

REVIEW

Unintended Feedbacks: Challenges and Opportunities for Improving Conservation Effectiveness

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Abstract

Human reactions to conservation interventions can trigger unintended feedbacks resulting in poor conservation outcomes. Understanding unintended feedbacks is a necessary first step toward the diagnosis and solution of environmental problems, but existing anecdotal evidence cannot support decision-making. Using conservation examples, we present a conceptual framework and typology of unintended feedbacks based on a social-ecological systems (SES) approach. Three types of causal mechanisms for unintended feedbacks are distinguished: (1) *flow unintended feedbacks* when pre-existing feedbacks are enhanced or dampened; (2) *deletion unintended feedbacks*; and (3) *addition unintended feedbacks* when interventions, respectively, remove or add actors or links to the SES structure. Application of this typology can improve conservation outcomes by enabling the inclusion of complex relationships into planning and evaluation. We show how widely used tools for conservation planning could produce misleading recommendations, and discuss future work to mitigate the effect of unintended feedbacks in conservation practice. There is an urgent need to collect evidence in a structured way in order to understand the mechanisms by which human decision-making feeds through to conservation outcomes at different scales, thereby minimizing negative unintended feedbacks. The framework presented in this article can support the development of this evidence-base.

Actions lead to reactions

Unintended effects of planned conservation interventions can have knock-on effects that result in perverse outcomes. For example, the threatened Javan hawk eagle was declared a National Rare/Precious Animal to promote public attention for its conservation, but this attention also increased trade demand for the species (Nijman *et al.* 2009). Potential land use restrictions under the Endangered Species Act resulted in preemptive timber harvesting, which destroyed an area of habitat that could have supported half the 129 colonies needed to meet the red-cockaded woodpecker's conservation target (Lueck & Michael 2003). In Indonesia, increased income from seaweed farming, promoted as a conservation tool to reduce pressure on fisheries, was invested in capital improve-

ment of fisheries businesses, potentially increasing pressure on fisheries (Sievanen *et al.* 2005).

Conservation science needs to be able to predict and design for human reactions to interventions (St John *et al.* 2013). Understanding the feedback loops that constitute the unintended knock-on effects of conservation interventions is a key element in achieving this goal. An unintended feedback exists when reactions to an intervention have an effect on the intended outcomes directly or indirectly, as illustrated in the examples above. Unintended feedbacks include both ecosystem dynamics and human reactions to interventions. There are multiple examples of perverse outcomes in natural resource management, such as management suppressing natural disturbance regimes or altering slowly changing ecological variables, leading to unintended detrimental

changes in soils, hydrology and biodiversity (Holling & Meffe 1996). However, the unintended feedbacks of conservation interventions modulated through human decision-making are poorly studied, and are likely to be significant determinants of conservation outcomes (Milner-Gulland 2012). Here, we highlight the role unintended feedbacks play in conservation outcomes, and the need for better evidence on their prevalence and types in different circumstances. In order to guide the collection and organization of evidence so that a strong empirical underpinning can be built for future research, we develop a new framework for understanding unintended feedbacks. First, we modify an existing social-ecological system (SES) approach to provide a theoretical understanding of how conservation interventions can trigger unintended feedbacks. Then, we present a new typology of unintended feedbacks, drawing on a wide range of conservation examples that show how unintended feedbacks undermine conservation efforts. Finally, we use the typology to reflect on how best to plan for and mitigate unintended feedbacks in conservation practice, and discuss implications for future work.

Undermined conservation efforts: how much do we know?

It has been recognized that unintended feedbacks can render conservation interventions inefficient and ineffective (Polasky 2006). However, there is still a relatively simplistic narrative regarding how people will react when planning conservation interventions (St John *et al.* 2013). For example, a lack of success in the alternative livelihoods approach is linked to its three simplistic assumptions of substitution, homogeneous community, and impact scalability (Wright *et al.* 2016). Even with the use of project design tools such as Miradi (Miradi 2007), which make the theory of change underlying the chosen intervention explicit, the indirect consequences of people's reactions to conservation can still remain unaccounted for. With conservation interventions increasingly centered on changing human behavior, understanding how these interventions alter the incentives and actions of the people causing biodiversity loss, and their knock-on effects, is of great relevance to the design and evaluation of such interventions.

The literature on unintended consequences of conservation interventions on people (Cerneja & Schmidt-Soltan 2006) or nontarget species (Harihar *et al.* 2011) is large; however, cases documenting how unintended consequences feedback to result in undermined conservation goals are uncommon and mostly anecdotal. Examples of potential unintended feedbacks mediated through human decisions include integrated conservation and de-

velopment projects enhancing the profitability of existing environmentally harmful activities such as land clearance (Jack *et al.* 2008), promoting development of new enterprises that may impact other ecosystem components (Spiteri & Nepalz 2006), or leading to positive net migration (Oates 1995). Widely used market-based approaches such as payments for ecosystem services (PES) bring into play spatial and temporal scales that can differ from the target system, broadening the scope of potential effects of feedbacks. For example, protection of forests from exploitation under Reducing Emissions from Deforestation and Forest Degradation initiatives can lead to displacement of exploitation to distant areas (Angelsen 2007).

Studies addressing real-world unintended feedbacks in conservation are scarce, but modeling has been used to explore how interventions can backfire. Damania *et al.* (2005) used a household utility model to show how an alternative livelihoods approach to alter hunting behavior could increase mortality of the most vulnerable species. Other modeling studies have shown how land market feedbacks lead to highly cost ineffective conservation planning (Jantke & Schneider 2011), or that buying land for conservation can sometimes condemn more species than it saves (Armstrong *et al.* 2006). Land purchase for conservation can increase the price of nondeveloped land, for example by reducing the stock of land for development, raising the prospect of future conservation land purchase, or increasing the amenity value of neighboring land. This can then displace development, potentially to other biologically sensitive areas, or limit the amount of land that can be purchased for a given conservation budget.

Reviews of unintended feedbacks are also few and scattered. A review examining the extent to which the peer-reviewed literature addressed feedbacks between conservation interventions and SESs found most articles focused either on the effect of conservation on people, or of people on the environment, with few studies empirically addressing both the social dynamics resulting from conservation initiatives and subsequent environmental effects (Miller *et al.* 2012). There is a lot more focus on feedbacks in the resilience and SESs literature (Gunderson & Holling 2002). This literature is based on a systems thinking approach that explicitly considers the interaction between the social and ecological components of a system, facilitating interdisciplinary analysis of human-nature dynamics (Glaser *et al.* 2008). Within the last decade, significant progress has been made with respect to interdisciplinary investigation and modeling of coupled SESs (Baur & Binder 2013).

Recently, the importance of explicitly accounting for feedbacks to better manage complex systems has been highlighted with a Special Feature published in Ecology

and Society (Hull *et al.* 2015). From a coupled human and natural systems perspective, the articles in this issue identify feedbacks that stabilize and destabilize systems across agricultural, forest, and urban landscapes. Emerging themes include multilevel feedbacks, time lags, and surprises as a result of feedbacks.

Building an understanding: an SES perspective

Systems thinking is especially attuned to explaining side effects and perverse outcomes due to its emphasis on feedback loops; it has been recommended as a theoretical approach to underpin behavioral change policy design (Lucas *et al.* 2008). Systems dynamics modeling has been applied to manage and avoid unintended consequences and their feedbacks in designing hazards management and disaster relief policy (Gillespie *et al.* 2004). For example forest fire management (Collins *et al.* 2013), emergency resource coordination (Wang *et al.* 2010), and efficient positioning of relief services (Widener *et al.* 2015). Clearly articulated with systems thinking theory, the SES literature is where most of the work on human-natural systems has been done, providing a strong grounding for work on unintended feedbacks.

An SES is a complex, adaptive system consisting of a bio-geophysical unit and its associated social actors and institutions, with boundaries that delimit a particular ecosystem and its problem context (Glaser *et al.* 2012). As complex systems, SESs present inherent properties such as nonlinearity, emergence and self-organization, path dependence, and positive/negative feedback loops (definitions in Table 1; Becker 2012). These properties are relevant to the analysis and planning of conservation interventions because they provide a framework for understanding and describing SES behavior. Given the increasing spatial teleconnectedness of social actors and institutions through international trade, information technologies and travel, the spatial boundaries of the SES can encompass multiple countries or represent a global system.

In systems thinking, a feedback loop exists when results from some action travel through the system and eventually return in some form to the original action, potentially influencing future actions. In a “negative or balancing” feedback the initial change to a system causes change in the opposite direction, dampening the effect; in a “positive or reinforcing” feedback the initial change to a system causes more change in the same direction, amplifying the effect (Chin *et al.* 2014). For example, a reinforcing feedback loop between fragmentation processes (fire, logging) and landscape pattern (connectivity, patch

characteristics, and edge effects) significantly accelerated the effect of deforestation on biodiversity in the Brazilian Amazon (Cumming *et al.* 2012).

There are several frameworks to analyze environmental problems in the context of SESs. We take as our starting point the SES Framework (SESF), developed by Ostrom (2009) as a diagnostic tool for understanding the sustainability of complex SESs. Binder *et al.* (2013) reviewed 10 SES frameworks that were explicitly designed for application by both researchers and practitioners (SM Table 1). Ostrom’s framework is the only one of these that conceptualizes the bi-directional interaction between the social and ecological systems, and treats both systems in almost equal depth (Binder *et al.* 2013). The SESF is also relevant to a wide range of natural resource issues, has been increasingly applied in conservation, and enables the visualization of the system’s structure with varying degrees of complexity. The extent to which the theories underlying different SES frameworks would lead to similar or diverging results would still require exploration.

Ostrom’s SESF (Figure 1) has a nested structure where actors use and provide for the maintenance of resource units, within a resource system, according to rules and procedures determined by a governance system, in the context of related ecological systems and broader social, political and economic settings (McGinnis & Ostrom 2014). The framework enables analyses of how attributes of the four core subsystems both affect and are affected by interactions and outcomes via feedbacks at a particular time and place (Ostrom 2007). These subsystems are: (i) resource systems (e.g., protected area, lake); (ii) resource units (e.g., trees, amount and flow of water); (iii) governance systems (e.g., the specific rules related to the use of the protected area or lake, and their implementation); and (iv) actors (e.g. resource users, managers; Figure 1).

Although the fact that conservation acts on complex SESs is well accepted, the consequences of considering the conservation intervention itself as embedded in the system are less well appreciated. The moment a conservation action or policy is mooted, it becomes part of the SES, redefining it, affecting all four subsystems directly or indirectly (Figure 1). The triggered reactions to the conservation intervention flow through the SES and in turn affect the intended outcomes, forming feedback loops. It is via these interactions that reactions have the potential to undermine conservation outcomes or generate policy resistant systems (Stermann 2000).

As it becomes a part of the SES, the conservation intervention can alter both the system’s structure and/or the dynamics of the processes within it. These dynamics include economic processes at the system scale, such as land market feedbacks (Armsworth *et al.* 2006) or

Table 1 Properties of social-ecological systems as complex adaptive systems

Property	Description	Example
Emergence	Emergence means that a system's behavior is more than the sum of its parts. Nonlinear interactions between elements of the system give rise to novel structures, patterns, and properties that cannot be explained only from the single elements (Ratter 2012).	Even without a specific blocking event we get traffic jams, merely as a result of car drivers following simple rules: drive at a certain speed and do not crash into the car in front; slow down if there is a car close ahead, speed up if not (Ratter 2012).
Self-organisation	Self-organization is the appearance of new system structures without explicit pressure from outside the system (Ratter 2012).	Emergent structures can be found in many natural phenomena, for example bird flocks or hurricanes (Ratter 2012).
Feedback loops	The process by which the results of an action define the situation we face in the future. In "negative or balancing" feedback the initial change to a system causes change in the opposite direction, dampening the effect; in "positive or reinforcing" feedback the initial change to a system causes more change in the same direction, amplifying the effect (Sterman 2000).	Increases in the size of farms increased investment, leading to agricultural intensification (reinforcing feedback). However, consequent soil degradation problems spurred wetland restoration that reversed degradation in croplands (balancing feedback; Steen-Adams <i>et al.</i> 2015).
Non-linearity	Interactions between elements of the system cannot be described by linear functions (e.g., s-shaped response curves; Folke 2006).	At low levels of herbivory overall community responses lead to nonproportional increases in production potential, whereas extreme herbivory causes extreme reduction in productivity (Dyer <i>et al.</i> 1993).
Path-dependence	Nonlinearity generates path dependence, which means that the evolution of the system depends on the history of the path it has so far taken. Path dependence leads to the existence of multiple equilibrium states and the potential for thresholds (tipping-points) and qualitative shifts in system dynamics under changing environmental conditions (Levin 1998).	Accumulation of nutrients in a lake (eutrophication) in combination with a trigger such as flooding or warming can shift the system from a clear water lake to a turbid water lake (Folke <i>et al.</i> 2004).

behavioral changes at the scale of the individual or community, such as are explored in psychology and decision science (Gintis 2007). For example, some PES schemes have increased inequity through processes such as marginalization, elite capture of benefits and increased vulnerability of some groups, resulting in reduced project legitimacy, non-participation, corruption and even active resistance (Pascual *et al.* 2014). These types of process at a smaller scale can drive feedbacks at the system scale.

A typology of unintended feedbacks

Schoon & Cox (2012) introduced a framework to analyze disturbance-response dyads in an SES that accounts

for both structure and flow, based on the SESF. We use their work as a basis for creating a typology of unintended feedbacks, whereby disturbance to the structure or flow of an SES, caused by a conservation intervention, triggers unintended feedbacks.

We define an unintended feedback as a feedback triggered by a conservation intervention, which was not built into intervention design, and that has an effect on conservation outcomes. It can consist of multiple reinforcing or balancing loops, and the net effect can either undermine or enhance conservation outcomes. Here, we focus on feedbacks that undermine conservation outcomes because they are of greater concern to implementers. Three types of unintended feedback are

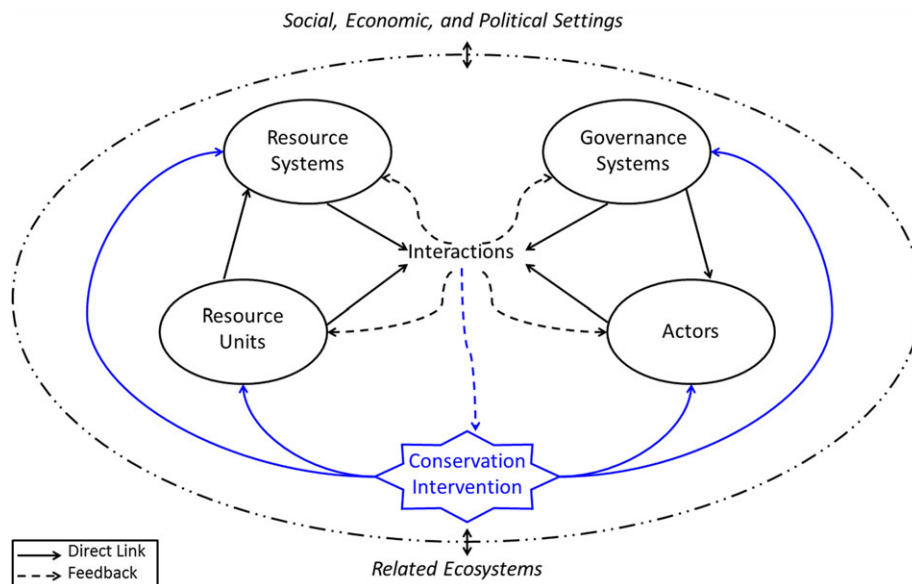


Figure 1 Theoretical framework for understanding unintended feedbacks from conservation interventions adapted from the social-ecological system (SES) framework (McGinnis & Ostrom 2014). In black the SES framework: solid ovals denote core subsystems and full arrows denote direct links between subsystems. Core subsystems interact to produce outcomes that have feedback effects denoted by dashed arrows. In blue (grey in printed version) a modification to the SES framework: the conservation intervention becomes part of the system jointly affecting and affected by interactions and outcomes. The dotted-and-dashed line indicates the boundary of SES; exogenous social, economic, and political settings or related ecosystems can affect any element of the SES.

identified: (1) Flow (relating to a change in a parameter within the SES), (2) Deletion, and (3) Addition (both relating to a change in SES structure).

- (1) Flow unintended feedbacks are due to the enhancement or dampening of preexisting feedback loops within the SES, caused by the conservation intervention. For example, in the USA, land use restrictions imposed on Federal forest concessions by the Endangered Species Act reduced lumber supply. This increased its price, thereby promoting logging in private forests within that region (Murray & Wear 1998; Polasky 2006). Another study showed that, depending on the structure of demand for bushmeat, a reduction in supply caused by enforcement of antipoaching laws could lead to an increase in prices inducing others to enter the market and increase hunting levels (Wilkie & Godoy 2001).
- (2) Deletion unintended feedbacks occur when preexisting feedback loops within the SES are lost due to the conservation intervention. For example, in Kenya, impoundment by the government of an area along the Turkwel River curtailed traditional management of this area. The loss of this institutional structure led to increased forest degradation (Stave *et al.* 2001).
- (3) Addition unintended feedbacks occur when interventions add components to the SES network struc-

ture. Most conservation interventions add actors, institutional structures or links, either human or natural. For example, new legislation aimed at creating incentives for biodiversity conservation in Mexico allowed landowners to benefit directly from wildlife exploitation through the creation of wildlife conservation units on their land. However, in some regions these new structures led to practices that reduced native biodiversity in the long term, such as fencing and cultivation of exotic grasslands (Sisk *et al.* 2007). Re-introducing wild dogs generated negative attitudes and persecution of existing wild dog populations in South Africa due to perceived and real threats of predation on livestock, despite a compensation scheme being in place (Gusset *et al.* 2007).

Multiple unintended feedback loops can interact to undermine an outcome. For example, Österblom *et al.* (2011) identified three unintended partial feedback loops that explained in part the European Common Fisheries Policy's failure to deliver on its social and ecological goals despite continuous efforts. These were: the maintenance of overcapacity leading to short-term decision-making and unsustainable quotas; depleted stocks creating an incentive for non-compliance, further reducing stocks; and undermined scientific legitimacy contributing to unsustainable decision-making,

Table 2 Examples for the operationalization of the typology of unintended feedbacks

Unintended feedback type	Example mechanisms	Potential indicators to monitor	Operationalization
Flow	Reduction in supply of lumber (Murray & Wear 1998), or bushmeat (Wilkie & Godoy 2001), or land available for agriculture (Jantke & Schneider 2011)	<ul style="list-style-type: none"> • Price of lumber/ bushmeat/ land • Volume traded/ sold in markets • Land use change • Traded species abundance 	<ul style="list-style-type: none"> • Surveys in key markets • Satellite data • Household surveys
Deletion	Loss of traditional management over an area (Stave <i>et al.</i> 2001) or loss of social norms regarding an area or species (Jones <i>et al.</i> 2008)	<ul style="list-style-type: none"> • Overlap between existing governance structures and new regulations • Accepted exploitation practices • Perceived social norms 	<ul style="list-style-type: none"> • Household surveys • Listings of traditionally used species or taboo species • Participatory land use mapping
Addition	Creating economic incentives for conservation (Sisk <i>et al.</i> 2007), species reintroduction (Gusset <i>et al.</i> 2007)	<ul style="list-style-type: none"> • Impact of new regulation on land tenure and equity • Land use change • Conflict: lost livestock or crops to reintroduced species 	<ul style="list-style-type: none"> • Household surveys • Satellite data • Conflict reports

further undermining the science. Additionally, a single intervention can produce different types of unintended feedbacks. For example, the establishment of protected areas can trigger a flow unintended feedback; increases in land allocated to protected areas could increase the prices of agricultural commodities due to forgone agricultural production, which can result in highly cost ineffective conservation (Jantke & Schneider 2011). The establishment of a protected area can also trigger a deletion unintended feedback: the imposition of external conservation rules brought by Ranomafana National Park in Madagascar resulted in a change of social norms concerning accepted behavior when harvesting pandans (*Pandanus spp.*) that led to unsustainable use in the villages surrounding the park (Jones *et al.* 2008). The establishment of a protected area can trigger an addition unintended feedback as well: Tarangire National Park, in Tanzania, is a source of added risk for household decision makers, some of whom pursued aggressive land conversion in anticipation of park expansion (Baird *et al.* 2009).

Implications for applied conservation

The prevalence and potentially disastrous effects of unintended feedbacks highlights the need to consider them more fully as important elements of conservation intervention design. By representing the way a conservation intervention alters an SES as three easily identifiable disturbances, the typology presented here facilitates a diagnostic approach to identifying the potential for different types of unintended feedbacks, supporting analysis of how they may affect outcomes.

A priori identification of potential unintended feedbacks can improve conservation practice by enabling the consideration of complex relationships. In Tarangire National Park, consideration of SES dynamics suggested that greater security of land tenure would be a better approach to forestalling preemptive land conversion in anticipation of park expansion than the proposed increase in land use restrictions (Baird *et al.* 2009). Explicitly considering the way in which all four subsystems shown in Figure 1 could be disturbed by the planned intervention, during construction of Theories of Change or results chains during the conservation intervention design process, could highlight potential unintended feedbacks. Each of the three types of feedback needs to be considered, individually and in interaction. This process could substantially improve the utility of project design tools such as Miradi (Miradi 2007).

Interventions could then be designed to address the most critical potential feedbacks that were identified at the planning stage. This could involve including monitoring for early warning of unintended consequences, or structuring the intervention differently (Table 2). Guidelines from other fields could be adapted. For example, evaluating the possible perverse outcomes of policy interventions is often highlighted as an important step in guidelines for social policy design (e.g., Hallsworth *et al.* 2011). To avoid feedbacks from negative impacts on equity, it has been suggested that policy development processes use standard assessment tools (such as Impact Assessments), on top of which additional criteria can be addressed (such as social or environmental justice; Brooks *et al.* 2006).

An incomplete understanding of an SES and its history is not the only cause of unintended feedbacks. Unintended behavior within an SES can also be due to emergent properties that, so far, cannot be predicted (Ratter 2012). An adaptive management approach that monitors feedback structure and behavior could improve the early detection of emerging properties of an SES. Recently, Mayer *et al.* (2014) proposed the use of specific indicators that give insight into the structure and behavior of feedbacks, such as Shannon entropy and Fisher information, as monitoring tools for sustainable management. Our typology could guide the focus of indicator development for conservation interventions, to better inform project monitoring and reporting.

Evaluations of conservation impact need to understand the mechanisms by which conservation interventions have impact, including both directly on the target and indirectly on other components of the ecosystem via changes in human behavior. A posteriori consideration of potential feedbacks operating in an SES can help identify the true drivers of observed patterns. For example, the change at national scale from net deforestation to net reforestation that took place in Vietnam was a consequence of two separate forces: endogenous socio-ecological feedbacks, such as local resource depletion, explained a slowing down of deforestation and stabilization of forest cover. However, it was exogenous socio-economic factors, such as global trade, that better accounted for reforestation. Neither process represented a planned response to ecosystem degradation (Lambin & Meyfroidt 2010). Identifying how a conservation intervention changed the SES's subsystems and their links after the project has finished would help to build the evidence base on the types of feedbacks which different interventions or SESs are prone to (Table 3). However, post-hoc quantification of the role of unintended feedbacks in project outcomes requires data from all subsystems, including social, institutional, individual/household and ecological variables. Robust and well-designed monitoring, including a baseline, is required in order to attribute causation (Ferraro 2009).

Implications for future work in conservation science

The current anecdotal and scattered evidence is not enough to support general principles for conservation decision-making that minimize unintended feedbacks. It is difficult to say at present under which circumstances unintended feedbacks may be most significant for conservation outcomes, or which mechanisms of human behavior underlie them. The type of conservation intervention, and the complexity of the SES, may play a crucial role. For example, it is expected that indirect approaches,

Table 3 Questions for future work on unintended feedbacks of conservation, and recommended next steps

Question for future work	Suggested next steps
1. How widespread are unintended feedbacks, and under what circumstances do different types of feedback occur?	Establish a comparative database that collates case studies, structured using our framework and typology.
2. When and how should unintended feedbacks be included in policy support tools?	Include mechanisms causing unintended feedbacks in models underlying policy support tools and explore tradeoffs between model complexity and gain in predictive power. For example include land market feedbacks from land purchases for protected areas in InVEST.
3. How do personal and social factors influencing behavior promote or inhibit unintended feedbacks from behavioral change based conservation interventions?	Use existing models of behavior that have been successful in explaining pro-environmental behavior to examine the roles these factors play. For example, theory of planned behavior.
4. What are the different mechanisms by which unintended feedbacks operate in conservation interventions at different scales?	Explore models that include individual and system dynamics and their interactions, to understand mechanisms by which human decision-making can have consequences for conservation at different scales

such as alternative livelihoods, may increase the likelihood of promoting unintended feedbacks due to the higher number of actors and links comprising the system. However, there is not enough evidence to substantiate this statement because currently the literature is inadequate to support a systematic review. Studies of the correlates of conservation success have encountered similar limitations (Brooks *et al.*, 2012). There is a need to establish comparative databases to collate case studies for analysis, in order to describe unintended feedbacks, their drivers and underlying mechanisms (Table 3). The typology presented provides a framework for comparative studies of the mechanisms involved in different types of feedback, hence promoting better project design in future.

Data collection efforts to gather examples of interventions that are underway could inform this comparative analysis. For example the social-ecological systems meta-analysis database (SESMA) project aims to enable analysis of case studies of a diversity of SESs by collating them in a comparable format (Cox 2015). SESMA data requirements include information on governance systems,

actor groups and environmental commons, as well as theories on the relationship between variables. Additional variables relating to the conservation intervention itself and the type of unintended feedback it triggers are also required if this database is to be useful for understanding unintended feedbacks in a conservation context.

Literature on behavioral change-based policy can shed light on which aspects of an intervention need to be considered when analyzing evidence of unintended feedbacks. Darnton's (2008) review of behavioral change found that three elements determine whether a policy intervention has negative impacts on equity or not: (1) what factors of a behavioral model are targeted by an intervention, (2) the way in which those factors are targeted, and (3) the theory of change underlying the intervention. These three elements could prove to be important aspects of a conservation intervention within the context of unintended feedbacks because policy interventions that have negative impacts on equity can result in unintended feedbacks such as corruption or sabotage (Pascual *et al.* 2014). They also provide a way of structuring research into the behavioral mechanisms underlying unintended feedbacks.

Feedbacks that enhance conservation outcomes are also possible, and present opportunities to magnify or extend conservation effectiveness by harnessing synergies within the system. Similarly, there is a need to collect case studies in order to start exploring the circumstances and mechanisms that enable this type of feedback.

Currently, policy support tools widely used to explore the potential impact of different interventions at large scales are based on static models that cannot account for unintended feedbacks. InVEST (Nelson *et al.* 2009), for example, ranks relative biodiversity and ecosystem services outputs under different scenarios; the tool currently focuses on developing relatively simple models to meet demand from decision-makers (Ruckelshaus *et al.* 2015). Under some circumstances incorporating unintended feedbacks might not have a large effect on model predictions (Zvoleff & An 2014), but this will depend on the system (Armstrong *et al.* 2006). Mechanisms by which unintended feedbacks occur could be incorporated into these models to assess the robustness of their predictions; however, there will be a tradeoff between model complexity and the gain in predictive power given the likely high uncertainties in developing and parameterizing a dynamic systems model. This tradeoff needs to be explored urgently to elucidate when more complex models are necessary, to avoid generating misleading recommendations from such tools, or when simpler models give robust results (Table 3).

In systematic conservation planning, effectiveness depends partly on accounting for natural and anthro-

pogenic dynamics (Pressey *et al.* 2007). Nonetheless, most conservation planning still uses static information to derive solutions. Scenario analysis is becoming more common, for example in designing landscapes robust to climate change (Singh & Milner-Gulland 2011; Levy & Ban 2013) but dynamic conservation planning studies that take into account trends in, for example, land prices are uncommon despite the existence of approaches to account for land market feedbacks (Dissanayake & Önal 2011). Dynamic conservation planning approaches need to be further developed, and assessed against static approaches (Table 3). For instance, empirical data have been used to suggest that the degree to which reserve selection could be improved by accounting for land market feedbacks varied across landscapes (Butsic *et al.* 2013).

Ultimately, conservation outcomes derive from human decision-making. Much work has been done using behavioral theory to explore conservation outcomes. Tools at the individual or household level include bio-economic models based on rational choice (e.g., Stephens *et al.*, 2012) and social-psychological models based on the theory of planned behavior (e.g. Williams *et al.*, 2012). The environmental psychology literature has identified social and personal factors that influence pro-environmental behavior (Gifford & Nilsson 2014). Personal factors include childhood experience, knowledge and education, personality and self-construal, sense of control, values, political and worldviews, goals, felt responsibility, cognitive biases, place attachment, age, gender, and chosen activities. Social factors include religion, urban–rural differences, norms, social class, proximity to problematic environmental sites, and cultural and ethnic variations. The role these factors play in inhibiting or promoting unintended feedbacks triggered by behavior at the individual level needs to be explored (Table 3). Existing models of pro-environmental behavior can inform this research by examining the role of different factors; for example, the theory of planned behavior has been successful in explaining environmental behavior and considers a wide range of factors, including contextual factors indirectly in the form of perceived behavioral control (Steg & Vlek 2009).

SEs have emergent properties that make responses to interventions different than the sum of individual responses. It is important to understand the ways in which system behavior emerges from the collection of many individual decisions, and how individual- and system-level dynamics interact (Ratter 2012). Agent-based models can capture these properties (Rounsevell *et al.* 2012), but also need to include institutional dynamics and external trends. Advanced tools for modeling complex adaptive systems can be applied to SES structure analysis, such as network topology (Janssen *et al.* 2006). Social

network theory has been applied within the context of social movement theory to explain how environmental social movements develop (Ernstson 2013). These tools applied to the study of SES properties such as emergent behaviour and self-organization can start to unveil the mechanisms by which human decision-making could have consequences for conservation (Table 3).

Conclusion

There is plenty of anecdotal evidence that understanding unintended feedbacks is vital for effective interventions to combat biodiversity loss. The recent interest in the central role of feedbacks in managing complex systems (Hull *et al.* 2015) provides the right arena where a literature on unintended feedbacks could flourish. The fact that people adapt and respond to conservation interventions, and that their actions feed through into changes in the conservation situation itself, is something that conservationists rely on for their impact. However these same responses are being overlooked when they affect outcomes indirectly through unintended feedbacks. There is an urgent need to collect evidence to understand the mechanisms by which human decision-making feeds through to conservation outcomes at different scales.

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Conflict of interest

The authors declare no conflict of interest.

Supporting Information

Additional Supporting Information may be found in the online version of this article at the publisher's web site:

Table S1. Frameworks considered for the analysis of unintended feedbacks in conservation.

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