Opinion

# Integrating resilience thinking and optimisation for conservation

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**Conservation strategies need to be both effective and efficient to be successful. To this end, two bodies of research should be integrated, namely 'resilience thinking' and 'optimisation for conservation,' both of which are highly policy relevant but to date have evolved largely separately. Resilience thinking provides an integrated perspective for analysis, emphasising the potential of nonlinear changes and the interdependency of social and ecological systems. By contrast, optimisation for conservation is an outcome-oriented tool that recognises resource scarcity and the need to make rational and transparent decisions. Here we propose that actively embedding optimisation analyses within a resilience-thinking framework could draw on the complementary strengths of the two bodies of work, thereby promoting cost-effective and enduring conservation outcomes.**

## The quest for new conservation strategies

Efforts are increasing to halt the current mass extinction of species [1,2]; for example, in 2008, under the Convention on Biological Diversity (CBD), countries committed hundreds of millions of Euros in funds to slow biodiversity loss, mainly through investing in additional protected areas [3]. Despite increasing resources, the target of the CBD 'to achieve by 2010 a significant reduction of the current rate of biodiversity loss' remains elusive (http://www.cbd.int/2010-target). Without a radical overhaul of existing strategies, biodiversity loss is likely to accelerate [4], suggesting that new conservation strategies are needed that use scarce resources efficiently and slow biodiversity loss effectively. Here we argue that a useful step forward should be the active integration of two bodies of research that are highly policy relevant but largely separate, namely 'resilience thinking' and 'optimisation for conservation.' Our aim is not to provide a comprehensive review, but to foster creative thinking on how these bodies of work can be used together to deliver improved conservation outcomes. To this end, we outline key themes that should be part of an ongoing dialogue between researchers working on resilience thinking and optimisation.

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## Background

Resilience thinking originated in ecology during the 1970s [5], and has evolved to be a perspective for analysing interdependent ecological and human systems [6]. Social–ecological systems are seen as constantly evolving, with uncertainty being crucial in shaping their trajectory [7]. For example, stochastic pulse disturbances are common in many ecosystems including forests and coral reefs, and such disturbances can permanently alter ecosystem dynamics [8]. Resilience is 'the capacity of a system to absorb disturbance and reorganise while undergoing change so as to retain essentially the same function, structure, identity, and feedbacks' [9]. Resilience thinking emphasises the interplay of gradual change with sudden disturbances, feedbacks, alternative stable states and regime shifts, cross-scale relationships and adaptive cycles (see Glossary). In conservation biology, resilience thinking has contributed insights into the importance of functional redundancy, functional diversity, response diversity [10] and cross-scale interactions of species [11]. It also emphasises connections between social and ecological systems,

### Glossary (Partly adapted from Ref. [22].)

**Adaptive cycle**: a metaphor to conceptualise the growth and reorganisation of systems. A stylised adaptive cycle includes a growth phase, a conservation phase, a collapse phase and a reorganisation phase.
**Alternative stable states**: alternative sets of self-reinforcing interactions among species, ecological patterns and processes. Changes in internal and/or external processes can produce shifts between these states.
**Cross-scale interactions**: the influences between the dynamics of systems at one scale and the dynamics of systems at smaller or larger scales.
**Feedback**: a signal within a system that loops back to control the system. In natural systems, feedback can help to maintain stability (negative feedback), or it can speed up processes and change (positive feedback).
**Functional diversity**: the diversity of ecological functions fulfilled by different species in a system.
**Functional redundancy**: the degree to which multiple species fulfil the same ecological function.
**Objective function**: a formal, mathematical expression weighing up the costs and benefits associated with a particular decision, subject to a set of constraints.
**Regime shift**: the rapid reorganisation of a system from one stable state to an alternative one (see also alternative stable states).
**Response diversity**: the diversity of responses to environmental change among species contributing to the same ecosystem function.
**Threshold**: the point of sudden change between alternative stable states.

0169-5347/$ – see front matter  doi:10.1016/j.tree.2009.03.020 Available online 7 August 2009

particularly in terms of the relationships among ecological dynamics, management practices and institutional arrangements [12]. Resilience-thinking concepts have made important contributions to the understanding and management of several ecosystems, including the Great Barrier Reef in Australia [13,14] and the Kristianstad wetlands in Sweden [7].

Optimisation for conservation has a rich history that can be traced back to decision theory [15], optimal harvesting problems [16,17] and systematic conservation planning [18]. Common to all applications of optimisation for conservation is the formal definition of a conservation problem before its quantitative solution. Solving a given optimisation problem typically requires a well-defined objective function that incorporates the costs, benefits and constraints applying to alternative management actions. In systematic conservation planning, the conservation problem typically is a variant of where to place new reserves to conserve the largest number of species for a given cost. However, optimisation approaches can also be useful outside protected areas. For example, optimisation analyses can inform the relative importance and timing of alternative management strategies targeting different threatening processes, such as invasive species or fire [19].

Both resilience thinking and optimisation for conservation have produced large volumes of literature, which are useful in their own right. In addition, there are signs that the two bodies of work are beginning to overlap in scope. For example, social factors are being increasingly considered by scholars specialising in optimisation [20], and resilience scholars have used formal optimisation methods to analyse how undesired regime shifts can be avoided [21]. Given that some overlap is already occurring between these two fields, it is timely to explore how they can be integrated more actively. Such integration could substantially contribute to improved conservation outcomes, because the strengths of the two bodies of work are complementary (Table 1).

## A perspective and a tool

Resilience thinking is a perspective for the analysis of social–ecological systems, whereas optimisation for conservation is a tool used to reach a defensible solution to a well-defined problem. This difference suggests that resilience thinking and optimisation apply to different stages or scales of a conservation problem and, therefore, can be complementary.

An important first stage of solving a conservation problem is its appropriate definition or framing. Resilience thinking can help with problem framing by providing a conceptual background for investigating important relationships and dynamics in social–ecological systems. Specifically, a formal 'resilience assessment' can provide a semistructured format for asking a series of questions that are relevant to problem framing [22,23]. A resilience assessment can help to determine the spatial and temporal boundaries of the focal system and identify key actors and institutions in the system.

Several resilience concepts are particularly relevant in the problem-framing stage, because they shed light on issues that might otherwise be glossed over or missed altogether. For example, through its focus on interconnected social–ecological systems, resilience thinking emphasises the importance of identifying key stakeholders and involving them in problem framing [22,23]. In doing so, it can draw on participatory approaches from the social sciences, thereby ensuring that the problem definition is informed by and relevant to the diversity of values held by stakeholders in the system. Resilience thinking can also help to identify important cross-scale relationships and encourages analysis of the historical trajectory of the focal system, including past disturbances and their effects on system dynamics. In combination, an understanding of social–ecological dynamics and stakeholder values that is characterised by temporal and spatial depth provides a useful starting point for more formal analyses of how to guide the system in a desirable direction in the future. A detailed workbook for conducting a semistructured resilience assessment for a given focal region is freely available on the internet [22].

Following the framing of a given management problem, in a subsequent stage of solving a conservation problem, meaningful management targets can be identified. For example, which processes regulate a 'safe' level of nutrient input into an aquatic system before there is an unacceptable risk of it degrading into an undesired state? Because the exact locations of thresholds are often unknown [24], resilience thinking advocates that management targets should be seen as working hypotheses that are revised as new insights emerge. For example, in Kruger National Park, South Africa, managers have identified 'thresholds of potential concern,' which, when approached, call for reevaluation of management practices [25]. One such threshold relates to the minimum proportion of tree cover needed in the landscape before the risk of extinction cascades becomes unacceptable [25].

An understanding of targets as working hypotheses has important implications for optimisation. It suggests that

**Table 1. Overview of characteristics of optimization for conservation and resilience thinking**

| | Optimisation for conservation | Resilience thinking |
|---|---|---|
| Strengths (inherent) | Recognises resource scarcity | Recognises system complexity |
| | Encourages transparency in resource allocation | Recognises interdependence of social and biophysical systems |
| Strengths (in practice) | Can provide specific answers to a well-defined problem | Encourages anticipation of undesirable surprises or thresholds |
| | Fits well with how business and governments operate | Encourages reflection on how a system works |
| Weaknesses (inherent) | Sensitive to accuracy of underlying assumptions and system model | Potentially difficult to apply to systems without identifiable alternate states |
| Weaknesses (in practice) | Targets or budget constraints are often informed by politics rather than an in-depth understanding of underlying system dynamics | Reliant on tools from other disciplines to be operational to inform policy |
| | The term 'optimal' can sound absolute to policymakers and the general public | The term 'resilience' can appear vague to policymakers and the general public |

no 'optimal' solution should be seen as final: to be consistent with resilience thinking, optimisation must be thought of in a dynamic sense, with optimal solutions changing through time as new insights emerge or conditions in the system change. A subtle but important point here is that the term 'optimal' is used differently in an everyday versus mathematical context. Researchers in optimisation tend to mean 'optimal within the context of a given objective function,' whereas 'optimal' to policymakers, managers and the public can sound absolute and has connotations of an ideal end-goal being reached [26]. Misunderstandings can be avoided by articulating clearly the implications of a given optimisation analysis in nontechnical language, especially in publicly accessible documents and journal abstracts.

Finally, careful problem framing also is important to avoid undesirable inefficiencies when formal optimisation is undertaken. For example, Polasky *et al.* [27,28] showed that the perceived conflict between conservation and economic objectives was reduced when the conservation value of agricultural and forestry lands was incorporated in quantitative models, leading to more efficient conservation outcomes. The systematic application of resilience assessments to conservation problems would help ensure that such considerations become the norm rather than the exception.

## Themes requiring particular attention

Beyond the general delineation of the roles for resilience thinking and optimisation outlined above, applications of both approaches need to pay particular attention to three themes: (i) dealing with social issues; (ii) dealing with uncertainties and the limited extent to which they can be controlled; and (iii) avoiding undesirable states that constrain reversibility. Both resilience thinking and optimisation can shed light on different facets of each of these themes.

### *Dealing with social issues*

Resilience thinking emphasises that effective conservation demands a sophisticated understanding of how social systems shape and respond to natural systems [29]. For social systems, key considerations include societal values, statutory frameworks, formal and informal institutions, human skills and financial costs [30].

Optimisation can consider social issues in two ways. First, some social factors can be directly incorporated into an optimisation problem. For example, the financial costs of conservation can sometimes be considered explicitly. Recognition of heterogeneity in land management costs can produce savings for a given conservation goal [31,32], because land acquisition and management is cheaper in some places (such as poor rural areas) than in others (such as rapidly developing urban fringes).

Financial costs aside, many other social factors, such as human values or cultural practices, are less readily accounted for in quantitative analyses. Nevertheless, such factors can be important. For example, common property systems can succeed or fail in managing a shared resource owing to complex interactions between culture, behaviour and institutional arrangements [33]. Similarly, apparently rational conservation actions can fail owing to their socioeconomic context [34], as in the Wolong Nature Reserve in China, which continued to degrade after establishment because of local increases in the human population and resource demands [35]. These examples point to a second, less direct way, in which optimisation can be linked with social factors: that is, a given optimisation analysis can be embedded explicitly within a social and political framework, acting as a source of transparent information to be considered and interpreted in the context of other factors.

The call to embed technical analyses within social frameworks is strongly echoed by recent work on systematic conservation planning [36,37]. Knight *et al.* [37], for example, discussed the importance of empowering communities and institutions, coupled with effective planning and monitoring, to translate a given systematic assessment into conservation action. The simultaneous importance of technical analyses and their social context is particularly apparent where informal institutions are important, such as in Madagascar (Box 1). Seeing optimisation as part of an inevitably larger suite of practices that are necessary for effective conservation action highlights the need to bridge gaps between academic disciplines, and between researchers and practitioners [37].

**Box 1. Tripling of protected areas in Madagascar: considering social–ecological complexity**

Madagascar is a global biodiversity hotspot and its government has recently taken significant steps to strengthen protection of the nation's biodiversity through extension of the country's protected area from 1.7 to 6 million ha over 5 years. Both technical analyses and their social context will be important to achieve effective conservation outcomes. Kremen *et al.* [67] used optimisation approaches considering multiple taxonomic groups to identify and prioritise areas for protection, and devise a systematic plan for their acquisition. The results of this technical analysis will be most useful if considered within a social–ecological context [26,36,37]. For example, Bode *et al.* [68] pointed out that it would be efficient to favour low-cost areas in the process of selecting new reserves, rather than focus solely on their ecological values.

More generally, Horning [69] argued that successful conservation in Madagascar was possible only under specific conditions, relating to the interests of key actors, the institutions that they negotiate and put in place to protect these interests, and the reaction of resource users to these institutions. In this context, institutions are structures of social order governing the behaviour of individuals. Formal institutions are those enforced by government (e.g. financial incentives or regulations), whereas informal institutions relate to norms and cultural practices. In Madagascar, informal institutions have an important role. For example, in southern Androy, 90% of the total remaining forest cover is protected through taboos [70]. These informal institutions represent an important and, presently, the only mechanism for conservation of the highly endemic fauna and flora in the south. Given that effective rule enforcement is a crucial but costly prerequisite for successful conservation in Madagascar, informal institutions represent a local governance system that can lower such transaction costs.

However, informal institutions can be vulnerable to conventional conservation measures and outside interventions [71], suggesting that the interplay between formal and informal protection must be carefully considered. In reaching the ambitious goal of tripling the protected area in Madagascar, formal optimisation for conservation is therefore likely to be most successful when undertaken as part of a framework that explicitly considers social institutions and social–ecological complexity.

### *Dealing with uncertainties and the extent to which they can be controlled*

Experimental work characterised by a high degree of control over unwanted variability is a powerful scientific strategy to understand ecological phenomena. In this tradition of 'analytical ecology,' uncertainty is undesirable, and is eliminated where possible [38]. By contrast, many applied ecological problems occur in complex social–ecological systems, where uncertainty is often high and not easily controlled [39].

Although optimisation for conservation has a long history of incorporating uncertainties [15,40], the combination of high uncertainty and low controllability can render formal optimisation difficult [39]. For example, 'Knightian uncertainty,' where probabilities cannot be assessed [41], can pose particular challenges to optimal investment choices [42]. Recent methodological advances in optimisation might help to overcome some of the problems associated with severe uncertainty [43,44], but some advances, such as information-gap theory, remain controversial.* Regardless of the benefits or limitations of particular optimisation methods, the fundamental problem remains that unanticipated, surprising events in complex systems make optimisation difficult.

An example of such a situation is the development of 'novel ecosystems,' where historically separate species co-occur in the same place for the first time, with unknown implications for ecological and evolutionary processes [45]. Novel ecosystems are likely to develop in many new locations during this century, as a result of land-use change, species introductions and range shifts triggered by climate change. Their development typically has far-reaching and unpredictable consequences. For example, invasive plants in Hawaii representing different functional groups have completely altered the three-dimensional structure of native forest systems, and traditional methods of weed control appear unlikely to succeed [46].

Resilience thinking suggests that when faced with large uncertainties, such as those posed by novel ecosystems, it is particularly important that optimisation, when it is applied, targets broadly defined objectives that are related to key drivers or controlling variables [47]. Narrowly defined objectives relating to more transient variables, such as the capture of a maximum number of species in reserves, might be inappropriate or fall short of what is needed in the presence of change. The importance of focussing on drivers rather than patterns is increasingly recognised in systematic conservation planning. For example, Pressey *et al.* [40] suggested that maintaining key ecological processes was a more appropriate objective for optimisation than was the maintenance of current species diversity. In part, important processes could be maintained by attempts to mirror the properties of natural ecosystems that have adapted to change in the past; such properties include high levels of spatial continuity, species diversity and spatial heterogeneity [48]. Optimisation can help to identify avenues for recreating such properties across entire landscapes. For example, how can managers of private land increase the heterogeneity of their land at least cost? Where and when could temporary fallows or dynamic reserves be deployed to maximise the benefits to biodiversity [8]? Which parts of a landscape should be targeted first for revegetation [49]? Despite potentially large uncertainties about future changes and limited ability to control them, 'optimal' answers to these problems could help to enhance the resilience of many landscapes dominated by human activity.

### *Avoiding undesirable states*

An important aspect of resilience thinking is the notion of regime shifts, where systems 'flip' from one state to another. Numerous examples of regime shifts have been documented, such as in coral reefs or rangeland systems [9]. A key issue is that regime shifts, once they have occurred, can be difficult or impossible to reverse, because degraded system states are often highly resilient. For example, Barlow and Peres [50] showed that repeated fires could alter the structure and species composition of old-growth Amazonian rainforest and transform it into a species-poor scrub system. This scrub system might be considered less desirable, but is likely to be highly resilient because it is more flammable, thus precluding succession and regeneration of old-growth rainforest.

From a conservation perspective, a key challenge is to maintain desirable states and avoid undesirable ones that are hard to get out of. This seems obvious, but many situations exist where optimisation of part of a social–ecological system has had negative long-term consequences for the system as a whole [51]. For example, optimisation for efficient dairy production in the Goulburn Broken catchment in Australia has incrementally undermined the ecological capacity of the system, to the extent that managers now depend on expensive engineering solutions, such as groundwater pumping, to avoid salinisation [52]. Similarly, Peterson *et al.* [53] showed that apparently optimal management decisions could steer a lake ecosystem to collapse if managers were unaware of potential thresholds in lake behaviour in response to nutrient inputs. The problem in cases such as these is not the tool of optimisation itself, but the difficulty of applying it in situations where important system dynamics are poorly understood, or where system dynamics are changing in unanticipated ways.

Perhaps less intuitively, well-intended optimisation that specifically targets conservation objectives also could have undesirable long-term consequences if it does not adequately consider social–ecological dynamics. For example, in the heavily cleared temperate agricultural zone in Australia, optimisation could focus on increasing the amount of land formally protected. However, such a traditional application of 'optimisation for conservation' might fail to enhance the long-term resilience of the region. This is because a lack of consideration of privately managed land is likely to mean that intensive land use continues in these areas. Such use, however, has been linked to ecosystem degradation and tree decline on private land [54]. Hence, a better reserve system, even if it appeared 'optimal' at present, might consist of structurally and functionally isolated protected areas. Such a

* Sniedovich, M. (2008) *A Call for the Reassessment of the Use and Promotion of Info-Gap Decision Theory in Australia*, personal website of Moshe Sniedovich (http://info-gap.moshe-online.com).

system would have low resilience to climate change because of its lack of connectedness. Of course, reserve networks could be specifically designed to include connecting corridors [55,56], but increasingly, conservation biologists are in agreement that reserves alone cannot guarantee the long-term conservation of biodiversity [57,58]. A more appropriate focus for optimisation therefore would be to focus on cost-effective conservation measures both inside and outside protected areas, including a careful assessment of socioeconomic dynamics of the entire system [49]. Again, a formal resilience assessment of the entire social–ecological system can be a valuable first step to define the fundamental objectives for optimisation. The most appropriate means of reaching an agreed objective can then be identified, and these might or might not include additional protected areas.

## Integration in practice

In practice, resilience thinking and optimisation could be effectively combined in an adaptive management framework, drawing both on formal experimentation and other quasi-experimental approaches such as natural experiments [59]. Adaptive management argues for management actions to be constructed as experiments (or quasi-experiments [59]) that balance the risks associated with policy implementation against the benefits of learning for future management. Decision analysis and optimisation can compare competing management strategies and suggest new ones [60]. For example, Rout *et al.* [61,62] compared different translocation strategies for the bridled nailtail wallaby (*Onychogalea fraenata*) in Australia to inform optimal adaptive management.

Despite the intuitive appeal of adaptive management, it has frequently failed in practice owing to social and institutional barriers [63,64]. Operationalising adaptive management therefore requires in-depth understanding of social–ecological systems and their adaptive governance [65]. Three social prerequisites for adaptive management have been identified [12]. First, creative synthesis is required to construct a holistic understanding of the dynamics of the system of interest that integrates the knowledge of multiple stakeholders and disciplines. Second, resilience must be developed in the social–ecological system, because experimental management is rarely feasible in highly vulnerable systems with low resilience. Third, connections with other places, stakeholders or external resources should be fostered, to enable more effective learning and bring new resources into the system [12]. Once these prerequisites are met, experimental approaches and formal optimisation are more likely to succeed.

## Conclusion

Our discussion suggests that there are no inherent obstacles to the active integration of resilience thinking and optimisation for conservation: one provides a perspective for analysis, whereas the other provides a formal decision aid. Together, these two bodies of work could make conservation more efficient, effective and resilient in the long term (Table 1). Formal collaboration on conservation problems involving researchers familiar with resilience thinking and those familiar with optimisation would be a useful next step toward the practical integration of the two bodies of work. New insights often emerge at the intersection of knowledge domains [66], suggesting that the challenge of integration will be not only useful to conservation but also intellectually rewarding.

## Acknowledgements

J.F. gratefully acknowledges funding from the Ian Potter Foundation to visit the Stockholm Resilience Centre. T.A.G. greatly appreciates funding from FAPEMIG (Brazil). Comments from K. Rawlings, A. Manning, B. Wintle and three anonymous referees greatly improved earlier drafts of this paper.

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