PLOS CLIMATE

RESEARCH ARTICLE

Levers for transformative nature-based adaptation initiatives in the Alps

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Citation: Dubo T, Palomo I, Zingraff-Hamed A, Bruley E, Collain G, Lavorel S (2023) Levers for transformative nature-based adaptation initiatives in the Alps. PLOS Clim 2(11): e0000193. https://doi.org/10.1371/journal.pclm.0000193

Editor: Pedro Fidelman, University of Queensland, AUSTRALIA

Received: March 10, 2023

Accepted: September 26, 2023

Published: November 2, 2023

Data Availability Statement: The data for the study can be access through supplementary information, and the authors-generated code is made available in GITHUB: https://github.com/Titouan-Dubo/NBS_VRK_TA/tree/Code.

Funding: This work was supported by the French National Research Agency's Programme d'Investissements d'Avenir — Make Our Planet Great Again (Grant Agreement No. ANR-19-MPGA-0009 to IP, TD, EB and GC), the LabEx OSUG@2020 (Investissements d'avenir – Grant Agreement No. ANR10 LABX56 to TD) and the

Abstract

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

1. Introduction

The interlinked climate and biodiversity crises urge societies to adapt to whatever the emissions scenarios [1–3]. However, incremental adaptation actions are likely to maintain the

H2020 PHUSICOS (Grant Agreement No. 776681 to AZH). The funders had no role in study design, data collection and analysis, decision to publish, or preparation of the manuscript.

Competing interests: The authors have declared that no competing interests exist.

system's current trajectory and prove insufficient in addressing new climate conditions [4]. Sustainable responses of social-ecological systems need transformative adaptation, i.e. fundamentally altering the entire system's properties and function to reduce the root cause of vulnerabilities [4–6]. Transformative adaptation encompasses a holistic approach that entails new governance systems, knowledge production, power relations, and a shift in values, assumptions, and policies [7–9]. Despite the growing interest in transformative adaptation within sustainability science and policy [1, 3, 10], empirical evidences of transformative responses to climate change remains limited [11, 12]. This implementation gap is mainly due to the inherent complexity involved in that transformation process that entails various elements such as governance, stakeholders' diversity, value systems, and habits [8]. Previous studies have proposed a set of characteristics for transformative adaptation such as, but not limited to, innovation, restructuration, shift to an alternative direction, and long-term impacts at large scale and across scales to measure transformative adaptation [8]. While some empirical studies have identified promising examples of transformative adaptation [13], many report incremental responses [12, 14]. Therefore, further research needs to evaluate different adaptation strategies and their relationships to transformative adaptation processes.

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

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

Despite the growing evidence of the abilities of NbS in addressing a wide range of issues and simultaneously providing diverse NCP co-benefits [26–28], they are not widely implemented [8, 22, 29], particularly in the areas where NbS are most needed [27, 30]. Technical or biophysical elements are often not the main barriers; instead, the NbS implementation is influenced by diverse social-ecological elements and the decision-making context [31–33]. Commonly identified barriers to NbS implementation are i) the lack of funds and financial instruments for implementing NbS [34]; ii) the path dependency in practices, leading to resistance to change among stakeholders and institutions [31, 35]; iii) the limited participation of local stakeholders [36]; iv) the limited coordination between stakeholders from different

sectors [37]; and v) the knowledge gap regarding the multiple co-benefits of NbS [37, 38]. Several levers have been highlighted to overcome the barriers, including the promotion and assessment of NbS co-benefits [39, 40], the collaboration and the co-construction of solutions between stakeholders [40, 41], the polycentric governance [37], the incentives and environmental law [7], the social innovation [31, 42] and overcoming path dependency [31, 43]. Most of these levers are identified and listed in the literature as general recommendations, with limited considerations of local contexts and the synergies or trade-offs between them [7, 19]. However, multiple levers and barriers to adaptation co-occur within decision-making contexts, such as place attachment and resistance to innovation [43]; subsidies for conservation action and the willingness (or unwillingness) of local actors to act [44]; the conservation of traditional practices and the need to adapt them to new conditions [44]; and the valuation of landscape aesthetics associated with the lack of instrumental benefits it provides [45]. While these findings improve the understanding of the decision-making process, it remains unclear how levers are activated jointly to achieve NbS implementation successfully and to what extent co-occurring levers contribute to transformative adaptation. This knowledge gap prompts the following research questions: What levers are activated jointly within the decision-making context of NbS? Which barriers have been overcome through levers co-occurrence? Do NbS from different decision-making contexts contribute equally to transformative adaptation? What factors enable or constrain the future implementation of transformative NbS?

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

2. Materials and methods

2.1 Geographical context

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

2.2 Theoretical background

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

2.2.1 The values-rules-knowledge framework. The *vrk* (*values-rules-knowledge*) framework analyses the decision-making context [60] with proven relevance to situations of uncertain environmental change [44, 45, 61]. This framework analyses decision-making for NbS design, funding, and realization, a step-by-step process which we hereafter refer to as

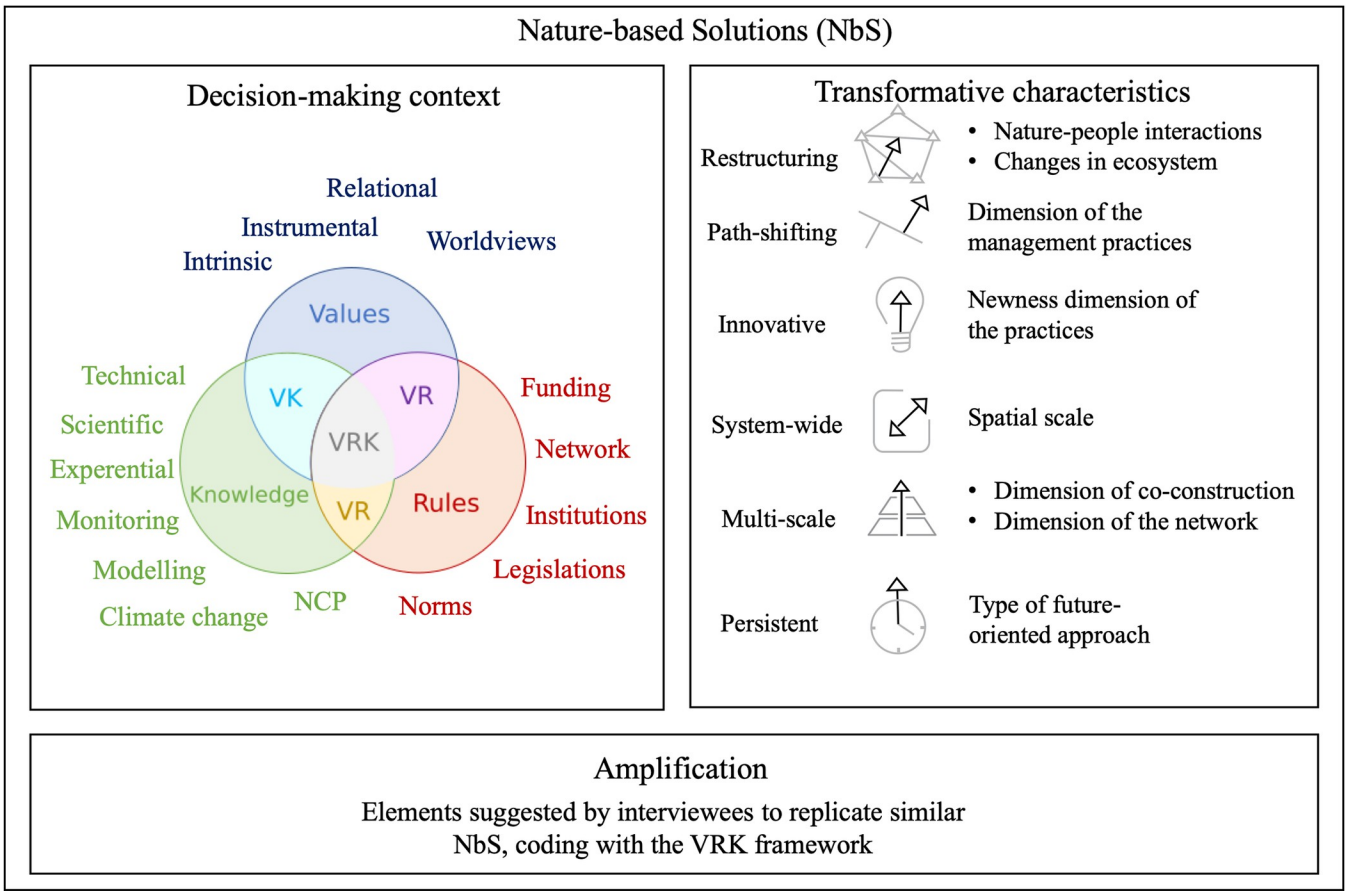

Fig 1. The two conceptual frameworks used for the analysis of Nature-based Solutions (NbS): (1) the values-rules-knowledge framework that defines the decision-context, and (2) the transformative characteristics of the implemented NbS. The variables used to code the interviews are also displayed. Adapted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

https://doi.org/10.1371/journal.pclm.0000193.g001

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

2.2.2 The transformative adaptation characteristics. Transformative adaptation extends beyond coping and incremental adaptation and encompasses various forms that have not been sufficiently assessed [4, 70]. To address this gap, Fedele et al. [8] developed a framework comprising six characteristics to qualify transformative adaptation based on a literature review of

transformative adaptation [8]. These characteristics examine whether an initiative is restructuring, i.e. involves major shifts in fundamental properties, functions, or interactions; path-shifting, i.e. alters the systems' current trajectory towards an alternative direction; innovative, i.e. changes in the system to new states that have not previously existed; multi-scale, i.e. impacts the system across multiple scales (e.g., trophic, spatial, jurisdictional, or sectoral scales); system-wide, i.e. occurs at large scale (e.g., regions, ecosystems, landscapes, or communities); persistent, i.e. with long-term impacts although not necessarily irreversible [8].

2.3 Semi-structured interviews with Nature-based Solutions managers

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

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

2.4 Data processing

The interviews were coded using Qualcoder software (version 3.1) enabling systematic textual analysis. First, the contextual information of each case study was extracted: the role of the

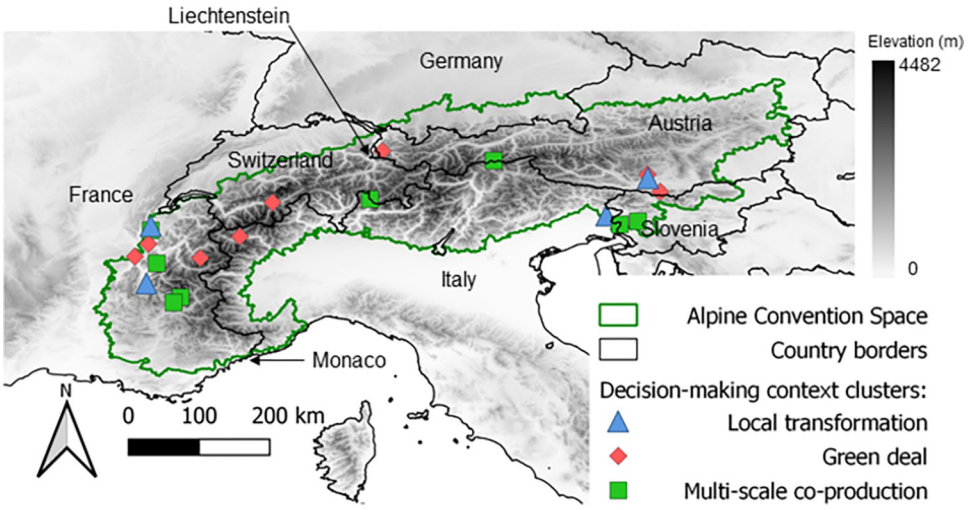

Fig 2. Map of the twenty studied Nature-based Solutions (NbS), coloured according to the clustering analysis based on the levers and barriers mentioned by the NbS managers during semi-structured interviews and the transformative characteristics of the NbS. Elevation data is publicly available for academic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

https://doi.org/10.1371/journal.pclm.0000193.g002

interviewee in the NbS implementation, the organisation(s) leading the implementation, funding sources, the ecosystem or land-use in which the NbS was implemented, the type(s) of interventions, and the climatic hazards targeted by the NbS.

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

A matrix (S3 Table) was created to describe each NbS, indicating whether each variable mentioned by interviewees as a lever (coded '1'), a barrier (coded '-1') or whether it was not mentioned (coded as '0'). Some variables were coded as a semi-quantitative factor, such as funding (e.g., no funding, partial funding, full funding). The levers and barriers to NbS amplification were coded according to the same process for each interview (S4 Table). The matrix (S1 Table) also included the contextual information of each NbS.

Finally, the transformative characteristics were coded using both an inductive approach based on the responses provided by the interviewees and a deductive approach based on indicators reviewed from published studies. For each transformative characteristic, the modalities of the indicators identified in the literature were adapted according to the response from the interviews (Table 2 and Fig 1). For example, the *innovative* characteristic was assessed in the

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

Element	Definition	Indicators	Coded variables
Values (*v*)	"Values refer to a set of ethical precepts that determine the way people select actions and evaluate events"[60]	Personal worldviews, beliefs [75, 76]	Cultural heritage; inclusiveness; valuing work; willingness to invest time and energy; worthiness of collective intelligence; quest for self-sufficiency; wish to deliver products of high quality
	Human-nature relationships include the multiple ways of considering ecosystems and biodiversity, from intrinsic value considering conservation of nature for itself; instrumental value considering utilitarian vision of nature for people; relational value considering conservation of nature for the specific relationship established with it [63, 74]	Intrinsic values; instrumental values; relational values [63, 74]	Landscape aesthetics; motivation to protect nature; intrinsic value of biodiversity; utilitarian value of nature
Values-Rules (*vr*)	"The favouring of particular sets of values that may be built into the way that rules are interpreted by decision-makers or can be imposed upon the decision process" [60]	Example from the literature: cost-benefit framing; legal liability excluding amenity and ecological values; public deliberation about policy options [60]	Co-production processes (consultation, concertation); local hero involvement; involvement of external actors; political interest in the initiative; cultural values of external actors; institutions with horizontal decision-making; shift in societal norms; previous collaboration; business-as-usual practices
Rules (*r*)	"Rules-in-use"	Norms, practices, taboos, habits, heuristics [60]	Multi-use landscape; conventional way of doing in the region; institutional expertise; informal sharing or trading
	"Rules-in-form"	Regulations, legislation, treaties and ordinances [60]	Legislation; funding opportunities; incentives; bureaucracy; owner's approval requirement
Rules-Knowledge (*rk*)	The favouring of particular knowledge that may be built into the way that rules play in the source of knowledge involved [60]	Example from the literature: standardized assessment; mandated hazard assessment; public consultation on knowledge base of adaptation options [60]	External knowledge involvement; Lack of discipline-specific expertise; Sharing experiential knowledge with peers; matching practices with institutional strategy or current policies; social inertia of adaptation; favourable conditions in the local social-ecological context; data accessibility; lack of policy support
Knowledge (*k*)	"The mix of evidence-based (scientific and technical) knowledge and experiential, meanings-based knowledge that forms part of constructed knowledge systems in the decision-making process" [60]	Scientific, technical and experiential evidence regarding: i) ecological functions and ecosystem state; ii) material, regulating and non-material NCP; iii) current and future climate change impacts, adaptation options; local knowledge regarding social-ecological system; knowledge gaps [45, 77, 78]	Local social-ecological knowledge; Time lag before getting benefits; previously acquired technical knowledge; feasibility of measurements; technical knowledge gap; NPC co-benefits; material NCP; regulating NCP; scientific ecological knowledge (food web, ecosystem resilience, biological regulation); adapted species; cumulative climate change impacts; uncertainties of future climate conditions
Values-Knowledge (*vk*)	The favouring of particular knowledge that may be built without considering multiple values [60]	Example from the literature: Focus on direct property scale impacts; decisions made on spatial planning without values; assessment of private property damage excluding primarily valued public assets [60]	Personal experience of climate change; interest in external perception of climate change; personal interest in scientific knowledge; willingness to apply eco-friendly practices; willingness to support the adaptive capacity of nature; willingness to learn by doing including failing; identification of required grey solutions; identification of grey solutions to be abandoned
vrk	"The *vrk* interactions described above determine which values, knowledge and rules influence decisions and which are excluded" [60]		Willingness to take economic risk; inspiration from traditional practices; Transdisciplinary approach; emergence of the initiative from external actor; social acceptance; Networking activities; path dependency of habits; personal mindset change; other priorities considered before climate adaptation; practices based on existing initiatives; applied outcomes; dialogue between peers; lack of structured sector

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Table 2. Definition of each transformative characteristic and their relative indicators identified in the literature, the variable, and its modalities.

Transformative characteristics	Definition from Fedele et al. [8]	Indicators from the literature [13, 20, 79–85]	Variable	Modalities
Restructuring (R)	"It is 'restructuring' in that it involves major shifts in fundamental properties, functions, or interactions within the social, ecological, or social-ecological system"	Indicators of restructured elements (flow of information, materials; management of ecosystem; system organisation and functions; system governance, power relations, values, land cover)	Type of people-nature values promoted (RPN)	no mentioned value < + instrumental < + relational < + intrinsic
			Level of change in ecosystem (RES)	Change in species < change in species richness < change in landscape connectivity < change in land-cover < change in NCP
Path-shifting (PS)	"It is 'path-shifting' in that it alters the systems' current trajectory by pushing it towards an alternative direction"	Change in social-ecological systems, from silos or monoculture to governance reforms, new financial mechanisms or resilient mix of species	Level of change in management	Business-as-usual < gradual change in practices < radical change in practices < change in social relationships < integrated/holistic vision of the system
Innovative (I)	"It is 'innovative' because it often changes systems to new states that have not previously existed in that area thanks to new knowledge, policies, or technologies"	Existing or new species, knowledge, practices, technologies, policies, behaviours, partnerships	Level of newness in practices	conventional < unusual in the region but known elsewhere < new species < non-conventional practices but known alternative way of doing < known experiments < novel
System-wide (SW)	"It is 'system-wide' in that it occurs at large-scale and leads to systemic changes across whole regions, ecosystems, landscapes, or communities"	Spatial scale; number of beneficiaries	Spatial scale	Pilot site; small, i.e. at local scale < municipality scale < region; interregional
Multi-scale (MS)	"It is 'multi-scale' in that it has impacts across multiple scales (e.g., trophic, spatial, jurisdictional, or sectoral scales)"	Number of trophic levels, sectors and governance level	Scale of co-production (MSC)	No collaboration < fostering collaboration < peer-to-peer < partnership within private sector < partnership between public and private sector < co-design
			Scale of network (MSN)	No network < single disciplinary network < Fostering interdisciplinarity < interdisciplinary network or transdisciplinary network (ITD)
Persistent (P)	"It is a 'persistent' shift with long-term impacts, although not necessarily irreversible"	Time of impact and institutional anchoring	Type of future-oriented approach	Aborted < Methods < funding-dependent longevity; policy-dependent longevity; planned to persist < adaptable initiative < anchored rules in-form or in-use

Some modalities are ranked by a less-than sign "<" according to increasing levels of transformative adaptation. The ones that cannot be ranked are separated by semicolons. The plus sign "+" indicates that the higher level of transformative adaptation cumulates the modalities of the lower level and the one mentioned after the plus sign.

https://doi.org/10.1371/journal.pclm.0000193.t002

existing literature by considering the introduction of new elements (species, practices, technologies, policies, behaviours, awareness or financial instruments) or from various perspectives (new to the region, sector, or world) [20]. Since the interview responses received did not cover all identified indicators, only those mentioned were selected. For example, the *innovative* characteristic was described by the type of practices, including conventional practices (not *innovative*), non-usual practices in the region but known elsewhere, non-conventional practices but known alternative way of doing (partially *innovative*), practices from known experiments but never applied, and practices never seen elsewhere (highly *innovative*). Some modalities of transformative characteristics cannot be ranked, e.g., to characterise the *persistence* of NbS; if one initiative developed new methods for successful NbS and another initiative has built a strong partnership between local actors, these two initiatives would be coded differently using non-ordered modalities. Each transformative characteristic was coded with a single variable, except the *multi-scale* and *restructuring* characteristics, which were coded using two types of

indicators to capture the multiple elements they encompassed. For the *multi-scale* characteristic, the type of collaboration (e.g., peer-to-peer or within a collaboration between public and private institutions) and the type of network (e.g., single-sector or cross-sectoral network) were used. For the *restructuring* characteristic, the type of nature-people relationships (e.g., with instrumental values only or combined with relational or intrinsic values) and the type of ecological changes (in species, species richness, landscape connectivity, land-cover, or NCP) were used. The coded information is summarized in Fig 1 and detailed in S5 Table.

2.5 Data analysis

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

3. Results

3.1 Shared levers and barriers in decision-making contexts

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

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

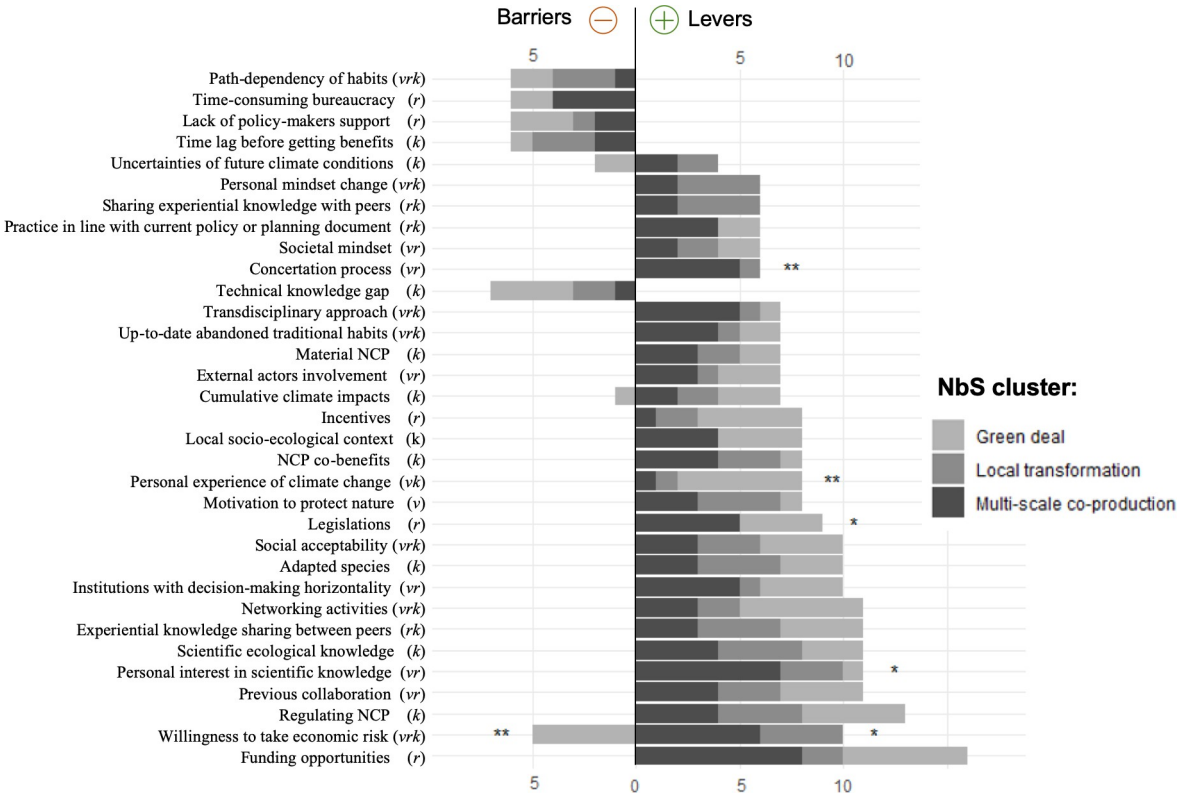

Fig 3. Barplot of the number of interviewees during which the levers and barriers to implementing their Nature-based Solutions were mentioned, plotted according to the decision-making context cluster, and for the subset of the levers and barriers mentioned by more than five interviewees. Significance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

https://doi.org/10.1371/journal.pclm.0000193.g003

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

3.2 Transformative adaptation characteristics

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

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

The correlation patterns across decision-making context indicators and transformative characteristics of the analyzed NbS formed three clusters of decision-making contexts (Fig 5). These

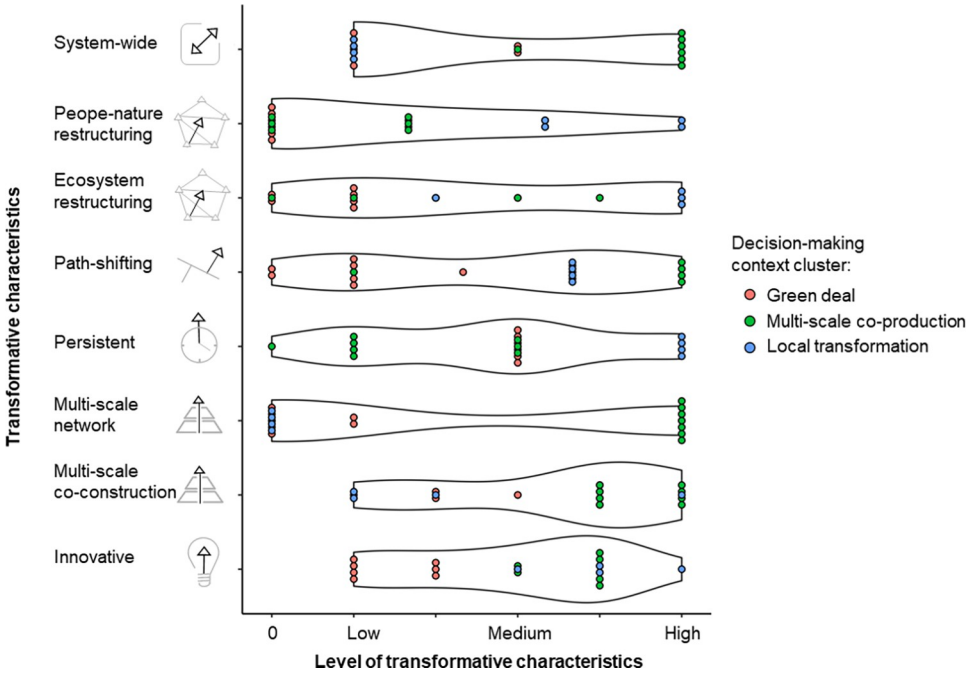

Fig 4. Violin boxplot of the level of the transformative characteristics of each Nature-based Solutions (NbS). Within each transformative characteristic, the dots represent individual NbS, coloured according to the decision-making context cluster they belong to.

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three clusters were labeled *Local transformation*, *Green deal*, and *Multi-scale co-production*, based on their main associated elements represented along the first two axes of the MCA (Fig 6).

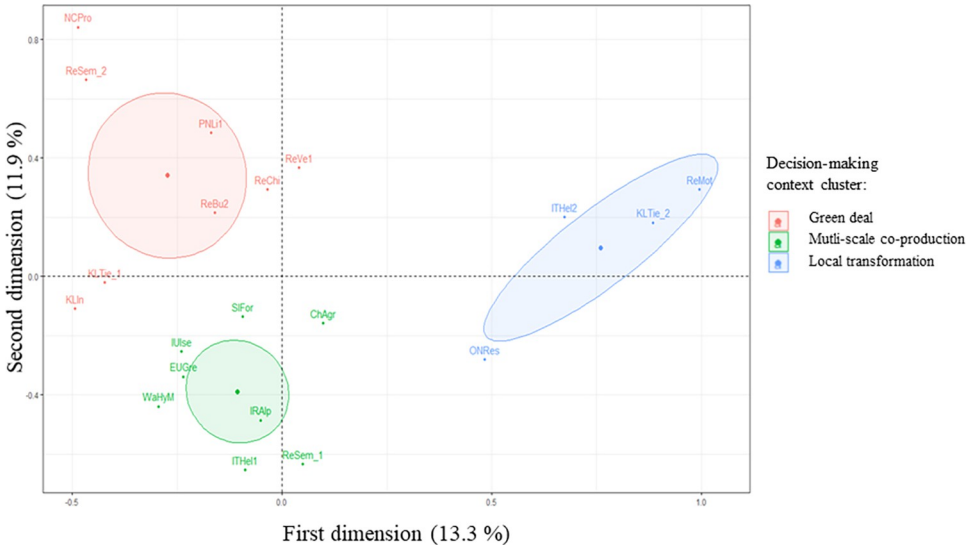

Fig 5. Clustering analysis of the levers and barriers identified in decision-making contexts for Nature-based Solutions (NbS) implementation. They show the clusters displayed on the first and the second axes of the Multiple Correspondence Analysis (MCA) used to compute the clustering algorithm. For each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

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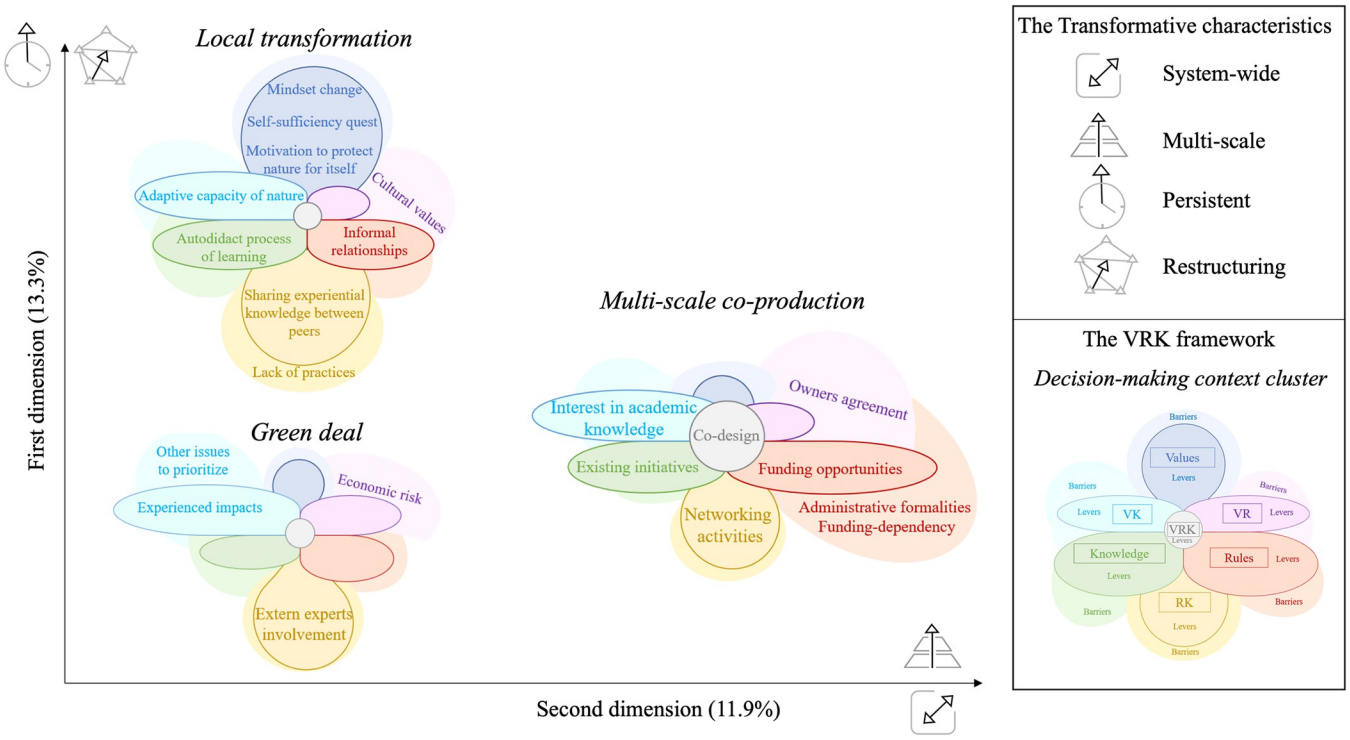

Fig 6. The decision-making context clusters of the implemented Nature-based Solutions shown through *vrk* (*values-rules-knowledge*) flowers, plotted according to the Multiple Correspondence Analysis (MCA) of their levers (inside the related petals), their barriers (around the related petals) and their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

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

> Quote n˚1: "As a result, we have biodiversity support since we have fungi, birds and entomofauna that is compatible with this type of fir. That is also why we chose fir: better social acceptance; it fits better with French biodiversity." (Translated from French, original quote in the S6 Table)

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

> Quote n˚2: "[the bramble] comes, it comes at a gallop, so afterward it questions what is going to be the management of the bramble, how are we going to manage it, how can we live with it, how can we live with the look of the people who are going to say [. . .] there are brambles everywhere in these vineyards." (Translated from French, original quote in the S6 Table)

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

> 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)

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

> 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 the S6 Table).

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

> 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 the S6 Table)

Still, interviewees of this cluster mentioned mainly instrumental values rather than intrinsic or relational values to nature. The resulting NbS were primarily based on their ability to

provide material or regulating NCP (*knowledge*) (Quote n˚6). In line with this, *path-shifting* or *restructuring* characteristics of these decision-making contexts are limited. Instead, they tended to support gradual changes of practices rather than radical shifts to alternative approaches.

> Quote n˚6: "And we can demonstrate that when I plant, I planted six hectares, I do not know how much it corresponds to, but I will capture carbon for 60 years, more maybe, for 100 years, if I build a house." (Translated from French, original quote in the S6 Table)

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

> Quote n˚7: "So the big idea was on the cards, but there were not so many, at least in France, projects of this scale which allowed us to go and find an example." (Translated from French, original quote in the S6 Table)

The implementation of these NbS was contingent upon funding (*r*), and for four of eight cases the interviewees perceived intense bureaucracy as a barrier (*r*) (quote n˚8). Consequently, the cluster presents a low to medium *restructuring* level, associated with the uncertainty of the *persistence* of these NbS due to their funding-dependency. The funding insecurity and the changes in institutional support were explained by the frequent turnover of policy-makers (*r*). Two of eight cases have overcome these barriers by leveraging the long-lasting reputation of the organisation from the effectiveness of their NbS (*vr*), and five of eight cases established strong collaboration between participants to ensure the viability of the NbS (*vr*).

> Quote n˚8: "And for me as the lead partner, but also I think many other partners had to fight with it, was the administration, the high level of administration." (Original)

3.4 Levers for Nature-based Solutions amplification. Among the suggestions provided by the interviewees to amplify NbS, a total of 25 levers and 23 barriers were identified. Additionally, three elements were identified either as a lever or a barrier, depending on the

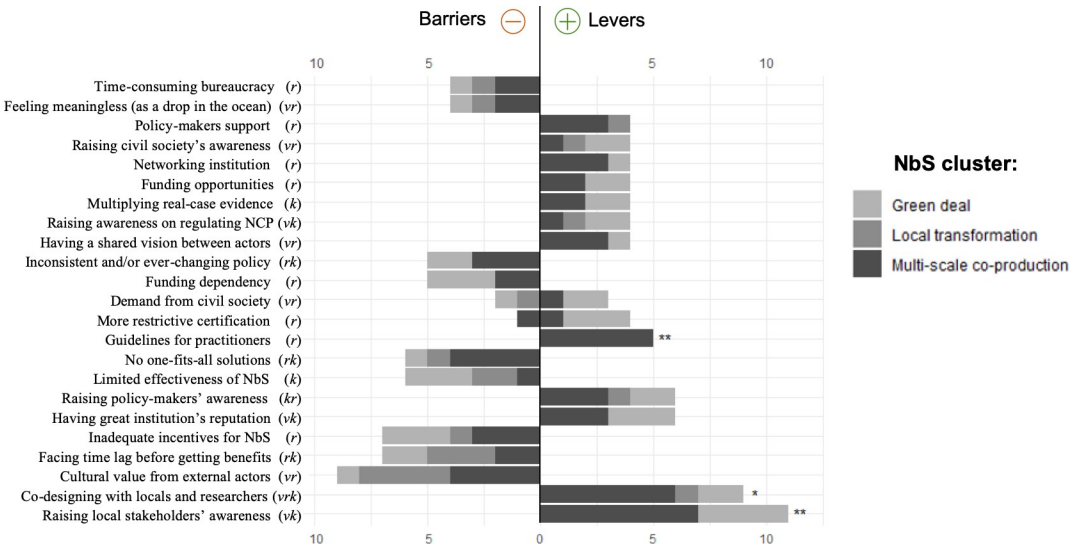

Fig 7. Barplot of the number of interviews during which the levers and barriers to future amplification of similar Nature-based Solutions were mentioned, plotted according to the decision-making context clusters, and for the subset of levers and barriers mentioned by more than four interviewees. Significance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

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

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

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

4. Discussion

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

This analysis integrated the *vrk* framework and the assessment of transformative adaptation characteristics to identify levers and barriers to NbS implementation in the Alps. The findings confirm the suitability of the *vrk* framework in identifying the key elements influencing adaptation initiatives [43, 86, 87]. The study reveals that formal rules, robust project coordination, positive cultural values within local communities, knowledge sharing through informal exchanges, collaborative planning, and academic support are currently the primary levers for NbS implementation. These insights align with the levers for NbS implementation identified in the literature's [31, 45, 83, 88, 89]. However, the findings show that not all levers mentioned in the literature co-occur within the same initiatives. For example, the levers involving values such as a "mindset change" and "willingness to self-sufficiency" appeared simultaneously with "experiential knowledge sharing", but they did not coincide with institutional levers such as governance processes and funding opportunities, which have been identified in the literature as priorities to amplify NbS [31, 90–92]. Additionally, the findings highlight the inherent uncertainty in the ability of NbS to deliver benefits as a prominent barrier to preferring NbS as an option over grey infrastructures [93, 94]. While grey solutions benefit from widespread societal acceptance [95, 96] due to their one-size-fits-all designs and short-term outcomes, NbS, in contrast, are site-specific, and their effectiveness is relatively less understood [26, 97].

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

The *vrk* framework highlights that transformative adaptation is supported by specific interactions between *values*, *rules*, and *knowledge* [60]. In this study, the *vrk* framework was combined with transformative adaptation characteristics rather than focusing on the coping-incremental-transformative trichotomy since real-life cases often combine these facets of

adaptation [4, 102, 103]. The approach covers the multiple aspects of transformative adaptation and provides a more detailed overview of the elements in place in transformative adaptation processes as well as their outcomes. According to the selected indicators, the findings confirm that greater interactions of *values*, *rules*, and *knowledge* in a decision-making context are expected to implement initiatives with more significant transformative adaptation potential. The results also reveal that transformative adaptation characteristics vary within individual decision-making contexts. For example, in the *Local transformation* type, NbS that were co-designed had more *multi-scale* co-construction than NbS that benefitted from peer-to-peer exchanges. Moreover, within the *Green deal* type, NbS that were initially designed for long-term persistence, whatever the evolving social-ecological conditions, have a higher level of *persistence* than NbS that depends on future funding opportunities. The analysis highlights the transformative adaptation characteristics each decision-making context can support and those for which high levels are less likely. Considering that each type of decision-making context falls short of achieving high levels of at least two transformative adaptation characteristics, the results emphasise the limited use of transformative adaptation in current initiatives [12, 14]. While assessing the contribution of individual initiatives to transformative adaptation remains challenging, the findings validate the potential of NbS to support transformative adaptation, aligning with other studies that have synthesized datasets of NbS elsewhere [13, 15, 104]. Moreover, there is a need for transformative NbS, namely in governance and policies supporting the adaptive capacity of nature, financial compensation for transition, co-creation of knowledge and solutions, monitoring systems, and disseminating knowledge [7, 31, 56, 83, 105].

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

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

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

The analysis highlights the valuable role of *values* within NbS decision-making contexts. *Values* have been identified as crucial determinants of transformation [111–113]. However, the

transformative adaptation characteristics of the NbS depended on the type of *values* involved in their implementation. For example, relational *values* to nature were involved in *innovative* practices that restructured relationships between nature and people, aligning with local ecological knowledge studies [33, 45]. The willingness to include the diverse range of values into NbS design, e.g. through participatory approaches, resulted in initiatives with a high level of *multi-scale* co-production and networking and the potential to benefit large communities and regions [37].

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

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

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

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

The findings revealed that institutional support plays a crucial role in NbS implementation, although the intensity and the nature of its contribution varies across decision-making contexts. Funding opportunities provided by governmental institutions are essential for the *Multi-scale co-production* of NbS for which the implementation might not have been possible without such financial support, aligning with previous insights [83]. These highly transformative NbS

benefited mostly from transdisciplinary research projects, with public funding from national or European programmes or incentives, and involved public administrations related to biodiversity conservation, protected areas, agriculture, forest, and water management [16, 83]. However, these initiatives encountered significant bureaucratic burdens imposed by funders, challenging their implementation.

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

The absence of a well-structured sector was also identified as a barrier to NbS implementation, such as the absence of local seeds markets for alpine grasslands restoration [130] or the absence of a value chain for new agricultural products [131]. While *Local transformation* NbS manage to diversify their marketing strategies [132], e.g., by developing direct marketing to local communities, the institutions involved in *Multi-scale co-production* NbS aim to develop emerging value chains for their products in collaboration with stakeholders [130]. However, this institutional involvement in enabling-NbS activities is limited due to cultural barriers [32, 132] and the time that stakeholders involvement consumes [133]. Only intense involvement related to personal values enables the implementation of *Multi-scale co-production* NbS [134].

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

4.4 Study limitations

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

The interviews were conducted with only one manager involved in the implementation process for each NbS. Although the perception of the NbS can depend on the interviewee [134, 141], the perception bias was reduced by employing structured questions specifically related to the implementation process. Moreover, in four cases, two interviewees were involved in the

same network despite not being involved in the same NbS, and their responses were consistent.

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

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

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

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

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

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

NbS, e.g., through strong incentives and establishing binding measures through legislation when required.

According to the findings of this study, the levers to be activated must be tailored to the local decision-making context and the transformative potential of the NbS they might support. For example, in the context of disaster risk reduction, supporting a transdisciplinary approach can enhance NbS co-design involving local communities and developing a network of stakeholders willing to collaborate. However, this approach could fail if local stakeholders focus only on adapting their own practices and do not want to be involved in new projects. A preliminary analysis of the decision-making context is, therefore, critical. Moreover, multiplying *Local transformations* NbS initiatives by non-governmental stakeholders is a powerful strategy to foster initiatives at a broader scale when complemented by the promotion of sharing networks and monitoring activities [36, 150]. Introducing new financial incentives or environmental regulations can support NbS amplification to stakeholders who are already willing to implement NbS, particularly those with economic or technical constraints. However, these instruments must be framed considering principles for effective NbS, namely economic viability, inclusive governance, equity, sustainability, and mainstreaming [106]. This approach may not support stakeholders unwilling to implement NbS, e.g. due to cultural barriers. Additional facilitating levers are required in such cases. For example, introducing new policies can be accompanied by activities aiming to raise stakeholders' awareness about the potential of NbS to mitigate climate impacts and to provide NCP co-benefits [35].

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

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

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

5. Conclusion

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

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

Supporting information

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

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

S3 Table. Matrix of levers and barriers expressed by the interviewees as involved within the decision-making contexts of the Nature-based Solutions (NbS) implementation identified in the Alps. The code "1" indicates that the element is mentioned by the interviewee as a lever to the NbS implementation. The cells code "-1" indicates that the element is mentioned by the interviewee as a barrier to the NbS implementation. The blank cell indicates that the element is not mentioned by the interviewee. Some elements are categorized according to ranked values.
(DOCX)

S4 Table. Matrix of the elements suggested by the interviewees involved in Nature-based Solutions implementation to amplify similar initiatives. The code "1" indicates that the element is expected to enhance the amplification of NbS. The code "-1" indicates that the element is expected to constrain the amplification of NbS. The blank cell indicates that the element is not mentioned by the interviewee.
(DOCX)

S5 Table. Matrix of the transformative adaptation characteristics of the Nature-based Solutions identified in the Alps.
(DOCX)

S6 Table. Original quotes from semi-structured interviews conducted with managers of implemented Nature-based Solutions to climate change adaptation in the European Alps, cited in the main text.
(DOCX)

Acknowledgments

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. We are grateful to Paula Acosta for her valuable insights, which improved the quality of the text. We thank the anonymous reviewer for its valuable feedback, which significantly improved this manuscript.

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