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# 1 **Assessing Nature-based Solutions for transformative change**

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## 32 **SUMMARY**

33

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

## 46 **INTRODUCTION**

47 Transformative change in the context of sustainability refers to profound and fundamental  
48 alterations in social-ecological interactions in a way that sustains the earth’s biophysical  
49 systems, while meeting human needs<sup>1-3</sup>. According to the Intergovernmental science-policy  
50 Platform on Biodiversity and Ecosystem Services (IPBES) and the Intergovernmental Panel on

51 Climate Change (IPCC), such transformative change is necessary to achieve the Paris  
52 Agreement, the post-2020 biodiversity targets and several of the Sustainable Development  
53 Goals (SDGs)<sup>4-6</sup>. Research on transformative change has grown exponentially, as well as the  
54 disciplines engaged with it<sup>7,8</sup>. However, few studies have empirically evaluated through large  
55 datasets the processes that successfully lead to transformative change and associated  
56 sustainability outcomes<sup>9-11</sup>.

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

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

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

## 90 **RESULTS**

### 91 **Box 1 here.**

### 92 **NbS identified**

94 We identified 93 NbS in mountain environments from 54 countries (Figure 1a). The Andes  
95 contains most reported NbS (18%) followed by the Himalayas (11%). 78% of NbS were located  
96 in upper- and lower-middle income countries (Figure 1b). Most NbS addressed challenges  
97 related to land degradation (75%), followed by poverty (68%), poor governance (65%) and

98 climate change (48%), highlighting a wide range of potential applications of NbS (Figure 1c).  
99 Most common specific challenges were land and forest degradation (53%), biodiversity loss  
100 (47%), ecosystem loss (39%), lack of public and decision-makers' awareness (39%), lack of  
101 alternative income opportunities (35%), poor governance and participation (35%), lack of  
102 access to long term funding (31%) and drought (31%) (Figure 1d).

### 103 **Elements of NbS linked to transformative change**

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

### 116 **Main outcomes of NbS**

117 Our analysis shows that 76% of NbS reported positive outcomes for biodiversity conservation  
118 and 86% mentioned an increase in nature's contributions to people. Regulating contributions  
119 were most frequently mentioned (68%), followed by material (45%) and non-material (25%)  
120 contributions. In terms of good quality of life, 87% of NbS reported some kind of positive  
121 outcomes. Those mentioned most frequently were increased system's knowledge (52%),  
122 followed by basic materials for a good life (37%), increased resilience (35%) and employment  
123 (32%).

### 124 **How do NbS combine elements of transformation?**

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

138 We also observed combinations of several variables within elements of transformation. For  
139 example, regarding nature's values, 55% of NbS were framed based on more than one nature's  
140 value; the most frequent combination being intrinsic and instrumental values (44% of NbS).  
141 Regarding knowledge types, 81% of NbS used more than one, and multiple combinations were  
142 found, with two or three types of knowledge (42% and 33% of NbS, respectively) being the  
143 most frequent combinations (see Table S1 in Supplemental Information). In relation to the  
144 political sphere, 94% of NbS combined two or more community engagement instruments and

145 60% combined two or more management practices. On average, each NbS involved four  
146 stakeholder types, mostly local communities (95% of NbS), followed by NGOs (75%), local  
147 authorities (59%), regional or national authorities (56%), private sector (29%), protected area  
148 managers (25%), universities (18%) and media (7%).

#### 149 **Typologies of NbS and transformative change**

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

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

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

180 *Climate adaptation and disaster risk reduction.* This cluster (37 cases) addresses climate change  
181 and associated erratic rainfall, droughts and floods. The type “Adapting productive land and  
182 natural resources” is characterized by instrumental values, indigenous and local knowledge and  
183 strategic planning. It contains various NbS in agricultural areas such as the implementation of  
184 climate-resilient crops and community-appointed members to regulate water use in Nepal. It  
185 often includes restoration actions such as the restoration of a cloud forest with native species in  
186 Mexico (#6). The most characteristic outcomes in terms of nature’s contributions to people are  
187 water regulation, soil conservation, and food and fodder production. This type is characterized  
188 by outcomes of increased resilience, knowledge and material resources. The type “Disaster risk  
189 reduction and infrastructure” contains NbS involving restoration of degraded hillslopes to  
190 protect communities from floods and landslides in Pakistan, and other NbS that combine green  
191 and hard infrastructure, such as the construction of gabion walls combined with willow trees by

192 a community in Tajikistan (#7). The main outcome in terms of nature’s contributions to people  
193 is the regulation of hazards. The type “Adapting watersheds to climate change” is characterized  
194 by instrumental values and indigenous and local knowledge, multi-level governance, traditional  
195 technologies, strategic planning and green and grey infrastructure. It contains NbS mostly  
196 linked to watershed management and the use of green infrastructure (e.g. restoration of  
197 mountain pastures and wetlands to provide regular water flows in Canchayllo, Peru, #8).

### 198 **How does transformative change happen? – examples based on indicators of** 199 **transformation**

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

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

### 225 **How do elements of NbS transform SES?**

226 Here we present, for each of the selected NbS, a summary of how different elements of the NbS  
227 lead to transformative changes at the SES level. In case #1, participation, capacity building and  
228 leadership programs, which combined various knowledge types, together with income  
229 diversification practices allowed a *path-shifting* change in the SES. Such a change involved  
230 switching old paradigms for conservation and farming, increasing revenues and improving the  
231 conservation of soils, nutrients and water. Case #2 combined intrinsic and instrumental values  
232 through the creation of a biosphere reserve and the introduction of organic coffee farming. This  
233 led to *path-shifting* changes in deforestation trends, *system-wide* involvement of foreign  
234 companies and NGOs providing the conditions to develop coffee, and *persistence* through the  
235 legal status of the biosphere reserve. Case #3 was strongly framed around the intrinsic value of  
236 the Priolo bird, and included awareness raising and dissemination, as well as restoration  
237 measures. In this case, *path-shifting* happened when the Priolo shifted status from critically  
238 endangered to vulnerable. *Restructuring* occurred at landscape-scale due to restoration actions  
239 and *persistence* was achieved through the creation of a new social identity with the Priolo as a

240 local symbol. In a context of continuous poaching, case #4 provided economic incentives to  
241 locals to act as eco-tourism guides and combined technical and indigenous knowledge. As a  
242 result, poaching was greatly reduced, leading to a *path-shifting* in conservation trends while  
243 social interactions were *restructured* with the participation of the private sector to bring in  
244 tourists to the region.

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

## 266 **DISCUSSION**

### 267 **Measuring the potential for transformative change of NbS**

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

280 The majority of NbS we assessed contained four elements linked to transformative change:  
281 nature's values, knowledge types, participative and capacity building approaches, and  
282 management practices such as restoration, biodiversity/ecosystem monitoring and nature  
283 protection. These results highlight the need for combining multiple strategies to make NbS  
284 work, as well as the importance of integrating social and ecological factors. The need to  
285 adequately manage both ecological and social processes has also been identified in studies of  
286 co-production of adaptation services in response to climate change<sup>9,64</sup>. Thus, the future design

287 and implementation of NbS, rather than using silver bullet approaches, may benefit from  
288 creating change with a social-ecological approach that is well-suited to the specific context of  
289 application.

290 Our results partly confirm the usefulness of applying integrated valuation approaches in  
291 landscape management, as half of the NbS combined various nature's values, mostly  
292 instrumental and intrinsic values<sup>65</sup>. Over 80% of NbS combined various knowledge types,  
293 highlighting the usefulness of knowledge combination for transformative change, from  
294 scientific knowledge to indigenous and local knowledge<sup>66</sup>.

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

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

309

### 310 **Challenges in assessing transformative change**

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

321

322 We have not differentiated between incremental and transformative change across all assessed  
323 NbS because what is considered transformative in one context or scale, may be perceived as  
324 incremental change in another. Also, incremental and transformative change have sometimes  
325 been considered part of a continuum<sup>73</sup>. Identifying what is a *profound and fundamental* change  
326 in social-ecological relationships, versus what is not, and then generalizing across a large set of  
327 case studies, is challenging. However, a recent work assessing empirical case studies of climate  
328 change driven shifts in trajectories of SES, reported that only in one-quarter of the cases  
329 transformative adaptation materialized, being the rest incremental adaptation or coping  
330 strategies<sup>74</sup>. In our dataset, the considerable number of positive outcomes in terms of path-  
331 shifting and re-structuring (newly established protected areas, new sustainable approaches for  
332 livelihoods, resolved conservation conflicts, etc.) suggests a higher proportion of transformative  
333 change cases. Nonetheless, further analysis of larger and more diverse datasets is needed to  
334 assess the transformative potential of NbS. Future applications of our framework may also use

335 semi-quantitative or quantitative approaches to address transformation. For example, one study  
336 on transformative adaptation in agriculture defined transformation as requiring changes of at  
337 least a third of the primary factors of production (land, labor, capital) in less than 25 years<sup>10</sup>.

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

346

### 347 **Assessing transformative change through a typology of NbS**

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

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

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

## 380 **EXPERIMENTAL PROCEDURES**

### 381 **Resource Availability**

382 **Lead Contact**

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

385

386 **Materials Availability**

387 This study did not generate new unique materials.

388 **Data and Code Availability Statement**

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

390 **Methods**

391 We searched the PANORAMA web platform (<https://panorama.solutions>), developed by GIZ  
392 (German Corporation for International Cooperation) and IUCN (International Union for  
393 Conservation of Nature) among other partners, and selected those NbS implemented in  
394 mountain environments. For the selection of NbS, we used a broad definition of mountains  
395 based on altitudinal gradient<sup>83</sup>. Our search, spanning English and Spanish languages, yielded  
396 122 cases. We discarded those that were not strictly NbS (i.e. without direct protection or use of  
397 nature or nature's contributions to people) and those with insufficient information to assess  
398 implementation. All assessed NbS related to direct or indirect positive outcomes for people. We  
399 excluded broad-scale governance initiatives (e.g. national policies), to focus on local and  
400 regional projects only. These selection criteria provided a total of 93 NbS (Table S5).

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

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

427 We acknowledge that the NbS analysed were obtained from a platform that showcases  
428 "examples of inspiring, replicable solutions across a range of conservation and sustainable

429 development topics, enabling cross-sectoral learning and inspiration” which limits our results to  
430 positive outcomes. Also, we didn’t conduct any parallel assessment of each NbS and its  
431 outcomes, and all our data is based on non-verified descriptions given by solution providers.  
432 Moreover, the framings that solution providers have applied (i.e. the way each solution is  
433 described) may have an influence on what is reported in the PANORAMA platform and thus  
434 may influence our results. However, we consider that the rich description of NbS and the  
435 standardized process to gather information allows for the comparative study of a relatively large  
436 number of case studies, which is fundamental to increase our knowledge on transformative  
437 change.

438 To establish a typology of NbS, we used the PANORAMA data on ‘themes’ (see Table S6 for  
439 the complete list of 52 themes), which are the tags selected by solution providers to describe  
440 each NbS. We used hclust in R, applied to binary distances between observations (for  
441 asymmetric binary variables). The optimal number of clusters was determined using an analysis  
442 of the heights in the hierarchical clustering dendrogram and a silhouette analysis. We found that  
443 3 and 8 were the optimal number of clusters (see Supplemental Information). We acknowledge  
444 that boundaries among NbS types are fuzzy. Thus, we identified the ‘best’ members of each  
445 cluster, i.e. the most representative NbS. In each cluster, we classified the members as parts of  
446 the ‘core’ (if the silhouette width was higher than the median of all widths across the whole  
447 dataset), ‘periphery’ (with positive silhouette width but lower than the median), or ‘in-between’  
448 (with negative silhouette width; in this case, we also identified the closest neighbouring cluster).  
449 Finally, we described the 3 clusters and 8 NbS types. To describe how descriptive binary  
450 variables or count variables (log.-transformed) differed among the clusters, we applied a V-  
451 test<sup>86</sup> to check whether frequencies or values for this variable were significantly higher in the  
452 cluster core and periphery (i.e., without the ‘in-between’ category) than in the whole set.

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#### 461 **Author Contributions**

462 Conceptualization, I.P., B.L. and S.L.; Workshop participation, I.P., B.L., I.O., M.C., E.C., A.C-  
463 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.;  
464 Investigation, I.P; Formal analysis, I.P., B.L. and B.M-L., Writing, all authors.

#### 465 **Declaration of Interests**

466 The authors declare no competing interests.

#### 467 **Inclusion and diversity statement**

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

#### 470 **References**

- 471 1. Feola, G. (2015). Societal transformation in response to global environmental  
472 change: a review of emerging concepts. *Ambio* 44(5), 376-390.

- 473 2. Gillard, R., Gouldson, A., Paavola, J., and Van Alstine, J. (2016).  
474 Transformational responses to climate change: beyond a systems perspective of  
475 social change in mitigation and adaptation. *Wires Clim. Change* 7(2), 251-265.
- 476 3. Patterson, J., Schulz, K., Vervoort, J., Van Der Hel, S., Widerberg, O., Adler, C.,  
477 Hulbert, M., Anderton, K., Sethi, M., and Barau, A. (2017). Exploring the  
478 governance and politics of transformations towards sustainability. *Environ.*  
479 *Innov. Soc. Transitions* 24, 1-16.
- 480 4. Díaz, S. M., Settele, J., Brondízio, E., Ngo, H., Guèze, M., Agard, J., Arneth, A.,  
481 Balvanera, P., Kate, B., Stuart, B., et al. (2019). The global assessment report on  
482 biodiversity and ecosystem services: Summary for policy makers. IPBES.
- 483 5. Hoegh-Guldberg, O., Jacob, D., Bindi, M., Brown, S., Camilloni, I., Diedhiou,  
484 A., Djalante, A., Ebi, K., Engelbrecht, F., and Guiot, J., et al. (2018). Impacts of  
485 1.5 °C global warming on natural and human systems. In *Global Warming of*  
486 *1.5° C: An IPCC Special Report on the impacts of global warming of 1.5° C*  
487 *above pre-industrial levels and related global greenhouse gas emission*  
488 *pathways, in the context of strengthening the global response to the threat of*  
489 *climate change, sustainable development, and efforts to eradicate poverty.* IPCC.
- 490 6. Chan, K.M., Boyd, D.R., Gould, R. K., Jetzkowitz, J., Liu, J., Muraca, B.,  
491 Naido, R., Olmsted, P., Satterfield, T., Selomane, O., Singh, G.G., et al. (2020).  
492 Levers and leverage points for pathways to sustainability. *People and Nature*  
493 2(3), 693-717.
- 494 7. Köhler, J., Geels, F.W., Kern, F., Markard, J., Onsongo, E., Wieczorek, A.,  
495 Alkemade, F., Avelino, F., Bergek, A., Boons, F., et al. (2019). An agenda for  
496 sustainability transitions research: State of the art and future directions. *Environ.*  
497 *Innov. Soc. Transitions* 31, 1-32.
- 498 8. Schneider, F., Kläy, A., Zimmermann, A. B., Buser, T., Ingalls, M., and  
499 Messerli, P. (2019). How can science support the 2030 Agenda for Sustainable  
500 Development? Four tasks to tackle the normative dimension of sustainability.  
501 *Sustainability Science* 14(6), 1593-1604.
- 502 9. Colloff, M.J., Wise, R.M., Palomo, I., Lavorel, S., and Pascual, U. (2020).  
503 Nature's contribution to adaptation: insights from examples of the  
504 transformation of social-ecological systems. *Ecosystems and People* 16(1), 137-  
505 150.
- 506 10. Fazey, I., Moug, P., Allen, S., Beckmann, K., Blackwood, D., Bonaventura, M.,  
507 Burnett, K., Danson, M., Falconer, R., Gagnon, A.S., et al. (2018).  
508 Transformation in a changing climate: a research agenda. *Clim. Dev.* 10(3), 197-  
509 217.
- 510 11. Vermeulen, S.J., Dinesh, D., Howden, S. M., Cramer, L., and Thornton, P. K.  
511 (2018). Transformation in practice: a review of empirical cases of  
512 transformational adaptation in agriculture under climate change. *Front. Sust.*  
513 *Food Systems* 2, 65.
- 514 12. Loorbach, D., Frantzeskaki, N., and Avelino, F. (2017). Sustainability  
515 transitions research: transforming science and practice for societal change.  
516 *Annu. Rev. Env. Resour.* 42, 599-626.
- 517 13. Geels, F. W. (2010). Ontologies, socio-technical transitions (to sustainability),  
518 and the multi-level perspective. *Research Policy* 39(4), 495-510.
- 519 14. Frantzeskaki N, Loorbach D, Meadowcroft J. (2012). Governing societal  
520 transitions to sustainability. *Int. J. Sust. Dev. World* 15, 19–36

- 521 15. Otto, I. M., Donges, J. F., Cremades, R., Bhowmik, A., Hewitt, R. J., Lucht, W.,  
522 Rockström, J., Allerberger, F., McCaffrey, M., Doe, S.S.P., et al. (2020). Social  
523 tipping dynamics for stabilizing Earth's climate by 2050. *P. Natl. Acad. Sci.*  
524 *USA* 117(5), 2354-2365.
- 525 16. Gunderson L, Holling CS, eds. (2002). *Panarchy: Understanding*  
526 *Transformations in Human and Natural Systems*. Washington, DC: Island Press.
- 527 17. Olsson, P., Galaz, V., and Boonstra, W.J. (2014). Sustainability transformations:  
528 a resilience perspective. *Ecol. Soc.* 19(4).
- 529 18. Faivre, N., Fritz, M., Freitas, T., de Boissezon, B., and Vandewoestijne, S.  
530 (2017). Nature-Based Solutions in the EU: Innovating with nature to address  
531 social, economic and environmental challenges. *Environ. Res.* 159, 509-518.
- 532 19. Seddon, N., Chausson, A., Berry, P., Girardin, C. A., Smith, A., and Turner, B.  
533 (2020). Understanding the value and limits of nature-based solutions to climate  
534 change and other global challenges. *Phil. T. Roy. Soc. B* 375(1794), 20190120.
- 535 20. Cohen-Shacham, E., Walters, G., Janzen, C., and Maginnis, S. (2016). Nature-  
536 based solutions to address global societal challenges. IUCN, Gland, Switzerland.
- 537 21. Jones, H. P., Hole, D.G., and Zavaleta, E.S. (2012). Harnessing nature to help  
538 people adapt to climate change. *Nat. Clim. Change* 2(7), 504-509.
- 539 22. Keesstra, S., Nunes, J., Novara, A., Finger, D., Avelar, D., Kalantari, Z., and  
540 Cerdà, A. (2018). The superior effect of nature based solutions in land  
541 management for enhancing ecosystem services. *Sci. Total Environ.* 610, 997-  
542 1009.
- 543 23. Maes, J., and Jacobs, S. (2017). Nature-based solutions for Europe's sustainable  
544 development. *Conserv. Lett.* 10(1), 121-124.
- 545 24. Chausson, A., Turner, B., Seddon, D., Chabaneix, N., Girardin, C. A., Kapos,  
546 Key, I., Roe, D., Smith, A., Woroniecki, S., et al. (2020). Mapping the  
547 effectiveness of nature-based solutions for climate change adaptation. *Glob.*  
548 *Change Biol.* 26(11), 6134-6155.
- 549 25. Donatti, C.I., Harvey, C. A., Hole, D., Panfil, S.N., and Schurman, H. (2020).  
550 Indicators to measure the climate change adaptation outcomes of ecosystem-  
551 based adaptation. *Climatic Change* 158(3), 413-433.
- 552 26. Wamsler, C., Niven, L., Beery, T.H., Bramryd, T., Ekelund, N., Jönsson, K.I.,  
553 Osmani, A., Palo, T., and Stålhammar, S. (2016). Operationalizing ecosystem-  
554 based adaptation: harnessing ecosystem services to buffer communities against  
555 climate change. *Ecol. Soc.* 21(1).
- 556 27. Nesshöver, C., Assmuth, T., Irvine, K. N., Rusch, G. M., Waylen, K. A.,  
557 Delbaere, B., Haase, D., Jones-Walters, L., Keune, H., Kovacs, E., et al. (2017).  
558 The science, policy and practice of nature-based solutions: An interdisciplinary  
559 perspective. *Sci. Total Environ.* 579, 1215-1227.
- 560 28. Cohen-Shacham, E., Andrade, A., Dalton, J., Dudley, N., Jones, M., Kumar, C.,  
561 Maginnis, S., Maynard, S., Nelson, C.R., Renaud, F.G. et al. (2019). Core  
562 principles for successfully implementing and upscaling Nature-based Solutions.  
563 *Environmental Sci. Policy* 98, 20-29.
- 564 29. van der Jagt, A. P., Raven, R., Dorst, H., and Runhaar, H. (2020). Nature-based  
565 innovation systems. *Environ. Innov. Soc. Transitions* 35, 202-216.
- 566 30. Milman, A., and Jagannathan, K. (2017). Conceptualization and implementation  
567 of ecosystems-based adaptation. *Climatic Change* 142(1-2), 113-127.

- 568 31. Springer, J. (2016). IUCN's Rights-Based Approach: A Systematization of the  
569 Union's Policy Instruments, Standards and Guidelines.
- 570 32. Turnheim, B., Berkhout, F., Geels, F., Hof, A., McMeekin, A., Nykvist, B., and  
571 van Vuuren, D. (2015). Evaluating sustainability transitions pathways: Bridging  
572 analytical approaches to address governance challenges. *Glob. Environ. Chang.*  
573 35, 239-253.
- 574 33. Rahbek, C., Borregaard, M.K., Colwell, R. K., Dalsgaard, B., Holt, B.G.,  
575 Morueta-Holme, N., Nogues-Bravo, D., Whittaker, R.J., and Fjeldsá, J. (2019).  
576 Humboldt's enigma: What causes global patterns of mountain biodiversity?  
577 *Science* 365(6458), 1108-1113.
- 578 34. Beniston, M. (2016). *Environmental change in mountains and uplands.*  
579 Routledge, Abingdon.
- 580 35. Palomo, I. (2017). Climate change impacts on ecosystem services in high  
581 mountain areas: a literature review. *Mt. Res. Dev.* 37(2), 179-187.
- 582 36. Schirpke, U., Tappeiner, U., and Tasser, E. (2019). A transnational perspective  
583 of global and regional ecosystem service flows from and to mountain regions.  
584 *Scientific reports* 9(1), 1-11.
- 585 37. Martin-Lopez, B., Leister, I., Lorenzo Cruz, P., Palomo, I., Grêt-Regamey, A.,  
586 Harrison, P.A., Lavorel, S., Locatelli, B., Luque, S., and Walz, A. (2019).  
587 Nature's contributions to people in mountains: A review. *PloS one* 14(6),  
588 e0217847.
- 589 38. Payne, D., Spehn, E. M., Snethlage, M., and Fischer, M. (2017). Opportunities  
590 for research on mountain biodiversity under global change. *Current. Opin. Env.*  
591 *Sust.* 29, 40-47.
- 592 39. O'Brien, K., and Sygna, L. (2013). Responding to climate change: the three  
593 spheres of transformation. In: *Proceedings of Transformation in a Changing*  
594 *Climate*, University of Oslo, Norway, pp. 19-21.
- 595 40. Meadows, D.H. (2009). *Thinking in Systems: A Primer.* (edited by Diana  
596 Wright). London: Earthscan.
- 597 41. Fedele, G., Donatti, C.I., Harvey, C.A., Hannah, L., and Hole, D. G. (2019).  
598 Transformative adaptation to climate change for sustainable social-ecological  
599 systems. *Environ. Sci. Policy* 101, 116-125.
- 600 42. Díaz, S., Pascual, U., Stenseke, M., Martín-López, B., Watson, R. T., Molnár,  
601 Z., Hill, R., Chan, K.M.A., Baste, I.A., Brauman, K.A., et al. (2018). Assessing  
602 nature's contributions to people. *Science* 359(6373), 270-272.
- 603 43. Díaz, S., Demissew, S., Carabias, J., Joly, C., Lonsdale, M., Ash, N.,  
604 Larigauderie, A., Adhikari, J.R., Arico, S., Báldi, A., et al. (2015). The IPBES  
605 Conceptual Framework—connecting nature and people. *Current. Opin. Env.*  
606 *Sust.* 14, 1-16.
- 607 44. Chan, K.M.A., Balvanera, P., Benessaiah, K., Chapman, M., Díaz, S., Gómez-  
608 Baggethun, E., Gould, R., Hannash, N., Jax, K., Klain, S., et al. (2016). Opinion:  
609 Why protect nature? Rethinking values and the environment. *P. Natl. Acad. Sci.*  
610 *USA* 113(6), 1462-1465.
- 611 45. Raymond, C. M., Fazey, I., Reed, M.S., Stringer, L.C., Robinson, G.M., and  
612 Evely, A.C. (2010). Integrating local and scientific knowledge for environmental  
613 management. *J. Environ. Manage.* 91(8), 1766-1777.

- 614 46. Armitage, D. (2008). Governance and the commons in a multi-level world. *Int.*  
615 *J. Commons* 2(1), 7-32.
- 616 47. Hooghe, L., Marks, G. (2003). Unraveling the central state, but how? Types of  
617 multi-level governance. *Am. Polit. Sci. Rev.* 233-243.
- 618 48. Pahl-Wostl, C. (2009). A conceptual framework for analysing adaptive capacity  
619 and multi-level learning processes in resource governance regimes. *Glob.*  
620 *Environ. Change* 19(3), 354-365.
- 621 49. Ring, I., Sandström, C., Acar, S., Adeishvili, M., Albert, C., Allard, C., Anker,  
622 Y., Arlettaz, R., Bela, G., Brink, B.T., et al. (2018) Chapter 6: Options for  
623 governance and decision-making across scales and sectors. In *IPBES: The*  
624 *IPBES regional assessment report on biodiversity and ecosystem services for*  
625 *Europe and Central Asia.* Rounsevell, M., Fischer, M., Torre-Marín Rando, A.  
626 and Mader, A. (eds.). Secretariat of the Intergovernmental Science-Policy  
627 Platform on Biodiversity and Ecosystem Services, Bonn, Germany.
- 628 50. Bawa, K. S., Rai, N. D., and Sodhi, N. S. (2011). Rights, governance, and  
629 conservation of biological diversity. *Conserv. Biol.* 25(3), 639-641.
- 630 51. Springer, J. (2016). IUCN's Rights-Based Approach: A Systematization of the  
631 Union's Policy Instruments, Standards and Guidelines.
- 632 52. Rodgers, C. (2013). *The Law of Nature Conservation.* OUP Oxford.
- 633 53. Heller, N.E., and Zavaleta, E.S. (2009). Biodiversity management in the face of  
634 climate change: a review of 22 years of recommendations. *Biol. Conserv.*  
635 142(1), 14-32.
- 636 54. Schmeller, D.S., Böhm, M., Arvanitidis, C., Barber-Meyer, S., Brummitt, N.,  
637 Chandler, M., Chatzinikolaou, E., Costello, M.J., Ding, H., García-Moreno, J., et  
638 al. (2017). Building capacity in biodiversity monitoring at the global scale.  
639 *Biodivers. Conserv.* 26(12), 2765-2790.
- 640 55. Wortley, L., Hero, J.M., and Howes, M. (2013). Evaluating ecological  
641 restoration success: a review of the literature. *Restor. Ecol.* 21(5), 537-543.
- 642 56. Albert, C., Schröter, B., Haase, D., Brillinger, M., Henze, J., Herrmann, S.,  
643 Gottwald, S., Guerrero, P., Nicolas, C., and Matzdorf, B. (2019). Addressing  
644 societal challenges through nature-based solutions: How can landscape planning  
645 and governance research contribute? *Landscape Urban Plan.* 182, 12-21.
- 646 57. Fournier, A.J. (2018). Direct-selling farming and urban externalities: What  
647 impact on product quality and market size? *Reg. Sci. Urban. Econ.* 70, 97-111.
- 648 58. Gatersleben, B., Murtagh, N., and Abrahamse, W. (2014). Values, identity and  
649 pro-environmental behaviour. *Contemporary Social Science* 9(4), 374-392.
- 650 59. Reardon, T., Berdegue, J., Barrett, C.B., and Stamoulis, K. (2007). Household  
651 income diversification into rural nonfarm activities. In: Haggblade, S., Hazell,  
652 P.B.R., and Reardon, T. (Eds). *Transforming the rural nonfarm economy:*  
653 *opportunities and threats in the developing world.* The Johns Hopkins University  
654 Press, Baltimore.
- 655 60. Santamouris, M. (2014). Cooling the cities—a review of reflective and green roof  
656 mitigation technologies to fight heat island and improve comfort in urban  
657 environments. *Solar Energy* 103, 682-703.
- 658 61. Singh, P.K., Dey, P., Jain, S.K., and Mujumdar, P. (2020). Hydrology and Water  
659 Resources Management in Ancient India. *Hydrology Earth Sys. Sci. Discussions*  
660 1-20.

- 661 62. Abson, D.J., Fischer, J., Leventon, J., Newig, J., Schomerus, T., Vilsmaier, U.,  
662 von Wehrden, H., Abernethy, P., Ives, C.D., Jager, N.W., et al. (2017). Leverage  
663 points for sustainability transformation. *Ambio* 46(1), 30-39.
- 664 63. Raymond, C. M., Frantzeskaki, N., Kabisch, N., Berry, P., Breil, M., Nita, M.  
665 R., Geneletti, D., and Calfapietra, C. (2017). A framework for assessing and  
666 implementing the co-benefits of nature-based solutions in urban areas. *Environ.*  
667 *Sci. Pol.* 77, 15-24.
- 668 64. Lavorel, S. Locatelli, B., Colloff, M.J., and Bruley, E. Co-producing ecosystem  
669 services for adapting to climate change. (2020). *Philos. T. Roy. Soc. B*  
670 375(1794), 20190119.
- 671 65. Jacobs, S., Dendoncker, N., Martín-López, B., Barton, D. N., Gomez-  
672 Baggethun, E., Boeraeve, F., McGrath, F.L., Vierikko, K., Geneletti, D.,  
673 Sevecke, K.J. et al. (2016). A new valuation school: integrating diverse values of  
674 nature in resource and land use decisions. *Ecosys. Serv.* 22, 213-220.
- 675 66. Lam, D.P., Hinz, E., Lang, D., Tengö, M., Wehrden, H., and Martín-López, B.  
676 (2020). Indigenous and local knowledge in sustainability transformations  
677 research: a literature review. *Ecol. Soc.* 25(1).
- 678 67. Ferreira, V., Barreira, A.P., Loures, L., Antunes, D., and Panagopoulos, T.  
679 (2020). Stakeholders' Engagement on Nature-Based Solutions: A Systematic  
680 Literature Review. *Sustainability* 12(2), 640.
- 681 68. Frantzeskaki, N. (2019). Seven lessons for planning nature-based solutions in  
682 cities. *Environ. Sci. Policy* 93, 101-111.
- 683 69. Grêt-Regamey, A., Huber, S. H., and Huber, R. (2019). Actors' diversity and the  
684 resilience of social-ecological systems to global change. *Nature Sustainability*  
685 2(4), 290-297.
- 686 70. Ershad Sarabi, S., Han, Q., Romme, A.G.L., de Vries, B., and Wendling, L.  
687 (2019). Key enablers of and barriers to the uptake and implementation of nature-  
688 based solutions in urban settings: a review. *Resources* 8(3), 121.
- 689 71. Bennett, E. M., Solan, M., Biggs, R., McPhearson, T., Norström, A. V., Olsson,  
690 P., Pereira, L., Peterson, G.D., Raudsepp-Hearne, C., Biermann, F., et al. (2016).  
691 Bright spots: seeds of a good Anthropocene. *Front. Ecol. Environ.* 14(8), 441-  
692 448.
- 693 72. Jiménez-Aceituno, A., Peterson, G. D., Norström, A.V., Wong, G.Y., and  
694 Downing, A.S. (2019). Local lens for SDG implementation: lessons from  
695 bottom-up approaches in Africa. *Sustainability Science* 15, 729-743.
- 696 73. Barnes, M. L., Bodin, Ö., Guerrero, A.M., McAllister, R.R., Alexander, S.M.,  
697 and Robins, G. (2017). The social structural foundations of adaptation and  
698 transformation in social-ecological systems. *Ecol. Soc.* 22(4).
- 699 74. Fedele, G., Donatti, C. I., Harvey, C. A., Hannah, L., and Hole, D. G. (2020).  
700 Limited use of transformative adaptation in response to social-ecological shifts  
701 driven by climate change. *Ecol. Soc.* 25(1), 25.
- 702 75. Keeler, B. L., Hamel, P., McPhearson, T., Hamann, M.H., Donahue, M.L.,  
703 Prado, K.A.M., Arkema, K.K., Bratman, G.N., Brauman, K.A., Finlay, J.C., et  
704 al. (2019). Social-ecological and technological factors moderate the value of  
705 urban nature. *Nat Sust* 2(1), 29-38.
- 706 76. Palomo, I., Dujardin, Y., Midler, E., Robin, M., Sanz, M.J., and Pascual, U.  
707 (2019). Modeling trade-offs across carbon sequestration, biodiversity

- 708 conservation, and equity in the distribution of global REDD+ funds. *P Natl Acad*  
709 *Sci USA* 116(45), 22645-22650.
- 710 77. Anderies, J.M., Folke, C., Walker, B., and Ostrom, E. (2013). Aligning key  
711 concepts for global change policy: robustness, resilience, and sustainability.  
712 *Ecol. Soc.* 18(2), 8.
- 713 78. Dentoni, D., Waddell, S., and Waddock, S. (2017). Pathways of transformation  
714 in global food and agricultural systems: implications from a large systems  
715 change theory perspective. *Current. Opin. Env. Sust.* 29, 8-13.
- 716 79. Scoones, I., Stirling, A., Abrol, D., Atela, J., Charli-Joseph, L., Eakin, H., Ely,  
717 A., Olsson, P., Pereira, L., and Priya, R. (2020). Transformations to  
718 sustainability: combining structural, systemic and enabling approaches. *Curr.*  
719 *Opin. Env. Sust.* 42, 65-75.
- 720 80. Norström, A.V., Cvitanovic, C., Löf, M.F., West, S., Wyborn, C., Balvanera, P.,  
721 Bednarek, A.T., Bennett, E.M., Biggs, R., de Bremond, A., et al. (2020).  
722 Principles for knowledge co-production in sustainability research. *Nature*  
723 *Sustainability* 1-9.
- 724 81. Barnes, M.L., Wang, P., Cinner, J.E., Graham, N.A., Guerrero, A.M., Jasny, L.,  
725 Lau, J., Sutcliffe, S.R, and Zamborain-Mason, J. (2020). Social determinants of  
726 adaptive and transformative responses to climate change. *Nat. Clim. Change* 1-  
727 6.
- 728 82. Tàbara, J.D., Jäger, J., Mangalagu, D., and Grasso, M. (2019). Defining  
729 transformative climate science to address high-end climate change. *Reg.*  
730 *Environ. Change* 19(3), 807-818.
- 731 83. Körner, C. Paulsen, J., and Spehn, E. M. (2011). A definition of mountains and  
732 their bioclimatic belts for global comparisons of biodiversity data. *Alpine Bot.*  
733 121(2), 73.
- 734 84. Gorddard, R., Colloff, M.J., Wise, R.M., Ware, D., and Dunlop, M. (2016).  
735 Values, rules and knowledge: adaptation as change in the decision context.  
736 *Environ. Sci. Policy* 57, 60-69.
- 737 85. Colloff, M.J., Martín-López, B., Lavorel, S., Locatelli, B., Gorddard, R.,  
738 Longaretti, P.Y., Walters, G., van Kerkhoff, L., Wyborn, C., Coreau, A., et al.  
739 (2017). An integrative research framework for enabling transformative  
740 adaptation. *Environ. Sci. Policy* 68, 87-96.
- 741 86. Cornillon, P.A., Guyader, A., Husson, F., Jegou, N., Josse, J., Kloareg, M.,  
742 Matzner-Lober, E., and Rouvière, L. (2012). *R for Statistics*. CRC Press.

#### 743 **BOX 1. Assessing transformative change through NbS**

747 The multi-dimensionality of NbS requires an all-encompassing framework to allow for their  
748 adequate assessment. Our approach builds upon three frameworks in the transformative change  
749 literature, transformative adaptation and interdisciplinary science. First, the ‘three spheres of  
750 transformation’ framework describes the dimensions of *personal* (with elements including  
751 knowledge, values and worldviews), *political* (rules, economic and legal instruments,  
752 governance) and *practical* (behaviours, management and technical responses) in which a  
753 transformation process is based<sup>39</sup>. These dimensions accord with the leverage points concept,  
754 which considers transformations based in the personal sphere as having greater systemic  
755 impacts than those based in other dimensions<sup>40</sup>. Second, the six indicators of transformative

756 adaptation (restructuring, path-shifting, multi-scale, innovative, system-wide, and persistent)  
 757 help to assess whether profound and fundamental alterations have occurred in SES using a  
 758 before-and-after analysis<sup>41</sup>. Third, the IPBES framework's elements of biodiversity, nature's  
 759 contributions to people and good quality of life, can help evaluate outcomes of NbS for nature  
 760 and people<sup>42,43</sup>. Combining these three frameworks, our approach allows to assess  
 761 transformative change as a process, including NbS elements, how transformative change has  
 762 occurred within an SES, and its main outcomes.

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

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

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

775 *Table 1. The ten elements of NbS related to transformative change across three spheres of*  
 776 *transformation<sup>39</sup>. The numbers in brackets show the percentage of the reviewed NbS that*  
 777 *addressed the spheres, the elements, and specific variables of the elements. We only present*  
 778 *variables with percentages > 5%.*

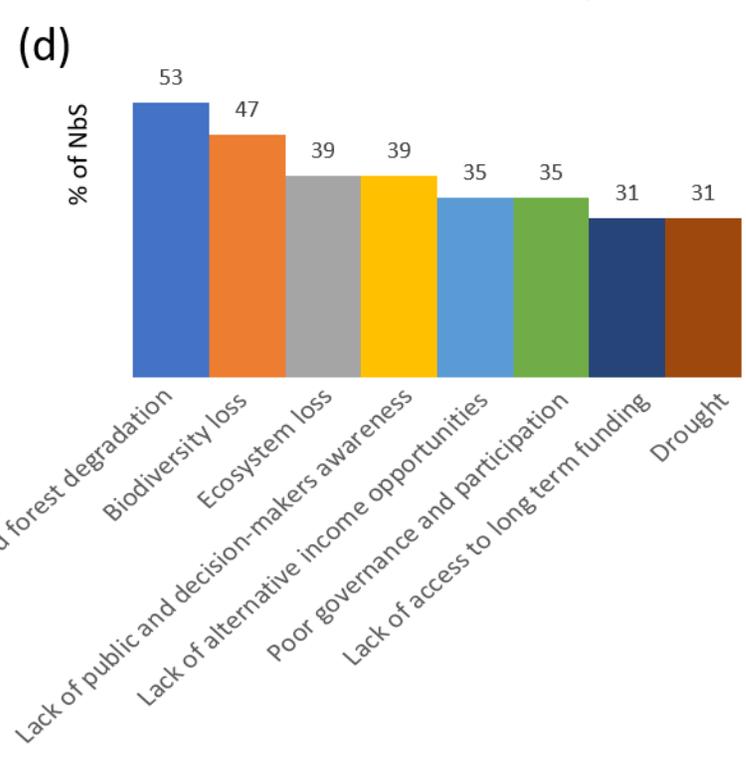
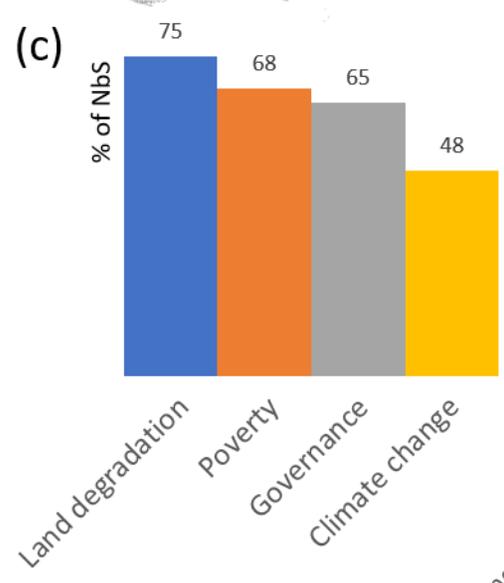
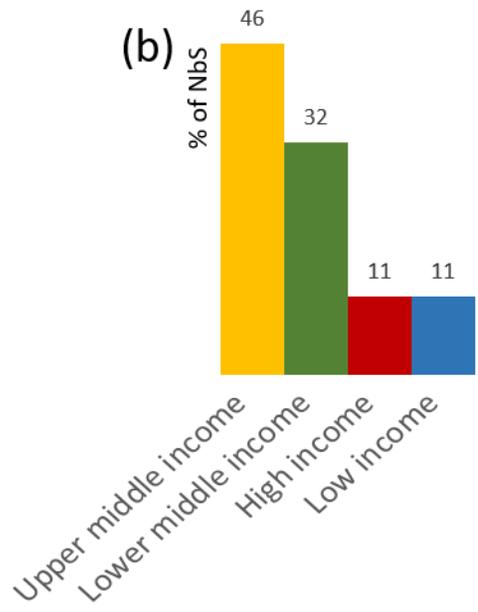
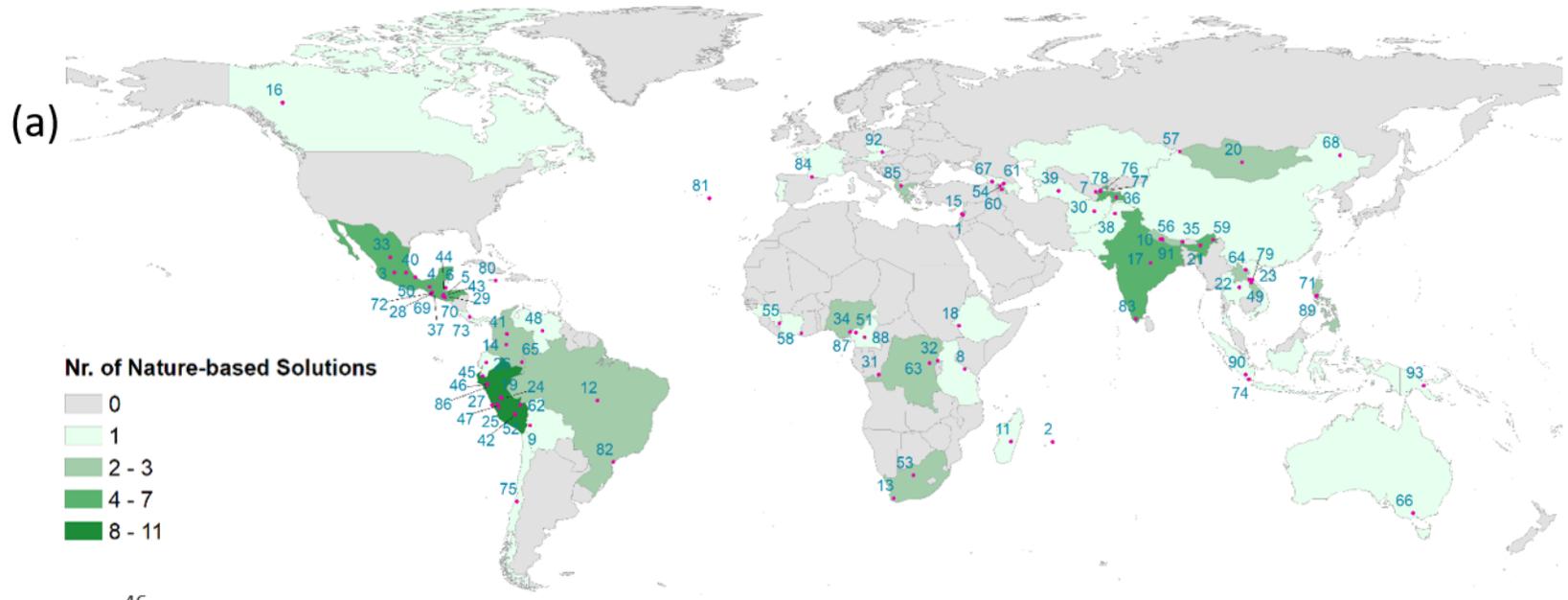
<i>Spheres of transformation</i>	<i>Elements</i>	<i>Variables</i>	<i>Supporting references</i>
<i>Personal: personal and collective beliefs, values, worldviews and knowledge types. (100%)</i>	<i>Nature's values: the principles, preferences, and importance of nature for humans. (100%)</i>	<i>Intrinsic (75%), Instrumental (75%), Relational (10%)</i>	44
	<i>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%)</i>	<i>Technical (96%), Scientific (55%), Lay and experiential (40%), Indigenous and local knowledge (34%)</i>	45
<i>Political: economic, legal, political, social and cultural elements. (100%)</i>	<i>Community engagement instruments: the mechanisms that allow the engagement of stakeholders and society in general, commonly known as participation. (99%)</i>	<i>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%)</i>	46-49
	<i>Economic and financial instruments: a wide range of traditional and modern approaches that include fiscal instruments and incentive schemes among others. (41%)</i>	<i>Payments for Ecosystem Services (10%), Low income loans (9%), Other economic incentives (12%)</i>	49
	<i>Rights-based instruments and customary norms: the approaches to conservation that respect and promote recognized human rights standards.</i>	<i>Community conserved areas (16%), Customary norms (9%)</i>	50-51

	(25%)		
	<i>Legal and regulatory instruments: the diverse politically binding regulations used in conservation. (23%)</i>	<i>Protected areas (17%)</i>	52
<i>Practical: technical, technological, strategic, practical and behavioural elements. (97%)</i>	<i>Management practice: the landscape management practices used in forestry, agriculture and related sectors. (87%)</i>	<i>Restoration (50%), Biodiversity/ecosystems monitoring (43%), Reduced pressure (35%), Biodiversity/ecosystems management (27%), Tree/crop nurseries (19%), Organic farming or smart agriculture (11%)</i>	53-55
	<i>Strategic planning: the approaches adopted in conservation (such as ecosystem-based adaptation or integrated landscape planning) and their strategic implementation. (67%)</i>	<i>Environmental management framework (49%), Management plan (40%), Diagnostic assessment (23%)</i>	56
	<i>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%)</i>	<i>Income diversification (30%), Direct sales of agricultural products (8%), Pro-environmental behaviour (8%)</i>	57-59
	<i>Technology: the body of techniques, methods and processes used to produce a certain good or (ecosystem) service. (28%)</i>	<i>Modern technology (15%), Ancient technology (15%), Grey infrastructure (12%), Green infrastructure (10%)</i>	60-61

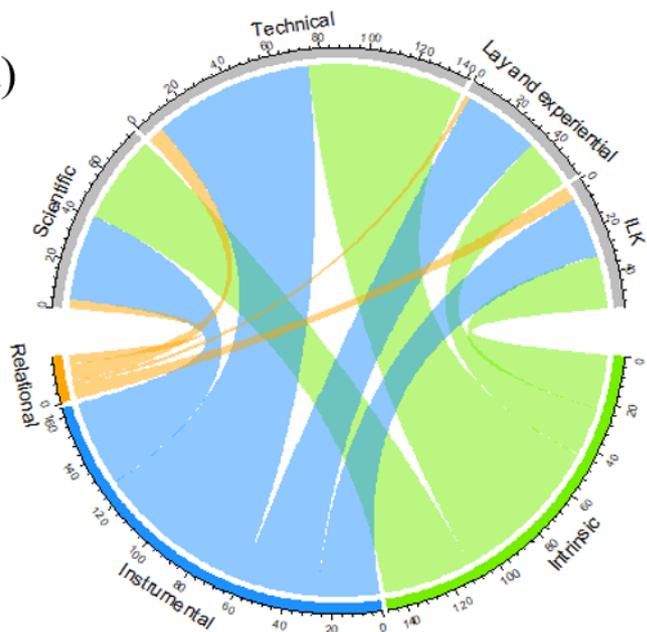
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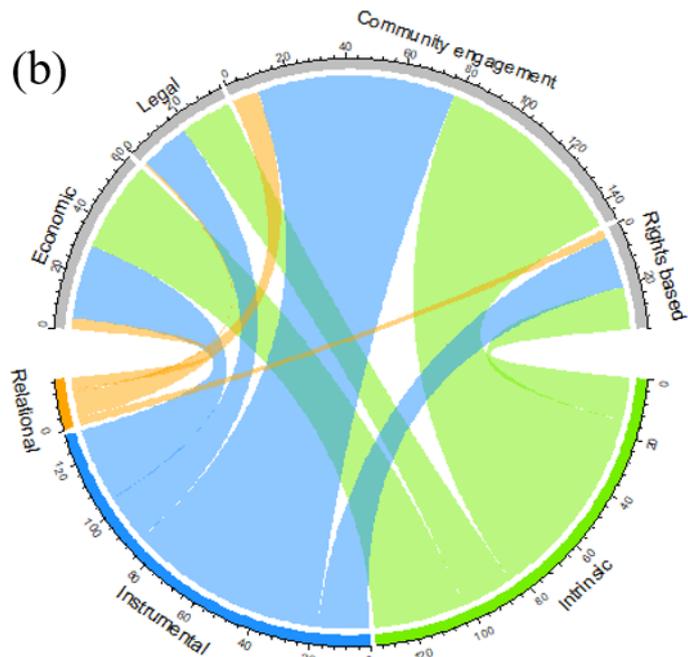
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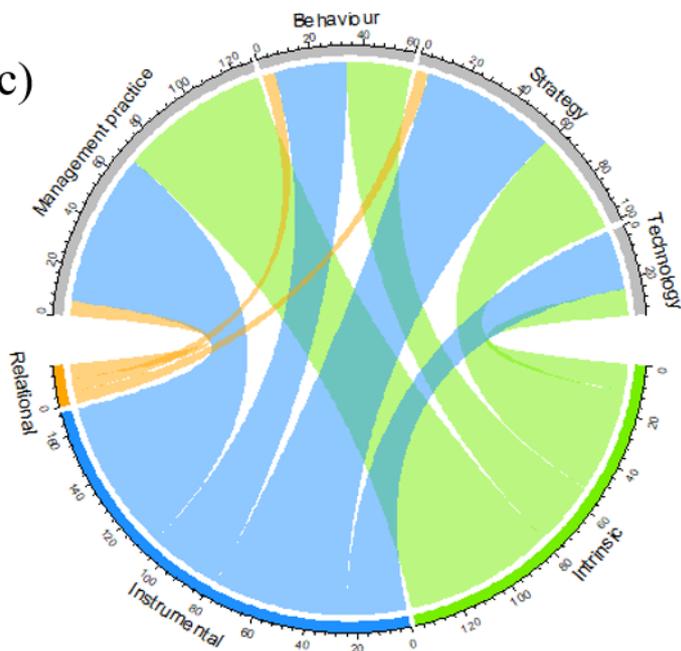
(a)



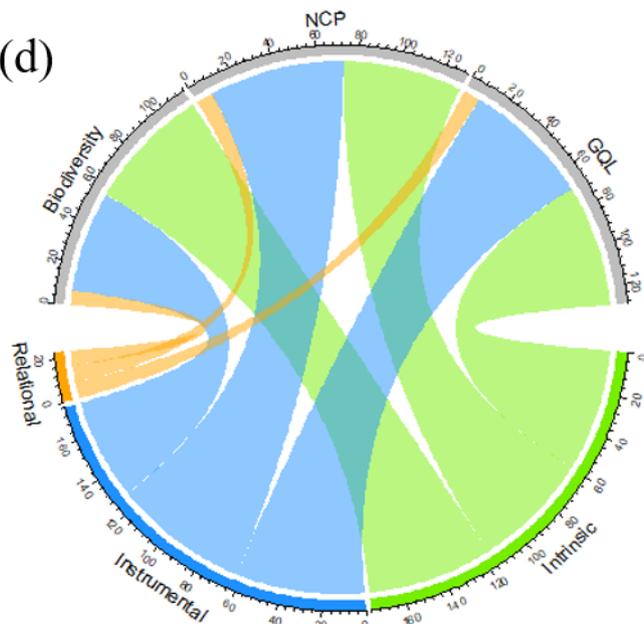
(b)



(c)



(d)



**A. Conserving biodiversity, reducing degradation**



1. Livelihoods and biodiversity in agricultural landscapes



2. Financing restoration and mitigation



3. Protected area governance

**B. Local and indigenous people, biodiversity-friendly development**



4. Local people, tourism and benefit sharing



5. Local communities and finance

**C. Climate adaptation and disaster risk reduction**



6. Adapting productive lands and natural resources



7. Disaster risk reduction and infrastructure



8. Adapting watersheds to climate change



#1. Farming to empower people and conserve ecosystem services in Mexico



# 2. Promotion of sustainable forest products from biosphere reserves in Ethiopia



# 3. Lands of Priolo: Integrated management to save a bird, natural habitats and sustainability in Portugal



# 4. Creating direct incentives through ecotourism for protecting wildlife in Lao



# 5. Achieving the sustainability of conservation agreements in El Caura, Venezuela



# 6. Food and water security in ejidos around the Tacaná Volcano, Mexico



# 7. Integrated disaster risk reduction in flood-affected areas in Tajikistan



# 8. Mountain pastures and wetlands and communal management in Canchayllo, Peru

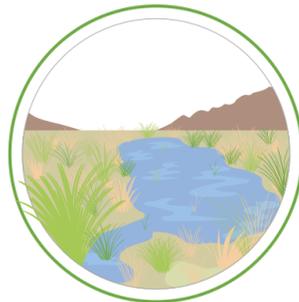
Land degradation

Climate Change

Poverty



TYPE A



TYPE B



TYPE C

Biodiversity

Nature's Contributions to People (NCP)

Good quality of life

COMPONENTS OF NBS

PERSONAL

Knowledge

Values

Worldviews

POLITICAL

Rules

Instruments

PRACTICAL

Technology

Ecosystem management

Behaviours

INDICATORS OF TRANSFORMATIVE CHANGE IN SOCIAL-ECOLOGICAL SYSTEMS



Path-shifting



Restructuring



Multiscale



Innovative



System-wide



Persistent