 and 2100.



S5. Fig. Distribution of log-transformed soil organic content (tC/ha; top) and Soil organic carbon saturation (%; bottom) in priority areas for adaptation to drought in the Alps with water deficit (D) or surplus (S) of groundwater, depending on the LULC and the status of ecosystem conservation in these areas (FV: favourable conservation status; U1: degraded ecosystem; U2: highly degraded ecosystem).



S6. Fig. Barplot of the proportions of the clusters identified for the priority areas for adaptation to drought considering bright (Surplus) and dark (Deficit) spots of groundwater for four LULC: croplands, grasslands, forests, and wetlands. The names of the landscapes grouped by similarity of NCP are given in relation to the clusters for each LULC.



Chapter V

General Discussion



French Alpine protected areas actively participated in the “Alpages Sentinelles” network to enhance the monitoring and understanding of climate change impacts on mountain pastures. This transdisciplinary program creates a space for fostering dialogue among stakeholders, enabling them to share about their initiatives for adapting to changing conditions.

Source: the author.

1. Discussion of the main findings

The main objective I pursued during my PhD thesis was to understand the current implementation of NbS in the Alps to guide their future scaling.

1.1. Positioning among databases of initiatives

Through this work, my first objective was to identify the diversity of NbS implemented in the Alps, addressing jointly climate change and biodiversity loss. Then, I aimed to characterise their location based on biophysical variables and to detect the main factors for the scaling of NbS implementation. The collection of nearly one hundred NbS provides novel insights into the existing range of NbS interventions. Although NbS have not been extensively implemented in the Alpine region, many on-ground NbS interventions were recognised for their efficiency in mitigating climate impacts, confirming prior research findings (Aguilera et al., 2020; Debele et al., 2023; Shah et al., 2023; Sudmeier-Rieux et al., 2021). Such NbS include the adoption of agroecological practices in agriculture including agroforestry practices, sustainable forest management to enhance their protective function against landslides, and river restoration aimed at improving ecological connectivity and flood mitigation. However, some of these previously identified approaches are rarely implemented at the scales of those I identified, indicating the actual adoption of some NbS practices outside pilot projects, e.g. agroforestry practices implemented at the vineyard scale (Torralba et al., 2016). Furthermore, certain identified NbS are still ongoing, with expected outcomes in the coming years or decades, given the maturation time required for ecosystems to fully develop. Monitoring these activities or contacting the person in charge of these NbS to gather information would provide valuable insights regarding these initiatives.

From a global perspective, the PORTAL database enriches the existing range of initiatives databases, which inadequately capture the diversity of NbS in the Alpine region (Johnson et al., 2022; Palomo et al., 2021). Although systematic literature review is more commonly used to identify NbS (Chausson et al., 2020; Johnson et al., 2022), I have shown that grey literature can also be effective to this purpose. The specificity of the PORTAL database lies in the number of collected initiatives compared to its scale. The coverage of a region as extensive as the Alpine one allowed me to document around one hundred initiatives within a social-ecological continuum. A coverage of this scale has already been found to provide the possibility of achieving the best ratio between completeness and easiness of documenting each initiative (Coppus et al., 2019). Global databases, such as Panorama and Oppla (Baills et al., 2021; Palomo et al., 2021; Schröter et al., 2021) or continent-specific ones, such as Naturvation and Climate-adapt which cover the EU (Baills et al., 2021; Schröter et al., 2021), gather hundreds of initiatives, while others databases gather a limited number of case studies because they either focus on local

regions or target sporadic initiatives across countries, such as PHUSICOS or OPERANDUM (Baills et al., 2021; Schröter et al., 2021; Solheim et al., 2021). The PORTAL database explores NbS implemented across all ecosystems and land-cover types, unlike other regional databases that focus on a specific type of land-cover, such as urban areas for Nature4cities, CLEVERCities and UrbanGreen Up databases (Schröter et al., 2021). Moreover, the PORTAL database is a valuable resource for future research with regards to its spatial data, and its ability to collect additional initiatives through an online questionnaire. Finally, the available information regarding NbS can contribute to the potential sharing of such initiatives, which is essential for fostering future implementation. However, in contrast with some other databases (Baills et al., 2021), I did not collect the costs of NbS due to unavailable information.

1.2. Mismatch of Nature-based Solutions location with climate hazards and Nature’s Contributions to People

The analysis of NCP and hazards addressed by NbS (Dubo et al., 2022) confirmed the multifunctional potential of these initiatives, emphasizing the fact that there is no one-size-fits-all solution to a given challenge (Chausson et al., 2020; Sudmeier-Rieux et al., 2021). Consequently, it is crucial to integrate local specificities into the design of NbS for effective adaptation (Albert et al., 2021; Raymond et al., 2017). The recent implementation of most of the identified NbS suggests their increasing adoption across various sectors within the Alpine region. However, their spatial distribution does not necessarily align with areas facing the highest current or anticipated climate hazards, or those with the highest sensitivity regarding NCP provision, use and demand. Acknowledging that our database is not exhaustive and that other NbS may have been implemented in the Alps, previous scholars did not identify biophysical variables and NCP as major drivers for implementing NbS within and outside the Alps (Houghton and Castillo-Salgado, 2020). However, this result is nuanced in existing literature, especially in regard to drought hazards (Harmanny and Malek, 2019), emphasizing the need for future regional analysis. Understanding the decision-making contexts of NbS implementations also requires to identify driving elements beyond biophysical conditions, including values, rules and knowledge (Gorrdard et al., 2016; Topp et al., 2021). Nonetheless, it is essential to acknowledge that the entire Alpine region is experiencing climate change and that these initiatives are, therefore, essential contributions to regional adaptation efforts. The results of Chapter II highlight the wide implementation gap, particularly in areas where NbS are the most urgently needed (UNEP, 2022a). The spatial planning of future NbS implementation should take into consideration both current and future climate conditions and NCP (Bourne et al., 2016; Comín et al., 2018).

1.3. Levers and barriers to the implementation of Nature-based Solutions

Given that local social-ecological variables alone did not drive the implementation of the identified NbS, I conducted interviews with NbS managers to gain an understanding of the decision-making contexts guiding these implementations (Chapter III). The primary levers I identified for NbS implementation align with those highlighted in the existing literature, encompassing binding regulations, robust project coordination, positive cultural values within local communities, knowledge sharing through informal exchanges, collaborative planning, and academic support (Bruley et al., 2021; Chan et al., 2020; Sarabi et al., 2019; Seddon et al., 2020). The analysis further revealed three categories of decision-making contexts, each associated with a specific combination of levers and a given level of transformation potential (Dubo et al., in press). These categories align with previously identified decision-making contexts. The *Local transformation* type, characterized by the sharing of experiential knowledge and motivated by relational values towards nature and the pursuit of self-sufficiency, resonates with previously identified alternative practices, such as the implementation of agroforestry practices (Vermeulen et al., 2018). Initiatives of this type are often considered ‘bottom-up’, involving grassroots governance within small areas and fostering informal rules (Diaz-Kope and Miller-Stevens, 2015; Midgley et al., 2021; Topp et al., 2021). These initiatives relate to transformative characteristics of restructuring, achieved through social innovation and the development of alternative market models (Augenstein et al., 2020). *Green deal* NbS are motivated by funding opportunities or binding regulation, and relate to technical knowledge and instrumental values (Fayet et al., 2022; Topp et al., 2021). These initiatives mostly refer to incremental adaptation, which involves step-by-step changes that may not be sufficient in addressing the challenges they face (Fedele et al., 2020; Kates et al., 2012), yet they serve as an entry point to adaptation in diverse situations (Vermeulen et al., 2018). *Multi-scale co-production* NbS are designed with participatory approaches, incorporating various human values for nature and knowledge systems. These initiatives foster interactions across different scales and sectors, through the creation of space for dialogue, enhancing their corresponding transformative characteristics (Diaz-Kope and Miller-Stevens, 2015; Schröter et al., 2022; Scolobig et al., 2023; Vermeulen et al., 2018). The identified transdisciplinary research projects related to NbS and adaptation belong to this type (Holzer et al., 2019).

These decision-making contexts often coexist within local regions, illustrating the complexity of creating enabling policy (Chhetri et al., 2019; Pelling et al., 2015). Consequently, I identified the main levers that promote the implementation of NbS in the Alps. Recognizing alternative practices from *Local transformation* NbS as a source of inspiration can enrich the knowledge system of *Multi-scale co-production* NbS. The former may constitute real-world case studies of cost-effective practices, enabling stakeholders to adopt them, similar to what *Green deal* NbS have achieved, fostering transformation if implemented at scale (Chhetri et al., 2019; Pelling et al., 2015). Leveraging these interconnected levers paves the way for transformative change (Bruley et al., in prep.; Chhetri et al., 2019; Pascual et al., 2023). Public agencies play a pivotal role in activating these levers, as they are found to be involved in the three types of decision-making contexts (Enqvist et al., 2020; Topp et al., 2021).

1.4. Priority areas to implement Nature-based Solutions for adaptation to drought and their few synergies

Identifying priority areas to implement NbS is crucial to concentrate efforts on scaling NbS where they are most needed. In Chapter IV, I focused on identifying priority areas to implement NbS for adaptation to drought in the Alps. The analysis revealed that NbS can simultaneously address biodiversity conservation, climate change mitigation and adaptation in some locations. However, the number of priority areas for adaptation overlapping priorities for these co-benefits is limited, contrasting with previous prioritisation findings (Jung et al., 2021; Villarreal-Rosas et al., 2023). Therefore, spatial prioritisation should primarily target locations where these synergies exist, e.g. within water-scarce areas that often exhibit ecosystems with a poorer status for biodiversity conservation. Next, priority areas for other goals should be considered, e.g. where the carbon sequestration potential is the highest, which may not necessarily overlap with an adaptation priority according to my results. Addressing these challenges requires more than implementing NbS solely in areas exhibiting favourable enabling conditions, such as protected areas (Dudley, 2010; Palomo et al., 2014), which would be insufficient alone (Etter et al., 2020).

Consequently, I shed light on some levers and barriers that may exist across the identified landscape types, underscoring the importance of considering local contexts when determining which levers to prioritize. While acknowledging the existence of other enabling factors for implementing NbS, such as the presence of local champions or local policies (Rouillard and Spray, 2017; Wamsler et al., 2014), I focused the analysis solely on a subset of potential recognised levers for which the resolution of the available spatial data was high enough. Notably, adaptation to climate change is also required in non-priority regions, as climate change impacts all municipalities. While adaptation initiatives for tackling climate hazards may cover broad areas, such as flood mitigation strategies concerning entire watersheds, municipalities must engage in collaborative and deliberative processes regarding climate change adaptation and biodiversity conservation (Hurlimann et al., 2021; Kruse and Pütz, 2014; Zölch et al., 2018). This necessitates close consultation with local communities to account for their specific social-ecological conditions (Langemeyer et al., 2018; Ruangpan et al., 2021). Given the overlapping nature of public policies at various scales (municipal, local, regional, national, and Alpine), ensuring policy coherence across these scales is crucial (Di Gregorio et al., 2019). In order to achieve this coherence at the Alpine scale, facilitating the alignment of strategies across Alpine countries is essential (Cattivelli, 2021).

This imperative extends to governmental agencies, such as agriculture chambers or protected areas, as well as private sectors, such as hydroelectricity or forestry companies and cooperatives (Martin et al., 2021; Méndez et al., 2022). For instance, although protected areas hold the potential to enable the implementation of NbS, colleagues and I revealed only limited mentions of NbS in their activity reports and future management plans (Bruley et al., in prep.).

2. Insights of the Nature-based Solutions concept

2.1. A double-edged concept

The NbS concept emerged to describe initiatives that seek to enhance synergies and align with different worldviews. Unlike grey infrastructures, which primarily focus on artificial structures, NbS aim to provide simultaneously societal benefits and habitats for biodiversity (Cohen-Shacham et al., 2016; Sowińska-Świerkosz and García, 2022). The recognized importance of green spaces for people's good quality of life has led to the increasing popularity of NbS when compared to grey infrastructure (Sturiale et al., 2023; Vogelsang et al., 2023). There is a growing argument that natural disaster risk reduction may miss valuable opportunities if the measures are designed without considering NCP (Pugliese et al., 2020). Through their definition, NbS promise to deliver social benefits, encompassing aspects related to people's good quality of life and economic benefits (Cohen-Shacham et al., 2016). This relates to a utilitarian vision of nature rooted in Western countries' vision, where "solutions" emerge to solve a problem, often disregarding the root causes of the problem's emergence (Melanidis and Hagerman, 2022; Muradian and Gómez-Baggethun, 2021; Stabinsky, 2020). The concept of NbS may dismiss initiatives aimed solely at conserving biodiversity for itself if they do not consider societal benefits. This perspective is less comprehensible from indigenous communities perspectives (Melanidis and Hagerman, 2022; Nalau et al., 2018), although NbS standard advocates for their inclusion (IUCN, 2020; Nalau et al., 2018).

The NbS concept is built upon the ecosystem services literature, with the intention of being embraced by decision-makers and stakeholders who hold either "living from" or "living in" human values for nature, aligning both with anthropocentric and pluricentric worldviews (Pascual et al., 2023). Indeed, those implementing NbS recognize the potential social benefits they can deliver to people (Margaryan and Stensland, 2017; Viti et al., 2022). These benefits include electoral interest in politics and the cultivation of a sustainable-friendly image for companies, as mentioned in the interviews I conducted (Dubo et al., in press).

Consequently, NbS hold significant promise for funders and investors, enabling them to shift from harmful to sustainable investments (Crick et al., 2018; Kang et al., 2023). Although private sector investments have recently increased, their contribution to global NbS investments remains scarce (17% to date, UNEP, 2022a). Nevertheless, many of those implementing the NbS I identified during this research are not funders or investors. Many of the implementers self-fund their NbS initiatives. Others have applied for external funding, through governmental subsidies or carbon offsets. They implemented initiatives and practices aligned with their personal values, often diverging from a solely instrumental vision of nature. This position is increasingly recognized as enhancing transformative NbS (Merçon et al., 2019; Pascual et al., 2023; Welden et al., 2021), necessitating a transition from the current dominant system towards a new vision that encompasses reconnection to nature, multi-level governance, justice, inclusiveness and funding mechanisms beyond market-based approaches (Basta et al., 2021; Chausson et al., 2023; Moreau et al., 2022; Welden et al., 2021).

Existing instruments tend to align with a utilitarian vision, such as Payment for Ecosystem Service which aims at preserving NCP (Kinzig et al., 2011). However, this instrument has faced criticism due to its instrumental vision of nature, and its potential shortcomings in conserving biodiversity, particularly when the financial incentives fail to dissuade stakeholders from harmful practices (Bremer et al., 2023). Similar caution is required for instruments related to NbS.

To summarize, the NbS concept does not introduce innovative practices or technical knowledge related to climate change adaptation and biodiversity conservation as its fundamentals are derived from already recognized practices (IUCN, 2020). Instead, NbS can serve as a social innovation instrument, aiming to drive societies towards a paradigm shift that integrates biodiversity conservation and diversity of human values for nature into an overall strategy (Bremer et al., 2023; CBD, 2009; Pascual et al., 2023). The concept facilitates the adoption of non-harmful practices by various stakeholders and provides a framework for researchers to explore how societies can shift from one siloed perspective to an integrated one. The IUCN Global Standard for NbS (IUCN, 2020) offers a framework for operationalising the certification of NbS. It offers clear guidelines that define the scope of NbS and may limit practices that lead to the degradation of social and ecological conditions (Holl and Brancalion, 2020; Jacobs et al., 2023; Stabinsky, 2020). The European Commission handbook on NbS offers an impact assessment framework for practitioners with a set of indicators to evaluate NbS interventions (European Commission, 2021). An increasing level of support for this standard and impact assessment may prevent the misuse of the NbS concept, and increase biodiversity-friendly practices. Nevertheless, context-specific research remains essential to improve the effectiveness of well-established approaches, such as agroecological practices, ecological restoration, and sustainable forest management.

2.2. Nature-based Solutions interlinkages with other sustainability concepts

The NbS concept emerged in parallel with other sustainability approaches. One of these is the One Health approach, developed in the early 2000s to promote an integrated vision that considers human health as a result of interactions between a healthy environment and healthy animals (OHHLEP et al., 2022). This approach shares some characteristics with NbS, including equity, social-ecological equilibrium, biodiversity consideration and multisectoral collaboration. However, the two approaches have differences. For instance, the One Health approach poorly addresses the impacts of natural disasters on human health (Elnaiem et al., 2023). In contrast, while many urban NbS aim to increase air quality to improve human health, the integration of pandemics and infectious disease outbreaks into NbS design and monitoring remains limited (Boriani et al., 2021; IPBES, 2020).

Another approach is the Nexus approach, considered by the IPBES as a holistic method for understanding the interlinkages between climate, agriculture, water, energy, and health (Ansari et al., 2023; Liu et al., 2018). This approach addresses challenges closely related to NbS. Furthermore, both approaches face similar barriers, particularly in terms of uptake in decision-making processes. However, the Nexus approach can promote incremental changes,

for instance promoting water-use efficiency instead of shifting practices or changing land-use (Ansari et al., 2023; González-Rosell et al., 2023). In contrast to some implementations of the Nexus approach (González-Rosell et al., 2023; Kellner, 2023), access to energy receives limited considerations in the NbS identified in the Alps and elsewhere (Chausson et al., 2020; Goodwin et al., 2023; Woroniecki et al., 2022).

Another recent approach, the Nature Futures Framework, has been developed to design visions of desirable futures integrating diverse human values for nature through participatory approaches (Pereira et al., 2020). This framework is based on a triangle in which each point is a perspective on nature's values, considering Nature for Nature, Nature for Society and Nature as Culture, and where the vision is located within the triangle space. Defining scenarios towards these visions may help emphasize the role of NbS for sustainable futures (Durán et al., 2023).

Some studies have explored the extent to which these approaches are redundant and complementary (Carvalho et al., 2022; Durán et al., 2023). Promoting interlinkages between them through regular knowledge sharing may offer opportunities for developing clear guidelines for decision-makers and practitioners, rather than having overlapping concepts that may increase confusion.

2.3. The need for Nature-based Solutions standard adoption

The NbS concept has been increasingly used in research over the last three years. While the definitions of NbS provided by the IUCN (Cohen-Shacham et al., 2016), the European Commission (European Commission, 2015) and the UNEA (United Nations Environmental Assembly; UNEA, 2022) have gained increasing recognition globally, the practical implementation of NbS principles remains unclear. In this thesis, I identified NbS based on inclusion criteria aligned with the IUCN definition: “actions to protect, sustainably manage and restore natural or modified ecosystems that address societal challenges effectively and adaptively, simultaneously providing human well-being and biodiversity benefits” (Cohen-Shacham et al., 2016). However, the majority of NbS implementers were either unaware of the NbS concept, or, if aware, did not categorise their initiatives as NbS. For instance, during interviews and workshops conducted by colleagues with farmers from Alpine valleys, some individuals reported implementing agro-ecological practices, although their interventions have not been reported as NbS (Bergeret and Lavorel, 2022; Bruley et al., 2021).

Recent studies have argued for the adoption of international guidelines and standards for NbS implementation (Albert et al., 2021; Cohen-Shacham et al., 2019; IUCN, 2020). My research aligns with these recommendations, while also raising questions regarding the recognition of

NbS that have been previously implemented. For instance, the H2020 RECONNECT¹ research project identified a case study of NbS implemented since the 1950s, even though the concept did not exist at that time. Moreover, additional initiatives could potentially be categorised as NbS if inclusion criteria were strictly applied. For instance, ecovillages that bring together individuals committed to sustainable management practices (Dal Borgo and Gambazza, 2017), community gardens in urban areas (Orta-Ortiz and Geneletti, 2023), and hedgerows in agricultural landscapes (Collier, 2021) have previously been considered as NbS. Therefore, I recommend that the NbS Standard explicitly and adaptively describes the range of NbS initiatives, with a particular focus on recognizing community-led initiatives.

3. Methodological constraints and challenges

Sustainability science, which first emerged in the 1980s, aims at bridging the gap between knowledge and actions towards sustainable development (Clark and Harley, 2020), i.e. that “meets the needs of the present while safeguarding Earth’s life-support system, on which the welfare of current and future generations depends” (Brundtland, 1987). This field is defined “by the problems it addresses rather than by the disciplines it employs” (Clark, 2007) and, therefore, constantly requires innovative methods to address the inherent complexity of interdisciplinary issues effectively (Bettencourt and Kaur, 2011; Kates et al., 2001). This PhD thesis aims to contribute to bridging the gap between disciplines and employing comprehensive approaches. Constructive critique of the methodological approaches I used is, therefore, essential to guide future research.

3.1. The Nature-based Solutions identification protocol

The research protocol for collecting NbS mostly focused on initiatives related to public agencies or research projects. Although the exhaustivity was not the main aim of the collection of the initiatives, the database might have understated the range of NbS implemented by local stakeholders who do not communicate about it. For instance, the agriculture sector has recorded a recent increase in participatory and collective processes, regarding sharing material, farm facilities, and commercialisation (Amichi et al., 2021; Raimbert and Raton, 2021). These processes, which primarily relate to trust, time savings and environmental stewardship, drive the increasing adoption of agroecological practices in accordance with personal values (Cockburn et al., 2019; Yazar and York, 2023). Future research aiming to collect local initiatives should engage with local stakeholders, such as farmers. This can be facilitated through various means, including online directories or emerging networks that were developed for them (e.g. Paysans de Nature² in France). Establishing initial connections with these stakeholders can promote the

1 The RECONNECT research project, funded by Horizon 2020 program of the European Union, aim to enhance large-scale NbS implementation for hydro-meteorological risk reduction. The project that ended in 2023 had based its findings on case studies across Europe. More information is available online: <http://www.reconnect.eu/about-reconnect/>

2 Paysans de Nature is a network of French farmers involved in biodiversity conservation. The involved farms are mapped and is available online: <https://www.paysansdenature.fr/>

snowballing method, which has proven to be effective in complementing the initiatives collection process from the literature review (Holzer et al., 2019; Sadler et al., 2010).

Although the tourism sector contributes significantly to the Alpine economy and the fact that it is likely vulnerable to climate change (Morin et al., 2021; Palomo, 2017), a limited number of identified NbS in the Alps are related to tourism. Some of the initiatives I identified are associated with the restoration of Alpine grasslands in ski slopes. However, the ongoing development of summer tourism activities is expected to increase human pressure on Alpine ecosystems (Pröbstl-Haider et al., 2015). If properly designed, this increasing level of visitation offers opportunities to develop environmentally friendly practices, such as NbS with ecotourism activities (Stubelj Ars and Bohanec, 2010). It is crucial to develop a shared adaptation vision to benefit from this window of opportunities. Existing initiatives from other regions, including those related to nature-based tourism (Arif et al., 2022) and rewilding initiatives (Cerqueira et al., 2015; Koninx, 2019), can serve as valuable starting points for these discussions.

3.2. Lack of homogeneous data at the Alpine scale

The methods used in my study were based on available data at the Alpine scale, including the assessment and mapping of NCP conducted by the AlpES project. Climate projections are available at the European scale by the Climate Data Centre hosted by Copernicus. However, additional relevant data needed to study the adaptation of social-ecological systems were not available at the Alpine scale. For instance, biophysical information such as soil organic carbon, carbon sequestration potential, and the status of ecosystems for biodiversity conservation are provided by the EEA at the EU level, leaving Switzerland as the blank spot of Europe (Matthies et al., 2023; Schmidt et al., 2018). Moreover, even across EU Alpine countries, data is not always consistent. For instance, national LULC mapping, such as the French RPG (Registre Parcellaire Graphique, in French) is more precise than the European Corine land-cover dataset, but the homogeneity of datasets is not achieved across countries. The Alpine Convention and ongoing research projects aim to bridge these data gaps by providing unique datasets that cover the entire Alpine region (Alpine Convention, 2018; Marsoner et al., 2023). These efforts to homogenize data are essential to define a macro-regional adaptation strategy.

3.3. The NbS at the interface of sectors and disciplines

Although the NbS concept has proven its ability to identify relevant initiatives, the collection of initiatives from various sectors poses a challenge when conducting comparative analyses. Such analyses require a deep understanding of how institutions function, policies in place, governance structures, and biophysical processes across diverse sectors like forestry, river management, agriculture and urban planning. Consequently, most NbS reviews have had a narrow focus, often concentrating on particular land-cover or specific sectors (Johnson et al., 2022).

Nevertheless, my analysis of decision-making contexts identified similar levers and barriers

across different sectors. For instance, the governance systems of the forest and agriculture sectors involved institutions with similar roles. In France, the Agriculture Chamber and the French National Centre of Forest Ownership (CNPF, Centre National de la Propriété Forestière, in French), which act as intermediaries between public policies and local stakeholders, provide support to farmers and foresters, respectively. Given these two sectors face similar changes, adopting a cross-sectoral perspective can reveal potential solutions to overcome shared barriers (Johnson et al., 2022; Kumar et al., 2020), although the responses to climate and biodiversity challenges may vary.

The implementation of cross-sectoral collaboration remains challenging because the prevailing governance systems are siloed and not designed to handle the inherent interdisciplinarity of NbS (Frantzeskaki et al., 2022; Martin et al., 2021). Consequently, conflicts may arise and collaboration may produce undesirable outcomes (Kiss et al., 2022; Wamsler et al., 2020). For instance, in France, Agriculture Chambers also support forest owners in their practices, although it is the main mission of the CRPF, and the government budget is divided into two parts. Collaborative efforts between institutions are suggested to benefit both farmers and foresters, although collaboration is not currently on the agenda (Demolis and Granger, 2016).

3.4. One perspective, one worldview

I characterised the decision-making contexts of the implementation of twenty NbS using the *vrk* framework, which has proven its effectiveness in identifying the main interactions between values, rules and knowledge within a given decision-making context (Lavorel et al., 2019; Topp et al., 2021). This framework originally developed by sustainability economists has been applied at the interface of social and natural sciences, including in projects led by natural scientists. Strengthening the interlinkage between social and natural science holds the potential to provide valuable insights for sustainability science (Beck et al., 2020; Eriksen et al., 2015; Sandbrook et al., 2023) and for framing recommendations (Ahvenharju et al., 2018; Kusmanoff et al., 2020). As for *vrk*, some methods from social science are increasingly integrated into interdisciplinary studies. Examples include the use of the welfare trade-off ratio to measure altruism in the face of climate exposure (Döring and Hall, 2023), the five A's framework (agency, adaptiveness, allocation and access, and accountability) to account for power distribution and equity (Patterson et al., 2017), the salience-valence analysis to integrate people's emotions into decision-making (Tang et al., 2022), and the hydrosocial cycle to assess social relations and understand human behaviour (Linton and Budds, 2014; Locatelli et al., 2022). In contrast, methods from natural sciences permeate social sciences, e.g. ecological indicators applied to evaluate stakeholders' diversity (Grêt-Regamey et al., 2019).

I considered only one approach to assess the transformative adaptation potential of NbS (Fedele et al., 2019), although previous scholars developed various methods to evaluate transformative change, such as the three spheres of transformation (O'Brien and Sygna, 2013), the amount of changes in the system (Goodwin et al., 2023), the period during which the change

will persist (Fedele et al., 2020; Vermeulen et al., 2018), and the scaling processes involved (Lam et al., 2022).

Coming from a natural science background (biology, agronomy, ecology), I faced significant challenges in integrating social science methods. I had minimal prior experience with questionnaires and limited knowledge of sociology, economics, psychology, and policy. To overcome these limitations, I adopted a ‘learning by doing’ approach and benefited from the interdisciplinary team that supported me throughout my PhD journey. Regarding the urgent global calls for more interdisciplinary studies to address sustainability challenges, I find it regrettable that universities, at least in France, offer limited interdisciplinary education (Medvecky, 2015; O’Byrne et al., 2015). Although interdisciplinary programs are gradually emerging within environmental disciplines, they remain on the margins of academic offerings, despite increasing demand from students (Pinton and Frascaria-Lacoste, 2022).

4. Perspectives for Nature-based Solutions research and planning

4.1. Scaling Nature-based Solutions

Scaling NbS, which involves the amplification processes in numbers, enabling conditions and mindset, is therefore a central challenge for the adaptation of social-ecological systems. Although the various levers for scaling NbS are recognised (Bruley et al., in prep.; Chan et al., 2020; Pörtner et al., 2021), the adaptation gap deepens (UNEP, 2022a) and my research confirms that NbS are not being implemented at scale in the Alps. This trend can be partly attributed to some of the barriers I identified in Chapter III, including the inertia of public policies to adopt commitment (Otto et al., 2020; Sarabi et al., 2020; Voulvoulis et al., 2017), the path-dependencies that lock-in stakeholders in current practices due to sectoral silos and anchored power dynamics (Barnett et al., 2015; Schreyögg and Sydow, 2011), and the lack of funding opportunities (Calliari et al., 2022; Chausson et al., 2023).

To overcome these barriers, examples of recommendations found in the literature about the scaling of NbS include “redesigning agroecosystems”, “reconnecting people to nature” or “building a new global food system” (Ives et al., 2018; Wezel et al., 2020). They have been identified as powerful levers for sustainability (Chan et al., 2020; Pascual et al., 2023), but they involve complex and long-term dynamics (Otto et al., 2020). However, the local population may be unwilling to change if conditions are not critical (Bruley et al., 2021; Djoudi et al., 2013), and decision-makers often seek single silver bullets (Holl and Brancalion, 2020; Pörtner et al., 2023), all together tending to favour inaction or reactive options when faced with the magnitude of efforts required to activate deep levers (Fedele et al., 2019).

In this work, I identified some levers that may help activate these deep levers to scale NbS (Abson et al., 2017), emphasizing the need for a paradigm shift to a learning-by-doing approach

(Chan et al., 2020). Although I have not identified knowledge as the main driver of the implementation of the NbS I explored, consistent with previous assessments (Chassé et al., 2021; Toomey, 2023), I have highlighted the significant role that knowledge of regulating NCP and ecological processes plays in driving decision-making. Scientific tools and knowledge have proven efficient in acting as a first filter, e.g. for spatial prioritisation (Chassé et al., 2021), and as a support to policy-makers (Pörtner et al., 2021) and civil society (Winkelmann et al., 2022). Researchers, therefore, play a pivotal role in advancing what science has always represented: being one step ahead (Bertuol-Garcia et al., 2018; Nuno et al., 2014). Alternative thinking systems have emerged in sustainability science, including knowledge co-production, transdisciplinary, and, more recently, research-action instruments such as Living labs, and T-lab (Charli-Joseph et al., 2018; Lupp et al., 2021). In these approaches, the researchers are considered as elements of the system, rather than situated at its centre or boundaries (Holzer et al., 2019).

4.2. The Landscape-based Solutions to go beyond site-based NbS

The implementation of site-specific NbS can contribute to provide NCP to surrounding communities, due to the flow of NCP (Palomo et al., 2013; Schirpke et al., 2019). However, the amplification of NbS in isolation is not the most optimal strategy for achieving effective regional climate adaptation (Hobbs et al., 2014; Midgley et al., 2021). To ensure effective adaptation, along with biodiversity conservation and NCP provision for all, an integrated landscape-scale approach is required (Hobbs et al., 2014). This approach is frequently advocated, at least in Europe, for water bodies, that are managed under the jurisdiction of locally designated environmental agencies operating at the catchment level (Keesstra et al., 2018). However, adopting a landscape approach becomes challenging when land ownership is fragmented (Estrada-Carmona et al., 2014). For instance, improving landslide regulation through forest management necessitates collaborative efforts encompassing forest owners covering the entire hillside. Moreover, individual actions which are recognized to enhance NCP such as hedges restoration in agricultural landscapes are likely to provide limited results when contrasted with collective efforts that encourage synergistic interactions across land parcels, e.g. connecting semi-natural habitats (Collier, 2021; Grass et al., 2019).

The application of landscape ecology to spatial planning is not a recent concept (Nassauer and Opdam, 2008). However, although various frameworks related to multifunctional landscape design exist, real-world implementations remain limited (Lamine, 2012; Takahashi et al., 2022). Ecological corridors have gained recognition as valuable instruments in spatial planning for restoring biodiversity and NCP through habitat connectivity enhancement (Grass et al., 2019; Plassmann et al., 2016), especially between protected areas (Kremen and Merenlender, 2018). More recently, a framework has been proposed to integrate NbS into agricultural landscapes, considering connections between NbS (Simelton et al., 2021). The IUCN has also introduced a multifunctional landscape approach for mountain regions, advocating the importance of diverse NbS to facilitate the NCP flow from upstream to downstream (IUCN, 2022; Pörtner et al., 2021). In multifunctional landscapes, NbS play a crucial role in bridging the gap between humans and nature, and in providing the best range of NCP for biodiversity and people's good quality of life (Pörtner et al., 2021).

Although achieving sustainable NCP provision needs at least 20% coverage of native habitat (Garibaldi et al., 2021), multifunctional landscape planning also requires innovative, transparent and inclusive governance between local stakeholders and landowners (Hobbs et al., 2014; Pörtner et al., 2021). Therefore, instead of promoting NbS scaling, I propose the concept of Landscape-based Solutions as a spatial planning approach of multifunctional landscapes for climate change adaptation through an integrated and inclusive regional planning vision based on interlinked NbS. This approach may incorporate NbS principles, and adopt a multicriteria approach. It explicitly considers that solutions are not purely technical but involve the intricate interplay between socioeconomic factors and biophysical compounds, thereby aligning with the foundational principle of social-ecological systems (Martín-López et al., 2009). However, even with multifunctional landscape management, trade-offs inevitably arise. These trade-offs can involve considerations of equity, biodiversity, NCP and human activities, such as agriculture and forest production (Eastburn et al., 2017; Neyret et al., 2023). Landscape-based Solutions may hold the potential to minimize these trade-offs through participatory approaches (Ruangpan et al., 2021; Saarikoski et al., 2019). This approach may promote the diversity and redundancy of ecosystem patches (Albert et al., 2019; Landis, 2017), and foster collaborative and cross-sector partnerships that support local culture and economy (Beller et al., 2019; Gretter et al., 2018).

Similar to the concept of multifunctional landscapes for sustainability, Landscape-based Solutions may consider NCP as a common-pool resource, which includes quantifiable resources such as fodder production and uncountable ones such as landscape aesthetics (Ostrom, 1999). Promoting local environmental stewardship and fostering solidarity within local communities, both with each other and with nature, supports sustainable and just NCP management (Bennett et al., 2018; Cockburn et al., 2019; Yazar and York, 2023). Common-pool resources can be collectively managed to cope with the tragedy of the commons, i.e. a possible scenario leading overuse of resources due to individualistic behaviour (Ostrom, 1999). Considering NCP provided or maintained by NbS across the entire landscape as common goods that benefit everyone can facilitate their effective management (Hubeau et al., 2017; Ostrom, 2009; Soliev and Theesfeld, 2017). Envisioning a scenario where local stewardship and solidarity contribute to individual fulfilment and preserve NCP is likely to cope with the overuse scenario (Ceddia et al., 2019; Herrmann-Pillath, 2023; Pörtner et al., 2021).

4.3. Future research directions

NbS are often considered as “no-regret” approaches, promising benefits regardless of their actual effectiveness. However, an increasing body of literature has attempted to evaluate NbS effectiveness, aiming to inform decisions related to their scaling. The results are mixed, with generally positive outcomes regarding biophysical aspects, though sometimes with moderate impacts (Antolini et al., 2020; Chausson et al., 2020; Debele et al., 2023). However, relatively few studies incorporate cost-benefit analyses or explore the social and cultural benefits associated with these interventions (Ansell et al., 2016). Given the potential for both positive and negative outcomes, it becomes crucial to address local considerations that may influence outcome direction. Indeed, each NbS is unique, and its design and co-construction process can influence its outcomes.

In this thesis, the primary focus was not to assess the effectiveness of the identified NbS. Instead, I collected information related to their implementation and spatial distribution. Consequently, I could not quantitatively assess the changes in NCP provision, or social benefits, as there was no prior assessment of the initial conditions. However, colleagues modelled the outcomes of some on-ground NbS I identified in the Alps, based on photointerpretation and NCP modelling (González-García et al., in prep). The analyses revealed that these NbS provided substantial priority habitats for biodiversity, carbon sequestration, and important NCP for local communities, including heatwave mitigation, flood regulation and landslide protection (González-García et al., in prep). As previously underscored, these results demonstrate the favourable investment that NbS constitute, exhibiting very high cost-effectiveness when considering mitigated impacts (European Commission. Directorate General for Environment., 2022). However, some scholars argue that NbS implemented today may not be effectively suited to tackle future conditions (Ossola and Lin, 2021). For instance, urban green infrastructures are often implemented to reduce urban heat islands during heatwaves. However, for these NbS to be effective, they relate to water resources that might become scarce during these extreme events (Cammalleri et al., 2020; Haas and Birk, 2017; Samaniego et al., 2018). Moreover, factors such as droughts and pest attacks are recognised to decrease forests' capacity to sequester carbon (Anderegg et al., 2020). Given these uncertainties regarding future climate and ecological conditions, exploring all the NbS options, with collective support and continuous monitoring, can be considered a “no-regret” approach (Berrang-Ford et al., 2021).

Based on these findings, I have identified four potential avenues for future research. Firstly, there is a need for future research to include the integrated assessment of NbS outcomes compared to alternative approaches, especially grey infrastructure (Chausson et al., 2020; Guerry et al., 2022; Johnson et al., 2022). This assessment should particularly focus on social aspects such as equity (Malekpour et al., 2023; Sandbrook et al., 2023; Yazar and York, 2023), as well as their integration into landscape planning (Costanza and Terando, 2019). Secondly, a knowledge gap remains concerning the governance processes required to scale just and transformative NbS, especially about the roles of local champions, collective actions, power relationships and social thresholds (Allen and Malekpour, 2023; Hobbs et al., 2014; Schoon and Cox, 2018; Yazar and York, 2023). This research should also address how to deal in practices with climate uncertainties (Costanza and Terando, 2019; Walker et al., 2013) and well-anchored values, rules and knowledge (Barnett et al., 2015; Malekpour et al., 2023). Particularly, I acknowledge the need to explore initiatives that failed to implement NbS, which I did not address here. Thirdly, although I confirmed their crucial role, the involvement of stakeholders and private sectors in NbS design and funding is still scarce compared to the challenge ahead, providing a much-needed avenue to explore the motivations and alternative funding opportunities that can encourage proactive NbS implementation (Berrang-Ford et al., 2021; Johnson et al., 2022; van Valkengoed and Steg, 2019). Lastly, addressing these research priorities will require the development of clear methodologies (Herrero-Jáuregui et al., 2018). Multi-criteria decision analysis tools, involving different stakeholder groups, as well as participatory scenario planning and modelling, can serve as entry points for developing a transdisciplinary approach regarding NbS (Bruley et al., 2021; de Mendonça et al., 2022; Semeraro et al., 2023; Vannier et al., 2019).

5. Conclusion

Climate change and biodiversity loss threaten human well-being and ecosystems on Earth. The Alps, where temperatures are rising at twice the global rate, are undergoing an increase in intensity and frequency of several hazards, including droughts, floods, heatwaves, wildfires, and landslides, as well as exacerbating snow cover reduction and glacier retreat. In addition, biodiversity loss resulting from habitat destruction, land-use changes, overexploitation, invasive species expansion, and pollution further exacerbates climate impacts. NbS have emerged as approaches to address these issues by working with and for nature. They may hold the potential to enable transformative adaptation by fundamentally altering the current system trajectory.

In my PhD research, I identified a range of NbS interventions in the Alps, designed to tackle various Alpine challenges while aiming at providing substantial NCP. These NbS are not located where they are most needed, considering the intensity of climate hazards and the amount of NCP supply, flow, and demand. To identify the main levers and barriers that had led to the implementation of NbS and guide future policies, I conducted twenty interviews to understand the decision-making contexts of the identified NbS. I identified three types of initiatives, comprising local self-sufficient transformations; green deal practices involving incremental changes; and co-production projects involving various stakeholders acting at multiple scales. Furthermore, I highlighted the interdependence between the three groups, emphasizing the necessity of involving all local stakeholders in designing a regional adaptation strategy. Each of these groups enables a significant level of some transformative characteristics, suggesting that transformative adaptation arises from the mix of these decision-making contexts. The main levers identified to foster future implementation include support of local communities facing economic or technical constraints in implementing NbS; the development of transdisciplinary programs to propose an inclusive space for dialogue around NbS practices; and shifting harmful subsidies to instruments enabling transformative NbS, implemented along with monitoring activities.

Given the limited human and financial resources available to activate these levers, the spatial prioritisation of NbS is needed. This spatial identification considered areas where there is a deficit or a surplus of freshwater, respectively aiming at enhancing or safeguarding this precious resource. The results confirm the spatial diversity of priority areas across the Alps, with a concentration in the southern and the northeastern lowlands and hillsides. Although a limited number of areas appears to optimise the multifunctional potential of NbS for biodiversity conservation, carbon sequestration and climate change adaptation, it became evident that implementing NbS in protected areas alone is insufficient to address climate change adaptation in these priority areas.

Overall, there is an urgent need for scaling NbS, and this research confirms some of the previously identified levers to achieve this challenge. The NbS concept holds the potential to engage local communities in breaking down silos of governance and overcoming path dependency towards a just and sustainable future. For doing so, robust criteria to implement and assess NbS may prevent the misuse of the concept and, therefore, mitigate the risk of maladaptation.

Further research is necessary to evaluate the technical effectiveness of these solutions in addressing climate change in various contexts and sectors. In addition, more effort is needed to explore the interrelations of NbS within a landscape and understand the role that local communities can play in enhancing their effectiveness. In particular, solidarity and stewardship have proven effective in addressing shared environmental issues (Cockburn et al., 2019; Hubeau et al., 2017). For instance, in Spain, the *acequias de careo* have been revived by local farmers, in collaboration with researchers, and reintegrated into current water management strategies to face the increasing occurrence of droughts (Martos-Rosillo et al., 2019).

Moreover, to address the current crises interplaying with climate and biodiversity, as well as economic, migratory, diplomatic, energetic, epidemic and wartime challenges, a deep understanding of the previous societal restructuring can serve as a valuable source of knowledge (Allen and Malekpour, 2023). On their own, the past two centuries abound with examples of societal transformations. For instance, the agricultural revolution, following World War II, serves as an example of how the intricate interplay between social, political, and technological spheres can fundamentally reshape a system, yielding large benefits but also introducing strong trade-offs (Daugbjerg, 2003).

The ongoing crises widen the windows of opportunity (Brown et al., 2017), allowing seeds of innovation to germinate and pave the way for the experimentation of new ways of doing (Bennett et al., 2016). At the local level, for instance, in Grenoble (France), emerging initiatives aim to reconcile sustainable agriculture production, fair compensation and equity through locally-based tax instruments. At a regional scale, the Rhone River's water management agency launched in 2022 a contest to recognize the best water management initiatives. The winning project, implemented in Echirolles (France), consisted of removing the concrete from a school courtyard, enabling water infiltration, and consequently reducing urban heat islands and floods (ARTISAN, 2022). The communication of this successful project has triggered the implementation of similar initiatives across France. At a national scale, Austria has introduced subsidies for municipalities interested in implementing adaptation strategies. Their actions are three-quarters funded by the government, with no restrictions on the number of applicants. This has resulted in about a third of municipalities engaging in adaptation efforts (KLAR!, 2021). At the international level, there is a growing spotlight on initiatives advocating for a reconnection with nature. This includes the recognition of rights for natural entities, such as rivers (Chaves et al., 2020; Strang, 2020).

Exploring a diversity of options appears to be a key strategy for addressing the most significant challenges, as life science taught us. However, to effectively implement transformative NbS, it is essential to consider the local conditions encompassing climate, biophysical, socio-ecological, economic, political, institutional, and power dynamics. In this context, innovative research methods must be found to provide an opportunity to encompass the full range of these elements and consequently detect how to activate the processes that lead to a just and sustainable future.

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