Levers for transformative nature-based adaptation initiatives in the Alps

Titouan Dubo[1*], Ignacio Palomo[2], Aude Zingraff-Hamed[3], Enora Bruley[2], Guillaume Collain[2], Sandra Lavorel[1]

[1] Univ. Grenoble-Alpes, Univ. Savoie Mont Blanc, CNRS, LECA, 38000 Grenoble, France

[2] Univ. Grenoble-Alpes, IRD, CNRS, Grenoble INP*, IGE, 38000 Grenoble, France

[3] Chair for Strategic Landscape Planning and Management, School of life science, Technical University of Munich, Freising 85354, Germany

* corresponding author

E-mail: titouan.dubo@univ-grenoble-alpes.fr (TD)

Abstract

Transformative adaptation is essential to face the unprecedented biodiversity and climate change crises. Nature-based Solutions (NbS) could accelerate the transformation of social-ecological systems to address climate change and biodiversity and Nature's Contribution to People (NCP) loss. However, they are not widely implemented. Understanding the drivers of decision-making context that support NbS implementation is crucial to address potential bottlenecks and barriers. Here, we conducted semi-structured interviews with managers of twenty NbS implemented in the Alps. We investigated their decision-making contexts using the *values-rules-knowledge* framework and their transformative characteristics. Using a clustering analysis we identified three types of initiatives sharing similar groups of levers and barriers: the *local transformation* type implemented self-sufficient initiatives motivated by relational values to nature, supporting the adaptive capacity of nature through informal governance and experiential knowledge sharing; the *green deal* type implemented gradual change in practices using funding opportunities or regulations to experiment with new approaches fostering instrumental values of nature; the *multi-scale co-production* type implemented socially accepted NbS through wide participatory process with local practitioners, and the inclusion of diverse values in initiatives designed to be persistent even when challenged by the instability of funding opportunities. Based on these results we recommend that NbS related policies should: i) foster NbS implementation by local communities who faced economic constraints when implementing new 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 face these challenges.

Key-words

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

1. Introduction

The interlinked crises of climate and biodiversity urge societies to adapt whatever the emissions scenarios (1–3). However, incremental adaptation actions are likely to maintain the system in its current trajectory and to be insufficient to face new climate conditions (4). Sustainable responses of socio-ecological systems need transformative adaptation, i.e. fundamentally altering the entire socio-ecological system's properties and function to reduce the root cause of vulnerabilities (4–6). Transformative adaptation aims to involve a holistic approach with new governance systems and knowledge production, different power relations, and a shift in values, assumptions, and policies (7–9). Despite the growing interest for transformative adaptation in sustainability science and policy (1,3,10), real case evidences of transformative responses to climate change are limited (11,12) mainly due to the inherent complexity of assessing transformation process that entails several and diverse elements including governance, stakeholders' plurality, value systems, and habits among others (8). Previous studies proposed a set of characteristics, including innovation, restructuration, shift to an alternative direction, with long-term impacts at large scale and across scales to measure transformative adaptation (Fedele et al., 2019). While some empirical studies have identified promising examples of transformative adaptation (Palomo et al., 2021), others regret having mainly found incremental responses (12,14). Further research is thus needed to evaluate different adaptation strategies and their relation to transformative processes.

There is a growing interest in Nature-based Solutions (NbS) as adaptation options with the potential for transformative change to address the joint climate and biodiversity crisis (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 transformative NbS for climate change adaptation are for examples small-scale greening projects in urban area co-created with local communities to reduce heatwaves impact (19); wetland restoration with the introduction of sivopastoral systems in mountains to adapt to reduced water provision (20); agroecology practices to reduce drought impacts, increase soil biodiversity, and secure food production (21,22). Transformative 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 biosphere reserve to reduce deforestation trends (13).

Despite the growing evidence of the abilities of NbS to address a wide range of issues and to simultaneously provide various NCP co-benefits (25–27), they are not widely implemented (8,22,28), and particularly not where they are most needed (26,29). Indeed, technical or biophysical parameters are often not the main barriers; rather, NbS implementation is shaped by the social-ecological decision-

making context (30–32). In order to amplify transformative NbS, i.e. to disseminate initiatives and to mainstream NbS into public action (33), there is a need to understand the main elements involved in the decision-making contexts of already implemented NbS, and what transformative characteristics these decision-making contexts foster.

The *vrk* (*values-rules-knowledge*) framework analyses the decision-making context (34) and is an established tool in the context of environmental changes (35–37). According to the framework, the decision-making leading to NbS design, funding and realisation, a step-by-step process which we refer to as 'implementation', involves an interconnected system of *values, rules and knowledge.* The *values* refer to "a set of ethical precepts that determine the way people select actions, evaluate events" (38). For human-nature relationships, *values* usually refer to the intrinsic value of species and ecosystems, the instrumental values and the relational values (39). *Rules* include informal norms, practices, taboos, habits, and heuristics, as well as formal regulations, legislation, treaties, and ordinances (Dopfer and Potts, 2009; Ostrom, 2011). *Knowledge* combines evidence-based (scientific and technical) knowledge, experiential, meanings-based knowledge (40,41) or indigenous knowledge (32,42). Identifying the *values*, *rules*, *knowledge,* and interactions involved in the decision-making context related to NbS implementation enables the characterisation of the set of levers and barriers to climate adaptation (34,43).

Commonly identified barriers to nature-based solutions implementation are i) the lack of funds and financial instruments for implementing NbS (44); ii) the path dependency of practices leading to a resistance to change from stakeholders and institutions (30,45); iii) the limited participation of local stakeholders (46); iv) the limited coordination between actors from different sectors (47); and v) the knowledge gap about the multiple co-benefits of NbS (47,48).

Several levers have been highlighted to overcome these barriers: promotion and assessment of NbS co-benefits (49,50), collaboration and co-construction of solutions between stakeholders (50,51), polycentric governance (47), incentives and environmental law (7), social innovation (30,52) and overcoming path dependency (30,43). Most of these levers are identified and listed in the literature as general recommendations, with low considerations of the local contexts and the synergies or trade-offs that may exist between them (7,19). However, multiple levers and barriers to adaptation co-occur within decision-making context, such as place attachment and resistance to innovation (43); subsidies for conservation action and the willingness (or unwillingness) of local actors to act (35); the protection of traditional practices and the need to adapt them to new conditions (35); the valuation of landscape aesthetics and the lack of instrumental benefits it provides (36). While these results improve our understanding of the decision-making process, it is still unclear how levers are activated jointly to successfully achieve NbS implementation, especially regarding their transformative characteristics.

Previous studies identified mountain areas as sentinels of climate change due to their high vulnerability regarding the rapidity of temperature increase in elevated areas (53,54), the increasing climatic hazards they are submitted to such as drought, floods and landslides (55,56). The resulting impacts threaten the unique habitats that mountains procured for biodiversity and the substantial NCP that benefit local communities and those living in lowlands (57–60).

In this study, we characterised the decision-making context and transformative characteristics of twenty NbS initiatives in the European Alps 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 levers are associated with transformative NbS.

2. Materials and Methods

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

We explored NbS implemented in the Alps through 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 natural hazards (likely enhanced by climate change) by safeguarding or increasing benefits in terms of NCP and/or biodiversity (26). In order to obtain a comparable subset of NbS, we identified the three climatic hazards the most addressed through all the NbS of the PORTAL database, namely droughts, floods and soil erosion (26), and we selected the NbS that aim to adapt to them. They included reforestation of plots by planting local or exotic adapted species trees to reduced drought impact, to safeguard the protective function of forests against natural hazards, or to protect crops from heatwaves; natural regeneration of degraded forests to increase their resilience to natural disturbances; river restoration to reduce flood impacts; restoration of grasslands to reduce landslides; transdisciplinary network to co-produce and share knowledge on adaptation to climate change in forestry, agricultural or natural disaster management sectors; enabling-NbS programme for local stakeholders. Each of the selected NbS mentions its potential benefits for biodiversity. Then, we contacted and performed semi-structured interviews with twenty managers of the selected NbS who had in-depth knowledge of the initiative implementation during spring 2022 (S1_Table). Semi-structured interviews are suitable methods for qualitative research, allowing open-ended questions within a flexible network (61,62). We designed the interview protocol in order to characterise the decision-making context of each NbS implementation, based on previously identified components of decision-making and NbS planning processes (30,34,36,49,63) (S2_Table). The questions addressed eight topics: i) the reasons and the context for the NbS implementation; ii) whether it targeted climate change adaptation only, or also biodiversity loss or socio-economic issues; iii) whether an alternative solution was considered and how the solution was chosen, 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 people 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 the NbS outcomes were in case they were monitored. Following questions targeted the barriers that were encountered and the levers that were activated to overcome them. Interviews ended by questioning the managers on what they would expect to foster or constrain the future implementation of similar NbS, named hereafter NbS amplification. Interviews lasted from 55 to 120 minutes, with a median of around 90 minutes. Interviews were recorded and transcribed for coding and analyses. The sites where the studied NbS were implemented were mapped with QGIS software (version 3.16.5) (Fig 2).

2.2. Data processing

We coded interviews using the Qualcoder software (version 3.1) that enables systematic textual analysis. We first extracted the contextual information of each case study: the role of the interviewee in the NbS implementation, the organisation(s) that led the NbS implementation, funding sources, the ecosystem or land-use in which the NbS was implemented, the type(s) of interventions, and the climatic hazards the NbS aimed to address.

We then used a combination of inductive and deductive approaches to code the levers and barriers mentioned by the interviewees for the implemented NbS using an assessment list based on the levers and barriers identified by a preliminary literature review (S3_Table). For example, we identified whether intrinsic, instrumental or relational values were involved in the implementation of each NbS, based on criteria found in the literature (39,64). Then, we adapted this classification regarding the context of the NbS, e.g., whether the involved values refer to the landscape's aesthetics, the willingness to not harm surroundings environment, the biodiversity for itself. We also created new variables not identified in the literature when more than one interviewee mentioned them. For example, we coded two interviewees with the labour value that was considered as a lever to NbS implementation, although we did not find it in the literature. Each resulting variable was coded as a *value*, a *rule*, a *knowledge*, or an interaction of two or three components of the *vrk* framework.

We extracted a matrix describing for each NbS whether each identified code was mentioned by interviewees as a lever (coded '1'), a barrier (coded '-1') or whether it was not mentioned (coded as '0'). A few variables were coded as a semi-quantitative factor (e.g., for funding, whether the project had no funding; was partially funded; or was entirely funded). The suggested elements for NbS amplification were coded according to the same process for each interview. The matrix also contained contextual information for each NbS.

Finally, based on the responses received from the interviewees, we combined both inductive and deductive approaches to code the transformative characteristics of each NbS based on a list of indicators adapted from ones previously used for NbS case studies (S4_Table). These characteristics explore whether an NbS is *restructuring*, i.e. involving major shifts in fundamental properties, functions or

interactions; *path-shifting*, i.e. altering the systems' current trajectory towards an alternative direction; *innovative*, i.e. changing to new states that have not previously existed; *multi-scale*, i.e. impacting the system across multiple scales (e.g., trophic, spatial, jurisdictional, or sectoral scales); *system-wide*, i.e. occurring at large scale (e.g., regions, ecosystems, landscapes, or communities); *persistent*, i.e. with long-term impacts although not necessarily irreversible (8). For each characteristic, we reviewed the indicators used in existing work and we adapted their modalities according to the response we had from the interviews (S4_Table). For example, *innovative* characteristics were assessed from previous literature as depending on new elements (species, practices, technologies, policies, behaviours, awareness or financial instruments) considering different perspectives (new in the region, in the sector, in the world) (20). Because the responses received from the interviewees were not adapted to the identified indicators, we selected the ones that were mentioned: 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 (*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, in the case where an initiative developed new methods for successful NbS and another has built a strong partnership between local actors, the two initiatives were coded differently with non-ordered modalities. Each transformative characteristic was coded with one variable, except the *multi-scale* and *restructuring* characteristics that were coded according to two types of variables because they cover the multiple dimensions of the characteristics: i) for *multi-scale,* 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); and ii) for *restructuring*, 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). The coded information is summarised in the Figure 1.

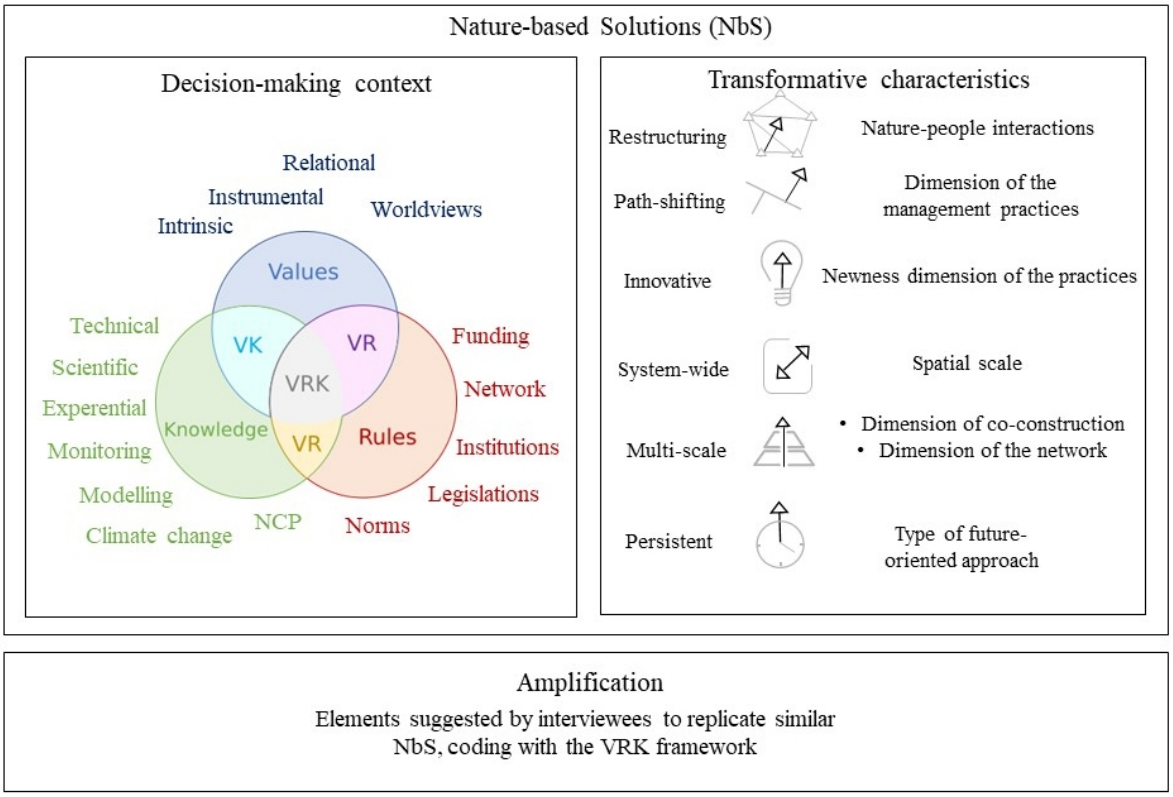


Figure 1: Variables used to code the interviews conducted to define the decision-making context (Values-Rules-Knowledge framework) and the transformative characteristics of the implemented Nature-based Solutions, adapted from (8,34)

2.3. Data analysis

The data analysis was performed using the FactoMineR package (version 2.4) of the R software (version 4.1.0). We first performed a Multiple Correspondence Analysis (MCA) with the involved levers and barriers in the NbS implementation as well as with the transformative characteristics of NbS to identify their simultaneous occurrences, named hereafter co-occurrence. We plotted the levers and barriers with the highest representation along the first three dimensions of the MCA. As a second step, we performed a hierarchical clustering of the performed MCA 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 following the level of the transformative characteristics highlighted by the analysis. Then, we predicted the amplification levers and barriers on the computed MCA as supplementary variables to identify whether each mentioned lever and barrier to amplify NbS were correlated to decision-making context clusters. Finally, we identified which levers and barriers of NbS implementation were the most mentioned across all the case studies and which elements were the most suggested for NbS amplification. We detected whether these elements were correlated to the NbS clusters with Khi2 tests.

3. Results

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

We identified 47 levers and twelve barriers across the twenty interviews, and ten additional elements mentioned as barriers or levers depending on the interviewee. Each interviewee mentioned in average twenty elements to characterise the decision-making contexts of the NbS implementation.

The hierarchical clustering identified three NbS clusters (case studies mapped in fig. 2), based on the correlation of levers and barriers of their decision-making contexts and their transformative characteristics (S6_ Figure). We named these three clusters *local transformation*, *green deal* and *multi-scale co-production* according to their key characteristics represented along the two first dimensions of the MCA (fig. 3, S7_Figure, S9_Figure).

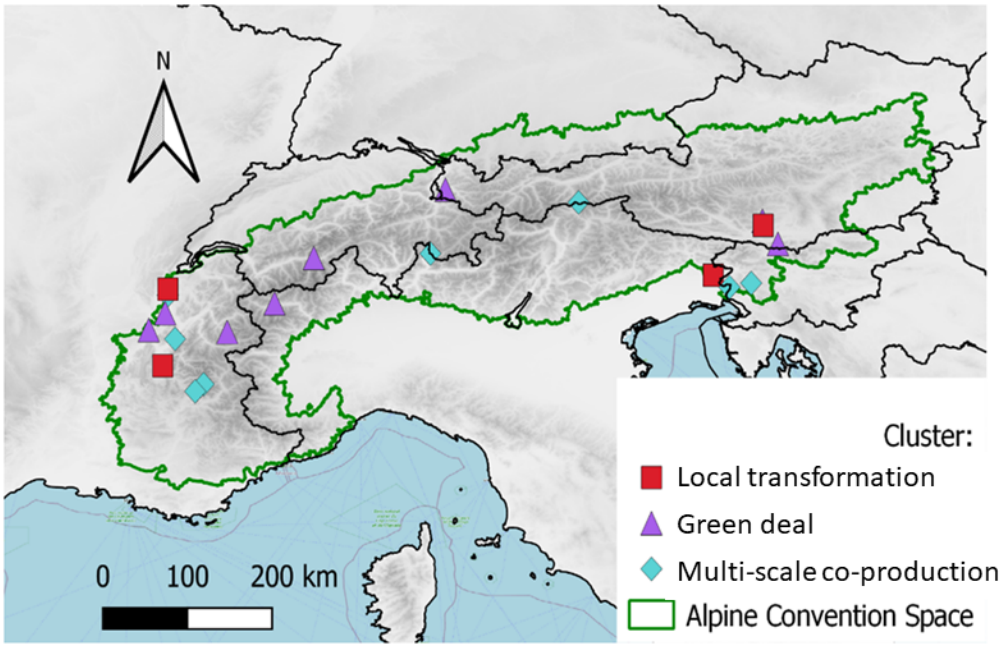


Figure 1: Map of the twenty studied Nature-based Solutions (NbS), coloured according to the clustering analysis based on the levers and barriers evoked by the NbS managers during semi-structured interviews and the transformative characteristics of the NbS.

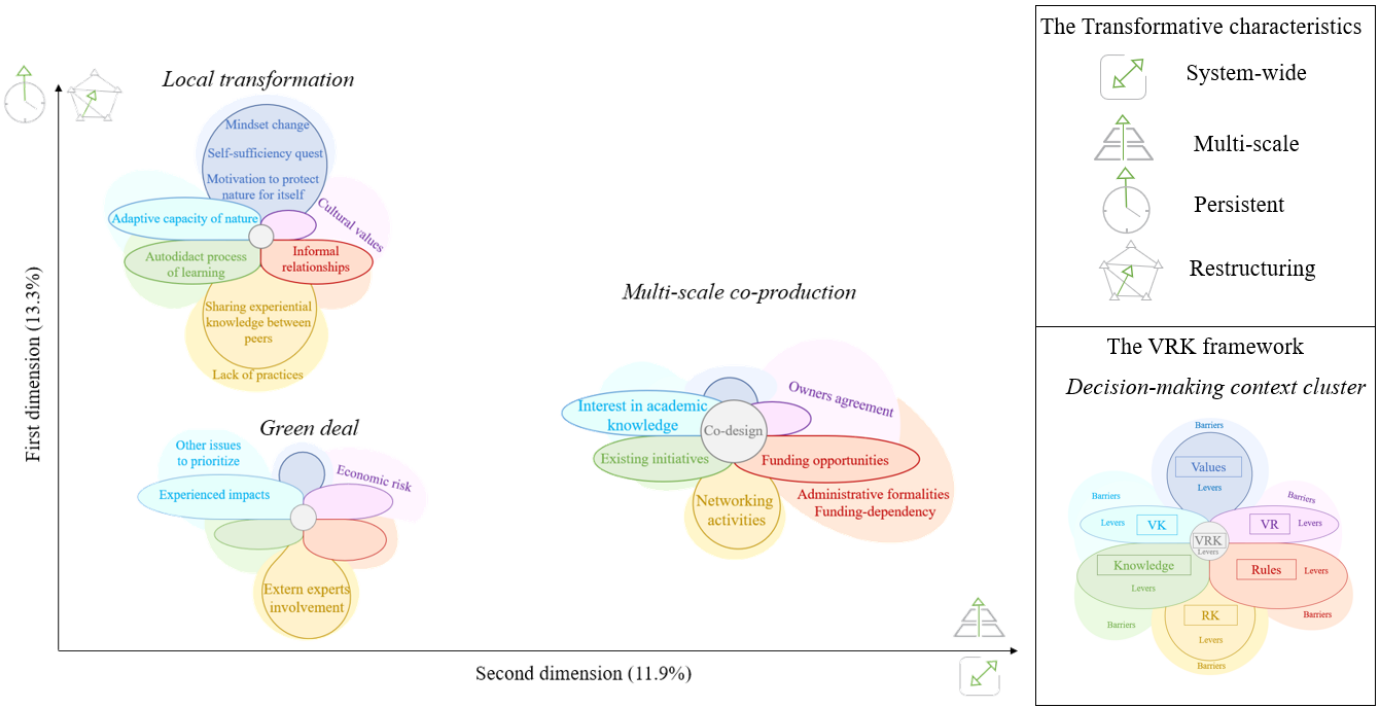


Figure 2: The decision-making context clusters of the implemented Nature-based Solutions shown through vrk (values-rules-knowledge) flowers, plotted according to the Multiple Correspondence Analysis (MCA) of their levers (inside the related petals), their barriers (around the related petals) and their transformative characteristics. The indicated levers and barriers are the ones that contributed the most to the clustering analysis and that are well represented in the MCA. The numbers indicate the variance percentage explained by each axis of the MCA. The symbols indicate the level of the transformative characteristic distributed on each axis.

3.1.1. Local transformation

The *local transformation* cluster (4 cases) is 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 strong role of sharing experiential knowledge with external stakeholders and with peers for advising the NbS implementation (*rk*). Stakeholders self-assessed that these NbS are adaptable to changing environmental conditions, and are willing to protect nature for itself (*v*) (quote n°1).

> Quote n°1: “As a result, we have a biodiversity support since we have fungi, birds, 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.” (translated from French, original quote in S5_Table)

This cluster strongly builds on nature to adapt to climatic hazards (*vk*). The interview analysis identified the significant role that personal values play in the decision-making, including a mindset shift and relational values to nature. Interviewees mentioned a solid willingness to adapt their activity towards self-sufficiency (*values*). The managers mentioned a strong willingness to learn by doing through

autodidact process to compensate for their lack of technical knowledge. They acquire new technical skills through open access platforms like YouTube© (mentioned by three of the four cases). Moreover, a shift in personal mindset (*values*), driven by relational values to biodiversity and by personal experience of climate change (*vk*), appears in this cluster to overcome the deep cultural barriers of the social context (*vr*) (quote n°2).

> Quote n°2: "[the bramble] comes, it comes at a gallop, so afterwards 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." (translated from French, original quote in S5_Table)

NbS in this cluster are transformative through their high level of *restructuring* explained by informal rules based on friendships, deep relationships built with neighbours and peers, rather than formal rules and the lack of institutional support (*rules*). This explains the small level of *multi-scale* and *system-wide* transformation. Nevertheless, this cluster supports *innovative* practices and new relationships to nature, e.g., promoting NCP co-benefits, or with an alternative socio-economic system, like introducing non-monetary trade (quote n°3).

> 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." (original)

3.1.2. Green deal

The *green deal* cluster (8 cases) was separated at the opposite end of l*ocal transformation* along the first axis of the MCA. One representative case of this type is led by a company to restore alpine grasslands degraded by ski slopes with local seeds to reduce soil erosion and promote biodiversity. This decision-making context involves experts acquiring technical knowledge from requested experts on how to adapt to climatic hazards (*rk*), but the uncertainty of the cost-efficiency of the measures is one of the main barriers (*vr*). While climate change adaptation is not perceived as a major issue, and despite managers' awareness of the lack of a one-fits-all solution due to uncertainties of future climate conditions, implementation decisions are urged by experiencing or having experienced climatic impact locally (*vk*), or by constraints related to the multifunctional use of the same resource, such as land for two cases (*vk*) (quote n°4).

> 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]." (translated from French, original quote in S5_Table)

Funding programmes and incentives were opportunities for five cases to experiment new practices in collaboration with experts from the specific sector of the activity (e.g., forestry technicians or academics for reforestation projects) who help overcome economic barriers (*vr*). Consequently, the cluster has low

to medium level of *multi-scale* characteristics. The cluster concerns larger areas or higher number of beneficiaries than *local transformation* NbS on average, but initiatives remain limited to one company, or to a small number of beneficiaries in municipalities, resulting in a low score for the *system-wide* criterion. For three cases of this cluster, the choice of NbS instead of grey solutions is strongly driven by the relational values of one or a few determined people with specific positions or highly connected to local networks (quote n°5).

> 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." (translated from French, original quote in S5_Table)

Still, interviewees of this cluster mentioned mainly instrumental values rather than intrinsic or relational values, and selected NbS based on their ability to provide material or regulating NCP (*knowledge*) (Quote n°6). In line with this, *path-shifting* or *restructuring* characteristics are limited in these decision-making contexts that support gradual changes of practices rather than radical shifts.

> 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." (translated from French, original quote in S5_Table)

3.1.3. Multi-scale co-production

The *multi-scale co-production* cluster (8 cases) is discriminated along the second axis of the MCA. One representative initiative is a river restoration to reduce floods, to increase ecological connectivity and to create space for outdoor recreation. It was led by unions of municipalities that make decisions based on participatory process with local stakeholders and civil society (*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 to the success of NbS implementation, by increasing social acceptance and sharing experiences from research and local initiatives (*vrk*). This explains the medium to high *multi-scale* score for this cluster, involving experts and academics of various sectors, from natural to social sciences and from public and private sectors. In addition, this multi-stakeholder engagement explains the large area or number of beneficiaries of the resulting NbS, i.e. a high *system-wide* score. Nevertheless, according to four of eight interviewees, existing local initiatives and pilot sites are essential to develop new practices at this scale (*k*), especially for three of eight cases involved in an emergent sector or that does not exist yet, explaining the lack of qualified experts (*rk*) (quote n°7). In line with this, the cluster promotes a favourable social context to implement existing practices through networking activities (*vr*) and participatory processes (*vrk*).

> Quote n°7: "So the big idea was in 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." (translated from French, original quote in S5_Table)

These NbS would not have emerged without funding (*rules*), and for four of eight cases, this is associated with intense bureaucracy perceived as a barrier by interviewees (*rules*) (quote n°8). This explains the low to medium *restructuring* level of the cluster, mainly based on the funding-dependent *persistence* of NbS. The funding insecurity and the perception of an uncertain institutional support in the future are due to the frequent turnover of policymakers (*rules*). These barriers are overcome for two of eight cases through the long-lasting reputation of the organisation as a result of the NbS (*vr*), and for five of eight cases through strong collaboration built 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" (original)

3.2. Shared levers and barriers in decision-making contexts

The most cited levers among all three decision-making contexts are related to formal *rules*, including funding opportunities shared by sixteen of the twenty interviewees and the incentives mentioned by eight interviewees (fig. 4). *Rules* are also mentioned to explain the success of the NbS in interaction: i) with: i) *values*, such as the network strength, especially for the eleven interviewees who indicated the relevance of a previous collaboration and for the eleven interviewees who had networking activities; ii) with *knowledge*, by sharing experiential knowledge in eleven cases, and for implementing practices in line with current policy or planning documents (seven cases); and iii) with both *knowledge* and *values*, regarding social acceptance of the initiatives (ten cases). Regarding *knowledge*, understanding ecological dynamics and the regulating NCP positively influences decision-making for respectively eleven and thirteen interviewees. K*nowledge* related to adapted species, NCP co-benefits and the cumulative impacts of climate change are recognised by more than seven interviewees to help implement NbS. *Knowledge* is also perceived as a lever in interaction with *values* by ten interviewees mentioning their motivation to benefit from academic *knowledge* to design NbS.

The most cited barrier is the uncertainty about the cost-efficiency of measures for the *green deal* cluster (*rk*), where it is identified as a necessary risk to take for adaptability in the *local transformation* and the *multi-scale co-production* NbS. The following most cited barriers are related to *knowledge*, namely the technical knowledge gap (7 cases) and the time lag of NbS to deliver benefits (6 cases).

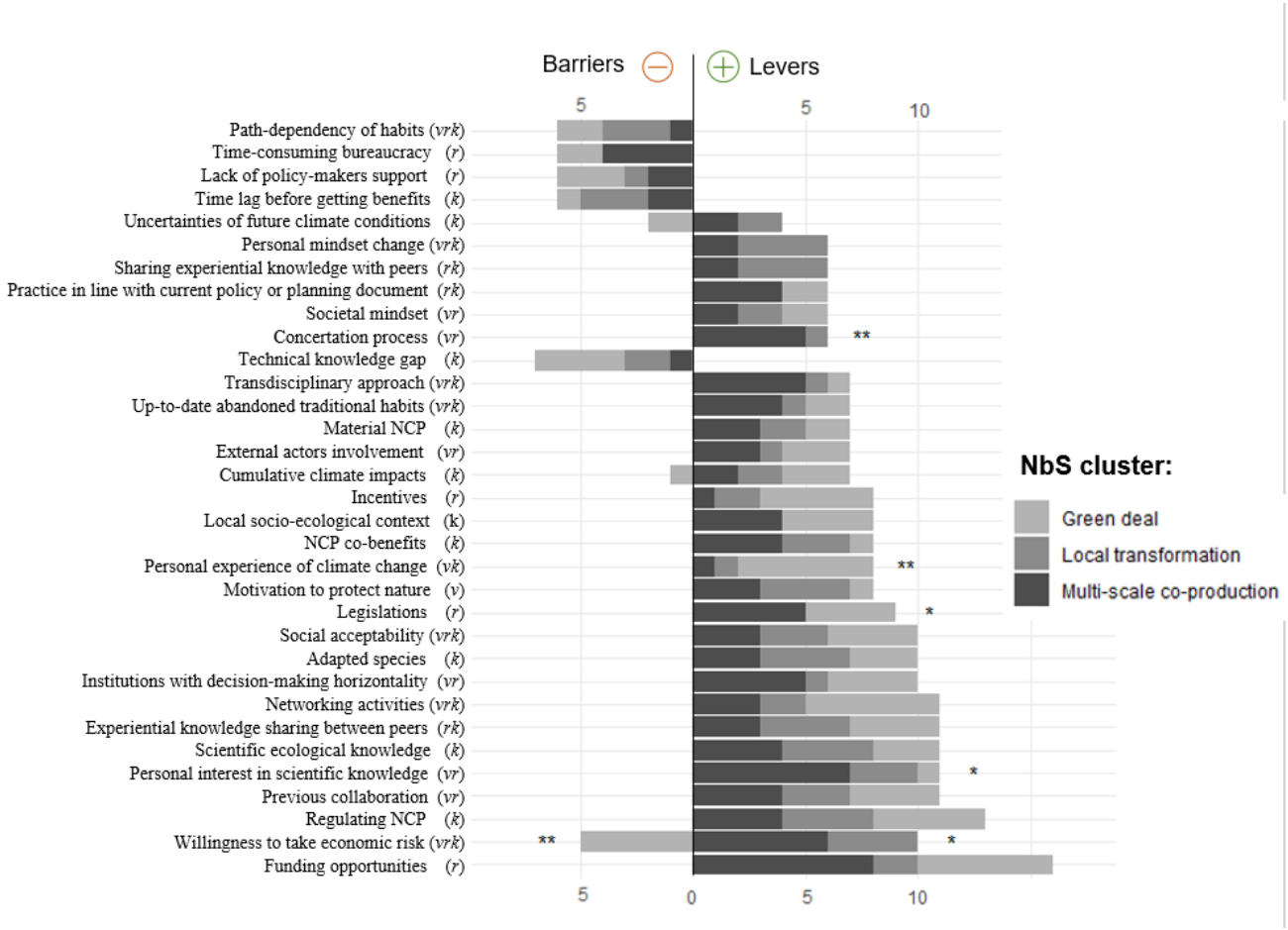


*Figure 3: Barplot of the number of interviewees who mentioned the levers (+) and barriers (-) to Nature-based Solutions implementation, plotted according to the decision-making context cluster, and for the levers and barriers mentioned by more than five interviewees. Significance level of the difference of occurrence between clusters for each lever or barrier: * p-value < 0.1; ** p-value < 0.05; ***p-value < 0.01*

3.3. Levers to activate for Nature-based Solutions amplification

We identified 25 levers and 23 barriers among the suggestions of the interviewees to amplify NbS, and three elements were mentioned as both a lever or a barrier depending on the interviewees. Only ten elements were mentioned by more than five interviewees (fig. 5). The majority of these levers and barriers are not correlated with one specific NbS cluster (S8_Figure). For example, at least one case of each cluster mentioned "policymakers' awareness-raising" as a lever to amplify NbS (*rk*) (6 cases). However, initiatives within *multi-scale co-production* were the only ones that claim, in four of eight cases, for "writing guidelines for stakeholders" to amplify NbS (*rules*) (5 cases). Likewise, levers involving *rules*, in interactions with *knowledge* through "raising local stakeholders' awareness" (*rk*) (9 cases) or with *values* through "co-designing NbS" (*vrk*) (8 cases) and "enhancing the institution's reputation" (*vr*) (6 cases), are little or even not mentioned by *local transformation* cases.

The most cited potential barrier that needs to be overcome is associated with formal *rules* (7 cases). Indeed, interviewees from the three clusters referred to the lack of "existing or adapted incentives" to

amplify NbS (*rules*). Other cited barriers refer to *knowledge* alone, e.g., about the "time lag for NbS to deliver benefits" (6 cases); or in interaction with *rules*, e.g., the "limited capacity of NbS to reduce climate impacts" (*rk*) (6 cases) or the dependency of these practices to social-ecological-context making "one-fits-all solution" not adapted (*rk*) (5 cases). Some interviewees (4 cases) from the *multi-scale co-production* and *green deal* clusters wished for more pilot sites and experiments to bridge the technical knowledge gap about implementing effective NbS (*rk*).

Two interviewees warned of the potential barrier from "civil society expectations" (*vr*) 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 foster NbS, e.g., through additional and more accessible funds. Similarly, while a few interviewees wished for more restrictive "access to incentives" to ensure biodiversity conservation and avoid greenwashing (*rules*), one interviewee warned on the already too specific requirement of incentives that discourage stakeholders from embracing NbS implementation (*rules*).

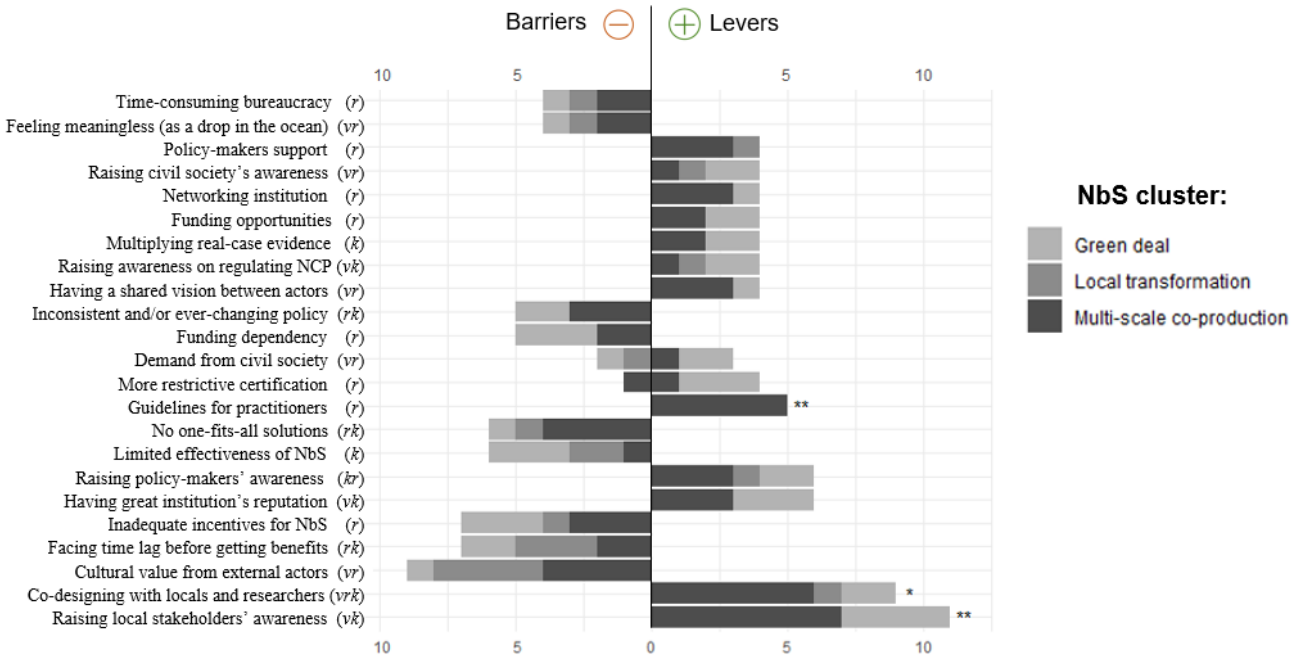


*Figure 4: Barplot of the number of interviewees who mentioned the levers and barriers to amplify similar Nature-based Solutions, plotted according to the decision-making context clusters, and for the levers and barriers mentioned by more than four interviewees. Significance level of the difference of occurrence between clusters for each lever or barrier: * p-value < 0.1; ** p-value < 0.05; ***p-value < 0.01*

4. Discussion

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

Our analysis combined the *vrk* framework with an assessment of transformative characteristics to identify levers and barriers to NbS implementation in the Alps. Our results are consistent to the suitability of the *vrk* framework to highlight the main elements that play a role in adaptation initiatives (43,65,66). Our study shows that formal rules, a robust project coordinator, positive cultural values of civil society, knowledge sharing through informal exchanges, collaborative planning and academic support are currently the main levers for NbS implementation. Results also highlight the inherent uncertainty of NbS effectiveness as a prominent barrier to choose NbS over grey infrastructures. While grey solutions benefit from high societal acceptance (67,68) due to one-size-fits-all designs with immediate outcomes, NbS are, in contrast, site-specific and their effectiveness is less known (25,69).

Our analyses are in line with the limited literature considering combinations of levers and barriers (36,70). For instance, the levers involving values such as a "mindset change" and "willingness to self-sufficiency" appear simultaneously with "experiential knowledge sharing", but without institutional levers such as governance processes and funding opportunities that were identified in literature as main levers to amplify NbS (30,71). By analysing the co-occurrence of perceived levers and barriers in the cases selected for this study, we highlighted three types of NbS decision contexts.

The *local transformation* type is similar to previously identified alternative practices in other regions (e.g., in agriculture worldwide), known as bottom-up approaches implemented by local stakeholders themselves, independent of institutional support (70,72), and involving experimental knowledge, relational values and informal rules (36). The *green deal* type is in line with the current European Green Deal policy strategy, resulting in a gradual change of practices towards sustainability through awareness-raising activities and revision of regulations and incentives (73). This type is similar to initiatives involving technical knowledge and instrumental values in the typology by Topp et al. (2021). Lastly, the *multi-scale co-production* type considers changes in interactions between sectors and within the research-policy-action sphere, previously illustrated in inclusive social-ecological decision-making and transdisciplinary initiatives (36,46). Despite its similarity with previously identified typologies, our types do not absolutely discriminate decision-making contexts depending on whether they were led by bottom-up or top-down approaches (36,74). Indeed, most of the initiatives in our dataset combined personal decision to involve institutions or were led by existing collaborations from the public and private sectors. Therefore, our typology enables a richer picture than the differentiation between bottom-up and top-down approaches, and a solution-oriented typology to help support projects in overcoming barriers. Given NbS are site-specific it may make more sense to focus on amplifying their decision-making process rather specific solutions, an approach that could be enabled by our typology.

The *vrk* framework highlights that transformative adaptation is supported by specific interactions between *values*, *rules* and *knowledge* (34). Here we combined the *vrk* framework with transformative characteristics covering the multiple dimensions of transformation, rather than focusing on the coping-incremental-transformative trichotomy given that real life cases usually combine these multiple facets of adaptation (4,75,76). We consider our approach provides a more detailed overview of the elements in place in transformative adaptation processes as well as their outcomes. Our results confirm that initiatives involving greater interactions of *values*, *rules* and *knowledge* are more likely to achieve greater transformation according to the set of indicators we used. We also found that within a single type, the NbS had different *multi-scale* levels (e.g., in *local transformation*, some NbS are co-design whereas others benefit from peer-to-peer exchanges), or different levels of *persistence* (e.g., some NbS from *green deal* type will last depending on funding opportunities, and others that have been designed initially to be maintained). The transformation indicators discriminate which dimension of transformative change each NbS can address, and which dimensions are less likely to reach transformation. Considering the limited transformative capacity of most of the analysed NbS, our results emphasise the limited use of transformative adaptation to address the climate and biodiversity crisis, as each identified type is missing significant level of at least two transformative characteristics (12,14). We confirmed that it remains challenging to assess transformation criteria for individual initiatives, but we nevertheless confirm the potential of NbS to support transformative adaptation as other studies analysing different datasets of NbS have found (13,15,77). 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 (7,30,70,78,79).

The three NbS types are new findings that complement previous classifications of NbS. While some scholars discriminated NbS according to climatic hazards, NCP co-benefits (25,26) or types of intervention (18,69), we found that different interventions, or NbS addressing different climatic hazards, can be implemented by similar decision-making contexts. In other words, different local contexts can achieve transformative adaptation to one climatic hazard. These findings align with the latest interdisciplinary studies reporting the plurality of stakeholders and governance models involved in NbS implementation (47,80–82). Although the NbS types identified from our cases do not discriminate governance models because the interview guideline did not target this aspect, we identified that transformative NbS implemented in *multi-scale co-production* are co-designed with a large range of stakeholders and are coordinated by one of them without necessarily more power (83,84).

Furthermore, our assessment of transformative characteristics of each NbS highlighted which aspect of transformation each NbS type is likely to support, and can therefore support future policymakers in highlighting levers to activate to foster transformative NbS. The two following sections focus on the way interactions, first with *values*, and then with *rules*, are able to enhance transformative NbS. We do

not focus on the interactions of *knowledge* for transformative NbS in a separate section because they are addressed in their interactions with *values* and *rules*.

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

Our synthesis highlighted the role of *values* within NbS decision-making contexts. *Values* have been identified as a critical element of transformation (85–87). However, we showed that NbS varied in their transformative characteristics depending on the type of *values* involved in their implementation. For example, relational *values* to nature are involved in *innovative* practices that restructured relationships between nature and people, in line with local ecological knowledge studies (32,36). The willingness to include the diversity of values into NbS design through participatory approaches led to *multi-scale* initiatives that are likely to benefit larger communities and regions (47).

Although having experienced climate impacts was not identified as a primary driver of adaptation (88), the impacts of climate change drove most of the decision-making contexts we analysed. Most NbS were mostly reactive rather than proactive, with adaptation arising when the social-ecological system is forced to adapt to new conditions (70,89,90). NbS within the *green deal* type have been implemented after experiencing impacts of climate change or natural disasters. Some NbS implemented within the *local transformation* type emerged because economic viability was threatened by climate change, requiring adaptation. This driver of change led to adaptation with different transformative characteristics, but had not been anticipated by stakeholders, except in *multi-scale co-production* NbS that anticipate future conditions, e.g. through climate model analysis. The main barrier often reported by interviewees is the uncertainty of future conditions, whether predicted or not, and consequently of the efficiency of implemented solutions (70). Each NbS type delivers one option to face this uncertainty. *Local transformations* NbS aim to support ecosystems' resilience to face unpredicted conditions through a learning-by-doing process (5,70), including failure; *green deal* NbS gradually change their practice to maintain the possibility to shift from one practice to another one, despite the unclear evidence of the effectiveness of this option (4,91,92). *Multi-scale co-production* NbS aim to build social resilience through new governance models to enhance collective support to face future conditions (47,70,93,94).

The *multi-scale co-production* type comprises existing initiatives and highly aware local stakeholders. These initiatives identify raising awareness of local stakeholders as a main lever to amplify NbS. However, value's constraints are known to be the most resistant dimension of decision contexts (66,85), especially to overcome path dependency through the inclusion of intrinsic and relational values where they are not commonly shared, or of non-material NCP (36,95). Social acceptance of the project was also a powerful lever in the *multi-scale co-production* type (67).

Cultural values of the local environment, or path dependency of practices, are perceived as barriers for *local transformation* and *green deal* initiatives. These barriers are overcome in different ways. *Green deal* NbS develop participatory approaches, whereas *local transformation* NbS fit with different cultural

value than the constraining one, such as the labour value or landscape aesthetics value, highlighting trade-offs within decision-making contexts (96,97).

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

Our results showed that institutional support helps NbS initiatives, but not equally among decision-making contexts, and differently according to the type of support. As commonly reported elsewhere, *multi-scale co-production* NbS depend on funding opportunities, and may not have been implemented without them (70). These highly transformative initiatives 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 (16,70). As a downside, they faced heavy bureaucratic burdens imposed by funders.

Interviewees from *local transformation* and *green deal* NbS reported adapted incentives to help implementers overcome economic viability uncertainty due to new practices implementation. *Local transformation* participants argued that incentives are needed, especially to overcome the time lag before getting the benefits of the implementation and the initial expenses that implementation requires, e.g., to purchase adapted equipment for *innovative* practices. For interviewees from *green deal* type, incentives are an effective instrument to mainstream biodiversity conservation into practices (70). Although this was not a main lever for all, many interviewees mentioned departmental or regional administrations at pivotal position to facilitate the interface between policies, including incentives management, and on-the-ground actions. For example, the roles of public institutions and research institutions have been identified as critical to co-design through transdisciplinary research programmes (98,99), or a regional adaptation plan (72,100). Still, local stakeholders emphasised the role of sharing experiences with peers to increase their willingness to implement new practices (101,102). Future research should explore the pivotal position of peer-to-peer governance in fostering NbS implementation (36,74).

The lack of a structured sector is also identified as a barrier to NbS implementation, for example in the absence of markets for local seeds to restore alpine grasslands (103) or the lack of a value chain for new agricultural products (104). While *local transformation* NbS manage to diversify their marketing strategy (105), e.g., developing direct marketing to local communities, the institutions involved in *multi-scale co-production* NbS aim to develop the emerging value chains with stakeholders (103). However, this institutional involvement in enabling-NbS activities is sparsely implemented because of cultural barriers (31,105), and the time-consuming involvement of stakeholders (106). Only intense involvement related to personal values enables the implementation of *multi-scale co-production* NbS (107).

A large part of the interviewees mentioned that NbS implementation guidelines and standards should support NbS amplification in the future (19,49,63,108). However, most of them also highlighted the unicity of each initiative, i.e. they are hardly replicated, confirming that NbS are not one-size-fits-all

solutions (81,96,109). Moreover, operationalising NbS guidelines might be useless or detrimental if the ambiguity surrounding the vision from different actors to NbS concept is not reduced (77,110,111). Finally, institutional support is needed to help monitor NbS outcomes with standardised methods (European Commission. Directorate General for Research and Innovation, 2021).

4.4. Study limitations

Our study focused on a small number of NbS implemented in the Alps. However, our sample captures the diversity of activities that have been identified to address drought, floods and soil erosion in this region (26,113). Our insights can support NbS amplification in other regions, as we identified common levers and barriers with studies from other socio-ecological systems worldwide (70,114).

For each NbS, we conducted interviews with only one manager involved in the implementation process. Although the perception of the NbS can depend on the interviewee (107,115), we reduced the perception bias by asking structured questions related to the implementation process. Moreover, in four cases, two interviewees were involved in the same network but not for the same NbS, and their responses were consistent.

We did not assess the adaptation pathways of these initiatives, i.e. the long-term adaptation process, shifting from one decision-making context to the one favourable to NbS implementation (66). However, we considered the NbS implemented to address an emerging issue in a specific context, and we therefore identified the perceived future of the initiatives. This combination of knowledge allows identifying what elements of the *vrk* play to inflect the system trajectory towards adaptation and would contribute to building pathways (43,65). We also questioned the potential levers and barriers towards NbS amplification, combining both vision and experiences of stakeholders to determine actions towards desired adaptation pathways (30).

We did not assess the effectiveness of NbS, but we addressed the interviewee's perception of the initiative and how they perceive its future, indicating whether the issues were already addressed or in process to be addressed (116). Moreover, although not all investigated NbS were at the same implementation stage, our analysis did not segregate different stages of implementation as NbS implementation and transformation is known to follow a variety of pathways (70,81,117).

Although the consideration of power relationships is essential to address the sustainability of adaptation in terms of equity, justice and gender (86,118,119), we did not explicitly consider these aspects in our analysis. However, some interviewees mentioned these aspects in the decision-making process, and we considered them, e.g., by coding the presence of participatory processes such as consultation, concertation and co-designing approaches that aim to benefit equally within local communities. Given our regional context, the NbS we identified did not integrate local indigenous knowledge that is needed

570 to implement sustainable initiatives (77,120). However, the role of experiential knowledge and the
571 relational value to nature emerged from interviews.

572 4.5. Perspectives and recommendations for policymakers: There is not one-fits-all lever

573 NbS have the potential for transformative change towards climate change adaptation, and their
574 amplification is fostered to reduce future impacts on ecosystems and human well-being. However, we
575 confirmed the limited use of transformative adaptation (12,14) and the preference of local stakeholders
576 for incremental adaptations (72,121). This reluctance is due to the complexity of elements considered
577 by NbS, including climate change adaptation, ecosystem functioning, NCP co-benefits as well as long-
578 term economic and social benefits and trade-offs (86,94,122).

579 We collected the levers and barriers suggested by NbS managers to amplify similar initiatives.
580 Complementing previous studies which identified different enabling contexts leading to NbS
581 implementation (123), our study shows that levers and barriers, and their combinations enable specific
582 activities. We found that policymakers can support three types of actions for amplifying NbS: creating
583 opportunities for non-governmental stakeholders (private sector, NGO, and civil society) to implement
584 transformative NbS, e.g. through networking and monitoring activities; changing public administration
585 strategies towards mainstreaming transformative NbS for public action (e.g., natural disaster risk
586 reduction, managing public land and commons good); encouraging, e.g., through incentives or even
587 making binding, e.g. through legislation, non-governmental stakeholders who are not willing to
588 implement transformative NbS.

589 Levers to action must be tailored to the NbS they might support. For example, supporting a
590 transdisciplinary approach to disaster risk reduction aims to enhance the co-design of NbS including
591 local communities and developing a network of stakeholders willing to collaborate. However, this action
592 might not support local stakeholders aiming to adapt their own practices if they are unwilling to be
593 involved in the new project. Moreover, multiplying *local transformations* NbS initiatives by non-
594 governmental stakeholders is a powerful means to build larger-scale initiatives, through sharing and
595 monitoring contributing initiatives. New financial incentives or environmental regulations can support
596 multiplying NbS implementation from stakeholders who are already willing to and who faced economic
597 or technical barriers, in case of these instruments are framed considering principles for effective NbS,
598 namely economic viability, inclusive governance, equity, sustainability, mainstreaming (124). However,
599 incentives or regulations cannot enhance uptake by stakeholders who are not willing to implement NbS,
600 and would require additional facilitating levers. For example, new policy might be associated with
601 raising awareness activities for stakeholders on NbS effectiveness and their capacity to provide NCP co-
602 benefits (45).

603 In order to increase the knowledge transfer, sustainability science might address the knowledge
604 mismatch between *local transformations* that are based on experiential knowledge, and *multi-scale co-*

production initiatives involving academic knowledge (83,125). Transdisciplinary research projects are therefore needed to bridge institutions and to co-produce knowledge with and for local communities (126), as well as public institutions to disseminate academic knowledge in an actionable way for stakeholders, e.g., through knowledge hubs or living labs (127). Knowledge hubs are also essential for multiplying local initiatives and sharing experiences without being considered as non-standard cases, pilot projects, or on the margins (46). Societal mindset and worldviews were strong motivations to NbS implementation. Thus, raising awareness of local communities in the role of ecosystems for adaptation might greatly increase social acceptance, as well as raising awareness of policymakers about the benefits of mainstreaming NbS (128). Lastly, as exemplified for *green deal* NbS, greater support from institutions can greater levels of innovation, persistency and cross-scaling, e.g., by fostering the inclusion of stakeholders into already existing information or knowledge systems, and by creating space for dialogue (70).

Together, these points suggest intensifying international cooperation towards NbS implementation in large connected regions like the Alps, that form a spatial continuum where cross-regional similarities are opportunities to benefit from shared knowledge and governance networks (78,129). Cross-regional institutions such as the Alpine Convention or EUSALP (European Union Strategy for the ALPine region) have shown their potential to engage macro-regional governance with biodiversity conservation or the energy transition in the Alps (130,131). Similar cooperation may foster transformative NbS-enabling activities, networking and transdisciplinary projects with cross-regional benefits from informal institutional networking to overcome the heterogeneity of formal rules between countries or regions (132,133).

5. Conclusion

Levers of transformative adaptation to the climatic and biodiversity crises are being increasingly studied. However, prevalent levers and barriers vary with the local decision-making context. We analysed the decision-making contexts of implemented NbS in the Alps and their transformative characteristics to identify context-specific levers and barriers. We identified three NbS types of co-occurring levers and barriers. *Local transformation* NbS implemented self-sufficient initiatives motivated by relational values to nature, supporting the adaptive capacity of nature through informal governance and experiential knowledge sharing. They incorporated the deep cultural value of their environment by creating an alternative system of practices. *Green deal* NbS implemented a gradual change of their practices using opportunities in incentives and regulations to experiment with new approaches. They prioritised instrumental values for fostering benefits from NbS and overcome path dependency in current practices. *Multi-scale co-production* implemented larger NbS, socially accepted through wide participatory approaches with local practitioners, and inclusion of diverse values into the decision-

making process. Although designed to be persistent, they are challenged by the instability of funding opportunities.

Amplifying transformative NbS will require better integrating *values*, *rules*, and *knowledge* and their interactions into NbS implementation processes. This could be achieved by creating new governance models and adapting incentives and regulation, supporting local NbS, increasing policymakers' awareness of NbS benefits, and creating long-lasting spaces for dialogue. Due to its socio-ecological continuum and its climate impact similarities, the alpine scale has the potential to address these issues, thanks to its pivotal position for a strategic macro-regional governance. Future research is needed to explore how to engage in NbS implementation those local communities with active peer-to-peer dialogues with other communities who benefit from scientific knowledge on NbS effectiveness to address the climate impacts they both face.

Acknowledgement

We thank all the interviewees for their willingness and openness to participate to this research. We thank Bruno Locatelli and Giacomo Fedele for their significant insights and the stimulating discussions regarding Nature-based Solutions and Transformative Adaptation.

References

1. Brondizio E, Diaz S, Settele J, Ngo HT, Gueze M, Aumeeruddy-Thomas Y, et al. Chapter 1 Assessing a planet in transformation: Rationale and approach of the IPBES Global Assessment on Biodiversity and Ecosystem Services [Internet]. Zenodo; 2019 May [cited 2022 Jun 17]. Available from: https://zenodo.org/record/3831852

2. Pörtner HO, Scholes RJ, Agard J, Archer E, Arneth A, Bai X, et al. Scientific outcome of the IPBES-IPCC co-sponsored workshop on biodiversity and climate change. Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES); 2021.

3. Roberts DC, Adams H, Adler C, Aldunce P, Ali E, ..., et al. Climate Change 2022: Impacts, Adaptation and Vulnerability. Netherlands: IPCC; 2022. 3675 p.

4. Kates RW, Travis WR, Wilbanks TJ. Transformational adaptation when incremental adaptations to climate change are insufficient. Proceedings of the National Academy of Sciences. 2012 May 8;109(19):7156–61.

5. Colloff MJ, Martín-López B, Lavorel S, Locatelli B, Gorddard R, Longaretti PY, et al. An integrative research framework for enabling transformative adaptation. Environmental Science & Policy. 2017 Feb 1;68:87–96.

6. Patterson J, Schulz K, Vervoort J, van der Hel S, Widerberg O, Adler C, et al. Exploring the governance and politics of transformations towards sustainability. Environmental Innovation and Societal Transitions. 2017 Sep 1;24:1–16.

7. Chan KMA, Boyd DR, Gould RK, Jetzkowitz J, Liu J, Muraca B, et al. Levers and leverage points for pathways to sustainability. Bridgewater P, editor. People and Nature. 2020 Sep;2(3):693–717.

8. Fedele G, Donatti CI, Harvey CA, Hannah L, Hole DG. Transformative adaptation to climate change for sustainable social-ecological systems. Environmental Science & Policy. 2019 Nov;101:116–25.

9. Jacobs S, Santos-Martín F, Primmer E, Boeraeve F, Morán-Ordóñez A, Proença V, et al. Transformative Change Needs Direction. Sustainability. 2022 Jan;14(22):14844.

10. Köhler J, Geels FW, Kern F, Markard J, Onsongo E, Wieczorek A, et al. An agenda for sustainability transitions research: State of the art and future directions. Environmental Innovation and Societal Transitions. 2019 Jun 1;31:1–32.

11. Berrang-Ford L, Siders AR, Lesnikowski A, Fischer AP, Callaghan MW, Haddaway NR, et al. A systematic global stocktake of evidence on human adaptation to climate change. Nat Clim Chang. 2021 Nov;11(11):989–1000.

12. Fedele G, Donatti CI, Harvey CA, Hannah L, Hole DG. Limited use of transformative adaptation in response to social-ecological shifts driven by climate change. E&S. 2020;25(1):art25.

13. Palomo I, Locatelli B, Otero I, Colloff M, Crouzat E, Cuni-Sanchez A, et al. Assessing nature-based solutions for transformative change. One Earth. 2021 May 21;4(5):730–41.

14. Goodwin S, Olazabal M, Castro AJ, Pascual U. Global mapping of urban nature-based solutions for climate change adaptation. Nat Sustain. 2023 Jan 30;1–12.

15. Colloff MJ, Wise RM, Palomo I, Lavorel S, Pascual U. Nature's contribution to adaptation: insights from examples of the transformation of social-ecological systems. Ecosystems and People. 2020 Jan 1;16(1):137–50.

16. Faivre N, Fritz M, Freitas T, de Boissezon B, Vandewoestijne S. Nature-Based Solutions in the EU: Innovating with nature to address social, economic and environmental challenges. Environmental Research. 2017 Nov;159:509–18.

17. Seddon N. Harnessing the potential of nature-based solutions for mitigating and adapting to climate change. Science. 2022 Jun 24;376(6600):1410–6.

18. Cohen-Shacham E, Walters G, Janzen C, Maginnis S, editors. Nature-based solutions to address global societal challenges [Internet]. Gland, Switzerland: IUCN International Union for Conservation of Nature; 2016 [cited 2021 Jul 27]. Available from: https://portals.iucn.org/library/node/46191

19. Frantzeskaki N. Seven lessons for planning nature-based solutions in cities. Environmental Science & Policy. 2019 Mar;93:101–11.

20. Fedele G. Nature-based Transformative Adaptation: a practical handbook. 2019 Sep 24 [cited 2022 Dec 16]; Available from: https://zenodo.org/record/3386441

21. Altieri MA, Nicholls CI. Agroecology: challenges and opportunities for farming in the Anthropocene. IJANR. 2020 Dec;47(3):204–15.

22. Nicholls CI, Altieri MA. Pathways for the amplification of agroecology. Agroecology and Sustainable Food Systems. 2018 Nov 26;42(10):1170–93.

23. Zandersen M, Oddershede JS, Pedersen AB, Nielsen HØ, Termansen M. Nature Based Solutions for Climate Adaptation - Paying Farmers for Flood Control. Ecological Economics. 2021 Jan;179:106705.

24. Dobremez L, Nettier B, Legeard JP, Caraguel B, Garde L, Vieux S, et al. Sentinel Alpine Pastures: An original programme for a new form of shared governance to face the climate challenge. Journal of Alpine Research | Revue de géographie alpine [Internet]. 2014 Mar 24 [cited 2022 Dec 16];(102–2). Available from: https://journals.openedition.org/rga/2455

25. Chausson A, Turner B, Seddon D, Chabaneix N, Girardin CAJ, Kapos V, et al. Mapping the effectiveness of nature-based solutions for climate change adaptation. Glob Change Biol. 2020 Nov;26(11):6134–55.

26. Dubo T, Palomo I, Laorden Camacho L, Locatelli B, Cugniet A, Racinais N, et al. Nature-based solutions for climate change adaptation are not located where they are most needed across the Alps. Reg Environ Change. 2022 Dec 13;23(1):12.

27. Jones HP, Hole DG, Zavaleta ES. Harnessing nature to help people adapt to climate change. Nature Clim Change. 2012 Jul;2(7):504–9.

28. Berard-Chenu L, Cognard J, François H, Morin S, George E. Do changes in snow conditions have an impact on snowmaking investments in French Alps ski resorts? Int J Biometeorol. 2021 May;65(5):659–75.

29. Houghton A, Castillo-Salgado C. Analysis of correlations between neighborhood-level vulnerability to climate change and protective green building design strategies: A spatial and ecological analysis. Building and Environment. 2020 Jan;168:106523.

30. Bruley E, Locatelli B, Colloff MJ, Salliou N, Métris T, Lavorel S. Actions and leverage points for ecosystem-based adaptation pathways in the Alps. Environmental Science & Policy. 2021 Oct;124:567–79.

31. Duffaut C, Frascaria-Lacoste N, Versini PA. Barriers and Levers for the Implantation of Sustainable Nature-Based Solutions in Cities: Insights from France. Sustainability. 2022 Jan;14(16):9975.

32. Nalau J, Becken S, Schliephack J, Parsons M, Brown C, Mackey B. The Role of Indigenous and Traditional Knowledge in Ecosystem-Based Adaptation: A Review of the Literature and Case Studies from the Pacific Islands. Weather, Climate, and Society. 2018 Oct 1;10(4):851–65.

33. Lam DPM, Martín-López B, Wiek A, Bennett EM, Frantzeskaki N, Horcea-Milcu AI, et al. Scaling the impact of sustainability initiatives: a typology of amplification processes. Urban Transform. 2020 Dec;2(1):3.

34. Gorddard R, Colloff MJ, Wise RM, Ware D, Dunlop M. Values, rules and knowledge: Adaptation as change in the decision context. Environmental Science & Policy. 2016 Mar;57:60–9.

35. Kirk NA, Cradock-Henry NA. Land Management Change as Adaptation to Climate and Other Stressors: A Systematic Review of Decision Contexts Using Values-Rules-Knowledge. Land. 2022 Jun;11(6):791.

36. Topp EN, Loos J, Martín-López B. Decision-making for nature's contributions to people in the Cape Floristic Region: the role of values, rules and knowledge. Sustain Sci [Internet]. 2021 Jan 8 [cited 2022 Jan 31]; Available from: https://doi.org/10.1007/s11625-020-00896-6

37. Zingraff-Hamed A, Serra-Llobet A, Kondolf GM. The Social, Economic, and Ecological Drivers of Planning and Management of Urban River Parks. Frontiers in Sustainable Cities [Internet]. 2022 [cited 2022 Dec 2];4. Available from: https://www.frontiersin.org/articles/10.3389/frsc.2022.907044

38. Schwartz SH. An Overview of the Schwartz Theory of Basic Values. Online Readings in Psychology and Culture [Internet]. 2012 Dec 1 [cited 2022 Jan 7];2(1). Available from: https://scholarworks.gvsu.edu/orpc/vol2/iss1/11

39. Pascual U, Balvanera P, Díaz S, Pataki G, Roth E, Stenseke M, et al. Valuing nature's contributions to people: the IPBES approach. Current Opinion in Environmental Sustainability. 2017 Jun 1;26–27:7–16.

40. Stoutenborough JW, Vedlitz A. The effect of perceived and assessed knowledge of climate change on public policy concerns: An empirical comparison. Environmental Science & Policy. 2014 Mar 1;37:23–33.

41. Vogel C, Moser SC, Kasperson RE, Dabelko GD. Linking vulnerability, adaptation, and resilience science to practice: Pathways, players, and partnerships. Global Environmental Change. 2007 Aug 1;17(3):349–64.

42. Gómez-Baggethun E, Corbera E, Reyes-García V. Traditional Ecological Knowledge and Global Environmental Change: Research findings and policy implications. Ecology and Society [Internet]. 2013 Dec 28 [cited 2023 Feb 27];18(4). Available from: https://www.ecologyandsociety.org/vol18/iss4/art72/

43. Lavorel S, Colloff MJ, Locatelli B, Gorddard R, Prober SM, Gabillet M, et al. Mustering the power of ecosystems for adaptation to climate change. Environmental Science & Policy. 2019 Feb;92:87–97.

44. Toxopeus H, Polzin F. Reviewing financing barriers and strategies for urban nature-based solutions. Journal of Environmental Management. 2021 Jul 1;289:112371.

45. Solheim A, Capobianco V, Oen A, Kalsnes B, Wullf-Knutsen T, Olsen M, et al. Implementing Nature-Based Solutions in Rural Landscapes: Barriers Experienced in the PHUSICOS Project. Sustainability. 2021 Jan 30;13(3):1461.

46. Schröter B, Hack J, Hüesker F, Kuhlicke C, Albert C. Beyond Demonstrators—tackling fundamental problems in amplifying nature-based solutions for the post-COVID-19 world. npj Urban Sustain. 2022 Feb 8;2(1):1–7.

47. Egusquiza A, Cortese M, Perfido D. Mapping of innovative governance models to overcome barriers for nature based urban regeneration. IOP Conf Ser: Earth Environ Sci. 2019 Aug;323(1):012081.

48. Nalau J, Becken S, Mackey B. Ecosystem-based Adaptation: A review of the constraints. Environmental Science & Policy. 2018 Nov;89:357–64.

49. Kumar P, Debele SE, Sahani J, Aragão L, Barisani F, Basu B, et al. Towards an operationalisation of nature-based solutions for natural hazards. Science of The Total Environment. 2020 Aug 20;731:138855.

50. Moreau C, Cottet M, Rivière-Honegger A, François A, Evette A. Nature-based solutions (NbS): A management paradigm shift in practitioners' perspectives on riverbank soil bioengineering. Journal of Environmental Management. 2022 Apr 15;308:114638.

799 51. Grêt-Regamey A, Huber SH, Huber R. Actors' diversity and the resilience of social-ecological
800 systems to global change. Nat Sustain. 2019 Apr;2(4):290–7.

801 52. Strout JM, Oen AMP, Kalsnes BG, Solheim A, Lupp G, Pugliese F, et al. Innovation in NBS Co-
802 Design and Implementation. Sustainability. 2021 Jan 19;13(2):986.

803 53. Pörtner HOtto, Roberts DC, Masson-Delmotte V, Zhai P. The Ocean and Cryosphere in a
804 Changing Climate: Special Report of the Intergovernmental Panel on Climate Change [Internet].
805 1st ed. Cambridge University Press; 2022 [cited 2023 Feb 16]. Available from:
806 https://www.cambridge.org/core/product/identifier/9781009157964/type/book

807 54. Pauli H, Halloy SRP. High Mountain Ecosystems Under Climate Change. In: Oxford Research
808 Encyclopedia of Climate Science [Internet]. Oxford University Press; 2019 [cited 2022 Nov 21].
809 Available from:
810 https://oxfordre.com/climatescience/view/10.1093/acrefore/9780190228620.001.0001/acrefore-
811 9780190228620-e-764

812 55. Gobiet A, Kotlarski S, Beniston M, Heinrich G, Rajczak J, Stoffel M. 21st century climate
813 change in the European Alps—A review. Science of The Total Environment. 2014
814 Sep;493:1138–51.

815 56. Kotlarski S, Gobiet A, Morin S, Olefs M, Rajczak J, Samacoïts R. 21st Century alpine climate
816 change. Clim Dyn [Internet]. 2022 May 10 [cited 2022 Jun 13]; Available from:
817 https://doi.org/10.1007/s00382-022-06303-3

818 57. Grêt-Regamey A, Weibel B. Global assessment of mountain ecosystem services using earth
819 observation data. Ecosystem Services. 2020 Dec 1;46:101213.

820 58. O'Connor LMJ, Pollock LJ, Renaud J, Verhagen W, Verburg PH, Lavorel S, et al. Balancing
821 conservation priorities for nature and for people in Europe. Science. 2021 May
822 21;372(6544):856–60.

823 59. Palomo I. Climate Change Impacts on Ecosystem Services in High Mountain Areas: A Literature
824 Review. Mountain Research and Development. 2017 May;37(2):179–87.

825 60. Schirpke U, Candiago S, Egarter Vigl L, Jäger H, Labadini A, Marsoner T, et al. Integrating
826 supply, flow and demand to enhance the understanding of interactions among multiple
827 ecosystem services. Science of The Total Environment. 2019 Feb;651:928–41.

828 61. Dearnley C. A reflection on the use of semi-structured interviews. Nurse Researcher. 2005
829 Jul;13(1):19–28.

830 62. Ritchie J, Lewis J, Lewis P of SPJ, Nicholls CM, Ormston R. Qualitative Research Practice: A
831 Guide for Social Science Students and Researchers. SAGE; 2013. 457 p.

832 63. Albert C, Brillinger M, Guerrero P, Gottwald S, Henze J, Schmidt S, et al. Planning nature-based
833 solutions: Principles, steps, and insights. Ambio. 2021 Aug 1;50(8):1446–61.

834 64. Chan KMA, Balvanera P, Benessaiah K, Chapman M, Díaz S, Gómez-Baggethun E, et al.
835 Opinion: Why protect nature? Rethinking values and the environment. Proc Natl Acad Sci USA.
836 2016 Feb 9;113(6):1462–5.

837 65. Costa MDP, Gorddard R, Fidelman P, Helmstedt KJ, Anthony KRN, Wilson KA, et al. Linking
838 social and biophysical systems to inform long-term, strategic management of coral reefs. Pac
839 Conserv Biol. 2020 Sep 16;27(2):126–32.

66. Prober SM, Colloff MJ, Abel N, Crimp S, Doherty MD, Dunlop M, et al. Informing climate adaptation pathways in multi-use woodland landscapes using the values-rules-knowledge framework. Agriculture, Ecosystems & Environment. 2017 Apr 1;241:39–53.

67. Anderson CC, Renaud FG, Hanscomb S, Munro KE, Gonzalez-Ollauri A, Thomson CS, et al. Public Acceptance of Nature-Based Solutions for Natural Hazard Risk Reduction: Survey Findings From Three Study Sites in Europe. Front Environ Sci. 2021 Jul 26;9:678938.

68. Dai L, Han Q, de Vries B, Wang Y. Applying Bayesian Belief Network to explore key determinants for nature-based solutions' acceptance of local stakeholders. Journal of Cleaner Production. 2021 Aug;310:127480.

69. Donatti CI, Harvey CA, Hole D, Panfil SN, Schurman H. Indicators to measure the climate change adaptation outcomes of ecosystem-based adaptation. Climatic Change. 2020 Feb;158(3–4):413–33.

70. Vermeulen SJ, Dinesh D, Howden SM, Cramer L, Thornton PK. Transformation in Practice: A Review of Empirical Cases of Transformational Adaptation in Agriculture Under Climate Change. Front Sustain Food Syst. 2018 Oct 10;2:65.

71. Pérez-Cirera V, Cornelius S, Zapata J. Powering Nature: Creating the Conditions to Enable Nature-based Solutions. Gland, Switzerland: WWF International; 2021 p. 88.

72. Bergeret A, Lavorel S. Stakeholder visions for trajectories of adaptation to climate change in the Drôme catchment (French Alps). Reg Environ Change. 2022 Mar 2;22(1):33.

73. Fayet CMJ, Reilly KH, Van Ham C, Verburg PH. The potential of European abandoned agricultural lands to contribute to the Green Deal objectives: Policy perspectives. Environmental Science & Policy. 2022 Jul 1;133:44–53.

74. Enqvist JP, Tengö M, Bodin Ö. Are bottom-up approaches good for promoting social–ecological fit in urban landscapes? Ambio. 2020 Jan 1;49(1):49–61.

75. Colloff MJ, Gorddard R, Abel N, Locatelli B, Wyborn C, Butler JRA, et al. Adapting transformation and transforming adaptation to climate change using a pathways approach. Environmental Science & Policy. 2021 Oct;124:163–74.

76. O'Brien K. Global environmental change II: From adaptation to deliberate transformation. Progress in Human Geography. 2012 Oct 1;36(5):667–76.

77. Melanidis MS, Hagerman S. Competing narratives of nature-based solutions: Leveraging the power of nature or dangerous distraction? Environmental Science & Policy. 2022 Jun 1;132:273–81.

78. Cattivelli V. Climate Adaptation Strategies and Associated Governance Structures in Mountain Areas. The Case of the Alpine Regions. Sustainability. 2021 Mar 5;13(5):2810.

79. Leach M, Reyers B, Bai X, Brondizio ES, Cook C, Díaz S, et al. Equity and sustainability in the Anthropocene: a social–ecological systems perspective on their intertwined futures. Glob Sustain. 2018;1:e13.

80. Méndez PF, Clement F, Palau-Salvador G, Diaz-Delgado R, Villamayor-Tomas S. Understanding the governance of sustainability pathways: hydraulic megaprojects, social–ecological traps, and power in networks of action situations. Sustain Sci [Internet]. 2022 Dec 17 [cited 2023 Jan 9]; Available from: https://doi.org/10.1007/s11625-022-01258-0

81. Zingraff-Hamed A, Hüesker F, Albert C, Brillinger M, Huang J, Lupp G, et al. Governance models for nature-based solutions: Seventeen cases from Germany. Ambio. 2021 Aug;50(8):1610–27.

82. Zingraff-Hamed A, Hüesker F, Lupp G, Begg C, Huang J, Oen A, et al. Stakeholder Mapping to Co-Create Nature-Based Solutions: Who Is on Board? Sustainability. 2020 Oct 18;12(20):8625.

83. Bastiaensen J, Huybrechs F, Merlet P, Romero M, Van Hecken G. Fostering bottom-up actor coalitions for transforming complex rural territorial pathways. Current Opinion in Environmental Sustainability. 2021 Apr 1;49:42–9.

84. Morrison TH, Adger WN, Brown K, Lemos MC, Huitema D, Phelps J, et al. The black box of power in polycentric environmental governance. Global Environmental Change. 2019 Jul;57:101934.

85. Abson DJ, Fischer J, Leventon J, Newig J, Schomerus T, Vilsmaier U, et al. Leverage points for sustainability transformation. Ambio. 2017 Feb;46(1):30–9.

86. Barnes ML, Wang P, Cinner JE, Graham NAJ, Guerrero AM, Jasny L, et al. Social determinants of adaptive and transformative responses to climate change. Nat Clim Chang. 2020 Sep;10(9):823–8.

87. Harmáčková ZV, Blättler L, Aguiar APD, Daněk J, Krpec P, Vačkářová D. Linking multiple values of nature with future impacts: value-based participatory scenario development for sustainable landscape governance. Sustain Sci [Internet]. 2021 May 12 [cited 2022 Jan 21]; Available from: https://doi.org/10.1007/s11625-021-00953-8

88. van Valkengoed AM, Steg L. Meta-analyses of factors motivating climate change adaptation behaviour. Nature Clim Change. 2019 Feb;9(2):158–63.

89. Brown K, Naylor LA, Quinn T. Making Space for Proactive Adaptation of Rapidly Changing Coasts: A Windows of Opportunity Approach. Sustainability. 2017 Aug;9(8):1408.

90. Hodgkinson JH, Hobday AJ, Pinkard EA. Climate adaptation in Australia's resource-extraction industries: ready or not? Reg Environ Change. 2014 Aug 1;14(4):1663–78.

91. Few R, Morchain D, Spear D, Mensah A, Bendapudi R. Transformation, adaptation and development: relating concepts to practice. Palgrave Commun. 2017 Sep 1;3(1):1–9.

92. Harvey CA, Rakotobe ZL, Rao NS, Dave R, Razafimahatratra H, Rabarijohn RH, et al. Extreme vulnerability of smallholder farmers to agricultural risks and climate change in Madagascar. Philosophical Transactions of the Royal Society B: Biological Sciences. 2014 Apr 5;369(1639):20130089.

93. Bosomworth K, Leith P, Harwood A, Wallis PJ. What's the problem in adaptation pathways planning? The potential of a diagnostic problem-structuring approach. Environmental Science & Policy. 2017 Oct 1;76:23–8.

94. Nelson DR, Bledsoe BP, Ferreira S, Nibbelink NP. Challenges to realizing the potential of nature-based solutions. Current Opinion in Environmental Sustainability. 2020 Aug;45:49–55.

95. O'Connor S, Kenter JO. Making intrinsic values work; integrating intrinsic values of the more-than-human world through the Life Framework of Values. Sustain Sci. 2019 Sep 1;14(5):1247–65.

96. Nixon R, Ma Z, Zanotti L, Khan B, Birkenholtz T, Lee L, et al. Adaptation to Social–Ecological Change in Northwestern Pakistan: Household Strategies and Decision-making Processes. Environmental Management. 2022 May;69(5):887–905.

97. Turkelboom F, Leone M, Jacobs S, Kelemen E, García-Llorente M, Baró F, et al. When we cannot have it all: Ecosystem services trade-offs in the context of spatial planning. Ecosystem Services. 2018 Feb;29:566–78.

98. Crouzat E, Arpin I, Brunet L, Colloff MJ, Turkelboom F, Lavorel S. Researchers must be aware of their roles at the interface of ecosystem services science and policy. Ambio. 2018 Feb;47(1):97–105.

99. Cullen BR, Ayre M, Reichelt N, Nettle RA, Hayman G, Armstrong DP, et al. Climate change adaptation for livestock production in southern Australia: transdisciplinary approaches for integrated solutions. Animal Frontiers. 2021 Oct 1;11(5):30–9.

100. Brillinger M, Dehnhardt A, Schwarze R, Albert C. Exploring the uptake of nature-based measures in flood risk management: Evidence from German federal states. Environmental Science & Policy. 2020 Aug 1;110:14–23.

101. Reed MS, Evely AC, Cundill G, Fazey I, Glass J, Laing A, et al. What is Social Learning? Ecology and Society [Internet]. 2010 [cited 2022 Dec 14];15(4). Available from: https://www.jstor.org/stable/26268235

102. Slijper T, Urquhart J, Poortvliet PM, Soriano B, Meuwissen MPM. Exploring how social capital and learning are related to the resilience of Dutch arable farmers. Agricultural Systems. 2022 Apr 1;198:103385.

103. De Vitis M, Abbandonato H, Dixon KW, Laverack G, Bonomi C, Pedrini S. The European Native Seed Industry: Characterization and Perspectives in Grassland Restoration. Sustainability. 2017 Oct;9(10):1682.

104. Nuijten E, de Wit J, Janmaat L, Schmitt A, Tamm L, Lammerts van Bueren ET. Understanding obstacles and opportunities for successful market introduction of crop varieties with resistance against major diseases. Org Agr. 2018 Dec 1;8(4):285–99.

105. Giraldo OF, Rosset PM. Agroecology as a territory in dispute: between institutionality and social movements. The Journal of Peasant Studies. 2018 Mar 19;45(3):545–64.

106. Gabillet M, Arpin I, Prévot AC. Between hope and boredom: Attending to long-term related emotions in participatory environmental monitoring programmes. Biological Conservation. 2020 Jun 1;246:108594.

107. Brillinger M, Henze J, Albert C, Schwarze R. Integrating nature-based solutions in flood risk management plans: A matter of individual beliefs? Science of The Total Environment. 2021 Nov 15;795:148896.

108. Souliotis I, Voulvoulis N. Operationalising nature-based solutions for the design of water management interventions. Nature-Based Solutions. 2022 Dec 1;2:100015.

109. Seddon N, Smith A, Smith P, Key I, Chausson A, Girardin C, et al. Getting the message right on nature-based solutions to climate change. Glob Change Biol. 2021 Apr;27(8):1518–46.

110. Osaka S, Bellamy R, Castree N. Framing “nature-based” solutions to climate change. WIREs Clim Change [Internet]. 2021 Jul 15 [cited 2021 Jul 30]; Available from: https://onlinelibrary.wiley.com/doi/10.1002/wcc.729

111. Sowińska-Świerkosz B, García J. What are Nature-based solutions (NBS)? Setting core ideas for concept clarification. Nature-Based Solutions. 2022 Dec;2:100009.

112. European Commission. Directorate General for Research and Innovation. Evaluating the impact of nature-based solutions: a handbook for practitioners. [Internet]. LU: Publications Office; 2021 [cited 2021 Dec 1]. Available from: https://data.europa.eu/doi/10.2777/244577

113. Zingraff-Hamed A, Lupp G, Schedler J, Huang J, Pauleit S. 156 Nature-based solutions in the German Alps to mitigate hydro-meteorological risks [Internet]. online: EGU General Assembly 2021; 2021 Mar [cited 2021 Oct 22]. Available from: https://meetingorganizer.copernicus.org/EGU21/EGU21-8522.html

114. Kalantari Z, Ferreira CSS, Keesstra S, Destouni G. Nature-based solutions for flood-drought risk mitigation in vulnerable urbanizing parts of East-Africa. Current Opinion in Environmental Science & Health. 2018 Oct 1;5:73–8.

115. Lupp G, Huang JJ, Zingraff-Hamed A, Oen A, Del Sepia N, Martinelli A, et al. Stakeholder Perceptions of Nature-Based Solutions and Their Collaborative Co-Design and Implementation Processes in Rural Mountain Areas—A Case Study From PHUSICOS. Front Environ Sci. 2021 Dec 7;9:678446.

116. Cohen-Shacham E, Andrade A, Dalton J, Dudley N, Jones M, Kumar C, et al. Core principles for successfully implementing and upscaling Nature-based Solutions. Environmental Science & Policy. 2019 Aug;98:20–9.

117. Scoones I, Stirling A, Abrol D, Atela J, Charli-Joseph L, Eakin H, et al. Transformations to sustainability: combining structural, systemic and enabling approaches. Current Opinion in Environmental Sustainability. 2020 Feb;42:65–75.

118. Loos J, Benra F, Berbés-Blázquez M, Bremer LL, Chan KMA, Egoh B, et al. An environmental justice perspective on ecosystem services. Ambio [Internet]. 2022 Dec 15 [cited 2022 Dec 18]; Available from: https://doi.org/10.1007/s13280-022-01812-1

119. Ravera F, Iniesta-Arandia I, Martín-López B, Pascual U, Bose P. Gender perspectives in resilience, vulnerability and adaptation to global environmental change. Ambio. 2016 Dec 1;45(3):235–47.

120. Reed G, Brunet ND, McGregor D, Scurr C, Sadik T, Lavigne J, et al. Toward Indigenous visions of nature-based solutions: an exploration into Canadian federal climate policy. Climate Policy. 2022 Apr 21;22(4):514–33.

121. Dias LF, Aparício BA, Nunes JP, Morais I, Fonseca AL, Pastor AV, et al. Integrating a hydrological model into regional water policies: Co-creation of climate change dynamic adaptive policy pathways for water resources in southern Portugal. Environmental Science & Policy. 2020 Dec 1;114:519–32.

122. Bennett EM, Cramer W, Begossi A, Cundill G, Díaz S, Egoh BN, et al. Linking biodiversity, ecosystem services, and human well-being: three challenges for designing research for sustainability. Current Opinion in Environmental Sustainability. 2015 Jun;14:76–85.

123. Zingraff-Hamed A. La rivière et des hommes : quelle gouvernance pour la restauration des rivières ? Sciences Eaux & Territoires. 2022 Dec 7;(39):31–8.

124. IUCN, International Union for Conservation of Nature. IUCN Global Standard for Nature-based Solutions: a user-friendly framework for the verification, design and scaling up of NbS: first

edition [Internet]. 1st ed. IUCN, International Union for Conservation of Nature; 2020 [cited 2021 Oct 6]. Available from: https://portals.iucn.org/library/node/49070

125. Wyborn C, Datta A, Montana J, Ryan M, Leith P, Chaffin B, et al. Co-Producing Sustainability: Reordering the Governance of Science, Policy, and Practice. Annual Review of Environment and Resources. 2019;44(1):319–46.

126. Norström AV, Cvitanovic C, Löf MF, West S, Wyborn C, Balvanera P, et al. Principles for knowledge co-production in sustainability research. Nat Sustain. 2020 Mar;3(3):182–90.

127. Lupp G, Zingraff-Hamed A, Huang JJ, Oen A, Pauleit S. Living Labs—A Concept for Co-Designing Nature-Based Solutions. Sustainability. 2021 Jan;13(1):188.

128. Wamsler C. Mainstreaming ecosystem-based adaptation: transformation toward sustainability in urban governance and planning. E&S. 2015;20(2):art30.

129. Egarter Vigl L, Marsoner T, Schirpke U, Tscholl S, Candiago S, Depellegrin D. A multi-pressure analysis of ecosystem services for conservation planning in the Alps. Ecosystem Services. 2021 Feb;47:101230.

130. Kohler Y, Scheurer T, Ullrich A. Ecological networks in the Alpine Arc. Journal of Alpine Research | Revue de géographie alpine [Internet]. 2009 May 26 [cited 2022 Dec 18];(97–1). Available from: https://journals.openedition.org/rga/808

131. Tomasi S, Garegnani G, Scaramuzzino C, Sparber W, Vettorato D, Meyer M, et al. EUSALP, a Model Region for Smart Energy Transition: Setting the Baseline. In: Calabrò F, Della Spina L, Bevilacqua C, editors. New Metropolitan Perspectives. Cham: Springer International Publishing; 2019. p. 132–41. (Smart Innovation, Systems and Technologies).

132. Echavarren JM, Balžekienė A, Telešienė A. Multilevel analysis of climate change risk perception in Europe: Natural hazards, political contexts and mediating individual effects. Safety Science. 2019 Dec 1;120:813–23.

133. Nordbeck R, Löschner L, Pelaez Jara M, Pregernig M. Exploring Science–Policy Interactions in a Technical Policy Field: Climate Change and Flood Risk Management in Austria, Southern Germany, and Switzerland. Water. 2019 Aug 13;11(8):1675.

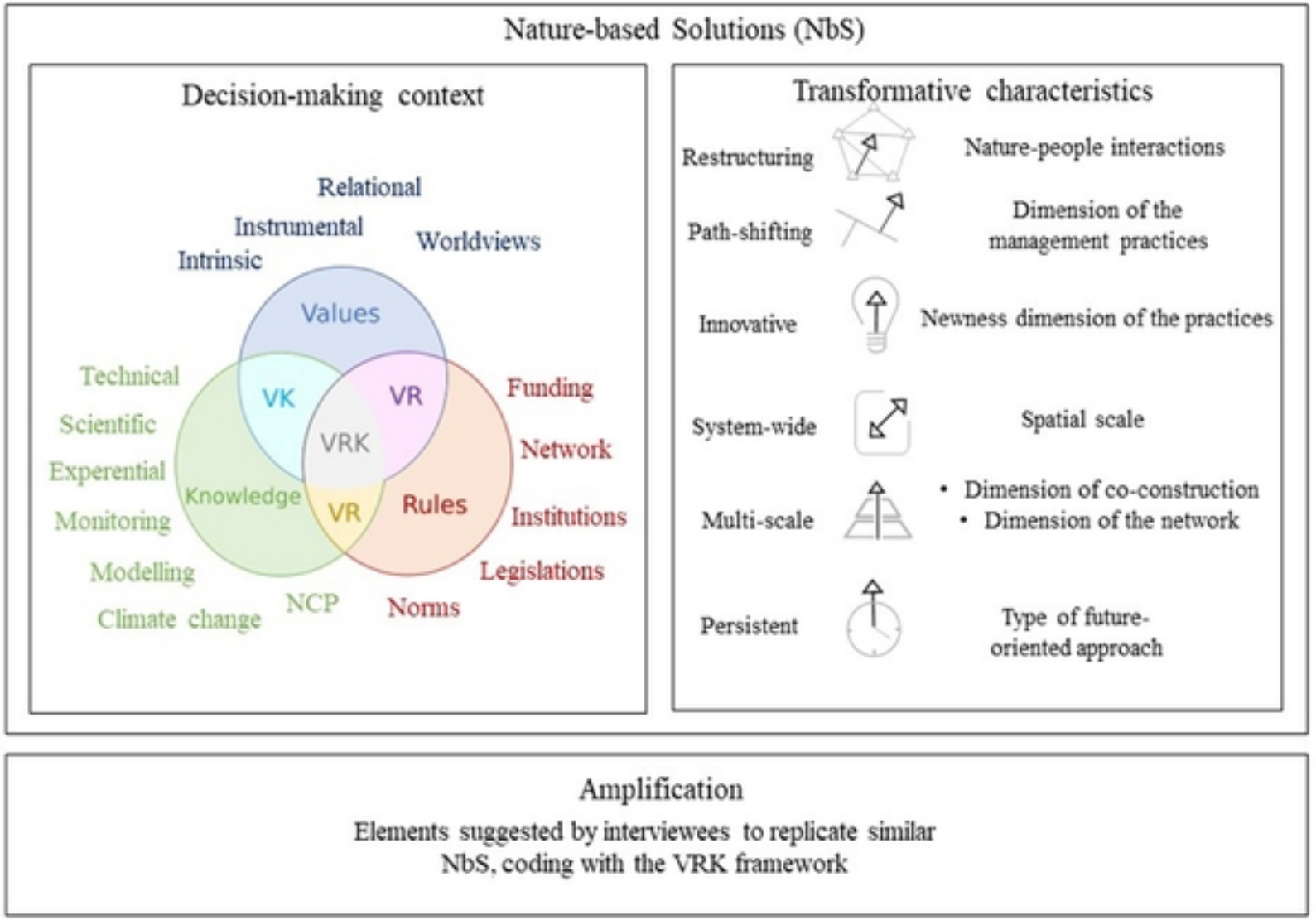
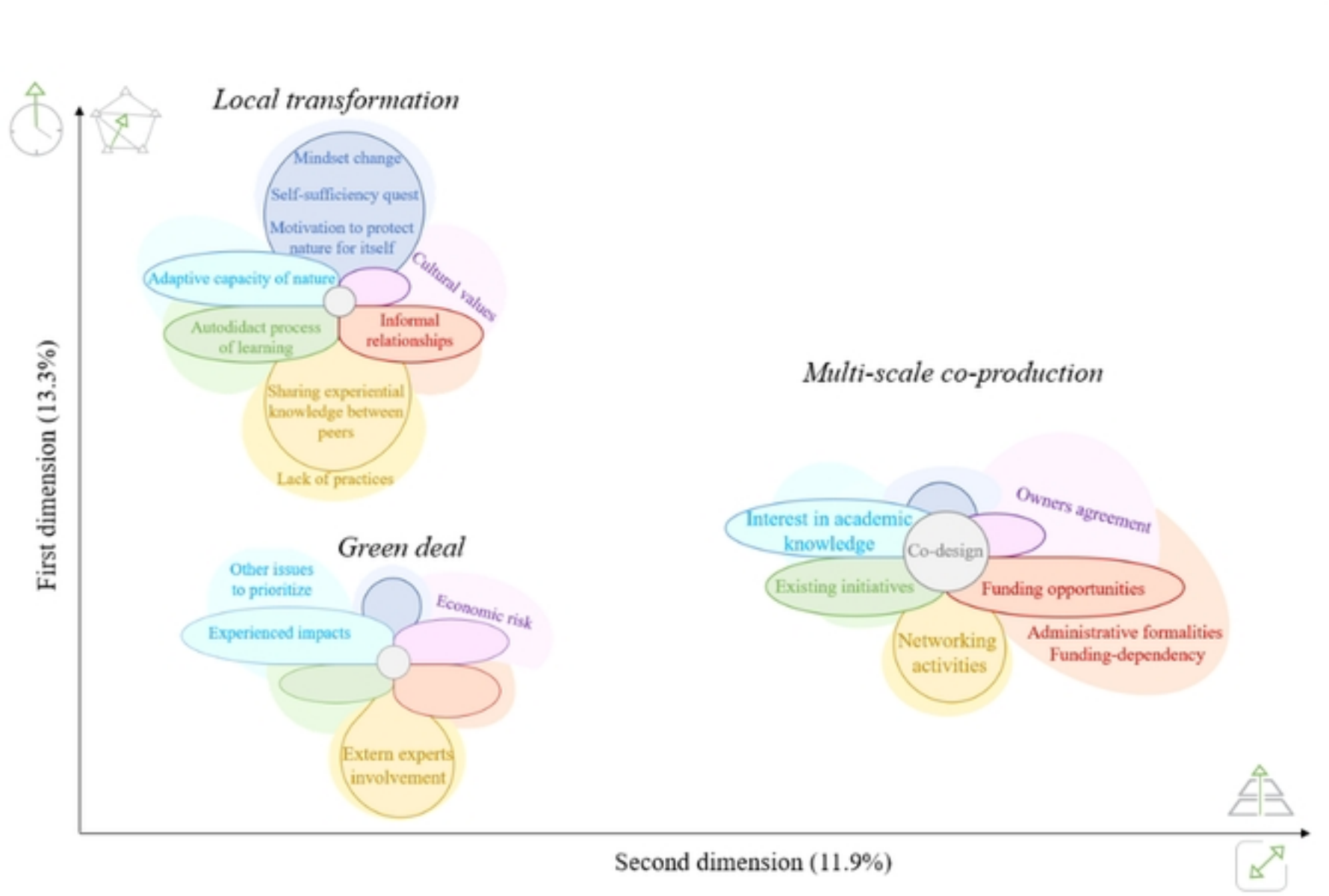

Nature-based Solutions (NbS)
Decision-making context
Relational
Instrumental
Intrinsic
Worldviews
Values
Technical
Scientific
Experential
Monitoring
Modelling
Climate change
VK
VR
VRK
Knowledge
VR
Rules
NCP
Norms
Funding
Network
Institutions
Legislations
Transformative characteristics
Restructuring
Nature-people interactions
Path-shifting
Dimension of the management practices
Innovative
Newness dimension of the practices
System-wide
Spatial scale
Multi-scale
• Dimension of co-construction
• Dimension of the network
Persistent
Type of future-oriented approach
Amplification
Elements suggested by interviewees to replicate similar NbS, coding with the VRK framework

Fig1


Local transformation
Mindset change
Self-sufficiency quest
Motivation to protect nature for itself
Adaptive capacity of nature
Cultural values
Autodidact process of learning
Informal relationships
Sharing experiential knowledge between peers
Lack of practices
Green deal
Other issues to prioritize
Economic risk
Experienced impacts
Extern experts involvement
Multi-scale co-production
Owners agreement
Interest in academic knowledge
Co-design
Existing initiatives
Funding opportunities
Networking activities
Administrative formalities
Funding-dependency
First dimension (13.3%)
Second dimension (11.9%)

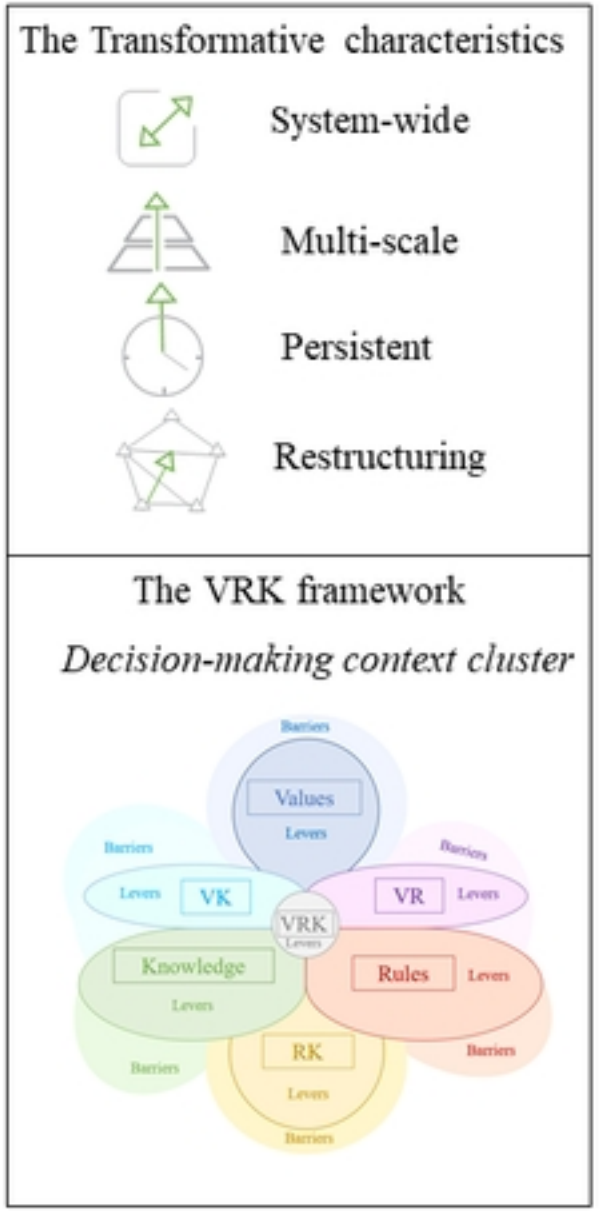

The Transformative characteristics
System-wide
Multi-scale
Persistent
Restructuring
The VRK framework
Decision-making context cluster
Barriers
Values
Levers
VK
VR
VRK
Knowledge
Rules
RK

Fig3

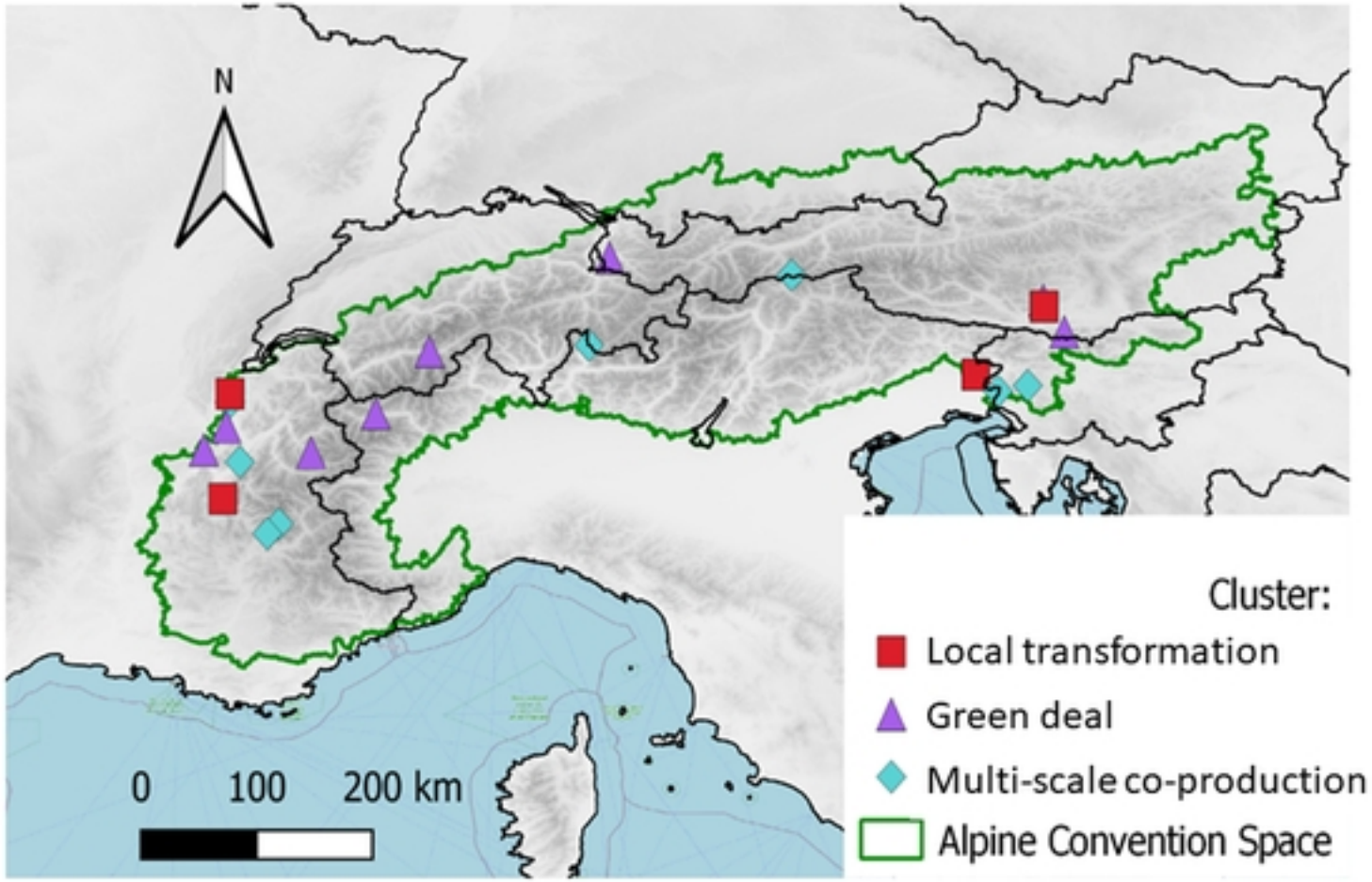

N
0
100
200 km
Cluster:
Local transformation
Green deal
Multi-scale co-production
Alpine Convention Space

Fig2

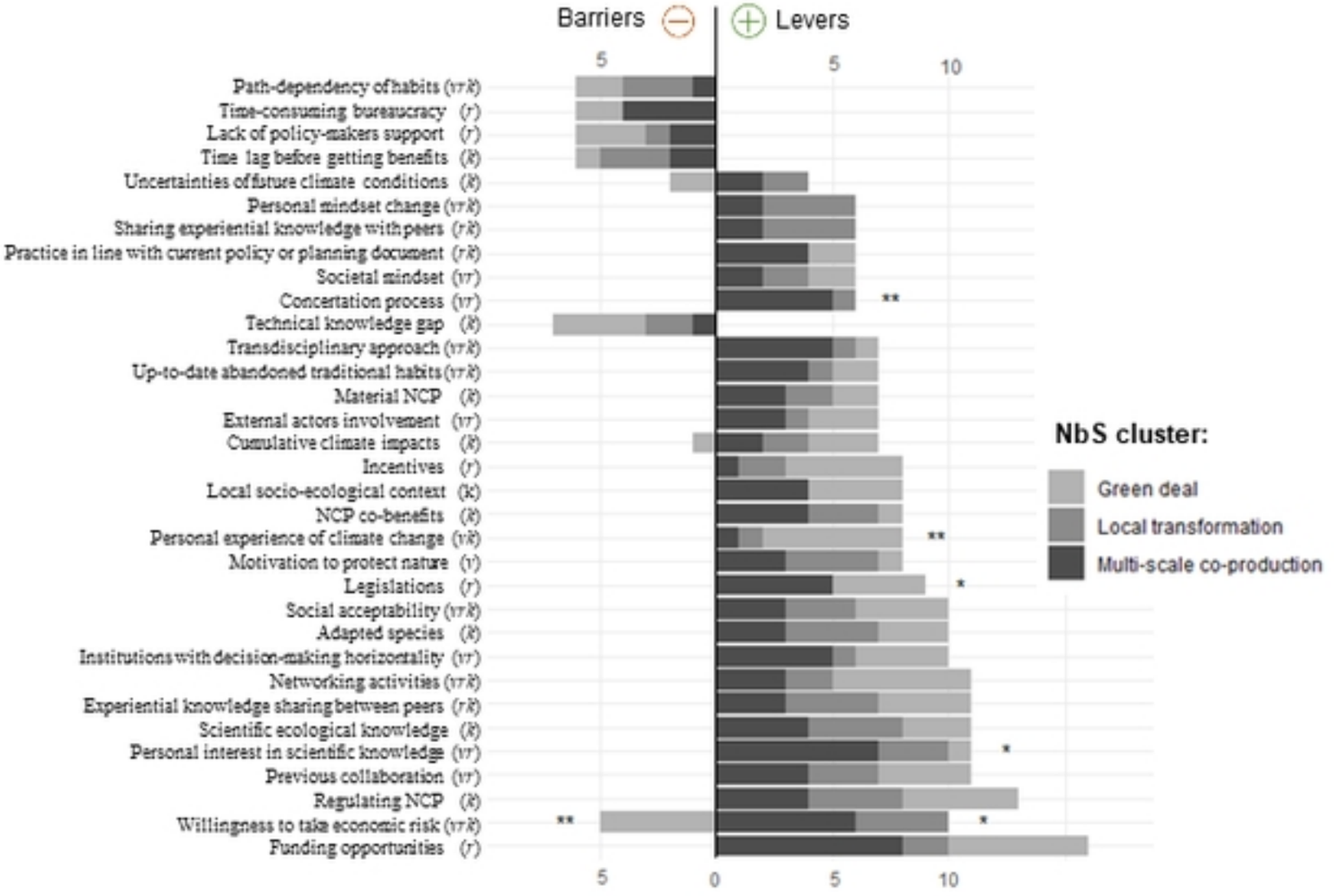

Barriers
Levers
5
5
10
Path-dependency of habits (vrk)
Time-consuming bureaucracy (r)
Lack of policy-makers support (r)
Time lag before getting benefits (k)
Uncertainties of future climate conditions (k)
Personal mindset change (vrk)
Sharing experiential knowledge with peers (rk)
Practice in line with current policy or planning document (rk)
Societal mindset (vr)
Concertation process (vr)
Technical knowledge gap (k)
Transdisciplinary approach (vrk)
Up-to-date abandoned traditional habits (vrk)
Material NCP (k)
External actors involvement (vr)
Cumulative climate impacts (k)
Incentives (r)
Local socio-ecological context (k)
NCP co-benefits (k)
Personal experience of climate change (vk)
Motivation to protect nature (v)
Legislations (r)
Social acceptability (vrk)
Adapted species (k)
Institutions with decision-making horizontality (vr)
Networking activities (vrk)
Experiential knowledge sharing between peers (rk)
Scientific ecological knowledge (k)
Personal interest in scientific knowledge (vr)
Previous collaboration (vr)
Regulating NCP (k)
Willingness to take economic risk (vrk)
Funding opportunities (r)
**
**
*
*
*
NbS cluster:
Green deal
Local transformation
Multi-scale co-production
5
0
5
10

Fig4

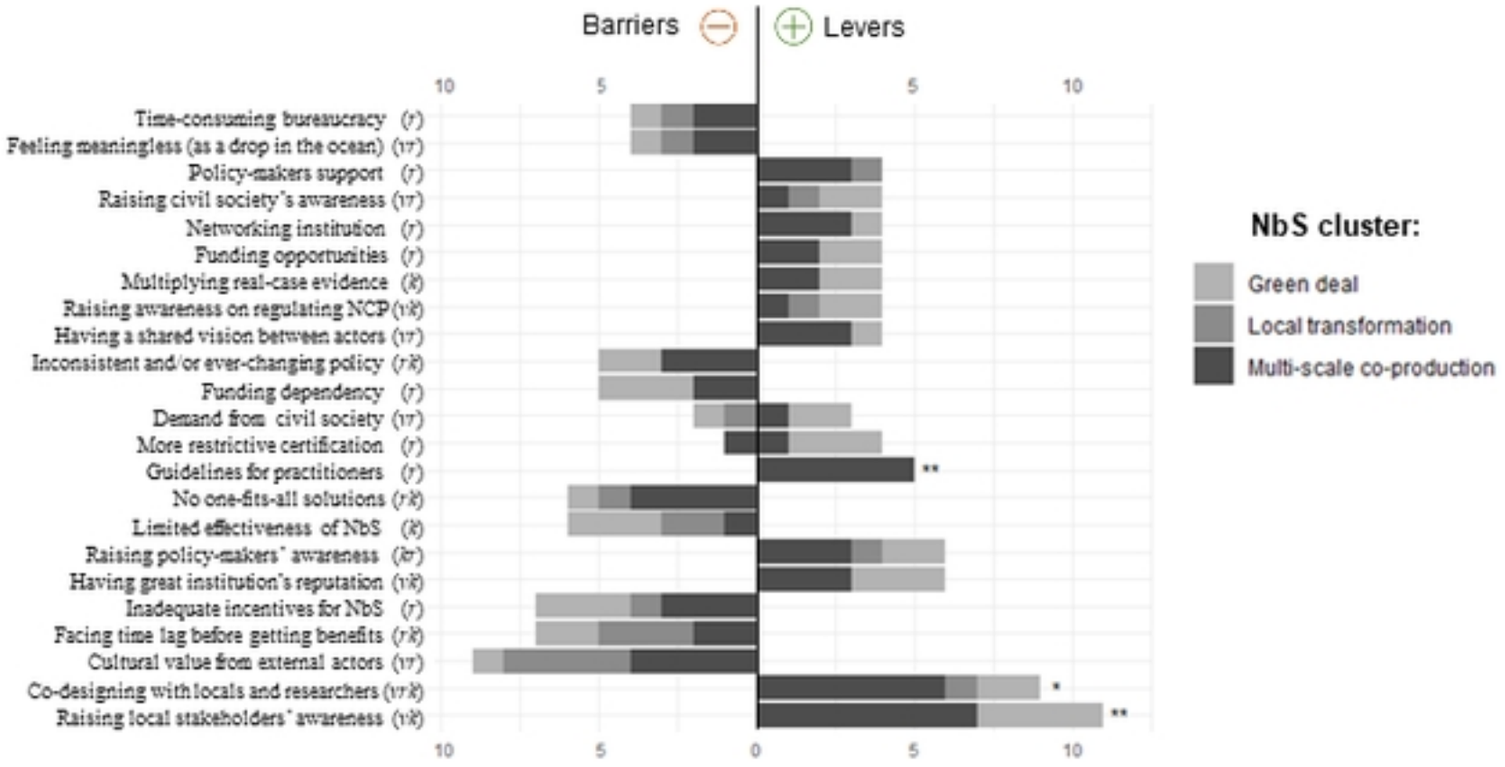
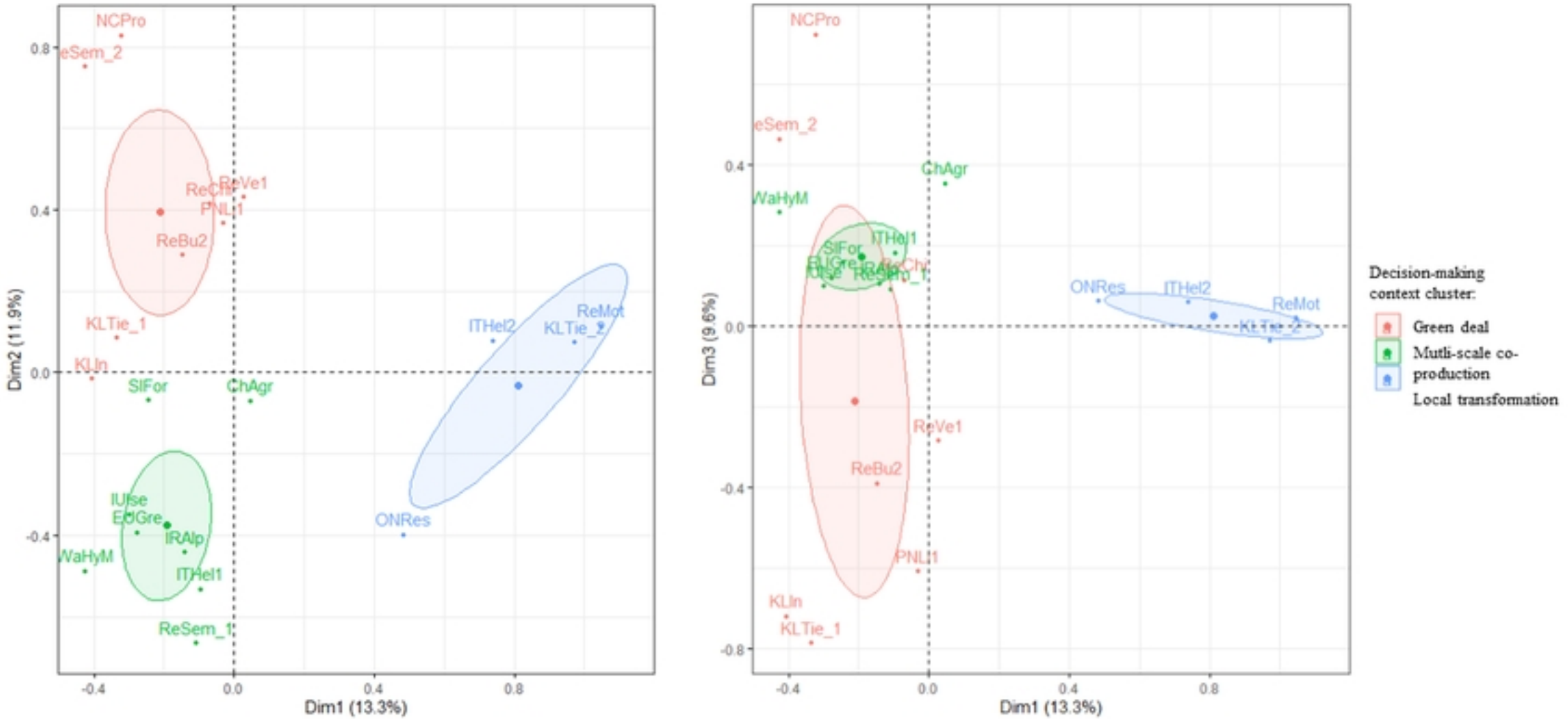

Barriers
Levers
10
5
0
5
10
Time-consuming bureaucracy (7)
Feeling meaningless (as a drop in the ocean) (17)
Policy-makers support (7)
Raising civil society's awareness (17)
Networking institution (7)
Funding opportunities (7)
Multiplying real-case evidence (8)
Raising awareness on regulating NCP (18)
Having a shared vision between actors (17)
Inconsistent and/or ever-changing policy (18)
Funding dependency (7)
Demand from civil society (17)
More restrictive certification (7)
Guidelines for practitioners (7)
No one-fits-all solutions (18)
Limited effectiveness of NbS (8)
Raising policy-makers' awareness (87)
Having great institution's reputation (18)
Inadequate incentives for NbS (7)
Facing time lag before getting benefits (18)
Cultural value from external actors (17)
Co-designing with locals and researchers (178)
Raising local stakeholders' awareness (18)
*
**
**
NbS cluster:
Green deal
Local transformation
Multi-scale co-production

Fig5


NCPro
eSem_2
ReVe1
ReBu2
PNL11
KLTie_1
KLIn
SIFor
ChAgr
ITHel2
ReMot
KLTie_2
IUse
EUGre
IRAlp
WaHyM
ITHel1
ReSem_1
ONRes
Dim2 (11.9%)
Dim1 (13.3%)
Dim3 (9.6%)
Decision-making context cluster:
Green deal
Mutli-scale co-production
Local transformation

FigS6

FigS7

FigS8


Private-private partnership
Required funding_Likely
Business-as-usual
Uncertainties of future climate conditions_-1
Cumulative climate impacts_-1
High inertia of society to adapt_-1
Incentives_Fully
New species
Labour value_1
Willingness to take economic risk_-1
RES_Change of species
Increasing non climatic disturbances_-1
Bureaucracy_Few
Grey solutions requirement_1
Extern.initiator_1
Radical change in practices
Constraints of ressource multi use_1
Grey solutions requirement_-1
Consultation process_1
Increasing non climatic disturbances_1
Funding opportunities_0
Business as usual approach_-1
Personal interest in scientific knowledge_0
Technical knowledge gap_-1
Small
Fostering collaboration
Required funding_No
Observation of climate change from extern.actors_1
Personal experience of climate change_1
Required funding_Unlikely
Incentives_Few
Grey solutions cons_1
Peer-to-peer
Knowledge from extern.experts_1
Favourable local socio ecological context_1
Networking activities_Extern.pairs
Known elsewhere
RPN_No
Gradual change in practices
Concertation process_0
Single disciplinary
Quality of the product_1
Landscape aesthetic recognition_1
Autodidact process of learning_1
Context-dependent
Intense personal involvement_0
Legacy of cultural values_1
Learning by doing approach_1
Labour value_-1
Towards self sufficient practices_1
RPN_Intrinsic values
Fostering interdisciplinarity
Legislations_1
Path dependency of habits_-1
Scientific ecological knowledge_1
Adapted species_0
Adapted species_-1
Motivation to protect nature_1
Known alternative
Adaptable
Municipalities
Methods
Labour value_0
Adaptive capacity of nature_1
RES_No
Legislations_0
Time lag before getting benefits_-1
Sharing experiential knowledge with peers_1
Regulating NCP_0
Personal experience of climate change_0
Societal mindset shift_1
Personal mindset change_1
Practice in line with current policy or planning
External actors involvement_1
Personal interest in scientific knowledge_1
RES_Change in NCP
ITD
Incentives_No
Political interest in the initiative_1
Uncertainties of future climate conditions_1
Constraints of ressource multi use_-1
Transdisciplinary approach_1
RES_Change in species richness
Change in social relationships
Known experiments
Willingness to take economic risk_1
Required funding_Yes
Owners approval requirement_-1
RPN_Relational values
Integrated vision of the system
Co-design
Intense personal involvement_1
Concertation process_1
Interregional
Never seen before
Lack of expertise in the field_-1
Designing from existing initiatives_1
Bureaucracy_Hard
Accessibility of the data_-1
Dialogue between peers_1
Lack of built sector_-1
Dim2 (11.9%)
Dim1 (13.3%)
Decision-making context cluster
Green deal
Multi-scale co-production
Local transformation
k
r
rk
TA
v
vk
vr
vrk

FigS9