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Actions and actors driving transformative change for global sustainability

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Abstract

The urgent need for transformative change to address the intertwined crises of climate change and biodiversity loss is widely recognized. Drawing on work originally conducted within the IPBES Transformative Change Assessment and using a bibliometric analysis of over 4 million scholarly documents, we examine the actions and actors driving transformative change for global sustainability. The literature disproportionately focuses on a limited set of available actions and actors, neglecting others and overlooking their potential interactions. Notably, the actions 'Changing social norms' and 'Technological change' and the communication and knowledge and private sectors are frequently discussed, while actions referring to transforming the economic and governance systems and the civil society and the public sector are

understudied. Moreover, actions and actors do not tend to appear together in consistent or systematic ways; instead, most action–actor combinations appear at rates similar to random chance, with only a few notable exceptions. The uneven distribution of scholarly attention may hinder the coordination and cross-sectoral coalitions required for effective transformative change. Our findings call for a more inclusive approach to research on actors and actions needed for transformative change towards a just and sustainable world and for a greater focus on synergies between actions and actors potentially driving transformative change.

Main text

Introduction

A rapid and profound shift toward a just and sustainable world, in which both human and non-human present and future generations can survive and flourish, is urgent and necessary to respond to the intertwined crises of climate change and biodiversity loss. The first Global Assessment of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) and the Kunming-Montreal Global Biodiversity Framework (GBF) acknowledge that direct and indirect drivers of biodiversity loss, rooted in dominant worldviews and exploitative values that treat nature primarily as a resource for human use, control, and profit, are responsible for biodiversity loss and nature's decline[1,2]. Both call for fundamental and systemic transformative change to achieve a just and sustainable world. The IPBES Transformative Change Assessment (TCA) defines transformative change as '*A fundamental, system-wide shift in views, structures and practices that address the underlying causes of biodiversity loss and nature's decline*'[3].

Building on existing research, the TCA identifies five overarching strategies, supported by 22 related actions, which can be implemented through various instruments to promote and accelerate transformative change. These strategies enable the conservation and regeneration of nature in specific places[4,5]. At the same time, they target the direct[6,7] and indirect[8,9] drivers and the underlying causes of biodiversity loss and nature's decline[10]. Transformative change requires coordinated progress across these interdependent strategies and actions for synergistic effects[11]. No single strategy or action alone drives transformative change across diverse contexts and scales[3].

System-wide transformative change thus demands a whole-of-society approach, engaging actors from all societal sectors to envision and contribute to change collectively[3,12]. Building on prior work, the TCA identifies four societal sectors —civil society, public, private, and communication and knowledge—comprising 17 distinct actors and numerous social agents, each capable of playing a critical role in promoting and accelerating change[13]. Different actors possess specific abilities, resources and powers and encounter different opportunities and barriers, enabling them to fulfill diverse and complementary roles in driving change. Actor coalitions bring together and connect actors from diverse groups and places, and with varying positions and roles, to influence policy, inter-organizational dynamics, and operational aspects[14]. By coordinating efforts and pooling complementary resources and capacities, actor coalitions can drive meaningful change[15].

What remains unclear is the extent to which the existing literature captures the breadth and interdependence of the actors and their actions that are necessary for transformative change. The dynamics of interactions—both among actors and between

diverse actions—also require deeper exploration. Previous research has reviewed conceptual frameworks for transformative change[16,17], examined the roles of actors in societal and sustainability transitions[18,19], and analyzed selected interactions[20]. However, studies that systematically map the full spectrum of actions and actors relevant to transformative change—or assess the types of actions pursued by different actors—are notably absent. A bibliometric approach is particularly well-suited to this task as it enables the structured and replicable analysis of patterns across a vast body of literature. By identifying which actions and actors are emphasized or overlooked, as well as their co-occurrence in the literature, our analysis helps reveal critical knowledge gaps. Filling them can support the development of more coherent and evidence-based strategies for advancing transformative change.

The analysis in this paper is based on an examination of the title and abstracts of studies included in the TCA Corpus[21]. The TCA Corpus is a purposefully assembled dataset of 4,226,943 scholarly works, created by intersecting key search terms related to 'transformative change' and 'nature' in the open-access scholarly database OpenAlex (see *Methods*).

Results

Actions

Our analysis started by assessing the occurrence of terms associated with the 22 actions for transformative change defined in the IPBES TCA[3]. Terms corresponding with the identified actions did not appear in the title or abstract of most of the documents in the TCA Corpus. Specifically, out of the 4,226,943 documents in the TCA Corpus, only 350,285 (8%) contain at least one of the 566 terms related to the 22 actions for transformative change defined in the IPBES TCA. We refer to this subset of studies mentioning any of the terms for actions as the Strategies Corpus (StC).

The occurrence of terms referring to the five strategies ranges from 10.5% to 32.2% in the StC (Extended Data Table 1). Occurrence is highest for '*Shifting societal views and values*' (32.2% of the StC), a strategy addressing underlying causes that shape, influence, and reinforce the direct and indirect drivers of biodiversity loss and nature's decline. Occurrence is also high for '*Addressing direct drivers of change*' (31.1% of the StC), a strategy including actions to change direct drivers of nature's decline, namely land- and sea-use change, direct exploitation of organisms, climate change, pollution, and invasive alien species. The next highest frequency of occurrence corresponds to '*Conserving and regenerating places of value for humans and nature*' (23.9% of the StC), a strategy focusing on place-based actions. In contrast, occurrence is particularly low for the two strategies focusing on addressing indirect drivers of nature's decline, or the ways in which people and societies organize themselves and their interactions with the rest of nature. In particular, terms related to the strategy '*Transforming governance systems*' occur in 10.5% of the StC documents, and those for the strategy '*Transforming economic systems*' occur in 3.3% of the StC documents.

The occurrence of terms varies across the 22 actions considered in the TCA (Fig. 1A, yellow histograms; Extended Data Table 1). Terms associated with the actions 'Change social norms' and 'Technological change' appear in ~20% of the StC. Terms

associated with 'Area-based protection' occur in 14.6% of the StC. Terms corresponding with the remaining actions occur below 10% of the StC, with the lowest frequencies observed for 'Knowledge co-creation' (1.0% of the StC) and 'Biocultural stewardship' (0.9%).

Terms for all actions co-occur with one another to varying degrees (Fig. 1A). The results for the Overlap Index (OI), which measures deviations from expected random co-occurrence, indicate that out of 462 action intersections, 394 (85.3%) are statistically significant. Most of these intersections exhibit co-occurrence values below what would be expected under a random distribution, although fewer have an OI greater than 0.1 or lower than -0.1 (Fig. 1A). The three most frequently occurring actions (i.e., 'Change social norms', 'Technological change', and 'Area-based protection') generally co-occur with other actions less often than what would be expected if they were distributed randomly across the StC ($OI<-0.1$, $p<0.05$). In other words, although terms for these three actions occur frequently, they tend to occur independently rather than in combination with other actions. Only one pair of actions exhibit higher-than-expected co-occurrence. Notably, 'Area-based protection' shows higher-than-expected co-occurrence with 'Biocultural stewardship'($OI>0.1$, $p<0.05$) (Fig. 1A; cells in blue in the lower left quadrant).

INSERT FIGURE 1

Actors

We conducted a similar analysis to assess the occurrence of terms associated with actors (Fig. 1.B). Similar to the analysis of actions, results from the analysis of actors also show that most of the terms used to identify actors do not appear in the title and abstract of most documents in the TCA Corpus. Specifically, only 1,275,069 (30%) of the documents in the TCA Corpus include any of the 316 search terms for actors potentially driving transformative change. We refer to the subset of works mentioning any of the terms for actors as the Sector Corpus (i.e., SeC).

The occurrence of terms referring to any of the four societal sectors ranges from 19.7% to 49.0% of the SeC (Extended Data Table 2). The highest occurrence is observed for the '*Communication and knowledge'* sector (49.0% of the SeC, referred to as "Knowledge sector" in Fig. 1), which includes media, educational institutions, research organizations, and think tanks. The *'Private'* sector, comprising businesses, companies, corporations, and funding bodies that primarily operate for profit, follows with a high occurrence (37.2% of the SeC). Following in levels of occurrence is the *'Civil society'* (29.6% of the SeC), encompassing non-governmental organizations (NGOs), faith-based organizations, labor unions, professional associations, social movements, and other advocacy groups. Finally, the *'Public'* sector, which includes international, national, regional, and local governmental institutions and agencies that aim to serve the public interest, has the lowest occurrence (19.7% of the SeC).

The occurrence of terms also varies across the 17 actors identified (Fig. 1B, yellow histograms; Extended Data Table 2). Terms associated with three of the 17 actors - 'Scientific community' (30.8% of the SeC), 'Business' (29.6% of the SeC), and 'Education community' (20.1% of the SeC)- appear in more than 20% of the SeC.

Terms referring to three additional actors - 'Individual citizens' (16.4% of the SeC), 'National government' (12.1% of the SeC), and 'Local communities' (12.1% of the SeC)- occur in more than 10% of the SeC. The lowest occurrences, each below 1% of the SeC, are observed for actors in the '*Civil society'* sector, namely 'Civil society organizations' (0.7% of the SeC), 'Environmental movements' (0.5% of the SeC), and 'Non-governmental organizations' (0.4% of the SeC).

All actors co-occur with one another to varying degrees (Fig. 1B). The Overlap Index (OI) shows that out of 270 actor interactions, 262 (97%) are statistically significant. While some actors co-occur less frequently than expected under a random distribution, others co-occur more frequently (Fig. 1B). Two of the three most frequently occurring actors—'Scientific community' and 'Business'—generally co-occur less often with other actors than expected under random distribution ($OI < -0.1$; $p < 0.05$). In contrast, only two actor pairs show higher-than-expected co-occurrence ($OI > 0.1$; $p < 0.05$). Notably, the 'Scientific community' co-occurs more frequently than expected with the 'Education community,' the third most frequently occurring actor (Fig. 1B; cells in blue in the upper right quadrant). Additionally, and despite their generally low levels of occurrence, two actors from the 'Civil society' sector—'NGOs' and 'Individual citizens'—also exhibit higher-than-expected co-occurrence (Fig. 1B; cells in blue in the lower left quadrant).

Actions and actors co-occurrence

As a last step, we analyzed the co-occurrence of terms associated with actions and actors (Fig. 1.C). When analyzed together, the terms identifying either actions or actors are found in the title and abstract of approximately 35% (n = 1,466,319) of the documents in the TCA Corpus. However, only 159,035 documents (3.8%) simultaneously contain at least one term referring to an action and one term referring to an actor.

The analysis reveals levels of co-occurrence between actions and actors resembling a random distribution, as indicated by the many cells with an OI close to zero (Fig. 1C). Nevertheless, out of 374 action-actor interactions, 364 (97.3%) are statistically significant. When co-occurrence is different from what would be expected under a random distribution, lower-than-expected co-occurrence is more common than higher-than-expected co-occurrence. The three most frequently occurring actions — 'Change social norms,' 'Technological change,' and 'Area-based protection'— tend to show random or lower-than-expected levels of co-occurrence with most actors. Similarly, the three most frequent actors —'Scientific community,' 'Business,' and 'Education community'— show random or lower-than-expected co-occurrence with most actions (Fig. 1C, Upper and 3rd line quadrants). There are some noteworthy exceptions to this pattern: the 'Scientific community' shows higher-than-expected co-occurrence with 'Multilateral governance,' 'Business' shows higher-than-expected co-occurrence with 'Conservation finance,' and the 'Education community' shows higher-than-expected co-occurrence with 'Transformative learning.' 'Citizens' show lower-than-expected co-occurrence levels ($OI <- 0.1$; $p < 0.05$) with 'Area-based protection' and 'Regenerative systems' but higher-than-expected co-occurrence levels ($OI > 0.1$; p

< 0.05) with ‘Knowledge co-creation,’ and ‘Changing narratives.’ Higher-than-expected co-occurrence levels (OI > 0.1; p < 0.05) are also found between ‘National governments’ and ‘Right-based conservation’, ‘Finance sector’ and ‘Financial reform.’

Discussion

Based on an assessment of the best available evidence, the IPBES TCA highlights the need for diverse actors from different societal sectors to implement complementary actions and strategies for synergistic effects to halt biodiversity loss and nature’s decline[3]. To quantitatively assess the current state of scholarly knowledge on actions and actors, and how the literature portrays their relationships, we analyzed a large collection of academic papers on transformative change and nature. Our bibliometric analysis examined the frequency with which specific actions and actors occur in this literature and how often they appear together.

Our analysis reveals three key findings. First, only a portion of the literature examined engages with the actions and actors identified by the TCA as critical for transformative change. Second, within this subset of the literature, there is a disproportionate emphasis on a narrow range of actions and actors, while many others receive little attention. Third, most studies overlook the interactions between different actions and actors. When actions and actors do appear together, their co-occurrence matches what would be expected by chance rather than showing meaningful connections. When differences occur, they usually indicate less connections than expected under random distribution.

Limited coverage

A key insight from this work is that only a portion of the analyzed literature addresses the actions and actors identified by the TCA as critical for transformative change. Despite extensive background searches (see *Methods*), references to actions appear in a relatively small subset of the documents in the TCA Corpus. While mentions of actors are somewhat more common, only a minority of the documents simultaneously include actions and actors.

While this limited coverage may point to a research gap in the literature on transformative change, an alternative explanation lies in the methodological approach used to define search terms. The selection of terms was shaped by earlier IPBES reports, potentially overlooking relevant concepts not highlighted in those assessments. Moreover, our reliance on English terms within a predominantly scholarly database most likely excludes potentially relevant content, such as content present in non-English documents, works without English abstracts, consultancy reports, policy briefs, materials from civil society organizations, and other forms of grey literature.

For example, civil society actors often engage in diverse forms of contestation - such as protests, petitions, referenda, or corporate pressure - to resist private interests threatening local environments[22,23]. They also engage in numerous social innovations, including commons-based organizations, alternative food networks, nature stewardship programs, and multi-sectoral and multi-stakeholder networks for land conservation[23]. Many of these initiatives are only partially documented in academic literature or might be described using non-English or localized terms absent by our search. Terms defining other actors or actions are likely to follow the same pattern.

In sum, the limited representation of the actions and actors identified by the TCA in the literature may reflect not only research gaps but also methodological and linguistic filters. This underscores a fundamental challenge in deriving insights from large-scale bibliometric analyses—especially when trying to capture the diversity and contextual nuance of real-world transformations. To advance our understanding of transformative change in practice, future analyses should adopt broader and more inclusive approaches to knowledge synthesis, such as expanding search terms or conducting more thematic and context-sensitive reviews. The open-access resources developed for this study[21] provide a solid foundation for reviewing and expanding future analyses of the actions and actors driving transformative change. To better understand where and how transformations can be more effectively supported, this work should be complemented by in-depth case studies that explore the relationship between scholarly attention and real-world implementation[24].

Some narratives dominate

The second key insight from this analysis is the disproportionate focus on a narrow subset of actions and actors, while neglecting others and overlooking potential interactions among them. The actions and actors emphasized or neglected in the literature reflect broader narratives in the literature about how transformative change toward sustainability occurs and who has a role in enacting it. Specifically, the occurrence patterns align with four broad narratives about how transformative change should be achieved and by whom.

First, the occurrence patterns reflect a narrative of individualization of responsibility. The clear dominance of the action 'Change social norms' and the relative frequency of the 'Citizens' contrast with the relatively low occurrence of other actions within the broader strategy of '*Shifting societal views and values*,' and with the low occurrence of actions tied to economic and governance transformation and actors in the *'Public'* sector.

In contrast with the high occurrence of the action 'Change social norms'—individual behavioral changes such as recycling or dietary shifts—, actions aimed at fostering nature connectedness, co-creating knowledge, or developing new narratives about transformation receive limited attention in the scholarly literature and may also be underrepresented in practice[25]. While altering social norms can be effective in denormalizing harmful behaviors and promoting widespread change[26,27], the strong emphasis on this single action may reflect a wider narrative in public discourse that shifts responsibility for environmental crises from systemic or institutional actors to individuals. Although this framing is not necessarily dominant in all academic work, it mirrors long-documented public communication strategies—used, for example, by the tobacco and fossil fuel industries—to deflect responsibility[28,29].

The prominence of the narrative signaling individual responsibility is reinforced by the low occurrence of actions tied to economic and governance transformation and the low representation of the *'Public'* sector in the analyzed literature. While governments can foster policy coherence, enact and enforce regulations to benefit nature, advance institutional sustainability, and integrate sustainability into policies and plans across various sectors (regulations, taxes, fees, tradable permits) to drive transformative change[30,31], current research shows that its potential leverage remains

underutilized or underexplored, with some evidence indicating the former as most likely[32]. For instance, a recent OECD report highlights that the breadth and scale of existing actions and policy tools enacted by governments are inadequate, with only marginal increases in their implementation [33]. Moreover, there is strong evidence that governments largely subsidize economic sectors that drive nature decline[34].

Second, occurrence patterns also reflect a narrative of science and technology solutionism. The frequent appearance of terms related to 'Technological change' and the 'Scientific community' also reflects a dominant narrative that highlights the control of decision-making by experts and institutions based on technical and scientific knowledge. The emphasis on 'Technological change' aligns with previous work showing that technological innovations tend to diffuse more rapidly than social innovations[35,36]. Business and researchers working in technology and innovation often promote emerging technologies—e.g., artificial intelligence, blockchain—as key drivers of sustainability, emphasizing their roles in increasing efficiency, reducing emissions, and enabling circular economy models[37,38]. Similarly, governments, particularly in the Global North, often view investments in renewable energy, electric vehicles, and digital infrastructure as central strategies for achieving sustainability goals[39]. The scientific community has traditionally been seen as central to understanding and advancing transformative change by generating knowledge, identifying critical environmental challenges, and proposing evidence-based solutions[13].

Despite this optimism, scholars and civil society actors have cautioned against overreliance on technology as a silver bullet. Without being embedded in normative frameworks that prioritize equity, justice, and contextual relevance, technological solutions may fail to deliver meaningful transformation—or may even exacerbate existing inequalities [6,36,40]. Thus, while technological change plays an important role, its transformative potential depends on how it is governed, by whom, and in whose interests[41,42]. Similarly, the role of the 'Scientific community' in driving change should not be taken for granted, particularly given the increasingly complex relationships between experts and policymakers[43]. Scientific credentials do not inherently ensure commitment to research leading to a just and sustainable outcome. In fact, segments of the scientific community have, at times, contributed to environmental disinformation, actively delaying policy action on urgent issues such as the ozone hole, acid rain, tropical deforestation, oil drilling, and climate change[29,44]. The current climate crisis illustrates that the agency of scientists to influence policy and societal change has often been overestimated, and that political shifts can rapidly dismantle regulatory progress.

To support more meaningful transformations, it is essential to incorporate diverse forms of knowledge and evidence. Embracing a more inclusive approach that values diverse perspectives and integrates non-academic knowledge, such as Indigenous, local, or experiential knowledge, can help leverage and scale-up successful situated stewardship practices, foster more equitable and sustainable outcomes, while addressing the shortcomings of an overly narrow focus on science and technology solutions[45,46].

The third narrative centers on protectionist conservation. The predominance of terms associated with 'Area-based protection' is not surprising, as it reflects prevailing narratives about how place-based conservation is expected to occur. Importantly, this focus persists despite continued debate over the effectiveness of assigning protected

status to areas in safeguarding nature[47] and the impacts of such designations on the livelihood needs of local communities[48]. In contrast, 'Biocultural stewardship,' an action that encompasses community-based or co-managed governance arrangements[49], such as the Satoyama Initiative in Japan[50], appears less frequently in the literature. Interestingly, the co-occurrence between 'Area-based protection' and 'Biocultural stewardship' is higher than expected by random distribution. However, interpreting this higher-than-expected co-occurrence is challenging without qualitative data to contextualize the direction of the relationship, as it could indicate either complementarity or opposition between the two actions.

Finally, the occurrence patterns also reflect a narrative of corporate environmentalism. The prominence of 'Business' as an actor in the literature on transformative change is somewhat surprising as the private sector has frequently portrayed environmental causes as an impediment for economic development. Indeed, the literature indicates that, while some companies adopt voluntary measures to offset the additional costs of protecting nature[51,52], most tend to approach environmental issues defensively, responding to external pressures rather than proactively engaging in reducing their environmental impact[53,54]. This reactive stance is frequently driven by regulatory measures, such as taxation or compliance with environmental standards[55,56], as well as by pressures and demands from civil society[57]. Considering this, the high occurrence of 'Business' as an actor in the transformative change literature might primarily reflect its role in driving nature's decline, rather than its proactive contributions to transformative change.

In contrast, 'Financial actors', who are also classified under the 'Private' sector and who are shown to be part of the complex system driving nature's decline[58], are underrepresented in the literature. This is significant because these actors can play an important role in transformative change, for instance, through shareholder activism to lobby for sustainability improvements in corporation practices[59,60], for sustainable investment decisions [61,62], or by allocating financial resources to transformative initiatives, which could have a high potential for positively influencing the financial sector[63–65].

This narrative bias that emerges from the broad analysis of the literature illustrates the operation of discursive power within sustainability scholarship and policymaking, whereby dominant framings shape both the perceived actions and actors that have a role in addressing the environmental crises. By privileging certain actions and actors while marginalizing others, discursive power consolidates narrow visions of sustainability. This has tangible policy consequences, as such framings influence which strategies receive funding, political support, and institutional legitimacy. Addressing this requires more pluralistic approaches to knowledge production and policy design that actively incorporate diverse epistemologies, values, and voices—particularly those historically excluded from global environmental discourse.

Linking actors and actions

A third key finding from this study is that most of the existing research rarely examines how actions and actors are connected. Very few of the documents we reviewed mention both an action and an actor within the same text. Even when combinations of actors and actions do appear together, there is no clear pattern in how they are linked. This limited attention to actor–action relationships may mirror real-

world dynamics, where actions unfold in isolation and actors operate independently, with limited coordination. Alternatively, this disconnect may reflect a general lack of focus on which actors are best positioned to implement certain actions and on the potential complementarities, trade-offs, and power dynamics between them.

Regardless of the interpretation, this finding has significant implications for achieving transformative change, because understanding who is responsible for—or capable of—carrying out particular actions is critical for enabling transformative change[58]. Actions do not just happen on their own, an actor needs to drive them. Lack of knowledge in actions-actors interactions can result in fragmented or piecemeal approaches in policy and implementation, missing opportunities for coordination, collaboration, and more systemic solutions.

This gap also intersects with questions of governance and equity in actions for transformative change. A stronger focus on actor–action interactions is needed to increase actor diversity without inadvertently deepening power asymmetries[66]. In some contexts, efforts to broaden participation have actually exacerbated existing inequalities and further marginalized vulnerable actors[67,68]. Addressing actor–action relationships is therefore not only a matter of improving implementation effectiveness—it is essential for ensuring that transformations are equitable and inclusive.

In conclusion, this study reveals significant gaps and biases in the scholarly literature on transformative change for biodiversity and sustainability. While the IPBES TCA calls for diverse actors implementing complementary actions in coordinated ways, our quantitative analysis shows that academic research tends to focus narrowly on a limited set of actions and actors, often overlooking their interactions and the complexity and diversity evident in practice. Understanding the patterns of low or high levels of co-occurrence could be strategically used to mobilize resources, increase coordination, and build inclusive, cross-sectoral coalitions to foster transformative change.

These insights carry important implications for both policy and research. For policy, they highlight the need for legal and institutional frameworks that support coordination across governance levels, including integration into biodiversity strategies, climate policies, and regulatory instruments. They also point to the importance of allocating targeted research funding to underrepresented knowledge areas—such as civil society roles, knowledge co-production, or actor–action interactions—as well as expanding future work to better reflect linguistic and conceptual diversity, drawing on fields like Political Ecology and Social Movement Studies. At the national level, biodiversity policy could explore new pathways for action, particularly those grounded in situated knowledge and successful stewardship practices. For research, greater attention to the dynamics between actors and actions—especially how alliances are formed, sustained, or challenged—could help illuminate the conditions under which diverse groups collaborate to drive transformative change. Supporting diverse engagement and integrating multiple knowledge systems remain essential to designing and implementing transformation that benefits both nature and people.

Methods

Our work followed two steps. First, we characterized knowledge of the actions and actors potentially driving transformative change by identifying and compiling terms for instruments and social agents, then classifying them into actions and actors. In the

second step, we assessed scholarly knowledge of these actions and actors by analyzing their occurrence within a large dataset of scholarly works referring to transformative change and nature. We also examined their potential interrelations by analyzing co-occurrence patterns in the literature. The analysis was conducted using the TCA Corpus[17], a dataset created by selecting works at the intersection of key search terms referring to '*transformative change*' and '*nature*' from OpenAlex— an open-access database with comprehensive global coverage of scholarly works across disciplines, including physical sciences, social sciences, and humanities. Data and codes used to conduct the searches, and the creation of the graphs are available[69].

Characterizing actions and actors

Step 1 consisted in the identification and classification of terms referring to actions and actors in transformative change. Term identification refers to the detection or extraction of relevant terms from a body of text. Term classification refers to the categorization of identified terms into specific categories. Specifically, our work began with a background search to create lists of terms for instruments and social agents potentially driving transformative change. We defined an 'instrument' as any intervention (e.g., formal rule, law, social norm, process) designed to promote biodiversity conservation, restoration, and sustainability. We defined a 'social agent' (or agent) as any entity (e.g., individual, organization, State) with interest, preferences, or decision-making capacities related to biodiversity conservation, restoration, and sustainability[70].

We compiled all terms referring to instruments and agents identified in previous IPBES work. Specifically, five authors of this study (KB, MB-M, RAM, RP, LP) reviewed three chapters of completed IPBES assessment reports[71–73] and one report of an Indigenous and local knowledge dialogue workshop[74], extracting terms for relevant instruments and social agents. We then employed an inductive process, identifying recurring themes, to classify instruments into actions. Actions were subsequently organized into strategies through a deductive process guided by the IPBES conceptual framework[75]. According to this framework, addressing biodiversity loss and nature's decline requires action on area-based conservation and regeneration, as well as on direct and indirect drivers and underlying causes of biodiversity loss. Following this logic, we categorized actions into five strategies based on their focus: (1) '*Conserving and regenerating places of value for humans and nature,'* (2) '*Addressing direct drivers of change,'* (3) '*Transforming economic systems,*' (4) '*Transforming governance systems,'* and (5) '*Shifting societal views and values'* (Extended Data Table 1).

We adopted a similar approach to classify search terms related to agents into actors and societal sectors. The grouping of actors into societal sectors followed the framework outlined in the IPBES TCA, which emphasizes the diverse roles actors play in transformative change[3]. Based on this framework, we categorized actors into four

societal sectors: (1) *'Public'* sector, (2) *'Civil society,'* (3) *'Private'* sector, and (4) *'Communication and knowledge'* sector (Extended Data Table 2).

The lists of instruments and agents identified, along with their classification, were refined using three complementary approaches designed to balance scholarly, expert, and broader discourse sources. First, we used artificial intelligence to supplement the lists. Specifically, for each action, we asked ChatGPT to 'List instruments used for [*name of action*]'. Similarly, for each actor, we asked ChatGPT to 'List agents that can be considered part of [*name of actor*]'. These prompts were intentionally broad, allowing the model to draw on its wide-ranging training data, which includes both academic and non-academic content. While this introduces the possibility of bias, we consider it an advantage in this context, as it helps capture commonly used terms that may be underrepresented in scholarly literature but relevant in practice, policy, or public discourse. The responses were reviewed by the lead author and, when relevant, included in the list of instruments or in the list of agents. Second, 20 authors of this work, from diverse disciplinary and geographical backgrounds, reviewed the lists of terms. They proposed additions, corrected typographical errors, removed duplicates, and consolidated synonyms. They also reviewed the classification of terms, suggesting adjustments where necessary. Final decisions on conflicting suggestions were made by the lead author. Third, we conducted individual keyword searches for each term in our lists of instruments and agents within the titles and abstracts of the documents in the TCA Corpus. These searches were performed using inverted commas for each term, without combining them using Boolean operators. The number of hits for individual search terms ranged from 0 to several million. We used these results to further refine the lists of search terms by eliminating those that were absent or had very few hits, and by modifying or removing terms with excessively high numbers of hits, relative to other terms. We observed that such high-frequency terms often appeared in overly broad or unrelated contexts, reducing the specificity of the analysis and capturing content not directly aligned with the intended definitions of transformative actions and actors. Our final list of instruments includes 566 individual search terms classified in 22 actions and five strategies. Our final list of agents includes 316 individual terms classified in 17 actors and four societal sectors.

We are aware that our literal approach to classifying actions and actors introduces certain limitations. In particular, our methodology assigns each term to a single action or actor category, which may not fully reflect real-world complexity. Many instruments can serve multiple purposes depending on context, and most agents engage in diverse roles. This one-to-one classification can therefore introduce bias. Additionally, our approach focuses on labeling actors without analyzing their functions, their relationship to transformative change, or the complexity of their agency across different societies and time periods. Since actors can assume different roles depending on the context, this reinforces the need to move beyond static labels. Future work

should explore the varied and dynamic functions that actors perform, recognizing that roles are context-dependent and often evolve over time.

Analyzing occurrence and co-occurrence of actions and actors

In the second step, we quantified the occurrence and co-occurrence of actions and actors in the literature by performing combined searches within the titles and abstracts of the documents in the TCA Corpus. To assess the occurrence of actions, we used the Boolean operator OR, combining all instruments classified under each action in a single search. Due to the OpenAlex API's character limit of approximately 750 characters per query, searches for four actions with lengthy lists of instruments were subdivided. The results of these subdivided searches were subsequently aggregated, with duplicates eliminated. A similar approach was applied to assess the occurrence of terms for actors, combining all agents classified under each actor group using OR. Occurrence values for actions and actors are presented in histograms. Additionally, we assessed occurrences within strategies and within sectors by counting all occurrences of actions within each strategy (or actors within each sector) after eliminating duplicates.

To analyze the co-occurrence of terms for actions and actors, we first calculated the number of works in which terms for two actions appeared together (i.e., co-occurred). This involved identifying the work IDs present in two sets. We then calculated an Overlap Index (OI) to evaluate whether the co-occurrence levels of any two actions significantly deviated from what would be expected under a random distribution. The OI, derived from a hypergeometric distribution, ranges from -1 to 1. A negative value indicates lower-than-expected co-occurrence, positive indicates higher-than-expected co-occurrence, and 0 suggests a random distribution. Co-occurrence is classified as ‘higher-than-expected’ when $OI > 0.1$, ‘lower-than-expected’ when $OI < -0.1$, and ‘random’ when $OI \leq 0.1$ and ≥ -0.1. To assess the statistical significance of each OI value, we applied the hypergeometric test to calculate the corresponding p-value. The same methodology was used to analyze co-occurrence between two different actors and to evaluate co-occurrence between any pair of action and actor terms.

Co-occurrence was visualized using heatmaps. Each cell in the heatmaps contains the number of times terms in the corresponding row and column co-occurred. Cell colors indicate deviations from randomness: white denotes no deviation, darker shades represent larger absolute deviations, with red indicating lower-than-expected co-occurrence and blue indicating higher-than-expected co-occurrence. Values that were not significantly different from the expected value are crossed out.

Data availability

The analysis was conducted using the TCA Corpus, a dataset created by selecting works at the intersection of key search terms referring to ‘transformative change’ and ‘nature’

from OpenAlex— an open-access database with comprehensive global coverage of scholarly works across disciplines, including physical sciences, social sciences, and humanities. Data used are available at https://zenodo.org/records/14712029[69].

Code availability

Codes used to conduct the searches and the creation of the graphs are available at https://zenodo.org/records/14712029.

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Authors' contribution statement

- VR-G and RK conceived the idea and designed the methodology.
- VR-G developed the theoretical framework and wrote the first draft.
- RK performed the computations.
- KB, MB-M, RM, RP and LP conducted background research.
- RK, AA, KB, MB-M, JC, TF, LG, BG-H, CG, BG, HG, XG, PH, CIS, JL, LL, RM, KM, JM, KO, RP, LP, KR, AS, PT, PU-L, SV, and YZ discussed the results and contributed to and approved the final manuscript.

Competing interest statement

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this article.

Inclusion and Ethics statement

This research was conducted collaboratively by researchers from institutions across Europe, North and South America, Africa, and Asia, emphasizing equitable international partnerships.

Figure Legends/Captions

Figure 1. Occurrence histograms and co-occurrence heatmaps of actions and actors. Panel A (Actions) and Panel B (Actors) are symmetric matrices, whereas Panel C (Actions x Actors) is a rectangular matrix. Yellow histograms represent the occurrence of actions (top, Panel A) and actors for transformative change (right, Panel B). Yellow cells along the diagonal of the symmetric matrices in Panels A and B also represent occurrences. The numerical value of occurrences of strategies and societal sectors is displayed on the margins of the corresponding histograms. Heatmaps illustrate co-occurrence patterns. Cell values indicate the frequency of co-occurrence based on combined searches of the terms corresponding to each column and row. Cell colors indicate deviations from randomness: white denotes no deviation, darker shades represent larger absolute deviations, with red indicating lower-than-expected co-occurrence and blue indicating higher-than-expected co-occurrence. Cells with darker borders have an Overlap Index greater than 0.1 (OI>0.1) or lower than -0.1 (OI <-0.1). Values not significantly different from the expected value are crossed out. **A.** Occurrence histograms and co-occurrence heatmap of actions grouped by strategies within the Strategies Corpus (n = 350,285). **B.** Occurrence histograms and co-occurrence heatmap of actors grouped by societal sectors within the Sector Corpus (n = 1,275,069). **C.** Heatmap of co-occurrence between actions and actors (n = 1,466,319).

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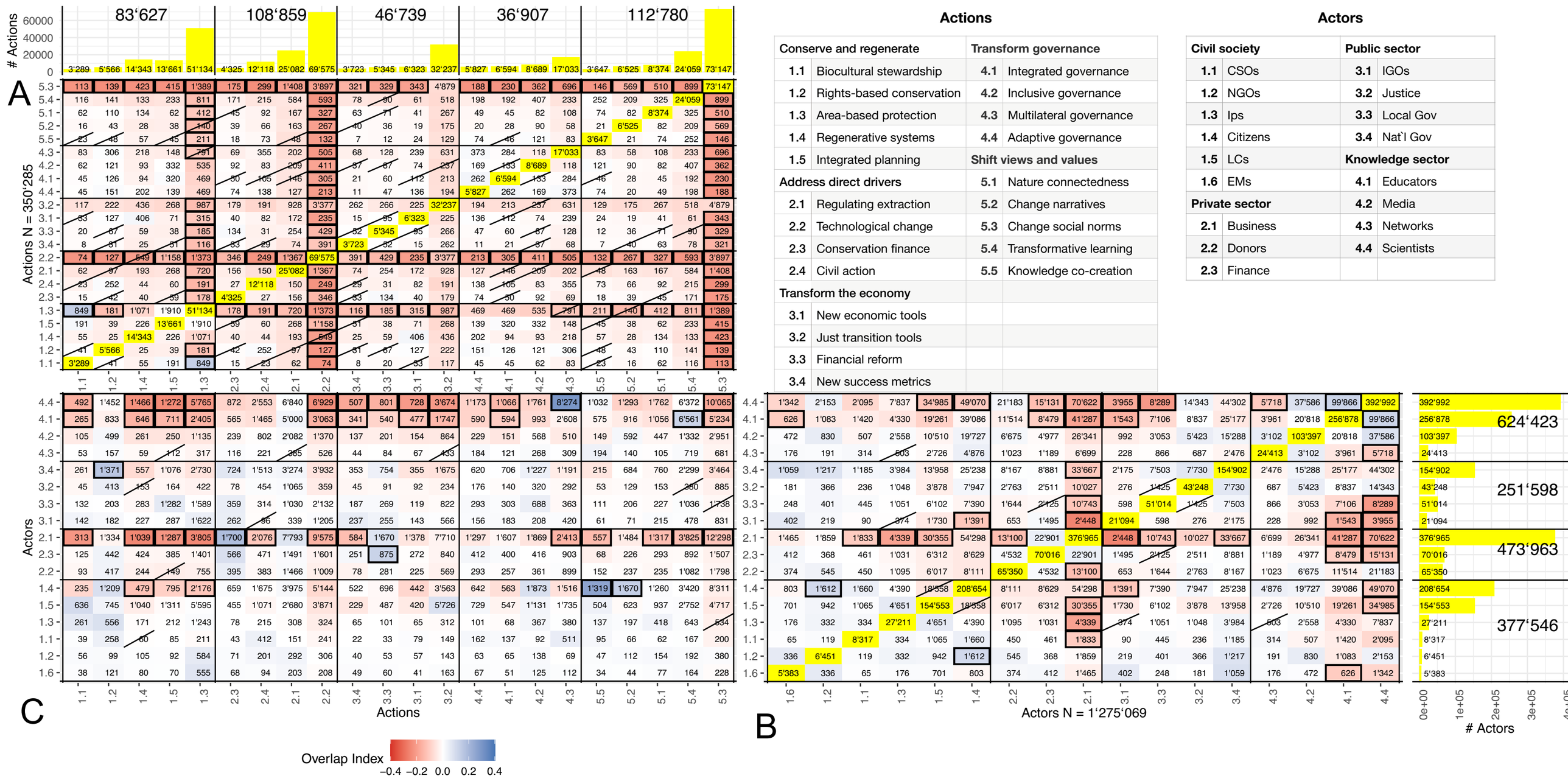
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Action	Examples of terms included	N	within	overall
Conserving and regenerating places		83,627		23.9
Biocultural stewardship	'Convivial conservation', 'Indigenous and community conserved area', 'Sacred grove'	3,289	3.9	0.9
Rights-based conservation	'Access and benefit sharing', 'Free prior informed consent', 'Nature rights', 'UNDRIP'	5,566	6.7	1.6
Area-based protection	'National Park', 'Environmental monitoring', 'Sustainable land management'	51,134	61.1	14.6
Regenerative systems	'Biodiversity restoration', 'Regenerative agriculture', 'Remedial action', 'Rewilding'	14,343	17.2	4,1
Integrated planning	'Buffer zone', 'Land use planning', 'National biodiversity strategy and action plan'	13,661	16.3	3.9
Addressing direct drivers of change		108,859		31.1
Regulating extraction	'Consumption tax', 'Ecolabel', 'Environmental certification', 'Green branding'	25,082	23.4	7.2
Technological change	'Climate-smart agriculture', 'Green technology', 'Renewable', 'Nature-based solution'	69,575	63.9	19.9
Conservation finance	'Biodiversity finance', 'Debt-for-nature swap', 'Lost and damage'	4,325	4.0	1.2
Civil action	'Environmental action', 'Food cooperative', 'Non-cooperation', 'Social innovation'	12,118	11.1	3.5
Transforming economic systems		46,739		13.3
New economic tools	'Biodiversity banking', 'Cap and trade', 'Financial disclosure', 'No net loss', 'PES'	6,323	13.5	1.8
Just transition tools	'Agroecology', 'Sustainable design', 'Bioeconomy', 'Circular economy', 'Degrowth'	32,237	69.0	9.2
Financial reform	'Biodiversity offset', 'Debt relief', 'Environmental impact bond', 'Trade ban'	5,345	11.4	1.5
New success metrics	'Ecological footprint', 'Green GDP', 'System of Environmental Economic Accounting'	3,723	8.0	1.1
Transforming governance systems		36,907		10.5
Integrated governance	'Biodiversity Policy Integration', 'Cross-sectoral planning', 'Transparent governance'	6,594	17.9	1.9
Inclusive governance	'Citizen assembly', 'Customary law', 'Deliberative democracy', 'Inclusive governance'	8,689	23.5	2.5
Multilateral governance	'Aichi Target', 'Convention Biological Diversity', 'Green Deal', 'Polycentric governance'	17,033	46.2	4.9
Adaptive governance	'Conflict resolution', 'Monitoring evaluation and learning', 'Whistleblower protection'	5,827	15.8	1.7
Shifting societal views and values		112,780		32.2
Change social norms	'Behavioral nudge', 'Dietary transition' 'Lifestyle change', 'Recycling', 'Shared ownership'	73,147	64.9	20.9
Transformative learning	'Capacity building', 'Environmental education', 'Inner development', 'Transformation lab'	24,059	21.3	6.9
Nature connectedness	'Biophilia', 'One health', 'Ecocentrism', 'Planetary health', 'Relational values'	8,374	7.4	2.4
Change narratives	'Awareness campaign', 'Environmental discourse', 'Environmental storytelling', 'Green discourse',	6,525	5.8	1.9
Knowledge co-creation	'Citizen science', 'Co-design', 'Multiple evidence-based approach', 'Participatory action research'	3,647	3.2	1.0

Actor group	Examples of terms included	N	within	overall
Civil society		**377,546**		**29.6**
CSOs	'Community-based organization', 'Consumer group', 'Faith community', 'Grassroots organization',	8,317	2.2	0.7
NGOs	'Conservation NGO', 'Environmental NGO', 'Independent sector', 'Third-sector organisation'	5,383	1.4	0.4
Indigenous people	'Aboriginal', 'Autochthonous People', 'First Nations', 'Indigenous People', 'Native People', 'Tribes'	27,211	7.2	2.1
Citizens	'Adolescent', 'Citizen', 'Common people', 'Consumer', 'Lay person', 'Neighbour', 'Youth', 'Woman'	208,654	55.3	16.4
Local communities	'Farmer', 'Fishing community', 'Forest dweller', 'Gatherer', 'Forest users' group', 'Local community'	154,553	40.9	12.1
Env. movements	'Conservation group', 'Environmental defender', 'Environmental justice', 'Environmental activist'	6,451	1.7	0.5
Private sector		**473,963**		**37.2**
Business	'Business', 'CEO', 'Company', 'Enterprise', 'Firm', 'Producer', 'Shareholder', 'Supplier', 'Vendor'	376,965	79.5	29.6
Donor/foundations	'Donor', 'Funding agency', 'Grantmaker', 'Impact investor', 'Philanthopic organization', 'Sponsor'	65,350	13.8	5.1
Financial actors	'Federal reserve system', 'Insurance company', 'Regulatory authority', 'Venture capital firm'	70,016	14.8	5.5
Public sector		**251,598**		**19.7**
IGOs	'Earth System Governance', 'Global Environment Facility', 'United Nations Development Programme'	21,094	8.4	1.7
Justice system	'Attorney', 'Court clerk', 'Court interpreter', 'Judge', 'Jury', 'Lawyer', 'Parole officer', 'Prosecutor'	43,248	17.2	3.4
Local government	'City council', 'Municipal government', 'Regional government', 'State government'	51,014	20.3	4.0
National government	'Congress', 'Department of environment', 'Ministry', 'National government', 'Parliament'	154,902	61.6	12.1
Communication and knowledge sector		**624,423**		**49.0**
Scientific community	'College', 'Lecturer', 'Research agency', 'Scientific institution', 'Think tank', 'University'	392,992	62.9	30.8
Education community	'Educator', 'Headmaster', 'Principal', 'School', 'Teachers association', 'Training institute'	256,878	41.1	20.1
Media	'Digital platform', 'Documentary', 'Journalist', 'Newspaper', 'Online media', 'Website'	103,397	16.6	8.1
Networks	'Broker', 'Community network', 'Learning network', 'Living lab', 'Social network',	24,413	3.9	1.9



Actions

Conserve and regenerate		**Transform governance**	
1.1	Biocultural stewardship	4.1	Integrated governance
1.2	Rights-based conservation	4.2	Inclusive governance
1.3	Area-based protection	4.3	Multilateral governance
1.4	Regenerative systems	4.4	Adaptive governance
1.5	Integrated planning	**Shift views and values**	
Address direct drivers		5.1	Nature connectedness
2.1	Regulating extraction	5.2	Change narratives
2.2	Technological change	5.3	Change social norms
2.3	Conservation finance	5.4	Transformative learning
2.4	Civil action	5.5	Knowledge co-creation
Transform the economy			
3.1	New economic tools		
3.2	Just transition tools		
3.3	Financial reform		
3.4	New success metrics		

Actors

Civil society		**Public sector**	
1.1	CSOs	3.1	IGOs
1.2	NGOs	3.2	Justice
1.3	Ips	3.3	Local Gov
1.4	Citizens	3.4	Nat`l Gov
1.5	LCs	**Knowledge sector**	
1.6	EMs	4.1	Educators
Private sector		4.2	Media
2.1	Business	4.3	Networks
2.2	Donors	4.4	Scientists
2.3	Finance		