SPECIAL FEATURE: PERSPECTIVE

Navigating complexity through knowledge coproduction: Mainstreaming ecosystem services into disaster risk reduction

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Achieving the policy and practice shifts needed to secure ecosystem services is hampered by the inherent complexities of ecosystem services and their management. Methods for the participatory production and exchange of knowledge offer an avenue to navigate this complexity together with the beneficiaries and managers of ecosystem services. We develop and apply a knowledge coproduction approach based on social–ecological systems research and assess its utility in generating shared knowledge and action for ecosystem services. The approach was piloted in South Africa across four case studies aimed at reducing the risk of disasters associated with floods, wildfires, storm waves, and droughts. Different configurations of stakeholders (knowledge brokers, assessment teams, implementers, and bridging agents) were involved in collaboratively designing each study, generating and exchanging knowledge, and planning for implementation. The approach proved useful in the development of shared knowledge on the sizable contribution of ecosystem services to disaster risk reduction. This knowledge was used by stakeholders to design and implement several actions to enhance ecosystem services, including new investments in ecosystem restoration, institutional changes in the private and public sector, and innovative partnerships of science, practice, and policy. By bringing together multiple disciplines, sectors, and stakeholders to jointly produce the knowledge needed to understand and manage a complex system, knowledge coproduction approaches offer an effective avenue for the improved integration of ecosystem services into decision making.

natural hazards | regulating services | resilience | participatory research | boundary work

Over the past decade, the global scientific community has developed the methods, data, and understanding to demonstrate and quantify many important links between nature and resilient societies and economies. This progress is clearly apparent in the abundance of publications, new scientific journals, datasets, frameworks, research funding, and initiatives that increasingly span the globe (1–7). Research efforts have begun to penetrate global policy and decision-making arenas: e.g., through the Intergovernmental Platform on Biodiversity and Ecosystem Services. At subglobal levels, a number of initiatives linking ecosystem services with decision making now exist in the public and private sectors (8, 9). Despite these successes, many scientists and practitioners remain frustrated by the limited pace, scale, and replicability of decisions that successfully incorporate (or mainstream) ecosystem services and yield desired outcomes for human well-being and nature (9–16).

Several reasons have been put forward to explain the limited impact of ecosystem service science on decision making, ranging from specific gaps in the necessary scientific information and tools (17–19) to more generic and transdisciplinary challenges associated with the complex social and political processes needed to catalyze action (10, 13, 20–25). Knowledge systems and knowledge-integration processes have been identified as central to navigating the social processes required to mainstream scientific data and understanding effectively into policy and decision making (26–28). By focusing on what knowledge is produced, as well as how it is produced and exchanged, research is more likely to create knowledge for effective use in decision making (26, 29–31). The need for new modes of knowledge production in research and decision making has led to more interdisciplinary and participatory processes that combine, interpret, and communicate knowledge from diverse disciplines and stakeholders (28, 29, 32–34).

The coproduction of knowledge—defined as "the collaborative process of bringing a plurality of knowledge sources and types together to address a defined problem and build an integrated or systems-oriented understanding of that problem" (32)—seems particularly relevant in the area of ecosystem services and decision making. Ecosystem services are produced by social–ecological systems. They are the emergent result of multiple ecosystem features (35), social factors such as tenure, access, and preferences (36, 37), and interactions between social and ecological components (38, 39). In addition, these interactions and benefit flows span multiple temporal and spatial scales (40–42), presenting a mismatch with the usual time and spatial frames of decision making (43, 44).

Making choices amid such complexity represents a substantial hurdle to decision makers, and, as a result, ecosystem services are rarely adequately captured or taken into account during decision making (45). In fact, as scientists innovate with new methods and models to account for this complexity, analytical outputs become increasingly complex,

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and the gap between science and practice risks widening further (46, 47).

The challenge of integrating complex information into decision making poses an obstacle to mainstreaming ecosystem services into promising decision-making arenas. Disaster risk reduction, which aims to analyze and reduce the causal factors and impacts of natural hazards that lead to disasters, is one such arena (7, 48–50). Ecosystem-service approaches for disaster risk reduction target the conservation and restoration of regulating ecosystem services to reduce the impacts of natural hazards like floods and droughts. Regulating services (e.g., water flow regulation and coastal protection) regulate the flow of energy and materials through ecosystems, mitigating and even preventing the impacts of natural hazards, thereby reducing the risk of disasters (36). However, the complexities inherent in regulating services and disaster risk reduction limit progress in the mainstreaming of ecosystem services. These complexities include the multiple and dynamic ecosystem features, processes, and cross-scale interactions associated with regulating services, as well as the social–ecological drivers, vulnerabilities, consequences, and actions involved in reducing the risk of disasters (40, 51, 52).

Acknowledging the complexity of regulating services and disaster risk reduction, by bringing together multiple disciplines, sectors, and stakeholders to collectively produce the knowledge needed to adequately understand and manage a social–ecological system, seems to hold much potential for improved integration of ecosystem-service knowledge into decision making (53). To demonstrate and explore the effectiveness of knowledge coproduction methods for mainstreaming ecosystem services, we develop, pilot, and evaluate a knowledge coproduction approach across four case studies of natural hazards in South Africa. We describe the case studies briefly and demonstrate the approach using experiences drawn from the case studies. Outcomes of applying the approach are then synthesized to reflect on the effectiveness of the methods used and to advance the theory and practice of knowledge coproduction approaches for mainstreaming ecosystem services.

Case Studies

All four case studies are located in the Southern Cape of South Africa, a mountainous area in the fynbos biome experiencing rapid urban and agricultural development (Fig. 1). The region receives rainfall throughout the year, with peaks in March and October accompanied by cutoff low pressure systems associated with extreme weather events. The area's rainfall pattern, together with its mountainous topography, makes it prone to flash floods interspersed by long droughts. High rainfall events are often accompanied by large storm waves, resulting in severe coastal flooding, especially if estuary mouths are closed. Fynbos is a fire-prone vegetation type that, during periods of hot, dry weather, can result in large wildfires. The area is widely infested with nonnative invasive shrubs and trees that induce declines in water availability and disrupt fire regimes (54). The extreme weather of this region results in a large number of disasters from floods, wildfires, droughts, and storm waves, evidenced by substantial insurance claims and damage costs (55). These costs motivated stakeholders from the public and private sector, in collaboration with research and nongovernmental organizations (NGOs), to develop four case studies each focused on a particular natural hazard. The four collaborative case studies were established to discover the causes of, and possible responses to, the observed increases in natural hazards (See Table 1 and ref. 56 for details on the case studies).

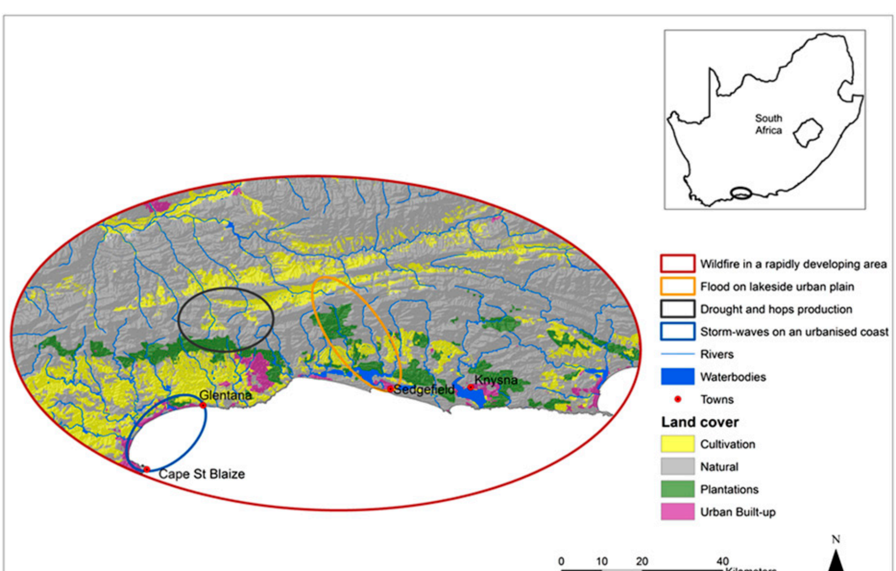

Fig. 1. Location of four case studies on flood, storm wave, drought, and wildfire in the Southern Cape of South Africa. The map depicts the distribution of current land use and is transposed over a digital elevation model for illustrative purposes.

A Knowledge Coproduction Approach for Mainstreaming Ecosystem Services

We developed an approach that aimed to coproduce credible and salient knowledge on the role of ecosystem services in mitigating natural hazards and their impacts. Participatory approaches and frameworks used in the study and management of social–ecological systems (57) and vulnerability and resilience frameworks (58, 59), as well as operational frameworks for mainstreaming ecosystem services (10), provided useful starting points from which to design an approach for piloting across all four case studies.

The resulting process (Fig. 2) took each case study through three stages: (*i*) codesign of the project, (*ii*) knowledge coproduction, and (*iii*) collaborative planning for implementation. All three stages were participatory, involving different configurations of participants drawn from research organizations, NGOs, public and private sectors, parastatals, and civil society. Table 1 summarizes the participants into four main groups involved: (*i*) knowledge brokers skilled in leading, facilitating, and translating the process of knowledge coproduction, (*ii*) assessment teams of technical experts who collate data, develop scenarios and models, and review outputs, (*iii*) implementers from the private and public sector and civil society who plan and implement actions, and (*iv*) bridging agents who interface between the research and implementation contexts. The four groups were often overlapping and included new members as the case study developed and new knowledge was gained. Furthermore, in line with South Africa's three spheres of government (national, provincial, and local), these four groups included representatives capturing specific legislative, coordination, or implementation powers and functions at each scale.

Table 1. Description of location, context, rationale, and participants of the four collaborative case studies where the knowledge coproduction approach was applied

Case study description	Participants
Case study 1. Flood on a lakeside urban plain: A national insurer and local disaster managers concerned about the causes and responses to increasing flood damage in this region after five severe weather events from 2003 to 2008. The town of Sedgefield, built on a low-lying coastal plain (<10 masl), is highly vulnerable to flooding from heavy rains. The surrounding catchment regulates water flows through infiltration, soil stabilization, flow regulation, and storage by soil, vegetation organic matter, and root systems. This flood regulation service is complemented by the role of the lake and estuary in breaching the estuary berm and reducing water levels.	Knowledge brokers Environmental NGO; research organization; insurance company; provincial disaster management Assessment team Research organization; insurance company; local authority disaster management Implementers Public Officials from planning, environment, disaster management, and conservation sectors at local and provincial scales; National Department of Cooperative Governance; South African Local Government Association; National Disaster Management Centre; South African National Parks Private Insurance company; forestry company Civil society Environmental NGO; land owners; community forums Bridging agents Provincial department of climate change and biodiversity, National Biodiversity Institute, local authority disaster management and environmental planning, environmental and conservation NGOs
Case study 2. Wildfire in a rapidly developing area: Forestry sector (private and public) and national insurer interest in an increase in impacts of wildfires. The Garden Route coastal plain lies within the fynbos biome, a fire-prone and fire-dependent system, which is vulnerable to wildfires. Natural ecosystems regulate fire extent, intensity, and occurrence through the interaction of vegetation flammability, fuel loads and connectivity, microclimate regulation, and ignition sources.	Knowledge brokers Environmental NGO; research organization; insurance company; forestry company; provincial disaster management Assessment team Research organization; forestry company; Fire Protection Association; provincial conservation authority Implementers Public Officials from environment, disaster management, conservation, agriculture, and forestry sectors at local and provincial scales; South African National Parks; public works program Private Insurance company; forestry company Civil society Fire Protection Association; environmental NGO Bridging agents Research organization; environmental NGO; local authority disaster management
Case study 3. Drought and hops production: A national brewery concerned about water-related risks to hops production initiated the project to explore the causes, consequences, and management options of water shortages to hops farmers in the area. The Waboomskraal and Herold subcatchments around the hops farms play an important role in capturing and storing rainfall in soil, rock, and organic material, thereby regulating flows and run-off. Of particular relevance to the drought mitigation service is the ability of these catchments to discharge and recharge groundwater, yielding higher baseflows in rivers and making more surface water available for irrigation in the stressed dry season.	Knowledge brokers Environmental NGO; research organization; brewery company Assessment team Research organization; brewery company; hops farmers Implementers Public Officials from disaster management, water, conservation, agriculture, and forestry sectors at local and provincial scales; catchment management agency; South African National Parks; public works program Private Insurance company; brewery company Civil society Fire Protection Association; hops farmers Bridging agents Research organization; environmental NGO; National Department of Water Affairs; local authority disaster management

Codesigning Projects for Knowledge Exchange

The first stage of the approach (Fig. 2) involved knowledge brokers, defined as individuals who "absorb complex ambivalent messages from diverse sources including technical, commercial and legislative developments and translate them into terms that can be understood and acted upon" (60). These individuals included high-level representatives responsible for initiating the projects, drawn from research institutions (academic and government), NGOs, and private and public sectors (Table 1). Private sector knowledge brokers were senior executives of a national insurer (in the case studies of flood, wildfire, and storm waves), and a large international brewery (in the case study on drought).

These knowledge brokers were involved throughout the case study: designing, coordinating, and facilitating the process of joint knowledge production, translating the findings for potential implementers, developing collective response strategies, and channeling these strategies back into their institutions for implementation. Several knowledge brokers were scientists, able to participate, guide, and integrate the findings in the assessment teams. Knowledge brokers were also well-versed and networked into specific implementation contexts relevant to each case study and thus were able to identify opportunities, partners, or gaps for implementation. Although the exact configuration of knowledge brokers differed across case studies, some individuals were involved in all case studies. This configuration of knowledge brokers was important in the identification of synergies and cross-cutting responses: e.g., revisions to national disaster management policy.

Knowledge Coproduction Using Social–Ecological Systems and Scenarios

The knowledge coproduction phase brought together knowledge brokers and a larger assessment team of technical experts to generate new knowledge on the causes, consequences, and possible responses to natural hazards. Technical experts were drawn from across research, NGO, public, and private institutions to represent multiple knowledge systems, as well as to involve all stakeholders in a transdisciplinary process aimed at producing and exchanging knowledge for disaster risk reduction (26, 30). The experts contributed their data and understanding to the coproduction process. This phase was iterative through the participatory engagement, review, and revision of knowledge and products. It was also adaptive to opportunities and changes in the implementation context. Although the process varied across

Table 1. Cont.

Case study description	Participants
Case study 4. Storm waves on an urbanized coast: A national insurer and local disaster managers, aware of increasing storm wave-related damage and claims, initiated the project to assess the causes and possible responses to storm waves. Along the coast from Cape St. Blaize to Glentana, floods resulting from storm waves (waves with high run-up, impacts, and scouring) driving up onto land cause extreme coastal flooding and subsidence, thus damaging infrastructure along the coast. Shoreline ecosystems (e.g., beaches and dunes) are important for ensuring natural sediment transport processes, which prevent landward migration of the shoreline, allow for recovery of beaches after storms, and thereby maintain shallow beach profiles that reduce wave run-up.	Knowledge brokers Environmental NGO; research organization; insurance company; provincial disaster management Assessment team Research organization; Insurance company; local authority Implementers Public Officials from planning, environment, disaster management, engineering sectors at local and provincial scales; National Department of Cooperative Governance; South African Local Government Association; National Disaster Management Centre; South African National Parks Private Insurance company Bridging agents Environmental NGO; research organization; local authority disaster management

Participant organizations in each case study are listed according to groups involved in different phases of the coproduction approach.

case studies depending on context and inputs from the codesign phase, we highlight three central elements that were consistent across case studies (Fig. 2): the equal participation of a broad range of technical experts, the adoption of a social–ecological systems approach, and the use of scenario planning to facilitate knowledge coproduction.

The choice of a social–ecological systems approach aimed to foster a joint understanding of the interacting social and ecological features, drivers, and consequences of natural hazards. It further aimed to help expand from the narrow and mostly social focus of disaster management in the region with its emphasis on built infrastructure, human capacity, and institutional components. This more integrated view enabled participants to collectively create a conceptual model of the system and its vulnerability to natural hazards, including the identification of key social and ecological components, ecosystem services, stakeholders, drivers of change, and institutional arrangements (Table S1). These conceptual models helped navigate the complexity of information while developing a consensus understanding of the contribution of regulating ecosystem services, identifying priority drivers of change in these services, and highlighting stakeholders responsible for managing these drivers of change (Table 1 and Table S1).

The flood case study identified vegetation cover changes associated with forestry clearing practices, the effects of wildfire on soil hardening, and estuary berm height as important drivers of change in the flood regulation services in the area. Similarly, in the fire case study, wildfire risks and impacts were found to be linked to infestations of nonnative invasive plants, substantially altering natural biomass, fuel loads, and fire processes in forestry and urban areas. These nonnative plants are intensive water users and linked to reductions in groundwater recharge and discharge processes associated with drought mitigation services in the drought case study. The erosion of coastal foredunes and coastal hardening from development were identified as main drivers of declines in the coastal protection services mitigating impacts of storm waves in the storm-wave case study.

The coproduction phase used a combination of participatory approaches, including interviews, meetings, reviews of literature and data from research and practice, policy analysis, and collaborative field trips. These joint activities were seen as crucial for knowledge exchange and building ongoing relationships for future work.

Scenario planning, a popular tool used across a range of domains to learn and plan for uncertain and complex futures, was a central focus of the coproduction approach (57, 61). Scenarios are plausible explorations of the future and were particularly useful in working with stakeholders to formulate responses to complex and unexpected events associated with natural hazards. In our tailoring and testing of the approach, we developed a baseline scenario of current or natural ecosystem conditions, and two scenarios to examine moderate and severe drivers of change to ecosystem features of relevance for regulating services (Table S1). For comparative purposes, scenarios of future climate change were also used (based on the A2 Special Report on Emissions Scenarios scenario of enhanced anthropogenic forcing) (56).

There is a wide diversity of qualitative and quantitative techniques for use in scenario planning. Quantitative process-based and statistical models were used in the four case studies to quantify changes in intensity of natural hazard impacts across scenarios (Table S1) (56). Fig. 3 summarizes the results of the scenario modeling indicating a 4% and 10% increase in the intensity of large floods (defined as floods with a current 1:100-y return period) for moderate and severe changes in vegetation cover in the catchment. Fireline intensity showed increases of 101% and 280% for moderate and severe infestations of nonnative plants. An approximate halving of flows due to degradation of groundwater recharge processes was found in scenarios examining spread of water use-intensive nonnative plants, with a 46% exacerbation in low flows associated with moderate droughts and 51% exacerbation in extreme low flows found during severe droughts. Moderate and severe erosion rates of beach slope from coastal hardening resulted in a 28% and 157% increase in extreme wave run-up height events (currently seen in 1:100-y return period) (Table S1 and Fig. 3). An empowering result from these codeveloped models was the finding that the natural hazard consequences of ecosystem change (where stakeholders can take action) were often as great as, or greater than, the consequences of the climate change scenario (Fig. 3).

Collaboratively Designing Actions for Disaster Risk Reduction

The resulting shared knowledge on natural hazards and their drivers of change was fed into the final phase of the process to codesign responses needed to mitigate impacts (Fig. 2). This phase involved knowledge brokers, implementing agencies, and bridging agents. It used the important drivers of ecosystem change identified in the previous step to codesign necessary actions and outcomes, with relevant stakeholders responsible for managing the drivers and implementing the actions (Table 1).

Currently implemented responses include new investments in ecosystem services and shifts in policy and practice, as well as new collaborations in the area of ecosystem-based disaster risk reduction. For example, a multimillion dollar investment has been made by South African National Parks to clear nonnative invasive plants to reduce wildfire risk in and around a large protected area embedded in the urban matrix of the region. A

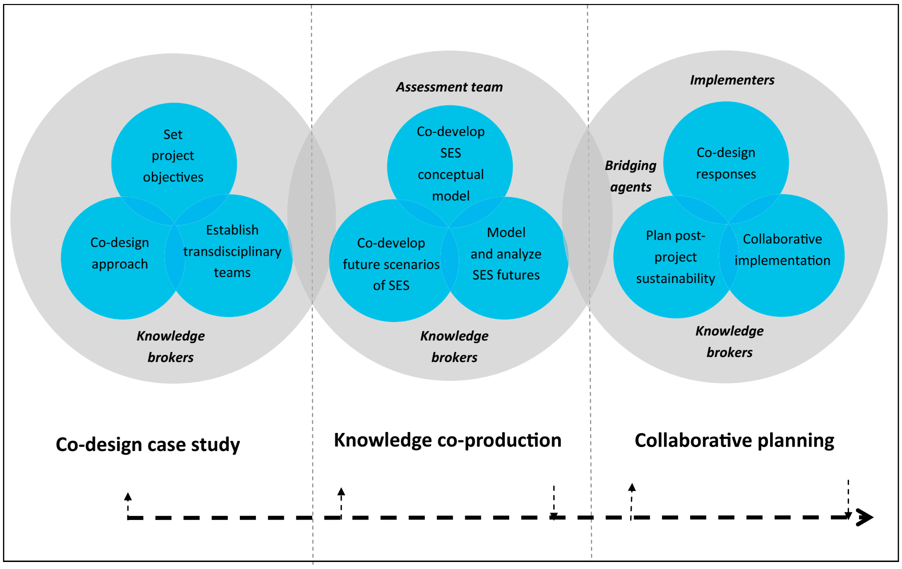

Fig. 2. Outline of the knowledge coproduction approach developed and evaluated across four case studies. The approach moves through three phases from codesigning the project, coproducing the knowledge using a social–ecological systems (SES) approach with scenario planning, and finally collaboratively designing and implementing responses to manage ecosystem services to mitigate natural hazard impacts. The groups of participants in each phase are indicated and include knowledge brokers leading and facilitating the case study, assessment teams of technical experts, implementers from public and private sectors, and bridging agents who interface between the research and implementation contexts.

similar large investment by the brewery company unlocked funds and new employment opportunities in clearing nonnative invasive trees from important catchments supplying water to the hops farms. A codesigned investment between businesses and an environmental NGO in the region to restore foredunes has also begun. Policy shifts incorporate the invited contribution of inputs into national disaster management legislation and budgeting to allow for proactive ecosystem-based management for disaster management.

The codesign of responses went beyond identifying who is mandated (but often unable) to manage the drivers, to design interventions needed to build additional skills and support for the responsible institutions, and to identify possible partners with resources and knowledge to help implement these interventions. For example, a newly expanded membership of the Southern Cape Fire Protection Association now includes both public and private sector agencies cooperating around the installation of strategic fire belts and fuel reduction strategies. In addition the brewery appointed a representative into public sector water-resource planning processes. Additional new collaborations to improve data, tools, and capacity for flood risk assessment and development planning also emerged: e.g., the Eden Disaster Resilience Learning Network was established to coordinate ecosystem-based approaches to disaster risk reduction. It is chaired by the provincial authority, with members from provincial, district, and local levels from environment and disaster risk reduction, as well as national and provincial conservation authorities, NGOs, scientists, and corporate partners in the insurance, timber, and beverage sectors. A newly launched process to decentralize insurance underwriters will also hopefully build new partnerships with local authorities involved in urban, coastal, and disaster management.

Bridging agents played a substantial role in this phase of the case studies, not only linking the knowledge coproduction to implementing agencies and opportunities, but also in ensuring postproject sustainability. The time frames of implementation are frequently cited as a challenge to successful project impact because funding and support frequently finish before implementation begins to take effect. For several of these case studies, the involvement of bridging agents will help continue this support beyond the time frames of the funded projects. Examples include the chairing of new collaborations by provincial officials, the support by parastatals in processes to change legislation, new streams of funding from the private sector, and the appointment of researchers into advisory roles within the public and private sector.

Reflections on the Approach

Knowledge coproduction is increasingly becoming central to many aspects of sustainability science and policy (32, 62–64). This model of knowledge exchange is linked to successes in building trust, capacity, knowledge flows, and learning within stakeholder groups, as well as to improvements in outputs and outcomes of applied research processes (34). The approach used here seems to have been successful in collectively developing new understanding and action. It proved effective at integrating knowledge about ecosystem services into the way stakeholders frame the causes of natural hazards and possible responses. In particular, the approach clarified the systems nature of natural hazards and the contribution of ecosystem services within these systems in determining natural hazard impacts. It was successful at broadening the focus from climate change to make clear the consequences of ecosystem change on natural hazard impacts. This increased awareness of the importance of ecosystem services in the area is evidenced in a survey of decision makers in the case studies (65).

The ability to reframe issues and broaden options for management is central to effective knowledge integration (26) and is evidenced in several recent communications involving private sector participants (e.g., ref. 66) and new high-level collaborations developed among implementing agencies. An example is the recently formed Business Adopt a Municipality—a forum set up by the insurance company and supported by the South African Local Government Association—for businesses to support local authorities in managing natural hazards. Further evidence of the impact of this approach is the range of novel ecosystem-based responses described above that were designed and implemented by participants. These actions are unlikely to have emerged in the absence of the collaborative case studies.

The knowledge coproduction approach helped move the case studies into deeply integrated learning processes where new knowledge was collectively produced, researchers and stakeholders shared learning experiences, interactions were facilitated, purposive, and deliberate, and all stakeholders had equal power to provide insight and take action (31). This shared learning was evident in the practitioner community, but also among researchers where stakeholder knowledge, on factors such as budgetary processes in disaster management and business operations of centralized insurance underwriting, was used to codesign responses. The approach was able to manage the boundaries between research and practice by the involvement of all stakeholders, their knowledge, and data in the development of collaborative products, such as conceptual models of natural hazards, scenarios, and models of future impacts. These products or "boundary objects" were based on credible, legitimate, and salient knowledge and proved

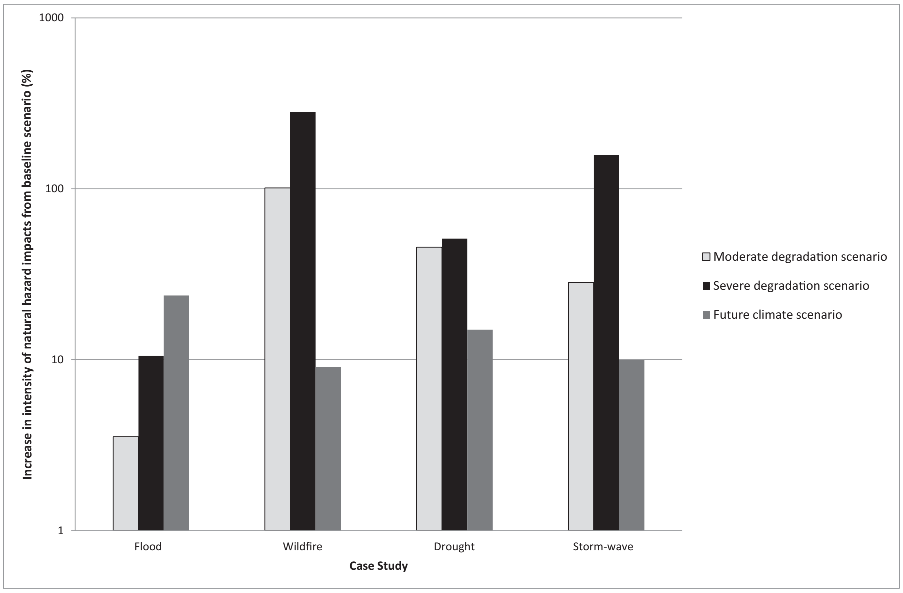

Fig. 3. Changes in natural hazard intensity across codeveloped scenarios of future ecosystem change in four case studies of flood, wildfire, sea storm, and drought in the Southern Cape of South Africa. Changes in intensity are measured for flood and sea storm as increases in daily flows (m^3) and wave run-up height (m) compared with flows and run-up height found during an existing 1:100-y event. Changes in wildfire intensity are measured as increases in fireline intensity ($kW \cdot m^{-1}$) whereas drought intensity is measured as decreases in monthly flows (million m^3) of droughts at 70% and 90% probability of exceedance on the flow duration curve (defined here as low flows and extreme low flows, respectively). Changes in intensity are extracted from ref. 56 and reflected for synthesis purposes as a percentage of the baseline scenario intensity using a logarithmic scale. Impacts of a future climate scenario (56) are also depicted.

important in making the case for ecosystem conservation and restoration (25, 26, 30).

The social–ecological systems perspective of the approach helped identify systemic responses involving multiple stakeholders, sectors, actions, and beneficiaries. Some responses targeted a common driver of change linked to multiple natural hazards: e.g., invasive nonnative plants. Others focused on delivering multiple benefits by addressing social and ecological vulnerability. For example, hops farmers partnered with a job-creation program to clear nonnative invasive plants to achieve multiple benefits: improved water yield, decreased water pumping costs, improved off-season job creation for vulnerable communities of seasonal harvesters, and improved protection of priority biodiversity areas.

A popular response across projects was the development of new partnerships that pooled resources held by the private sector, civil society, and research organizations with the authorities mandated to implement the work. These partnership responses also enabled the movement away from the existing pattern of coping with natural hazards, to longer term, proactive responses that explored adaptation options targeted at reducing the sensitivity and exposure of the systems to natural hazards (59, 67). In many of these responses, enhancements of regulating services were a priority. Such responses are often referred to as ecosystem-based adaptation approaches to climate change (7, 52).

Several partnerships took the form of learning networks between different stakeholder groups. This focus on learning, often referred to as social learning, has been highlighted by several authors as a key element in building the adaptive capacity and resilience needed to deal with change and uncertainty (59, 68–70). Such learning has been shown to be particularly useful in bringing together different knowledge systems and approaches necessary for developing an understanding of the system and designing management responses (28, 31, 71). It has also enabled ongoing learning about the system and its responses to management interventions (32, 34). This learning, in turn, facilitates a more adaptive management approach that adjusts responses as new knowledge is developed and actively shapes future change (72, 73). This development also reflects a growing movement away from sector- and stakeholder-specific approaches, toward systemic disaster risk reduction that focuses on collective management of vulnerability in the landscape (68).

Conclusion

Efforts to reduce the risks and impacts of natural hazards present potential opportunities to mainstream ecosystem services into decisions. Across the four case studies, we found that a knowledge coproduction approach helped navigate complex information to develop an integrated understanding of the natural hazard and its drivers and impacts, among a broad range of stakeholders. The approach supports strongly integrated learning between researchers and practitioners, where communication, translation, and me diation are fundamental processes of the interaction, supported by intermediary (or boundary) organizations able to create and sustain mutually beneficial problem-solving activities (26, 27, 60). This "boundary work," in turn, provided the necessary credibility and legitimacy needed to support proactive strategies to manage and reduce natural hazard impacts (74, 75). By moving to a broader reframing of the social and ecological determinants of natural hazard impacts, the role of ecosystems and their services were made visible. Furthermore, the suite of responses identified was substantially diversified, and stakeholders became more empowered to act locally. These responses require novel partnerships for combining resources, mandates, knowledge, and values held by different stakeholder groups to ensure ongoing coproduction of knowledge and action.

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