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Evidence-Based Causal Chains for Linking Health, Development, and Conservation Actions

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Evidence-Based Causal Chains for Linking Health, Development, and Conservation Actions

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Sustainability challenges for nature and people are complex and interconnected, such that effective solutions require approaches and a common theory of change that bridge disparate disciplines and sectors. Causal chains offer promising approaches to achieving an integrated understanding of how actions affect ecosystems, the goods and services they provide, and ultimately, human well-being. Although causal chains and their variants are common tools across disciplines, their use remains highly inconsistent, limiting their ability to support and create a shared evidence base for joint actions. In this article, we present the foundational concepts and guidance of causal chains linking disciplines and sectors that do not often intersect to elucidate the effects of actions on ecosystems and society. We further discuss considerations for establishing and implementing causal chains, including nonlinearity, trade-offs and synergies, heterogeneity, scale, and confounding factors. Finally, we highlight the science, practice, and policy implications of causal chains to address real-world linked human–nature challenges.

Keywords: interdisciplinary science, sustainability, complex systems, landscape ecology, environmental health

Human-induced environmental changes present significant challenges to the functioning and resilience of our Earth's systems, with negative consequences for human society (Scholes et al. 2005). These challenges are becoming increasingly complex and interconnected (Whitmee et al. 2015). Prominent examples include intertwined issues among public health, poverty, and environmental sustainability (Sutherland et al. 2011, Griggs et al. 2013). Therefore, effective solutions require a transdisciplinary approach (Choi and Pak 2006) that integrates knowledge across different fields and sectors to address the linkages and feedback loops between social and environmental systems (Van Kerkhoff and Lebel 2006, Komiyama and Takeuchi 2006, Biggs R et al. 2012). Such an integrated perspective is crucial for not only promoting joint actions to advance sustainable development but also for strengthening science-policy dialogue and prioritizing research investments (Fox et al. 2006, Young et al. 2014, Tallis et al. 2017).

In the realm of conservation science, there has been a paradigm shift from "nature for itself" and "nature despite people" to "people and nature" (Mace 2014). Recent reviews have also called for integrating human dimensions and social sciences into conservation to facilitate robust and effective policies, governance, and actions (Bennett NJ et al. 2016, Rissman and Gillon 2016). In fact, the notion that people and nature are intrinsically connected has been widely acknowledged by global conservation organizations (e.g., The Nature Conservancy, Conservation International, and Wildlife Conservation Society), as is evidenced in their vision statements. It is therefore imperative for conservation communities to understand how conservation efforts affect human development and how environmental policies and management exert effects on natural systems and, in turn, the multifaceted aspects of human well-being (e.g., health, education, income, security, and social cohesion; Tallis et al. 2008, Sutherland et al. 2009, Game et al. 2014).

Research frameworks bridging disparate disciplinary and sectoral boundaries have advanced over the past decades. Examples include the social–ecological systems framework (Ostrom 2009), coupled human and natural systems (Liu et al. 2007), ecosystem service (Daily et al. 1997), and resilience theory (Folke 2006). These frameworks share a common element of systems thinking and system-based solutions toward sustainability (Liu et al. 2015) and have been applied in an increasing number of social–ecological studies (Mooney 2016). Nonetheless, implementation has

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been constrained by a lack of agreement regarding their consistent uses across different fields and sectors, precluding systems integration and creation of a “shared evidence base” (Pullin and Knight 2009, Tallis et al. 2017). Paths forward are unclear because (a) the knowledge required for solving linked challenges for people and nature is inherently transdisciplinary but often originates from individual disciplines and isolated policy sectors; (b) there is no practical approach to amassing and synthesizing evidence on a full spectrum of social and ecological changes (Cartwright et al. 2010); and (c) coordinated actions and collaborations among scientists, stakeholders, practitioners, and policymakers are essential for furthering this research agenda but frequently lack persistence and depth (Barlow et al. 2011, Clark et al. 2016).

Causal chains (variously called logic models, log frames, conceptual models, result chains, or theory of change) is an approach to identifying logical and ordered sequences of effects on how a system responds to interventions, actions, or perturbations. Despite being used in a range of disciplines and policy domains, there is remarkable variation in the purpose, structure, terminology, and methodology associated with causal chains, presenting a significant obstacle to cross-disciplinary integration. For example, in environmental science, result chains are used to evaluate the multiple and possibly interrelated ecological impacts of management (Niemeijer and Groot 2006). In epidemiology, directed acyclic graphs (DAG)—one variant of the causal chain approach—are used to infer and predict clinical outcomes of a treatment while accounting for other confounding biases (VanderWeele and Robins 2007). However, these seemingly distinct forms of causal chains share common ground in their fundamental theories and processes (Margoluis et al. 2013). Therefore, we argue that causal chains hold promise as a coherent framework that can incorporate solutions and outcomes from multiple sectors (e.g., health, development, and conservation), present an integrated model for encompassing varied components of social–ecological systems originated from different concepts and theories, and provide a scaffold for collecting shared evidence across these communities and disciplines. Rather than focusing on specific domain-bounded issues, causal chains can be extended toward a more holistic and systematic understanding of how management and policy actions affect different aspects of human welfare through social–ecological pathways (Foundation of Success 2007, Margoluis et al. 2013, Mupepele et al. 2016). They can also be lenses through which the evidence associated with causal pathways can be evaluated.

Although causal chains have garnered increased popularity in conservation science, there is no normative consensus about the principles and guidelines necessary to create causal chains relevant for dealing with human–nature challenges, resulting in wide variations in practice and disconnects across disciplines (Tallis et al. 2017). Nonetheless, such frameworks and principles could provide the basis for identifying common research and policy priorities and for establishing a shared social–ecological evidence base for concerted actions across sectors. It may also help each sector and discipline identify where their focus fits into a larger, complex problem and choose metrics that facilitate integrated analysis and knowledge transfer. Such a need is key for achieving global sustainability goals such as the United Nations Sustainable Development Goals (Griggs et al. 2013) and the Paris Agreement on climate actions (Rogelj et al. 2016).

To advance a shared understanding of how causal chains can illuminate environment and human well-being linkages and develop evidence-based management actions, we first review concepts and theories from different fields pertaining to causal chains and then present a framework that connects actions with a range of ecological and social outcomes in regards to the health, development, and conservation sectors. We then propose a set of guidance for building cross-sectoral causal chains compatible with subsequent collation and synthesis of evidence. Third, we discuss five considerations relevant for understanding, establishing, and implementing causal chains in research and practice. Finally, we highlight the research, practice, and policy implications of causal chains in addressing linked human–nature challenges.

Foundational concepts: Causal chains linking ecosystem changes and society

Causal chains did not rise *de novo* but rather have been built on a rich legacy of concepts and theories, including, among others, theory of change, decision tree, causal decision theory, and causal theories of reference (Margoluis et al. 2013). In principle, they are used to analyze logical and ordered sequences of effects regarding how systems respond to interventions, actions, or perturbations. Variants of causal chains have been used in a wide range of research and practice communities. Table 1 presents a nonexhaustive list of causal chain variants in different fields for different uses, such as building shared strategy, exploring hypotheses, identifying data and knowledge gaps, and laying the foundation for analytical models and communications.

Grounded on the common underlying principles of causal chains, we introduce the foundational concepts (figure 1) that connect actions with integrated ecological and social outcomes in a cross-disciplinary space. Figure 1 starts from specifying the decision context and scope and identifying outstanding challenges that confront the focal social–ecological system. These challenges can be identified through a situational analysis, which considers broad-context drivers, including policy, economics, geography, climate, and culture, that contribute to current states of affairs and problems (TNC 2016). To address the challenges, management and policy actions are proposed, in many cases capturing individual actions already being undertaken. The determination of scope and actions is also an opportunity to evaluate cross-sectoral strategies and feedback processes, as well as transformative solutions. Once candidate actions are determined, the next step is to map out the causal chains for both people and nature. It is important to consider where to start

Table 1. Variants of causal chains adopted in different sectors and disciplines.

Discipline and sector	Causal-chain variants	Exemplary references
Public health and epidemiology	Directed Acyclic Graph (DAG)	(VanderWeele and Robins 2007)
	Logical framework analysis (Logframe)	(Lerer 1999)
	Single-chain epidemiology modeling	(Joffe et al. 2012)
Development	Path diagram analysis	(Duncan 1966)
	Input–output model	(Miller and Blair 2009)
	Logframe	(Coleman 1987)
Environment	Result chain	(Margoluis et al. 2013)
	Structural path analysis	(Grace 2006)
	Fuzzy modeling	(Özesmi and Özesmi 2004)
	Bayesian belief network	(Marcot et al. 2006)
	Drivers–Pressures–State–Impacts–Responses (DPSIR)	(Svarstad et al. 2008)
	Causal Analysis/Diagnosis Decision Information System (CADDIS)	(EPA 2004)

Note: This is a nonexhaustive list, and certain approaches can be applicable in multiple sectors and disciplines.

the causal chain; in some cases, there will be opportunities to directly implement an action (e.g., public managers on public lands), whereas in other cases, programs or policies (e.g., education or incentives) will be needed to lead other actors to take the proposed actions. If such a program or policy is a prerequisite leading to a desired action, then it is crucial to think about the outcomes and effects of such a program or policy, including and beyond those of the intended action.

There are two possible pathways by which an initiating policy or program or actions can affect human well-being. Management strategies can (a) exert direct impacts on human systems (the arrow of “direct social impacts” in figure 1) or (b) propagate through biophysical systems to alter ecosystem services, which by definition can affect human well-being. In traditional ecological assessments, causal chains often begin with management or policy actions, end with environmental changes, and thus omit impacts on or benefits to society (Niemeijer and Groot 2006, Olander et al. 2015). In contrast, in our proposed framework, we expanded to social outcomes of management and close the cycle of systemic changes between nature and people. Different topologies are available to identify human dimension and social outcomes, such as The Nature Conservancy’s Focal Areas (TNC 2016), the Millennium Ecosystem Assessment (MEA 2005), and the Final Ecosystem Goods and Services Classification System (Landers and Nahlik 2013). Changes in human systems could then affect natural systems and vice versa (the arrow of “social–ecological feedback” in figure 1). One example of a social feedback system with impacts on the biophysical system occurs in Kenya, where local residents convert forests into intensively cultivated lands without supplying additional nutrients, leading to soil degradation with resulting food insecurity and reduced household income while further accelerating the degradation of the remaining forests (Liu et al. 2007). Another important feedback loop is adaptive management (figure 1), in which social–ecological outcomes are monitored, analyzed, and evaluated. Results from analyses and evaluations can foster social learning and the adaptation of implemented management goals and actions, thereby leading to more resilient social–ecological systems (Holling 1978, Fernandez-Gimenez 2008). Furthermore, the local causal pathways can also interact with global processes such as climate change and global trade (the interactions with “global change drivers” box in figure 1; Adger et al. 2009, Biggs D et al. 2011). These interactions affect how the goals and targets are set, what actions take place, and pathways through which changes are cascaded in the social–ecological systems. In regional watersheds, for example, management such as riparian buffers or nutrient management plans is essential to control eutrophication and improve human consumptive uses of freshwater; however, increased climate variability and extremes can overwhelm local land-use and management effects on reducing nutrients losses (Bettez et al. 2015, Usinowicz et al. 2017). Coral reefs offer another example where local nutrient runoff and overfishing can interact with increasing sea surface temperature to cause coral degradation and bleaching (Ban et al. 2014, Zaneveld et al. 2016).

Guidance for creating causal chains for cross-disciplinary integration

In this section, we present stepwise guidance for developing causal chains in social–ecological systems that integrate environmental and human outcomes and serve as the basis for creating a shared evidence base (figure 2). Our intent is to illustrate this process in a general sense while providing sufficient technical details so that it can be operationalized in a wide range of decision contexts (see box 1 for a list of exemplary research and practical questions that can be addressed with the causal chain framework). The guidance

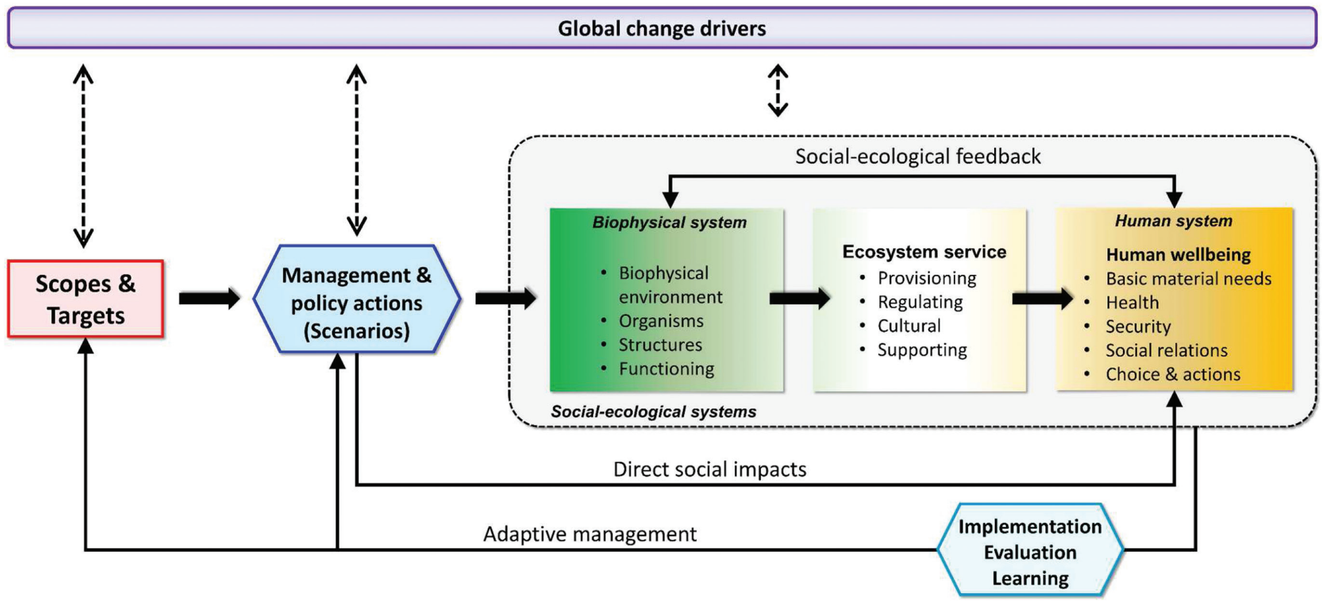

Figure 1. The components of causal chains that link ecological and social outcomes to management actions in the context of global environmental changes. The green-to-yellow gradient shows the integration of human–natural systems.

was developed through a series of workshops and real-world examples involving participants from academia, nongovernmental organizations, federal agencies, and research organizations representing multiple fields and sectors (see supplemental tables S1 and S2 on the list of the workshops' participants).

Below, we summarize each step with an illustrative causal chain example of managing wildfires in western US forests (figure 3) developed from the workshop in May 2016; please see Olander and colleagues (2016) for the full version of this forest wildfires example. It is important to note that the illustrated causal pathways are based on expert knowledge from the workshops and thus should be considered as hypotheses subject to changes during evidence assessment and synthesis. Moreover, because the structure of causal chains is inherently a product of the expertise involved, it is crucial to have experts and stakeholders spanning the appropriate range of disciplines at the onset and planning stage of the causal-chain development.

Phase I. The first phase for creating causal chains is to specify decision context, define shared visions and anticipated goals, and identify focal actions (figure 2). Decision context will include the social–ecological systems of interest, as well as relevant human–nature components and interactions, sociopolitical context, topical constraints (e.g., forest habitats, biodiversity, human health, and bioenergy production), geographic scope, scale, actors (e.g., stakeholders, decision-makers, and managers who are expected to take actions), and power dynamics among different stakeholder groups (Robards et al. 2011, Groves and Game 2016). The decision context can be identified through conducting a formal situational analysis (Salafsky et al. 2002, Lemos and Morehouse 2005). This is the stage at which cross-sector links first emerge, and it is critical to take a systems perspective (Tallis et al. 2017).

Once decision context is determined, the next step is to build up a shared vision of how the focal system operates, what factors matter most for its resilience, and how they are affected by multiple drivers of change (Kahane 2012). This process may be iterative and requires drawing conclusions from different perspectives, observations, facts, and interpretations that members of the development team and stakeholders have as a result of their different histories and roles in the system (Kahane 2012). The shared vision will then inform the determination of a set of directional, measurable, and time-bounded goals. Ideally, the goals need to reflect the human–natural links and cut across three dimensions: ecological, social, and economic—where ecological aspects need to be specific to ecosystem structure and functions (e.g., reducing fire-induced losses in wildlife habitats and timber production in the example of figure 3) and social or economic aspects should be specific to beneficiary groups (e.g., reducing losses in the property and impacts on the health and lives of visitors and local residents in figure 3). In addition, temporal scale is another important aspect for setting the goals, where certain goals such as reducing pollutant emissions from wildfires are more responsive to management, whereas other goals (e.g., increasing carbon sequestration) take a much longer time frame to achieve (Qiu et al. 2017a).

The last step in this phase is to identify candidate actions (e.g., mechanical thinning as a potential forest-management strategy to reduce large canopy fires and their associated

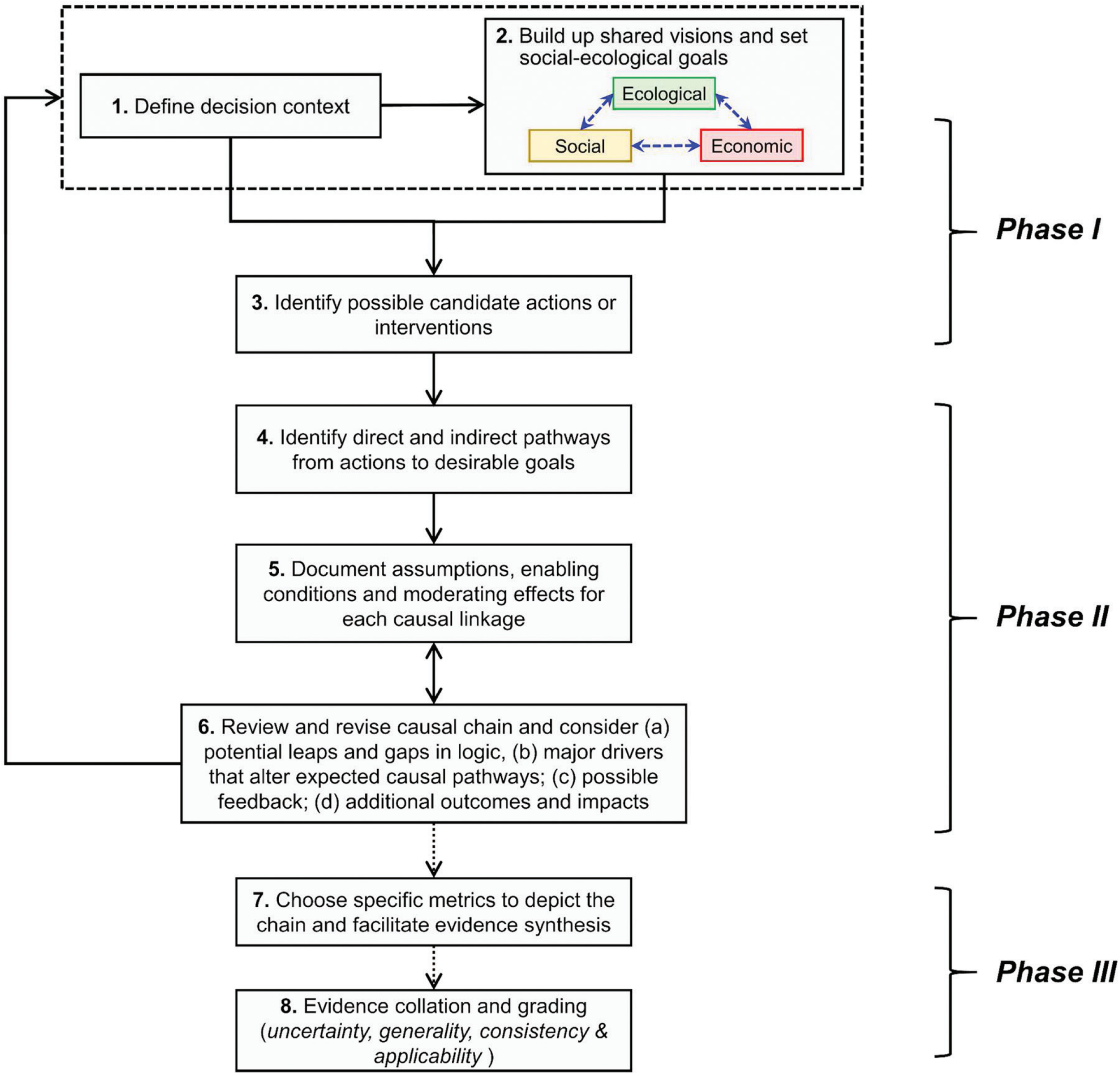

Figure 2. Stepwise principles and guidance for building evidence-based causal chains.

risks in the example of figure 3) for achieving desirable goals. A set of alternative scenarios of actions can be identified (with one causal chain constructed for each scenario) for comparing their effectiveness (Alcamo 2008). Often, a no-action or business-as-usual option would be used as the baseline for comparison. It is also vital to consider what policy, program, or institutional conditions are needed for the successful implementation of proposed actions.

Phase II. The key steps in this stage are to analyze possible actions by identifying pathways between actions and social–ecological goals and adding nontarget cobenefits and unintended consequences. This is an important stage because explicitly mapping out detailed stepwise causal pathways can promote cross-disciplinary integration, facilitate subsequent evidence collation and grading, and also allow for the analysis of trade-offs among social–ecological outcomes through the causal chains (Tallis et al. 2017).

In these causal chains, there are two types of causal pathways: direct and indirect. *Direct pathways* usually refer to the direct human well-being or social impacts of an action, and *indirect pathways* are the changes cascaded or mediated through alterations in ecosystems and the goods and services they provide (Biggs D et al. 2016). Both pathways are

Box 1. Exemplary research questions that are cross-disciplinary and addressable with the causal chain framework and approach.

- How will local land management and community-based changes in agricultural systems sustain food production, reduce impacts on human health, and decrease water and airborne pollution and greenhouse-gas emissions while at the same time enhancing equity in food access and distribution?
- Which management interventions are most effective in maintaining longleaf pine forests in the southeastern United States while reducing fire risks; conserving native biodiversity and freshwater resources; and providing income and job security, social cohesion, and equity to the communities?
- How can urban landscapes be managed to maintain intact and connected habitats for organisms, mitigate impacts on microclimate and water resources, and also provide sufficient economic structure and social services to people?
- What are the optimal methods to ensure that forest- or landscape-restoration projects improve connectivity between populations and habitats, thereby facilitating gene flow and species migration, and maintain complementary land uses and the livelihoods of local people?
- How can local knowledge, wisdom, and experiences be effectively combined with national and subnational forest assessment, monitoring, and management efforts to sustain forest production and maintain local livelihoods?
- How do natural and social communities respond to increased frequencies of extreme weather events, and do these community responses enhance the social–ecological resilience to anticipated future climate variability and extremes?

critical and need to be explicitly considered. One example of the direct causal pathway in the forest wildfire management case (figure 3) is the hypothesized positive effects of mechanical thinning on the number of forest-management jobs, and one example of the indirect causal pathway is the hypothesized positive effects of mechanical thinning on ecotourism-related income and employment through enhancing forest structure and aesthetics.

One common question at this step is when to stop building the causal pathways. Two strategies can be considered: (1) stopping at the first human well-being outcomes unless extending further is essential to the decision context for facilitating the integration of outcomes of interests to different disciplines and sectors and (2) consulting with local communities or affected parties to understand which changes might have the greatest importance (either quantitative or qualitative) and using that information to define the endpoints (Vogel 2012, Piggot-Irvine et al. 2015, Valters 2015). For instance, in the forest-wildfire-management example (figure 3), human well-being outcomes such as respiratory illness or death, property damage, timber production, or ecotourism-related income and employment are where this causal chain ends.

Once the causal chains are created, the next step is to draft the assumptions, enabling conditions, and moderating effects of each link. The *key assumptions* describe *a priori* understanding (or hypotheses if unknown) of mechanistic or behavioral relationships of causal pathways, which could be enhanced by subsequent evidence synthesis. The *enabling conditions* refer to the conditions under which the causal pathways are likely valid and the expected outcomes from actions can be achieved (Biggs D et al. 2016). The *moderating effects* refer to factors that may alter the expected magnitude or strength of causal pathways. This step of detailing assumptions, enabling conditions, and moderating effects is fundamental for building causal chains because it (1) underlies the basis for integrating knowledge across fields or sectors and establishing a shared evidence base, (2) creates a credible process through which different stakeholders will buy into and support proposed actions, and (3) provides an important opportunity to identify areas in which new evidence and research are critical to understand how decisions affect key stakeholders.

The last step in this phase is to review and revise the constructed causal chain by considering (a) potential "leaps and gaps" in the logical sequences, (b) other major drivers of change that could alter expected causal pathways, (c) possible social and ecological feedback loops, and (d) additional human well-being outcomes and impacts whose scopes are not previously considered. In theory, the causal chains should be comprehensive and expansive, and include changes even those that are difficult to measure. In practice, the causal chains can be simplified or tailored according to different audiences. For example, a simplified causal chain (e.g., with a small number of intermediate causal pathways and more succinct structure) might be more appropriate for policy- and decision-makers, whereas a more complex and inclusive causal chain (e.g., the inclusion of detailed stepwise effects and enabling conditions that underlie each causal pathway) can be more useful for researchers, agency analysts, and on-the-ground practitioners.

Phase III. Causal chains can be supported by an evidence base that demonstrates the validity of associated assumptions, hypotheses, and strength of causal relationships (Mupepele et al. 2016). Ultimately, the causal chains need to be supported

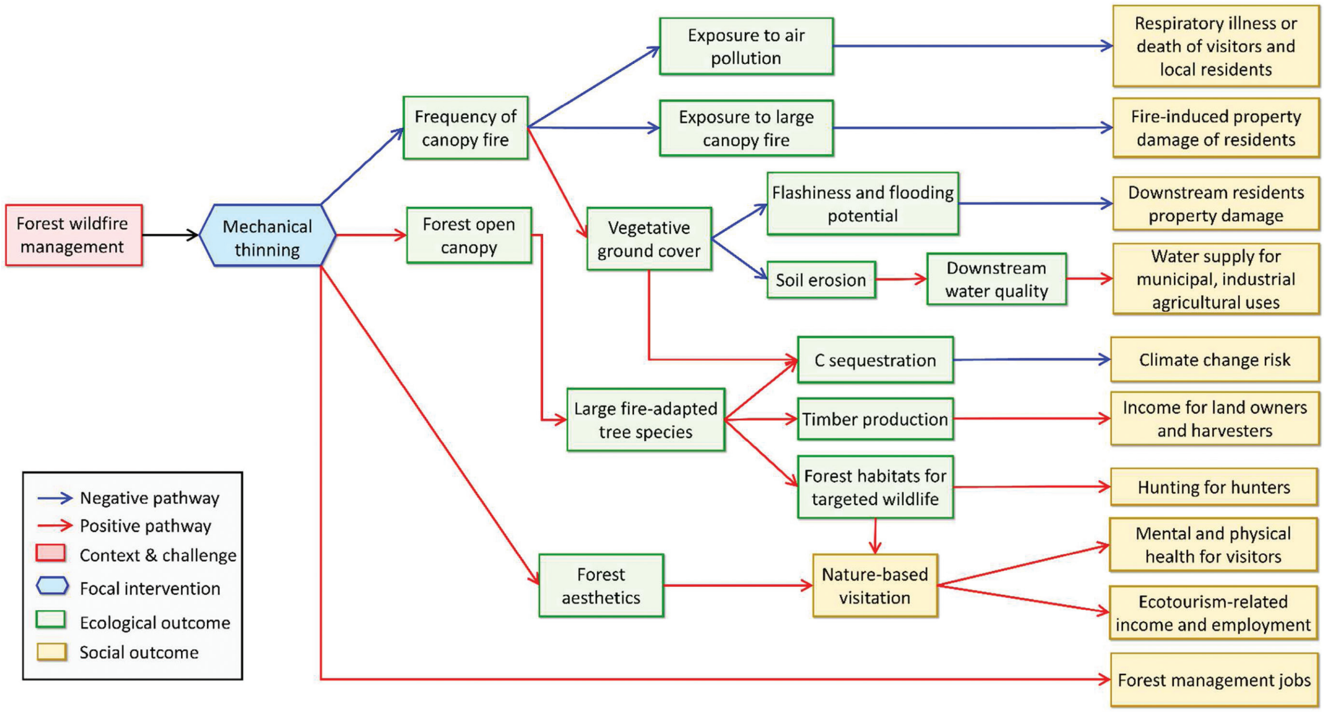

Figure 3. An illustrative example of a causal chain developed by the workshop participants that focuses on managing wildfires in western US forests to reduce impacts and risks for people and nature. A full draft of developed causal chains can be found in Olander and colleagues (2016). Please note that the directions of causal pathways were based on expert knowledge and opinions and therefore should be viewed as hypotheses rather than results. Subsequent evidence assessment and synthesis may change the expected direction and magnitude of the causal pathways.

by evidence (the so-called evidence-based causal chain) so that management and policy actions are well informed. Evidence comes from a range of sources, including expert judgment (local knowledge, traditional ecological knowledge, and subject-matter expertise), quantitative empirical studies, qualitative empirical studies, models, or theories. The evidence-collation process can be facilitated if the causal chains are represented using specific and quantifiable metrics and the assumptions and associated conditions respecting each causal link are made explicit (Reyers et al. 2013, Piggot-Irvine et al. 2015). In that way, evidence from different disciplines and sources can be readily compared, analyzed, and synthesized. Different approaches exist to assess different aspects of evidence, including uncertainty, generality, consistency, and applicability. Considering these characteristics of evidence would provide robust support (or lack thereof) for the causal links while retaining the ability to incorporate different types of evidence from multiple disciplines.

A detailed review of the key considerations of evidence collation, assessment, and grading is beyond the scope of this article but is provided in Sutherland and colleagues (2015).

Key considerations in establishing and implementing evidence-based causal chains

In this section, we highlight five considerations—nonlinearity, trade-offs and synergies, heterogeneity, scale, and confounding factors—relevant to applying evidence-based causal chains in research and practice. We use a schematic case of a causal chain (the upper left panel of figure 4) and draw a balance of empirical terrestrial and aquatic examples from published studies.

Nonlinearity. Many ecological and social processes are nonlinear and exhibit thresholds or tipping points (figure 4a), at which small changes in drivers produce large and irreversible (or costly-to-reverse) consequences for people and nature (i.e., regime shift; Scheffer and Carpenter 2003, Lindenmayer and Luck 2005, Groffman et al. 2006). Nonlinearity and thresholds occur in a range of social–ecological systems (Walker and Meyer 2004). Thresholds have been reported on cropland, mangrove, and shoreline development for water quality (Qiu and Turner 2015), coastal protection (Barbier et al. 2008) and fish populations (Biggs R et al. 2008), respectively. Therefore, it is crucial to consider not only the direction and magnitude but also the shape of causal links and the conditions under which thresholds or nonlinear responses would occur. Understanding and identifying such nonlinearities, although not easy and straightforward, could inform where, when, and how actions can maximize management outcomes from limited resources (Qiu and Turner 2015). In particular, the nonlinear responses of social impacts and drivers (e.g., the

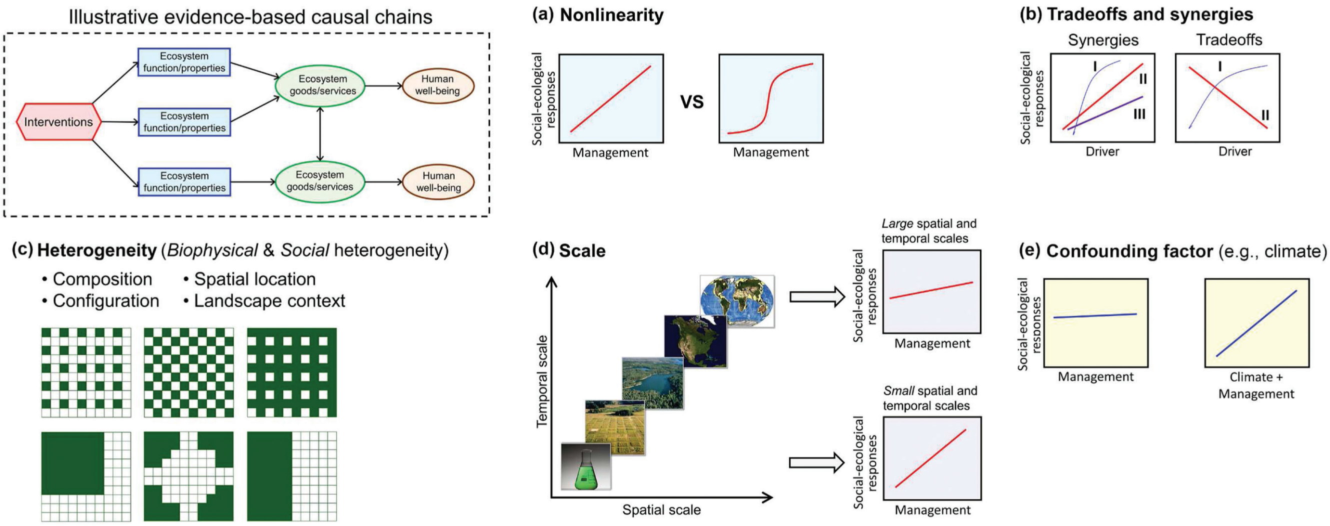

Figure 4. The key considerations for establishing and implementing causal chains illustrated using a hypothetical example (upper left panel). (a) Nonlinearity: causal links can be nonlinear and exhibit thresholds. (b) Trade-offs and synergies: complex interactions among outcomes may exist in causal chains; synergies and trade-offs among social–ecological outcomes can be produced as a result of common drivers and management actions (modified from Bennett EM et al. 2009). (c) Heterogeneity: biophysical and social heterogeneity could alter the causal pathways. In this example, the same amount of habitats or ecosystems (indicated by green) can have completely different spatial configuration, location, and surrounding biophysical and social elements, which may mediate the effects of management practices (example modified from Turner and Gardner 2005). (d) Scale: spatial, temporal, and social scales could also affect the existence and strengths of causal links such that management effects at one scale may differ or diminish at a different scale. (e) Confounding factors: factors at broader scales, such as climate change, that may mask or override effects of local interventions.

threshold effects of temperature on heat-related deaths and infectious disease transmissions; McMichael et al. 2006) and their identifications remain an important research gap (Walker and Meyer 2004).

Trade-offs and synergies. Human actions could enhance multiple ecosystem services simultaneously (i.e., synergies), increase one service at the expenses of others (i.e., trade-off), or favor benefits to one group over another (i.e., trade-off). Causal links might be perceived as directional flows from actions to outcomes. However, it is possible that actions can have multiple consequences, and intermediate or final outcomes can also interact with each other, creating trade-offs or synergies (figure 4b). Trade-offs and synergies among ecosystem services have been active areas of research (Rodríguez et al. 2006, Bennett EM et al. 2009). For example, it has been demonstrated that agricultural intensification can lead to trade-offs with water quality, and afforestation and wetland restoration can produce synergies among multiple regulating services, such as carbon storage and nutrient retention (Qiu and Turner 2013). Therefore, it is essential to explicitly consider the interactions among ecological and social outcomes in causal chains to avoid unanticipated trade-offs and take advantage of synergistic effects.

Heterogeneity. Human interactions with nature vary across space, meaning that it is necessary to consider the spatial heterogeneity of the system and the broader landscape context within which the studied system is situated (figure 4c). Understanding when and how spatial heterogeneity matters is crucial for the rigor and effectiveness of causal chains and can inform the spatial planning of conservation management and policy (Qiu et al. 2017b). A variety of theoretical and empirical studies have demonstrated that landscape composition (type and amount of cover), configuration (spatial arrangement of different cover types), and position, as well as the pattern of surrounding landscapes, can play a vital role in ecosystem functioning and organisms and thus mediating the influences of management actions (Robbins and Bell 1994, Turner 2005). However, how environmental heterogeneity interacts with social heterogeneity and what the consequences are for the linked human–natural systems identified by the causal chains remain less well understood and deserve more considerations for future research.

Scale. Scale (including spatial, temporal, and social scales) could also influence causal pathways (figure 4d). A rich body of research has revealed that social–ecological phenomena are scale dependent (Wiens 1989, Levin 1992); therefore, the effects of conservation and management actions are contingent on the scale at which they operate. Recent studies also demonstrated that ecosystem services relationships vary by spatial, temporal, and social scales, and therefore, scale matters for designing effective and fair management strategies to enhance ecosystem services and human well-being (Raudsepp-Hearne and Peterson 2016). In building causal chains, it is useful to indicate scales at which assumptions of causal pathways are specified and their evidence holds valid. This helps to avoid scale mismatches while extrapolating and helps to understand potential cross-scale interactions and dynamics in the effects of management actions for linked human–natural systems (Cash et al. 2006, Cumming et al. 2006, Folke 2006).

Confounding factors. Although the major focal driver in causal chains is human actions, which often occur at local scales, it is also important to consider global processes, such as climate change and international trade, and the extent to which they may become confounding factors that override or obscure local effects (figures 1 and 4e). For example, a number of studies have revealed that climate variability could overwhelm local land-use and management effects on water quality (Bettez et al. 2015) and quantity (Qiu et al. 2017a). Therefore, in building evidence-based causal chains, in particular at the evidence-synthesis and -grading phases, it would be useful to specify which causal pathways can be altered by other confounding factors, by how much, and in which directions. Otherwise, the expected outcomes from the causal chains might be misleading.

The science, practice, and policy implications of evidence-based causal chains in addressing linked human–nature challenges

Evidence-based causal chains provide a useful tool for addressing linked human–nature challenges because they are systematic, transdisciplinary and multisector oriented, quantitative, transferrable, and adaptive.

Systematic. Causal chains have the potential to evaluate a range of social and ecological outcomes, as well as their interactions (i.e., trade-offs and synergies), arising from management actions. This is crucial because the sustainability challenges we are confronting today are increasingly intertwined and require a holistic rather than piecemeal or sectorial perspective to reconcile the needs for conserving nature and satisfying human development (Reed et al. 2016).

Transdisciplinary and multisector oriented. The framework of causal chains moves from conceptual acknowledgment to a practical approach that explicitly unites knowledge across disparate disciplines (e.g., ecology, economics, policy, public health, anthropology, and sociology) and sectors (e.g., environment, health, and development sectors). With such a framework, people and decision-makers in turn are more compelled to recognize the complexity of linked human–nature challenges and the need for concerted actions and solutions, which facilitate collaborations, knowledge transfer, and the creation of a shared evidence base (Game et al. 2017).

Quantitative. Causal chains can be integrated with evidence (including both qualitative and quantitative evidence) to inform the strength, direction, and response curve of causal pathways, which provide the scientific foundations in assessing effectiveness and rigor of management actions. In addition, a multitude of modeling and statistical approaches can be adopted, including formal meta-analysis, systematic review, structural equation modeling, Bayesian belief network, and so forth.

Transferrable. One of the benefits of using evidence-based causal chains is the capacity to establish a shared evidence base so that it can be transferred to other regions or systems with similar decision contexts and threats. This avoids the costs of reinventing the wheel and enhances the efficiency and efficacy of conservation planning and management practices (Olander et al. 2016). However, it is important to verify the contexts, assumptions, enabling conditions, and evidence associated with causal pathways when transferring causal chains from one context to another to avoid unforeseen risk and surprises (Valters 2015). In particular, context-specific beneficiaries need to be consulted so that the newly developed causal chains are grounded in true local realities and are acceptable to local communities for successful implementation (Valters 2015).

Adaptive. Causal chains can be flexible and adaptive in their structure, with submodels underpinning each component and link. Therefore, causal chains can be modified (e.g., expanding or removing certain ecological and social pathways) according to different uses and knowledge gathered through learning and monitoring. This character and the lens of perceiving causal chains as a “compass” rather than a “map” are important, because they can facilitate learning during the process of building and applying causal chains and promote robust decision-making in the face of uncertainty (Valters 2015).

Causal chains can also be instrumental for communication and prioritization. Causal chains are powerful tools for communicating scientific knowledge to a wide range of audiences, including the general public, managers, policy- and decision-makers, and different stakeholders. Logical pathways and flow diagrams supported with evidence describe the expected outcomes from proposed actions and can thus help guide appropriate expectations. Although causal chains can sometimes be complex in structure, they can also be simplified or tailored for different purposes. Furthermore, the process of building evidence-based causal chains can help identify knowledge gaps and future research needs, especially those essential for transcending disciplinary boundaries. Specifically, causal linkages that lack sufficient or have inconsistent evidence suggest where future research and monitoring are urgently needed.

Conclusions

Sustainability challenges are increasingly recognized as complex in nature. It becomes apparent that a single discipline or sector can no longer provide solutions to these complex sustainability issues. Rather, we need to move toward the coalition of knowledge, approaches, and understanding across a range of relevant fields and sectors around the creation of a shared evidence base. We argue that causal chains are well positioned to bridge this gap, to provide a common framework to understand the dynamics and interactions of coupled human–natural systems, to support evidence-based decision-making, and to serve as a transformative approach for systems integration in the new era of complex human–nature linked research, practice, and policy. Such a perspective and approach also help unite actions across a range of players, including researchers, managers, decision-makers, and different stakeholders for allied and shared actions fundamental for achieving prominent sustainable development goals.

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Supplemental material

Supplementary data are available at *BIOSCI* online.

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