Assessing Nature-based Solutions for transformative change

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SUMMARY

Global sustainability targets demand transformative changes. However, empirical studies of large datasets that assess transformative change are scarce. We provide a framework to evaluate how Nature-based Solutions (NbS) contribute to transformative change and apply it to 93 NbS from mountain social-ecological systems (SES). The framework contains elements of NbS that may catalyse transformative change as well as indicators to evaluate how transformative change occurs and what its outcomes are. Our results show that NbS are as much "people-based" as "nature-based". Most NbS are based on four elements with transformation potential: nature´s values, knowledge types, community engagement, and nature management practices. Our results confirm the potential of NbS for transformative change, observed through changes in non-sustainable trajectories of SES. We illustrate the components of our framework through a novel classification of NbS. The framework provides key components for assessing the effectiveness of NbS and allows tracking long-term transformative change processes.

INTRODUCTION

Transformative change in the context of sustainability refers to profound and fundamental alterations in social-ecological interactions in a way that sustains the earth's biophysical systems, while meeting human needs[1-3]. According to the Intergovernmental science-policy Platform on Biodiversity and Ecosystem Services (IPBES) and the Intergovernmental Panel on Climate Change (IPCC), such transformative change is necessary to achieve the Paris Agreement, the post-2020 biodiversity targets and several of the Sustainable Development Goals (SDGs)[4-6]. Research on transformative change has grown exponentially, as well as the disciplines engaged with it[7,8]. However, few studies have empirically evaluated through large datasets the processes that successfully lead to transformative change and associated sustainability outcomes[9-11].

Three broad perspectives on transformative change have been described[12], namely the socio-technical[13], the socio-institutional[14,15], and the socio-ecological[16]. Here we focus on the socio-ecological perspective, which assumes that transformative change requires reframing social-ecological relationships[17]. Particularly, we present an analysis of Nature-based Solutions (NbS), which are gaining influence in science, policy and practice, and could play an important role in the implementation of the international sustainability agenda[18,19]. NbS are defined as "actions to protect, sustainably manage and restore natural or modified ecosystems that address societal challenges effectively and adaptively, simultaneously providing human well-being and biodiversity benefits"[20]. NbS are considered a cost-effective, multi-functional and broadly-applicable approach to deal with global change challenges compared to those relying on built infrastructure[20,21] . Due to their contributions to nature conservation and human livelihoods and wellbeing[22], NbS could be central in transformative long-term pathways to sustainability if they can integrate nature conservation with socio-economic benefits[23].

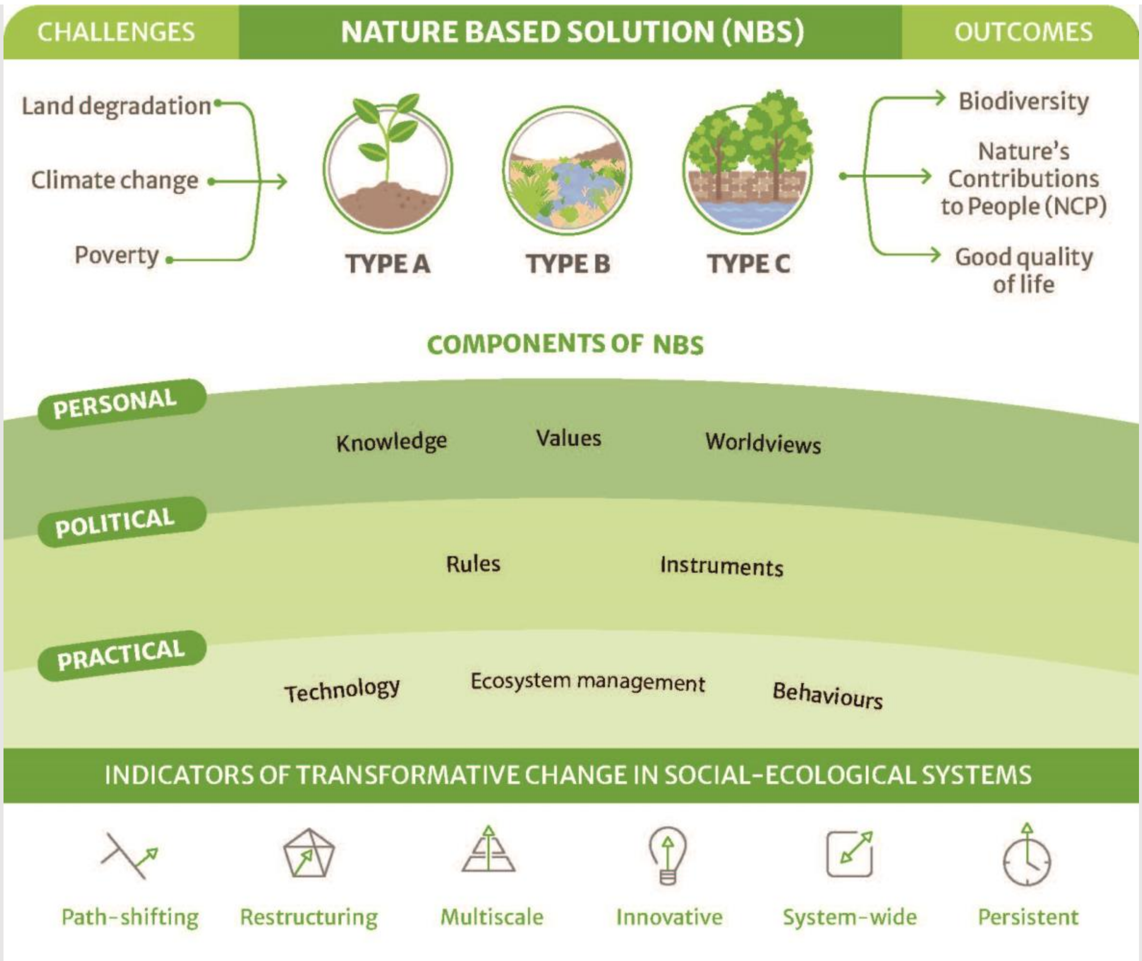
Results from the design and application of NbS are varied and there is no consensus on methods for monitoring their performance[24-26]. Clarity over applications and outcomes is further required[27-30] and recently a global standard for NbS has been released[31]. Still, it is necessary to assess how NbS relate to transformative change in its multiple dimensions and what their potential to foster transformation pathways is. Assessing NbS and their transformative potential is also needed to support initiative-based learning of transformative processes[32].

Here, we present an operational framework to assess the potential of NbS to support transformative change and apply it to the global dataset of PANORAMA, a platform showcasing solutions to global environmental change challenges (https://panorama.solutions). We analyse NbS in mountain regions as an exemplar because of their vulnerability to climate change and their capacity to act as early-warning systems, which make them priority regions for adaptation actions. Mountain regions are also important because of their high biodiversity[33] and supply of nature's contributions to people to both upland and lowland human communities[34-38]. Our research questions are: (1) What elements of transformative change are present in NbS? (2) How do NbS contribute to transformative change in social-ecological systems (SES)? (3) How does transformative change occur across a typology of NbS? Our approach is informed by our collective experience on SES science, sustainability transformations, and transformative adaptation to climate change. Our results confirm the potential of NbS for transformative change, as observed by changes in non-sustainable trajectories of SES. The presented framework allows tracking the effectiveness of NbS towards transformative change.

RESULTS

BOX 1. Assessing transformative change through NbS

The multi-dimensionality of NbS requires an all-encompassing framework to allow for their adequate assessment. Our approach builds upon three frameworks in the transformative change literature, transformative adaptation and interdisciplinary science. First, the 'three spheres of transformation' framework describes the dimensions of *personal* (with elements including knowledge, values and worldviews), *political* (rules, economic and legal instruments, governance) and *practical* (behaviours, management and technical responses) in which a transformation process is based[39]. These dimensions accord with the leverage points concept, which considers transformations based in the personal sphere as having greater systemic impacts than those based in other dimensions[40]. Second, the six indicators of transformative adaptation (restructuring, path-shifting, multi-scale, innovative, system-wide, and persistent) help to assess whether profound and fundamental alterations have occurred in SES using a before-and-after analysis[41]. Third, the IPBES framework´s elements of biodiversity, nature´s contributions to people and good quality of life, can help evaluate outcomes of NbS for nature and people[42,43]. Combining these three frameworks, our approach allows to assess transformative change as a process, including NbS elements, how transformative change has occurred within an SES, and its main outcomes.



NbS identified

We identified 93 NbS in mountain environments from 54 countries (Figure 1a). The Andes contains most reported NbS (18%) followed by the Himalayas (11%). 78% of NbS were located in upper- and lower-middle income countries (Figure 1b). Most NbS addressed challenges related to land degradation (75%), followed by poverty (68%), poor governance (65%) and climate change (48%), highlighting a wide range of potential applications of NbS (Figure 1c). Most common specific challenges were land and forest degradation (53%), biodiversity loss (47%), ecosystem loss (39%), lack of public and decision-makers' awareness (39%), lack of alternative income opportunities (35%), poor governance and participation (35%), lack of access to long term funding (31%) and drought (31%) (Figure 1d).

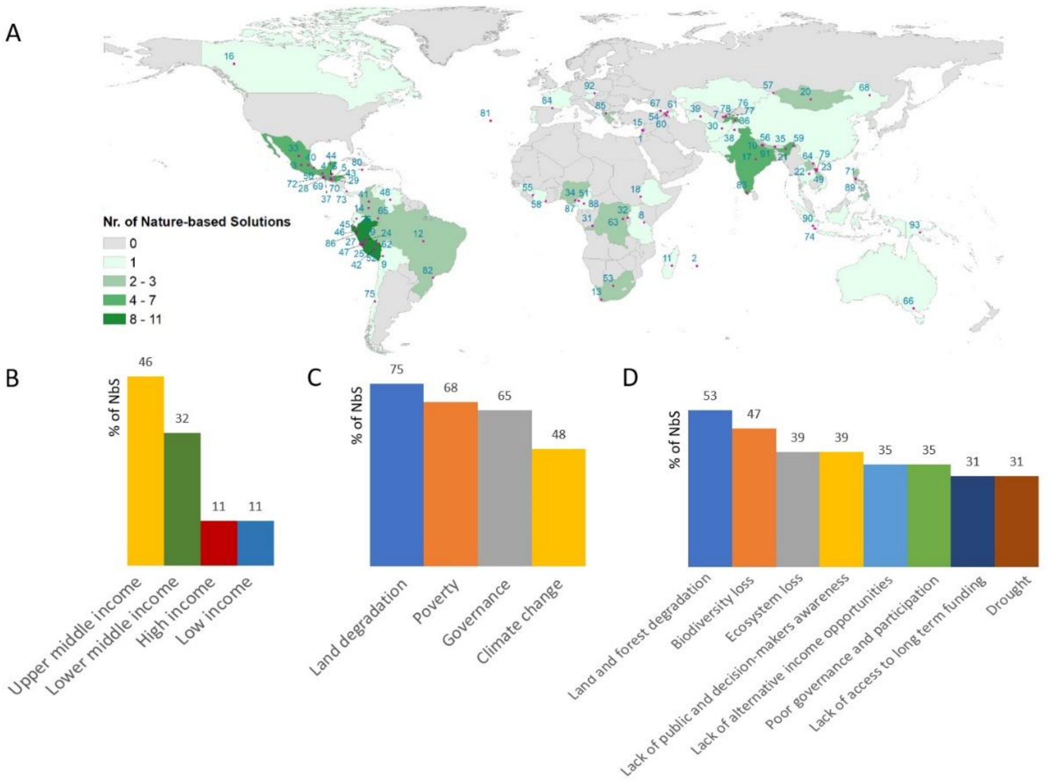


Figure 1. (a) Location of the mountain nature-based solutions reported in the PANORAMA database. The numbers in blue are the identifiers of each NbS (see Supplemental Information); (b) Distribution by income groups as defined by the World Bank; (c) Broad challenges addressed; and (d) Specific challenges addressed.

Elements of NbS linked to transformative change

Most NbS contained elements of the three spheres of transformation (Table 1). The most frequent elements belonged to the personal sphere, as all NbS were framed within particular nature´s values and used certain knowledge types. The next most frequent elements were community engagement instruments (political sphere) and management practices (practical sphere). Within nature's values, equally frequent were intrinsic and instrumental ones, often in combination, while relational values were less frequent. The most frequent knowledge type reported was technical, then scientific, then lay and experiential, and finally indigenous and local knowledge. Among community engagement instruments, the large majority of NbS reported participation and capacity building. Finally, among management practices, half of NbS reported restoration, followed by biodiversity/ecosystems monitoring and reduced pressure on ecosystems. Other recurrent elements of NbS include: strategic planning, economic incentives, behavioural practices, technology, rights-based instruments and legal incentives.

Table 1. The ten elements of NbS related to transformative change across three spheres of transformation[39]. The numbers in brackets show the percentage of the reviewed NbS that addressed the spheres, the elements, and specific variables of the elements. We only present variables with percentages > 5%.

Spheres of transformation	***Elements***	***Variables***	***Supporting references***

Personal: personal and collective beliefs, values, worldviews and knowledge types. *(100%)*	*Nature´s values*: the principles, preferences, and importance of nature for humans. *(100%)*	*Intrinsic (75%), Instrumental (75%), Relational (10%)*	*44*
	Knowledge types: a body of propositions that are adhered to by people, whether formally or informally, and are routinely used to claim truth. They are organized structures and dynamic processes. *(100%)*	*Technical (96%), Scientific (55%), Lay and experiential (40%), Indigenous and local knowledge (34%)*	*45*
Political: economic, legal, political, social and cultural elements. *(100%)*	*Community engagement instruments*: the mechanisms that allow the engagement of stakeholders and society in general, commonly known as participation. *(99%)*	*Participation (90%), Capacity building (77%), Awareness raising (41%), Advisory committee (28%), Access to information (24%), Dissemination (22%), Vision creation (19%), Facilitation (13%), Leadership program (12%)*	*46-49*
	Economic and financial instruments: a wide range of traditional and modern approaches that include fiscal instruments and incentive schemes among others. *(41%)*	*Payments for Ecosystem Services (10%), Low income loans (9%), Other economic incentives (12%)*	*49*
	Rights-based instruments and customary norms: the approaches to conservation that respect and promote recognized human rights standards. *(25%)*	*Community conserved areas (16%), Customary norms (9%)*	*50-51*
	Legal and regulatory instruments: the diverse politically binding regulations used in conservation. *(23%)*	*Protected areas (17%)*	*52*
Practical: technical, technological, strategic, practical and behavioural elements. *(97%)*	*Management practice*: the landscape management practices used in forestry, agriculture and related sectors. *(87%)*	*Restoration (50%), Biodiversity/ecosystems monitoring (43%), Reduced pressure (35%), Biodiversity/ecosystems management (27%), Tree/crop nurseries (19%), Organic farming or smart agriculture (11%)*	*53-55*
	Strategic planning: the approaches adopted in conservation (such as ecosystem-based adaptation or integrated landscape planning) and their strategic implementation. *(67%)*	*Environmental management framework (49%), Management plan (40%), Diagnostic assessment (23%)*	*56*
	Behaviour: the practical changes in the habits and lifestyle of individuals which are positive for the environment or for the livelihoods of those concerned. *(35%)*	*Income diversification (30%), Direct sales of agricultural products (8%), Pro-environmental behaviour (8%)*	*57-59*
	Technology: the body of techniques, methods and processes used to produce a certain good or (ecosystem) service. *(28%)*	*Modern technology (15%), Ancient technology (15%), Grey infrastructure (12%), Green infrastructure (10%)*	*60-61*

Main outcomes of NbS

Our analysis shows that 76% of NbS reported positive outcomes for biodiversity conservation and 86% mentioned an increase in nature´s contributions to people. Regulating contributions were most frequently mentioned (68%), followed by material (45%) and non-material (25%) contributions. In terms of good quality of life, 87% of NbS reported some kind of positive outcomes. Those mentioned most frequently were increased system's knowledge (52%), followed by basic materials for a good life (37%), increased resilience (35%) and employment (32%).

How do NbS combine elements of transformation?

In this section, we illustrate how NbS combine several elements of transformative change. Figure 2 shows the relations between, on the one hand, the framing of NbS in terms of intrinsic, instrumental and relational nature´s values (elements of the personal sphere) and, on the other hand, the rest of the components of our framework: knowledge types (Fig. 2a), the elements of the political sphere (Fig. 2b), the elements of the practical sphere (Fig. 2c) and the outcomes (Fig. 2d). We found that intrinsic nature´s values often associate with lay and experiential knowledge (X^2=3.84; p=0.001), strategic planning (X^2=7.81; p=0.007), technology (X^2=9.48; p<0.0001) and the outcome of improving biodiversity (X^2=3.84; p=0.000). Instrumental values are associated with strategic planning (X^2=7.81; p=0.000) and the outcome of enhancing nature´s contributions to people (X^2=15.50; p=0.000). Relational values associate with technical knowledge (X^2=3.84; p=0.005), indigenous and local knowledge (X^2=3.84; p=0.032), rights based instruments and customary norms (X^2=5.99; p=0.003) and the outcome of enhancing nature´s contributions to people (X^2=15.50; p=0.007).

We also observed combinations of several variables within elements of transformation. For example, regarding nature´s values, 55% of NbS were framed based on more than one nature´s value; the most frequent combination being intrinsic and instrumental values (44% of NbS). Regarding knowledge types, 81% of NbS used more than one, and multiple combinations were found, with two or three types of knowledge (42% and 33% of NbS, respectively) being the most frequent combinations (see Table S1 in Supplemental Information). In relation to the political sphere, 94% of NbS combined two or more community engagement instruments and 60% combined two or more management practices. On average, each NbS involved four stakeholder types, mostly local communities (95% of NbS), followed by NGOs (75%), local authorities (59%), regional or national authorities (56%), private sector (29%), protected area managers (25%), universities (18%) and media (7%).

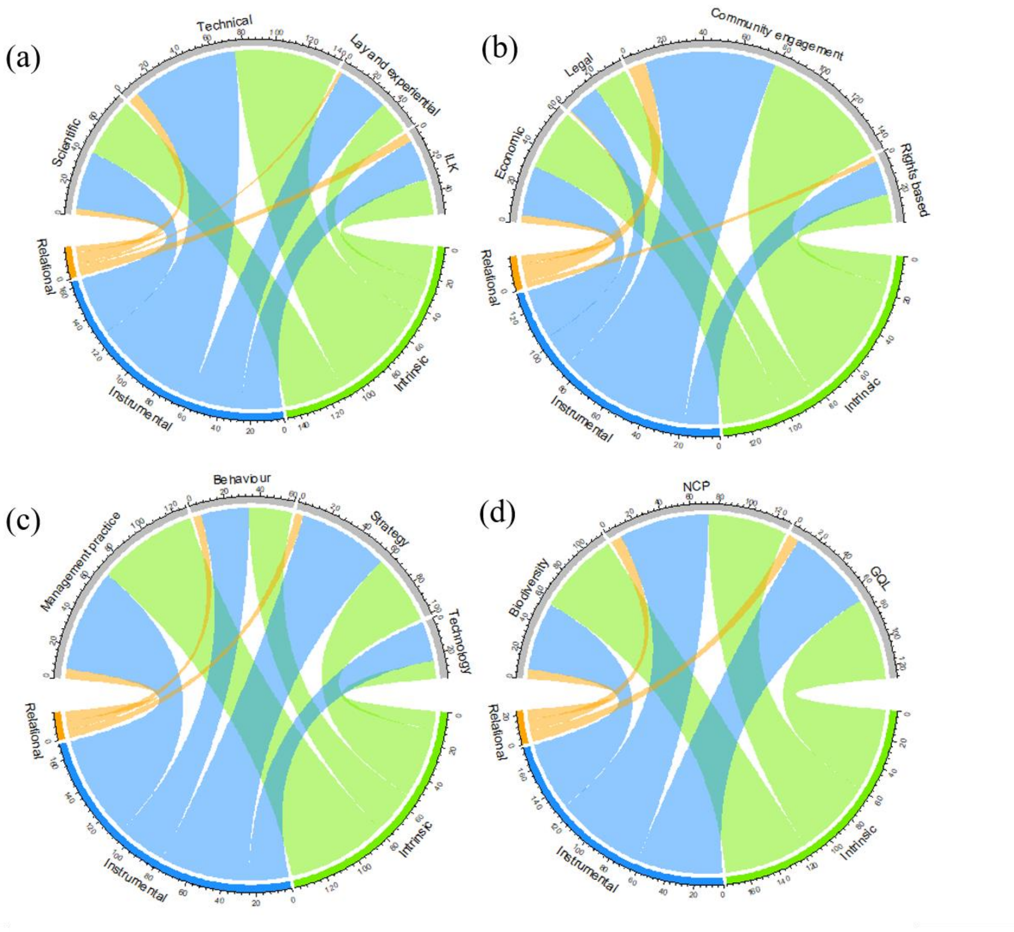


Figure 2. Chord Diagrams of the linkages between types of nature´s values (intrinsic, instrumental and relational) and (a) types of knowledge; (b) elements from the political sphere; (c) elements from the practical sphere; (d) outcomes. Abbreviations: ILK = Indigenous and Local Knowledge; Economic = Economic and financial instruments; Legal = Legal and regulatory instruments; Community engagement = Community engagement instruments; Rights based = Rights based instruments and customary norms.

Typologies of NbS and transformative change

A hierarchical clustering of the 93 NbS identified eight NbS types, grouped in three broad clusters (Figure 3 and Tables S2-S4 in Supplemental Information): (A) 'Conserving biodiversity, reducing degradation'; (B) 'Local and Indigenous Peoples, biodiversity friendly development'; and (C) 'Climate adaptation and disaster risk reduction'.

Conserving biodiversity, reducing degradation. This cluster (34 cases) mostly addresses human impacts on biodiversity and ecosystems through habitat fragmentation and degradation using conservation and restoration actions. The first type, "Livelihoods and biodiversity in agricultural landscapes", is characterized by capacity building programs and community conserved areas. It includes NbS that foster capacity building and empowerment of landless farmers in Mexico (example #1), and other NbS such as the establishment and management of biocultural heritage in Peru. Material nature´s contributions to people often result from these NbS. The second type, "Financing restoration and mitigation", is characterized by the application of legal instruments such as the creation of protected areas. It contains NbS that include use of carbon taxes to transform agriculture and forestry, and the creation of a biosphere reserve incorporating sustainable coffee production in Ethiopia (#2). Climate regulation is the natural contribution to people mostly mentioned within this group. The third type, “Protected area governance”, is framed within intrinsic values. It contains NbS such as restoration and conservation actions to protect the Azores bullfinch in Portugal (#3) and a program for the declaration of private protected areas in South Africa. The most cited outcome is biodiversity conservation.

Local and Indigenous Peoples, biodiversity-friendly development. This cluster (22 cases) addresses human impacts on biodiversity and ecosystems, poor governance, and participation. The type “Local people, tourism and benefit sharing” includes several NbS related to nature tourism regulated by local communities. For example, economic incentives to local guides for biodiversity sightings, which reduced poaching in Laos (#4), and a community conservation area for sustainable livelihoods in India. The main outcomes of this type are non-material nature´s contributions to people and employment. The type “Local communities and finance” contains cases in which donors facilitate implementation of NbS, as the Prespa Ohrid Nature Trust, which supports transboundary conservation actions in eastern Europe, or a conservation agreement involving a private company at El Caura, Venezuela (#5). Employment creation and education are the most common outcomes of this type of NbS.

Climate adaptation and disaster risk reduction. This cluster (37 cases) addresses climate change and associated erratic rainfall, droughts and floods. The type “Adapting productive land and natural resources” is characterized by instrumental values, indigenous and local knowledge and strategic planning. It contains various NbS in agricultural areas such as the implementation of climate-resilient crops and community-appointed members to regulate water use in Nepal. It often includes restoration actions such as the restoration of a cloud forest with native species in Mexico (#6). The most characteristic outcomes in terms of nature´s contributions to people are water regulation, soil conservation, and food and fodder production. This type is characterized by outcomes of increased resilience, knowledge and material resources. The type “Disaster risk reduction and infrastructure” contains NbS involving restoration of degraded hillslopes to protect communities from floods and landslides in Pakistan, and other NbS that combine green and hard infrastructure, such as the construction of gabion walls combined with willow trees by a community in Tajikistan (#7). The main outcome in terms of nature´s contributions to people is the regulation of hazards. The type “Adapting watersheds to climate change” is characterized by instrumental values and indigenous and local knowledge, multi-level governance, traditional technologies, strategic planning and green and grey infrastructure. It contains NbS mostly linked to watershed management and the use of green infrastructure (e.g. restoration of mountain pastures and wetlands to provide regular water flows in Canchayllo, Peru, #8).

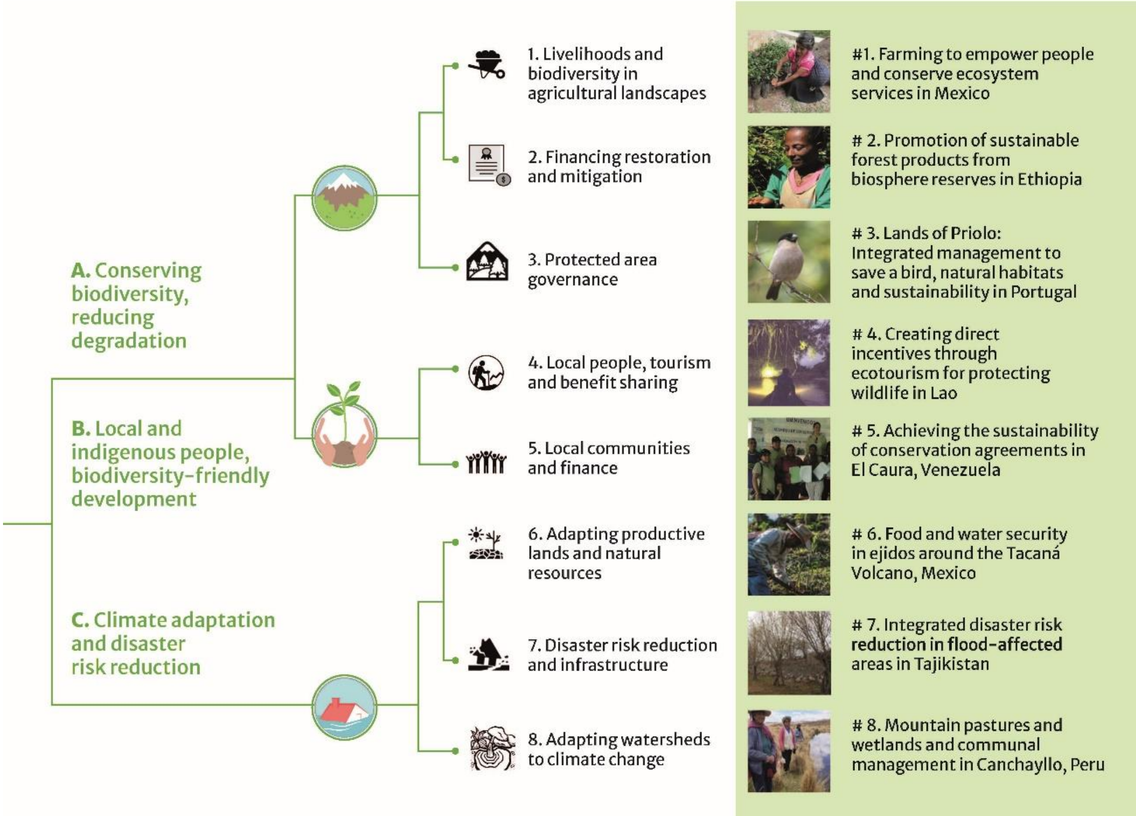


Figure 3. Overview of the three clusters and eight types of NbS emerging from our analysis, and selected examples of NbS.

How does transformative change happen? – examples based on indicators of transformation

In this section, we use the six indicators of transformative adaptation (restructuring, path-shifting, multi-scale, innovative, system-wide and persistent)[41] to illustrate *profound and fundamental* changes in SES (see also Table S4 in Supplemental Information for a more detailed analysis). To structure the results, descriptions here are organized according to either social, ecological or joint social-ecological changes.

Several of the assessed NbS entail ecological *restructuring* of the landscape through restoration, as in an NbS in the Azores which removed invasive species and restored laurel forests (#3). Others include social *restructuring* through reorganizing stakeholder networks as in the case of sustainable coffee production in Ethiopia (#2), which established cooperative structures and public-private partnerships. We identified *path-shifting* transformations in the ecological system through reduced deforestation or increased water flows, but also in the social system through, for example, increased revenues and empowerment of vulnerable farming communities in Mexico (#1). We identified cases of ecological *innovation* through the use of new crop varieties resilient to climate change, and of social *innovation* through the creation of novel private funds, or the emergence of new sources of income such as eco-tourism, as in Laos, where local guides were employed and poaching reduced (#4). *Multi-scale* aspects existed in various NbS, for example some state and federal agencies co-engaged in funding to increase food and water security in communal land in Mexico (#6). This case recognised the need to be *system-wide* and work at the basin scale to be successful. *System-wide* perspectives are anchored on a social-ecological perspective and were present in various NbS, for example in the restoration of upper-watershed infrastructure to provide water to the lower-watershed in Canchayllo, Perú (#8). Though it is too early to evaluate if the NbS we assessed will be *persistent*, some of the transformative actions implemented are likely to persist. This is the case of legislative changes, such as the establishment of a biosphere reserve in Ethiopia (#2), and of the creation of new social identities as exemplified by the protection of the Priolo bird in the Azores (#3).

How do elements of NbS transform SES?

Here we present, for each of the selected NbS, a summary of how different elements of the NbS lead to transformative changes at the SES level. In case #1, participation, capacity building and leadership programs, which combined various knowledge types, together with income diversification practices allowed a *path-shifting* change in the SES. Such a change involved switching old paradigms for conservation and farming, increasing revenues and improving the conservation of soils, nutrients and water. Case #2 combined intrinsic and instrumental values through the creation of a biosphere reserve and the introduction of organic coffee farming. This led to *path-shifting* changes in deforestation trends, *system-wide* involvement of foreign companies and NGOs providing the conditions to develop coffee, and *persistence* through the legal status of the biosphere reserve. Case #3 was strongly framed around the intrinsic value of the Priolo bird, and included awareness raising and dissemination, as well as restoration measures. In this case, *path-shifting* happened when the Priolo shifted status from critically endangered to vulnerable. *Restructuring* occurred at landscape-scale due to restoration actions and *persistence* was achieved through the creation of a new social identity with the Priolo as a local symbol. In a context of continuous poaching, case #4 provided economic incentives to locals to act as eco-tourism guides and combined technical and indigenous knowledge. As a result, poaching was greatly reduced, leading to a *path-shifting* in conservation trends while social interactions were *restructured* with the participation of the private sector to bring in tourists to the region.

Case #5 combined intrinsic and instrumental values, a conservation agreement with a private company and biodiversity monitoring activities. *Path-shifting* changes occurred through reduced deforestation in 6% of the basin together with *restructuring* of social actors through the partnership with a private company. *Persistence* was promoted by the conservation agreement signed by the parties. Case #6 was mostly framed within instrumental values and included participation and capacity building, a diagnostic assessment, restoration actions and the implementation of agro-forestry. *Path-shifting* changes occurred through halting the advance of the agricultural frontier and several *multi-scale* aspects were present, with the engagement of state, federal and the local agencies in funding. *System-wide* properties were addressed by taking measures at the basin scale to secure water-related ecosystem services. Case #7 employed green and grey infrastructure to reduce flood risks and also included various knowledge types, capacity building and restoration actions. The greatest changes at the SES level occurred through *path-shifting*, with decreased flooding and an improved sense of security, which fostered cultivation of previously flood-prone areas. Landscape *restructuring* through restoration undertaken by community volunteers had a *system-wide* perspective by involving actors from upper and lower watersheds. Case #8 combined various knowledge types, grey and green infrastructure and restoration measures to adapt a watershed to climate change-related droughts. The combination of knowledge types, with participation from universities and local communities, provided a broad social *restructuring* that led to a communal decision to act on climate change. The whole community participated in the NbS, thus making it *system-wide*, and *path-shifting* was attained through increased water availability and reduced wildfire risks.

DISCUSSION

Measuring the potential for transformative change of NbS

Several frameworks have been proposed to understand what catalyses transformative change, such as levers and leverage points[6,40,62], and to assess what are the main co-benefits generated by NbS[63]. Here, we complement such efforts by integrating previously unconnected frameworks to explore how elements of NbS linked to transformative change produce *profound changes* in SES. The 10 elements of NbS linked to transformation allow the identification of those factors (e.g. knowledge, nature´s values, formal and non-formal institutions and management practices) that are mobilized during the process of change[39]. In turn, the six indicators of transformative adaptation[41] help assess how the SES as a whole has changed. Outcomes for biodiversity, nature´s contributions to people and good quality of life show the co-benefits generated by the NbS. We believe that this framework can contribute towards an integrative assessment and monitoring of NbS through a transformative change lens that is useful both for researchers and practitioners in the field.

The majority of NbS we assessed contained four elements linked to transformative change: nature´s values, knowledge types, participative and capacity building approaches, and management practices such as restoration, biodiversity/ecosystem monitoring and nature protection. These results highlight the need for combining multiple strategies to make NbS work, as well as the importance of integrating social and ecological factors. The need to adequately manage both ecological and social processes has also been identified in studies of co-production of adaptation services in response to climate change[9,64]. Thus, the future design and implementation of NbS, rather than using silver bullet approaches, may benefit from creating change with a social-ecological approach that is well-suited to the specific context of application.

Our results partly confirm the usefulness of applying integrated valuation approaches in landscape management, as half of the NbS combined various nature´s values, mostly instrumental and intrinsic values[65]. Over 80% of NbS combined various knowledge types, highlighting the usefulness of knowledge combination for transformative change, from scientific knowledge to indigenous and local knowledge[66].

The strong involvement of local communities with other stakeholder types is another characteristic in the NbS assessed. The fact that they address the interests of various stakeholder groups may be one of the reasons why they are strongly multifaceted. These aspects, together with the finding that 94% of NbS applied more than one type of community engagement process, align with studies showing that broad participation, capacity building and collaborative governance are central components in NbS[28,29,67,68]. Previous research has also shown that a higher number of actors and of skills and management capabilities results in higher resilience to climate change in mountain SES[69].This need for strong stakeholder engagement confirms previous studies that put agency as a core component in NbS-driven transformative change[9,29].

Funding is a fundamental aspect in NbS, although we could not collate quantitative data on the projects' finances. Nonetheless, several of the NbS assessed were started by international NGOs, and had at least some initial funding to be developed and implemented. Previous work also identified financial resources as the most frequently reported barrier to the development and uptake of NbS[70].

Challenges in assessing transformative change

It is important to consider that the primary material of our dataset was written by "solution providers" who openly contributed sustainability initiatives (see more details on the PANORAMA platform in the Experimental Procedures section). This may have biased our dataset towards successful NbS examples. We have not provided counterfactual arguments based on failed NbS to confirm our analysis of what makes NbS work, which future studies may do. Other recent efforts in cataloguing environmental solutions in multiple platforms towards a good Anthropocene also provide a useful starting point for assessing NbS and potential empirical examples of transformative change[71,72]. Based on our results, these platforms should include space for explicitly assessing transformative change-related variables in various dimensions and also for acknowledging limitations and challenges faced by the solutions.

We have not differentiated between incremental and transformative change across all assessed NbS because what is considered transformative in one context or scale, may be perceived as incremental change in another. Also, incremental and transformative change have sometimes been considered part of a continuum[73]. Identifying what is a *profound and fundamental* change in social-ecological relationships, versus what is not, and then generalizing across a large set of case studies, is challenging. However, a recent work assessing empirical case studies of climate change driven shifts in trajectories of SES, reported that only in one-quarter of the cases transformative adaptation materialized, being the rest incremental adaptation or coping strategies[74]. In our dataset, the considerable number of positive outcomes in terms of path-shifting and re-structuring (newly established protected areas, new sustainable approaches for livelihoods, resolved conservation conflicts, etc.) suggests a higher proportion of transformative change cases. Nonetheless, further analysis of larger and more diverse datasets is needed to assess the transformative potential of NbS. Future applications of our framework may also use semi-quantitative or quantitative approaches to address transformation. For example, one study on transformative adaptation in agriculture defined transformation as requiring changes of at least a third of the primary factors of production (land, labor, capital) in less than 25 years[10].

Previous work has emphasized the relevance of equity and justice in NbS and environmental governance[75,76]. In our dataset, we only found limited information regarding equity, with 23% of NbS explicitly reporting a net increase in this factor. Further studies about the effect of NbS on the different dimensions of equity are thus needed. Moreover, we couldn't assess if our results in relation to equity would change according to which stakeholder type provided the solution to PANORAMA. Additionally, co-creating change has shown to be necessary but insufficient for success in some reported case studies[77]. Thus, it remains necessary to evaluate how power dynamics influence equity and the outcomes of NbS[78].

Assessing transformative change through a typology of NbS

Here, we have presented a typology of NbS based on extensive descriptions of NbS made by solution providers (see Methods section for details). Previous typologies of NbS were based on either the challenges addressed by them or the level of nature-engineering and its co-benefits[18]. We believe the major contribution of our classification is that it reveals the complex interactions among various challenges and the multiple options used to address them through the lens of transformation. In relation to the challenges addressed, the majority of NbS addressed land degradation related challenges, in combination with other challenges, such as poverty, governance issues and climate change, which often appeared in combination. Climate change being one of the main challenges possibly indicates a response to higher rates of warming in mountain regions than elsewhere, and emphasises the downstream impacts for lowland regions if global warming is not addressed.

Our typology of NbS from a transformation perspective may enhance understanding of which elements linked to transformation are common across NbS and which are context-specific. We found that elements within the political sphere, i.e. relating to governance, more frequently serve to differentiate among NbS types (Table S2). This confirms the importance of adapting governance for the design and implementation of NbS[62] and to achieve transformative change[3,79]. From the examples given in each NbS type, we found that those related to protected areas (NbS type 3), finance (2 & 5) and climate change (6-8) had a stronger emphasis on environmental management, including conservation and restoration actions. NbS types 1 and 5, which face major challenges of community development, emphasized capacity building activities and raising revenues through sustainable practices (Table S3).

Sustainability science needs to provide robust approaches to monitor progress towards sustainability and transformative change. Any research agenda for transformative change needs to be co-produced to be most effective[80]. The forthcoming IPBES thematic assessment of transformative change will contribute to this endeavour. Evaluating transformative change becomes increasingly complex when we move from approaches that assess single variables such as greenhouse gas emissions to inter- and transdisciplinary approaches that assess several dimensions[81,82]. Thus, sustainability science should provide frameworks for evaluating both the processes and outcomes of transformative change. Our framework bridges the broad literature on social-ecological transformative change and transformative adaptation with the application of promising socio-environmental practices such as NbS. In so doing, it enhances our understanding of the links between the design, implementation and outcomes of NbS.

EXPERIMENTAL PROCEDURES

Resource Availability

Lead Contact

Further questions about the analysis and data should be directed to and will be fulfilled by the Lead Contact, Ignacio Palomo (ignacio.palomo@univ-grenoble-alpes.fr).

Materials Availability

This study did not generate new unique materials.

Data and Code Availability Statement

Data generated in this study are available in the Supplemental on-line information (Data S1).

Methods

We searched the PANORAMA web platform (https://panorama.solutions), developed by GIZ (German Corporation for International Cooperation) and IUCN (International Union for Conservation of Nature) among other partners, and selected those NbS implemented in mountain environments. For the selection of NbS, we used a broad definition of mountains based on altitudinal gradient[83]. Our search, spanning English and Spanish languages, yielded 122 cases. We discarded those that were not strictly NbS (i.e. without direct protection or use of nature or nature´s contributions to people) and those with insufficient information to assess implementation. All assessed NbS related to direct or indirect positive outcomes for people. We excluded broad-scale governance initiatives (e.g. national policies), to focus on local and regional projects only. These selection criteria provided a total of 93 NbS (Table S5).

The framework of the three spheres of transformation[39] was expanded to include a total of ten NbS elements. These elements were selected using a deductive and inductive iterative process by coding the information provided by the PANORAMA platform on the selected NbS and contrasting this information with published literature on aspects known to influence transformative change. These aspects include knowledge, nature´s values, stakeholder participation, institutions, human behaviour and technology among others. For this, we built on previous frameworks such as the Values-Rules-Knowledge framework[84] of the Transformative Adaptation Research Alliance to which various co-authors belong[85]. The information regarding the ten elements of transformation was extracted from the extensive NbS descriptions given by the solution providers (the individuals who upload a solution into the platform) in the solutions case study template, and was often present within the Building blocks and Story sections of the template.

The specific challenges that each NbS responds to were directly taken from the solution description on the platform as submitted by solution providers. We grouped the specific challenges into four main broad types: land degradation, poverty, governance and climate change. Among all coded variables, we found the ones referring to outcomes the most difficult to assess because of the diversity of NbS outcome descriptions. The categories used for outputs included biodiversity, the 17 nature´s contributions to people from the IPBES framework, the five components of human wellbeing from the Millennium Ecosystem Assessment report (health, security, basic materials for good life, good social relations and freedom of choice and action) and six additional components (resilience, knowledge, education, employment, equity and reduced conflicts). The information for the outputs was mostly present in the Impacts section of the solutions template, although sometimes it was present in other sections. To evaluate the interactions among components of the framework, and assess if certain elements of the spheres are frequently applied in combination, or if they more often result in a certain type of outcomes than others, we performed Chi-square test analysis.

We acknowledge that the NbS analysed were obtained from a platform that showcases "examples of inspiring, replicable solutions across a range of conservation and sustainable development topics, enabling cross-sectoral learning and inspiration" which limits our results to positive outcomes. Also, we didn't conduct any parallel assessment of each NbS and its outcomes, and all our data is based on non-verified descriptions given by solution providers. Moreover, the framings that solution providers have applied (i.e. the way each solution is described) may have an influence on what is reported in the PANORAMA platform and thus may influence our results. However, we consider that the rich description of NbS and the standardized process to gather information allows for the comparative study of a relatively large number of case studies, which is fundamental to increase our knowledge on transformative change.

To establish a typology of NbS, we used the PANORAMA data on 'themes' (see Table S6 for the complete list of 52 themes), which are the tags selected by solution providers to describe each NbS. We used hclust in R, applied to binary distances between observations (for asymmetric binary variables). The optimal number of clusters was determined using an analysis of the heights in the hierarchical clustering dendrogram and a silhouette analysis. We found that 3 and 8 were the optimal number of clusters (see Supplemental Information). We acknowledge that boundaries among NbS types are fuzzy. Thus, we identified the 'best' members of each cluster, i.e. the most representative NbS. In each cluster, we classified the members as parts of the 'core' (if the silhouette width was higher than the median of all widths across the whole dataset), 'periphery' (with positive silhouette width but lower than the median), or 'in-between' (with negative silhouette width; in this case, we also identified the closest neighbouring cluster). Finally, we described the 3 clusters and 8 NbS types. To describe how descriptive binary variables or count variables (log.-transformed) differed among the clusters, we applied a V-test[86] to check whether frequencies or values for this variable were significantly higher in the cluster core and periphery (i.e., without the 'in-between' category) than in the whole set.

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Author Contributions

Conceptualization, I.P., B.L. and S.L.; Workshop participation, I.P., B.L., I.O., M.C., E.C., A.C-S., E.G-B., A.G-G., A.G-R, A.J-A., U.P., N.Z-C., E.B. and S.L.; Resources, M.F. and R.M.; Investigation, I.P; Formal analysis, I.P., B.L. and B.M-L., Writing, all authors.

Declaration of Interests

The authors declare no competing interests.

Inclusion and diversity statement

We worked to ensure gender balance in the team of co-authors that participated in the workshop.

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