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STRATEGIC ISSUES ARTICLE

Thinking systemically about ecological interventions: what do system archetypes teach us?

Lauren M. Hallett[1,2], Richard J. Hobbs[3]

To address the need for more holistic approaches to ecological management and restoration, we examine ecosystem interventions through the lens of systems thinking and in reference to systems archetypes, as developed in relation to organizational management in the business world. Systems thinking is a holistic approach to analysis that focuses on how a system's constituent parts interrelate and how systems work over time and within the context of larger systems. Systems archetypes represent patterns of behavior that have been observed repeatedly. These archetypes help relate commonly observed responses to environmental problems with their effect on important feedback processes to better anticipate connections between actions and results. They highlight situations where perceived solutions actually result in worse or unintended consequences, and where changing goals may be either appropriate or inappropriate. The archetypes can be applied to practical examples, and can provide guidance to help make appropriate intervention decisions in similar circumstances. Their use requires stepping back from immediately obvious management decisions and taking a more systemic view of the situation. A catalog of archetypes that describe common patterns of systems behavior may inform management by helping to diagnose system dynamics earlier and identifying interactions among them.

Key words: ecosystem management, fixes that fail, intervention, leverage points, system archetypes

Implications for Practice

- In ecosystem management and restoration, there are numerous examples of simplistic solutions to complex problems. While there is general recognition of this, there have been few serious attempts to place interventions in a more holistic systems-based perspective.
- One way of facilitating thinking in this area is to consider the use of systems archetypes, borrowed from business management, that can illustrate repeating scenarios and point to ways in which more effective interventions can be designed.
- Systems archetypes also illustrate the development of various ongoing debates in restoration and could provide a heuristic to find agreement in these discussions.

Interventions into ecologically complex systems may yield surprises and potentially new problems, especially when those ecosystems are experiencing the effects of global change (Lindenmayer et al. 2010). Consequently, a systems approach—one that accounts for the interactive and interdependent components of an ecosystem and feedbacks between them—may help guide effective ecological restoration and management (Hobbs et al. 2011). The science of ecology has a long history of taking a systems perspective, through ecosystem theory, food webs and trophic cascades, and networks—with a focus on understanding how natural systems work (Odum 1994; Evans et al. 2013; Westgate et al. 2013). However, translating this systems perspective into an actionable management framework has remained a challenge. Adaptive management, which emphasizes the need for a structured, iterative process of decision making and monitoring, is perhaps the most widely adopted systems-based framework for ecosystem management (Holling 1978; Walters & Hilborn 1978; Armitage et al. 2009). Adaptive management is typically applied on a case-by-case basis (Westgate et al. 2013). A typology of common systems models would aid in generalizing and streamlining this process, but to date systems frameworks are often applied in retrospect. For instance, the social-ecological systems framework aims to provide a context for analyzing social-ecological systems but its application is still largely descriptive of past events (e.g. Partelow 2018).

The use of heuristic models of system dynamics to guide management interventions has been examined more fully in other fields (e.g. Ross & Wade 2015; Duboz et al. 2018), particularly in business. In business literature, common system structures and dynamics are identified to assist decision makers in reliably inferring how change will affect the system and identifying "leverage points" where intervention will result in efficient achievement of the desired

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[1]Environmental Studies Program and Department of Biology, University of Oregon, Eugene, OR 97403, U.S.A.
[2]Address correspondence to Lauren M. Hallett, email richard.hobbs@uwa.edu.au
[3]Department of Biological Sciences, University of Western Australia, Crawley, WA 6009, Australia

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change (Kim 1993; Meadows 1999, 2008). Here, we translate a typology of system models from the business literature into a framework for high-leverage ecological restoration and management. We extend the approach of "intervention ecology" (Hobbs et al. 2011) by examining environmental systems through the lens of systems thinking and in particular systems archetypes, as developed by Senge (1990) in relation to organizational management in the business world. Ideally, a framework to organize common patterns of systems behavior will make it easier to diagnose dynamics early and identify relationships among them.

The Business of System Archetypes

In his seminal work on organizational management, *The Fifth Discipline*, Senge (2013) introduced the idea of a learning organization—an organization that facilitates the learning of its members and continuously transforms itself in response to internal and external change. Systemic thinking is an integral component of a learning organization by shifting inquiry to explore situations holistically, recognizing that although events appear to be distinct in space and time, they are often interconnected. Consequently, Senge argued that the standard reductionist approach of breaking systems into parts to make problems more manageable in fact reduces the ability to see interrelatedness, and that it is impossible to reassemble the whole from the fragments thus created (Senge 1990). In the context of ecological restoration and management, organizations sit at the intersection of social and ecological systems, and management interventions feedback to affect both dimensions. Systems thinking is consequently a particularly important component of intervention ecology (Hobbs et al. 2011).

Key dynamics explored by systems models include the consequences of non-linear relationships, delays and feedbacks. In ecological restoration and management, reacting to problematic events (e.g. a species invasion, a catastrophic fire) is common practice and frequently important (Hobbs et al. 2011). However, environmental management that relies solely on reactive interventions can create a culture of crisis-to-crisis management. Identifying the relationships and potential feedbacks underlying each event can allow more proactive interventions (e.g. propagule management, prescribed burns) (Butterfield et al. 2017). Problematic events therefore become the starting point to identify larger patterns as well as triggers for reactive intervention.

Senge and others noted that a number of types of recurring patterns can be recognized, and developed "system archetypes" that describe typical patterns of system behavior and explain why certain complexes of behavior occur (Senge 1990; Kim 1993). These archetypes offer the potential to recognize particular opportunities for changing system behavior by locating where and when in the system actions are likely to have the largest impact (known as leverage points). System archetypes consist of different combinations of balancing loops (i.e. negative feedback cycles), reinforcing loops (i.e. positive feedback cycles), and time lags or delays (Fig. 1(A)). For environmental management, the archetypes related to fixing problems are typically most relevant, and are our focus here. This class of archetypes illustrates system dynamics in which actions to respond to a problem become associated with worsening conditions over time. Often these dynamics are amplified by time lags between when the action is taken and the long-term effect is felt, which can mask the ultimate effect, and make it politically challenging to stop the corrective actions.

Systems Archetypes and Environmental Management

Here we describe select systems archetypes, originally developed for business management, as they relate to environmental management aimed at maintaining or restoring ecological communities, with goals such as maintaining or increasing the abundances of desirable or valued species or decreasing the abundances of undesirable or harmful species. A typology of common systems archetypes can assist managers in rapidly assessing, communicating, and ideally optimizing the impact of potential management actions. Ecosystem management is a socio-ecological process, and we include archetypes that characterize both potential ecological and social barriers to success.

Fixes That Fail

"Fixes that fail" or "unintended consequences" (Larrosa et al. 2016) occur when action is taken that alleviates the problem temporarily, but eventually makes it worse via an unintended feedback (Fig. 1(A)). In ecosystem management, the development of herbicide resistance in agricultural weeds (Powles & Yu 2010; Heap 2014; Shaner & Beckie 2014) is a well-known example of a response to a particular problem that has ended up with unforeseen consequences. Herbicide use that initially reduces a problem weed, but ultimately selects for herbicide-resistant genotypes, follows a "fixes that fail" pattern of initial success followed by a worsening problem. A variant of this archetype is known as "accidental adversaries" and occurs when actors cooperating to address a problem accidentally undermine one another. More broadly, this archetype also manifests when the proximal solution to a problem results in new problems. For example, the implication of pesticides in bee colony collapse (Sánchez-Bayo et al. 2016; Motta et al. 2018) reflects an "accidental adversaries" pattern.

Examples abound of land management actions taken with good intentions that later prove to have unexpected and unwanted consequences (Larrosa et al. 2016; Lim et al. 2017). For example, in Patagonia, Wittmer et al. (2013) documented a case where the removal of abundant non-native herbivores as a restoration measure to protect endangered deer species resulted in greatly increased predation of the deer by native predators (Fig. 1(B)). In the United States, the Forest Service has been directed to reduce hazardous fuels through prescribed burning, thinning, and logging (Kerns et al. 2020). However, these practices can also introduce invasive grasses and facilitate their spread, which can trigger a grass-fire cycle. As such, these practices can result in a fuel tradeoff rather than reduction (Kerns et al. 2020). Across North America and Europe, the introduction of mysids (shrimp) as a "biological fix" to provide food to sustain fish populations failed both because fish often did not eat

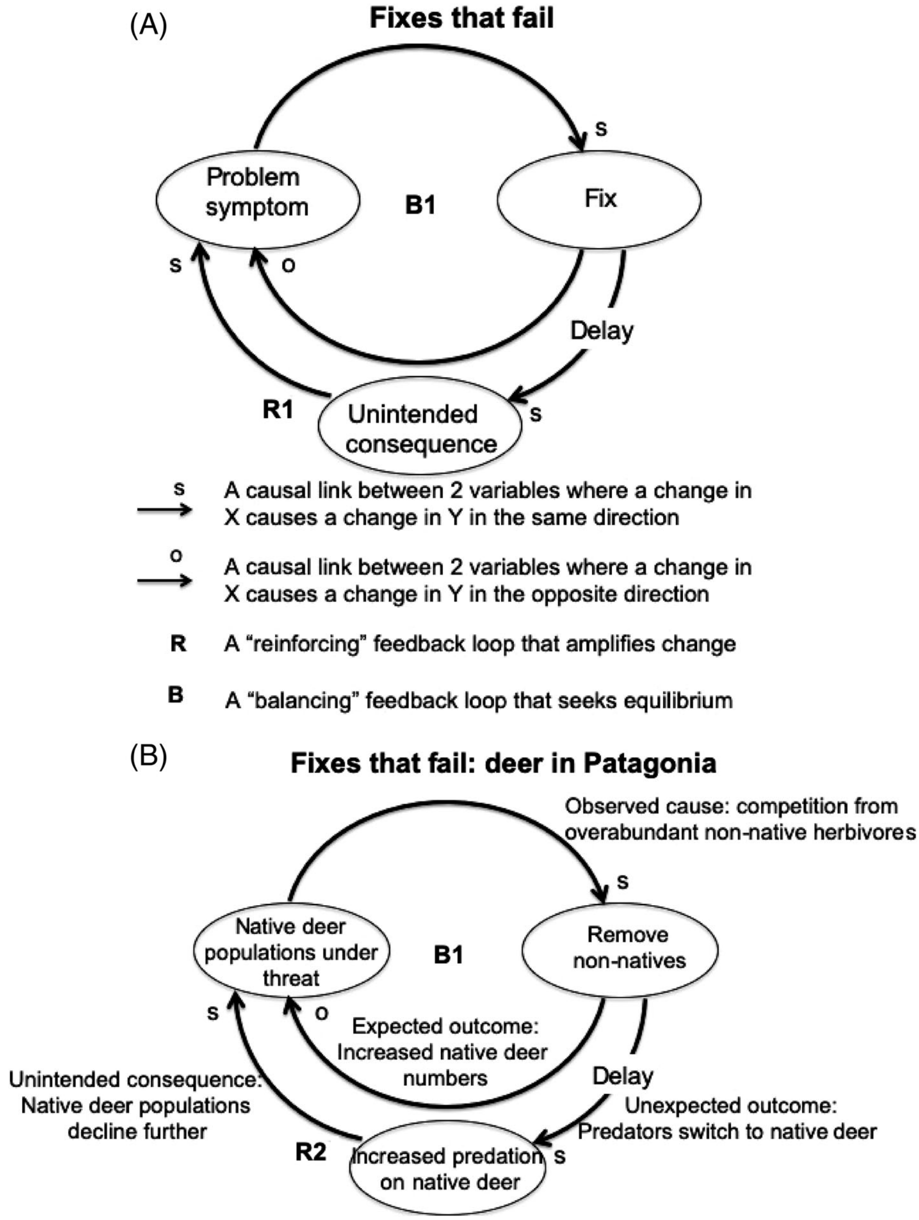

Figure 1 (A) Fixes that fail: A problem symptom requires resolution, and a solution is quickly implemented that alleviates the symptom (B1), but the unintended consequences of the "fix" exacerbate the problem (R1). Here and in subsequent diagrams the systems archetype is derived from Kim (1993). (B) The fixes that fail archetype applied to the example of endangered deer conservation in Patagonia (Wittmer et al. 2013).

the mysids and because the mysids often directly competed with fish for food, leading to fishery collapses (Frederickson 2017).

The prevalence of fixes that fail may feed an inclination toward a hands-off approach. Relating these dynamics to the archetype, however, may help improve proactive interventions. For instance, mapping food webs can help managers anticipate how the network will change when a species is removed or added (Zavaleta et al. 2001). Testing how an intervention affects non-focal but desirable species can help managers identify potential drawbacks of the intervention on other ecosystem goals. Dealing with this archetype includes acknowledging when actions are merely fixing the symptom and pursuing other interventions that target the relevant features of the system. For example, juniper removal in the Great Basin is sometimes considered important for sage grouse protection (juniper provide a perch for predatory birds) (Boyd et al. 2017). However, seedling recruitment is high under downed trees, and cutting junipers can ultimately increase juniper population size (Dittel et al. 2018). Ultimately, managers may decide that an immediate solution is needed. To avoid a "fixes that fail" scenario, however, these choices typically need to be made in conjunction with a long-term plan aimed at breaking resulting feedbacks.

The "fixes that fail" archetype is a useful heuristic to break the link between the "fix" and the unintended consequences, or between the unintended consequences and the original problem symptom. This often involves developing solutions that account for system feedbacks as opposed to developing solutions in reaction to one system component. For example, the dingo is the apex predator in Australia, and its management has been, and remains, highly contentious (e.g. Letnic et al. 2012; Allen et al. 2013; Nimmo et al. 2015). These studies discuss the fact that dingoes are controlled or excluded over large parts of Australia, mainly because of concern for livestock predation. Dingo control, however, also can increase the number of large herbivores and mesopredators, and an increase in mesopredators in turn reduces the number of medium-sized native mammals (Letnic et al. 2012). These shifts in the food web can feedback on livestock production as well as conservation efforts. For example, where dingo numbers are allowed to increase, there is anecdotal evidence that cattle production can increase because a reduced grazing pressure from kangaroos and goats leads to more available forage (e.g. Pollock 2019). Similarly, there is accumulating evidence that elevating the populations of medium-sized native mammal species can improve soil conditions through digging activities, increasing plant regeneration, and also possibly regulating fire behavior (Fleming et al. 2014; Johnson et al. 2018; Valentine et al. 2018). Hence, through cascading effects, maintaining or replacing dingoes may have counterbalancing benefits for livestock production. The net benefits of these maintaining dingoes may be particularly large in areas managed for cattle and larger livestock, where the direct costs from dingo predation are less than for sheep. Consequently, avoiding a "fixes that fail" dynamic requires a systems approach that considers both the direct and indirect effects of dingo control on livestock. This requires a shift from adversarial discussion between pro- and anti-dingo camps, together with ongoing research that further clarifies how dingoes affect the full ecosystem.

Shifting the Burden

A particular form of "fixes that fail" is the "shifting the burden" archetype (also known as "addiction"), which occurs when a solution to treat the symptoms diverts attention from the more systemic problem (Fig. 2(A)). This can degrade into an addictive pattern in which the unintended side effect becomes entrenched and inescapable. As a result, the "fixes" divert attention away from the real or fundamental source of the problem. For example, non-native species invasions in Hawaiian lowland forests have prompted large-scale removal to facilitate the success of native species plantings (Burnett et al. 2007; Ostertag et al. 2009). However, high residual non-native seedbanks can maintain non-native invasion pressure (Cordell et al. 2016), and land managers, having invested enough to not want to give up, may respond by escalating removal efforts (Kettenring & Adams 2011). Cordell et al. (2016) identified this potential cycle in their efforts to restore Hawaiian forests (Fig. 2(B)). In order to avoid a "shifting the burden/addiction" scenario, they designed a new experiment that still aimed to remove invasive species, but expanded the restoration plantings to include native and also non-native but non-invasive species. Including these non-native species expanded the functional traits represented in the community and promoted invasive species resistance. Moreover, they experienced far greater community buy-in with this approach, which then doubled back to support the project (Cordell et al. 2016).

More subtly, within a "shifting the burden/addiction" scenario, symptomatic solutions may cause the viability of the fundamental solution to deteriorate over time, reinforcing the perceived need for more of the symptomatic solution. This is an emerging concern for post-fire direct-seeding of native perennial grasses, a common approach to combat the invasion of the noxious annual cheatgrass in the Great Basin (Davies et al. 2011; Leger & Baughman 2015). Adding large quantities of native seeds is a tempting solution, but repeatedly adding external seed may impede the long-term adaptation of resident native species (e.g. Leger 2008). While the increasing dominance of cheatgrass can create an "addiction" to adding yet more native seed, researchers in this system increasingly suggest that effective management refrain from skewing the seed bank toward less-adapted natives. Instead, avoiding a "shifting the burden" scenario may involve prioritizing interventions that facilitate rapid evolutionary change and source seeds from adapted native populations (Leger & Espeland 2010).

Drifting Goals

The "drifting goals" archetype can occur in an effort to close a gap between a goal and the current reality (Fig. 3(A)). This can be resolved by either taking corrective action (Fig. 3(A), B1) or by lowering the goal (Fig. 3(A), B2). Lowering the goal immediately closes the gap and can appear cost-effective, whereas corrective action often takes time and resources. As such, it can be tempting to "drift" goals downward in an effort to appear successful, although this approach may ultimately be costly. For example, when confronted with a persistent weed it may be tempting to lower the goal (e.g. from a goal of complete eradication to one of population reduction), but uncritically eroding the goal can ultimately result in expansive weed populations.

This systemsarchetype lies at the center of the debate over novel ecosystems, or the concept that there are many altered systems resulting from changed biotic and abiotic conditions that are now not amenable to standard restoration approaches due to ecological or socio-economic thresholds (Hobbs et al. 2009; Hobbs et al. 2013) (Fig. 3(B)). The idea of thresholds and changing goals emerged when evidence of "fixes that fail" began to accumulate in relation to non-native species management. As such, developers of the novel ecosystem idea argued that traditional goals could result in the loss of too much of what you value by intervening, or endless fighting of Sisyphean battles (Heller & Hobbs 2014), and potentially losing good will and resources for other problems. Critics of the novel ecosystem argument, however, liken this to a "shifting baselines" scenario. If we are constantly lowering our standards to meet what is currently feasible, we end up with nothing left of value. Moreover, this mindset could also open the door to bad actors (Murcia et al. 2014).

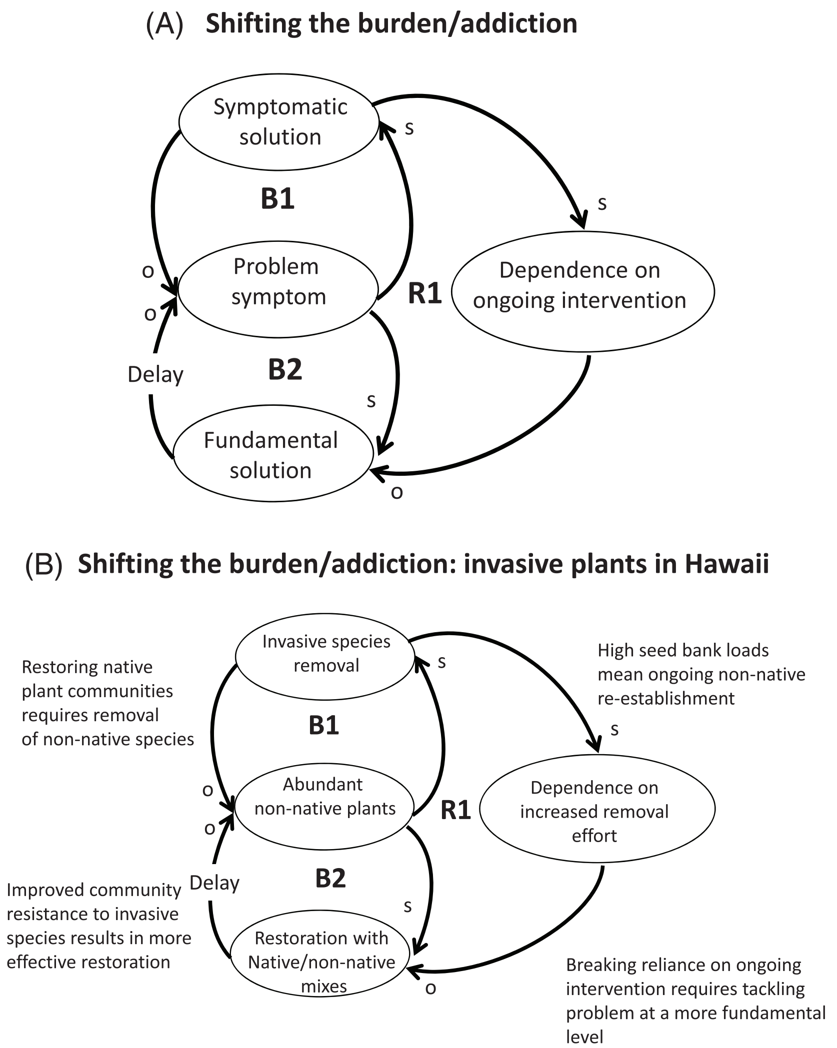

Figure 2 (A) Shifting the burden/addiction: A problem is "solved" by applying a symptomatic solution (B1) which diverts attention away from more fundamental solutions (R1). This can develop into an addictive pattern in which the side-effect gets so entrenched that it overwhelms the original problem symptom. (B) The shifting the burden/addiction archetype applied to management of invasive plants in restoration efforts in Hawaii (Cordell et al. 2016). Symbols as in Figure 1(A).

Avoiding a potential "drifting goals" scenario requires vigilance as to what goals are set and why. Are goals being set on the basis of perceived values, feasibility, or existing dogma? Setting and changing goals should be done deliberately and without undermining other objectives. The importance of explicit goal setting has been integral to the development of applied sciences such as restoration ecology (Hobbs & Norton 1996). Once the goal is explicit, one can look for ways to anchor that goal to an external standard (which breaks the link between pressure to lower the goal and the goal itself). For example, the recent development of the Society for Ecological Restoration Standards has set out to avoid "drifting goals" by setting an external standard (McDonald et al. 2016; Gann et al. 2019). There has been debate about the form of these standards, in part because setting universal standards across different ecosystems may avoid a "drifting goals" scenario in some systems while generating a "fixes that fail" scenario in others (Higgs et al. 2018; Hobbs 2018). The Society of Ecological Restoration has put considerable effort into creating standards that are simultaneously external to a site but also adaptable to individual sites (Gann et al. 2018), reflecting the difficulty in balancing management frameworks to avoid both a "drifting goals" and a "fixes that fail" scenario.

The crux of the matter—easier to state than to ascertain—is the appropriateness of the goals being set. Unlike other archetypes, drifting goals describes present behavior that is the result of forecasts made in the past. Although adjusting the goal can be viewed as the quick (and inappropriate) fix in this situation, there are times when an understanding of the system could indicate that modifying a goal is the appropriate choice. If past forecasts of the future turn out to be inaccurate, it may be desirable to make adjustments that reflect the updated information. This requires an open discussion about setting appropriate goals based on an up-to-date understanding of the system and an

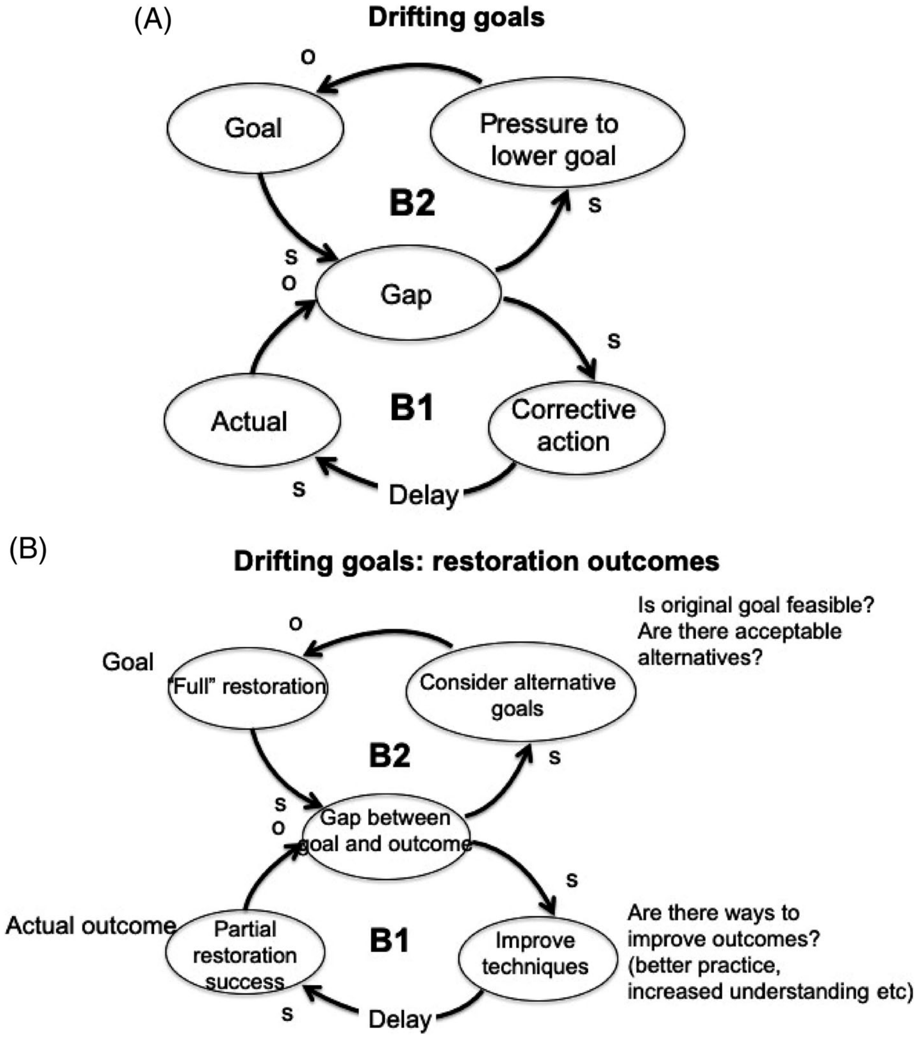

Figure 3 (A) Drifting goals: A gap between the goal and current reality can be resolved by taking corrective action (B1) or lowering/changing the goal (B2). (B) The drifting goals archetype applied to the question of setting restoration goals. Symbols as in Figure 1(A).

assessment of opportunities and limitations. Changing the goal may be perceived as "lowering" the goal by some people and an appropriate course correction by others. Lawler et al. (2015) have recently commented that, "Most fundamentally, practicing restoration in a changing climate requires embracing uncertainty and accepting that the goals of a project may need to change over time." As such, effective ecosystem management in a changing world will require finding a balance between avoiding a "drifting goals" and a "fixes that fail" scenario—and understanding how this balance changes with available resources and increased system knowledge.

Escalation

The "escalation" archetype can occur when one actor takes action that is perceived as a threat by the other, causing the other to retaliate (Fig. 4(A)). This leads to a complex reinforcing loop resulting from two interacting balancing loops. In the case of environmental management, this often emerges as a social barrier in which different stakeholders have different goals for the land and their actions are seen as undermining each other's interests. For instance, forest management often raises conflict between those seeking to harvest timber and those seeking to conserve old-growth forests and forest biodiversity (e.g. Mackovjak 2010) (Fig. 4(B)). It can also occur within groups of people who theoretically should be working together. Recent debates in conservation biology and restoration ecology arise from the perception by one group that the approaches suggested by another represent a threat to the practice overall (Karieva et al. 2017).

Dealing with this archetype involves breaking the cycle of threat and retaliation by acknowledging the system concerns that are leading to the initial divergence. Recognition of the dynamic involved can lead one party to reverse the factors involved in the reinforcing loop by initiating unilateral action that leads to de-escalation, for instance by shifting the focus

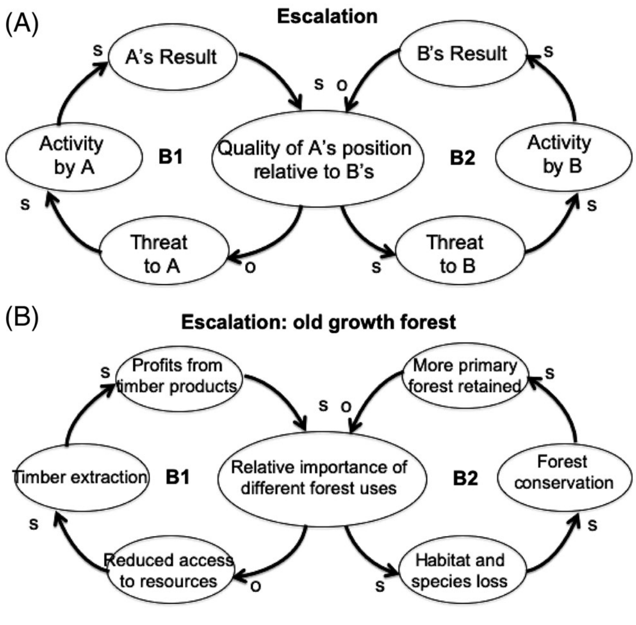

Figure 4 (A) Escalation: One party (a) takes actions that are perceived as a threat. The other party (b) responds in a similar manner, increasing the threat to a, and resulting in more threatening actions by a. The reinforcing loop is the figure-8 produced by the two balancing loops. (B) The escalation archetype applied to old growth forest management. Symbols as in Figure 1(A).

to a different measure that is not win-lose. This might involve examining the relative measures by which threats are perceived and potentially changing to a different measure that does not involve a win-lose situation. In the forest management example, this might involve changing harvest practices, zoning multiple-use landscapes, or shifting to plantation forestry. Deep-rooted assumptions may lie beneath the actions taken in response to a perceived threat—for instance, the assumption of a zero-sum game (someone benefitting automatically results in someone losing). There may also be important delays in the system that prevent the accurate perception of the true nature of the threat. Extinction debt, or substantial delay in the local extinction of species following habitat loss or degradation (Kuussaari et al. 2009), is a classic example of time lags that obscure the true magnitude of the problem.

Establishing trust among participants is a key component of avoiding an "escalation" archetype. A participatory approach, in which all stakeholders are involved in a planning process, can help build this trust (Enquist et al. 2017). Participatory approaches take longer and can be hijacked by vested interests and people adhering to simplistic or partial perspectives of both the problem and the solution, but have been shown to work in a variety of settings. For example, urban planning can often be top-down, and resentment can arise from urban restoration and greening efforts that do not account for local needs. Stringer et al. (2006) document this type of situation in Bangkok, Thailand, in which potential escalation was averted through early and frequent dialog between planners and community members. This approach drew in initially skeptical members, who became part of the planning and ultimately management of the greenspace. Similarly, the rise of cooperatives in the western United States have helped develop paths forward in response to complex and contentious land management issues such as sage grouse (www.sagegrouseinitiative.com).

Conclusion: Does This Help?

To ensure that good management intentions result in good environmental outcomes, there is a pressing need to ensure that the following questions can be answered: (1) Is the desired overall impact being achieved?; (2) Have the best interventions been selected to achieve the desired impact?; and (3) Are the interventions being executed in the best possible manner? (Margoluis et al. 2013).

The size of many conservation problems and the near-impossibility of tasks (e.g. removing all non-native species), especially in situations of constrained budgets, frequently mean that the answer to the above questions is "no." This can result in a loss of time and resources and without slowing environmental and biological declines, constituting a major burden on managers (Head et al. 2015). Faced with near-insurmountable problems, managers can feel overwhelmed and powerless. Overcoming this may require seeking solutions that are not immediately obvious but that take fuller account of the various factors at play. Using systems archetypes as a heuristic to target and implement ecosystem interventions seems to make sense at a theoretical level. The systems approach was widely explored in business management in the 1990s and 2000s and retains some degree of currency through the classic works of Senge and others who followed. It has also been explored in broader contexts (Meadows 2008; Reynolds & Holwell 2010; Gharajedaghi 2011; Williams & Hummelbrunner 2011). Why then is it utilized so seldom in environmental management, and is there any evidence that it would actually help? Can the ideas presented here be applied to particular problems in a practical way?

The literature on systems archetypes in business management is full of hypothetical examples of particular archetypes and how interventions might be designed to deal with the problems inherent in each archetype, but rarely provides actual examples from real life that illustrate how the archetypes helped an organization work through a problem. Similarly, in ecosystem management, there are few examples where there has been active consideration of feedback loops and potential leverage points, despite the recognition of the likely importance of these features.

Why is this? The simple answer may be that it is hard to do this effectively. The problems being described in the different systems archetypes are often complex and sometimes "wicked"—defined as intractable problems owing to contradictory or changing requirements that can be hard to foresee (Game et al. 2014). Identifying symptoms is much easier than working out feedback relationships and searching for and treating fundamental causes. Larrosa et al. (2016) suggest that "SESs (social-ecological systems) have emergent properties that make responses to interventions different than the sum of individual responses." In other words, working out the causal relationships is likely to be a daunting task. We nevertheless consider it is worthwhile looking further into whether systems thinking and looking at systems archetypes might be useful. We have found it a useful frame in which to consider our own work—for instance, discussions on novel ecosystems and restoration started from the perspective of "fixes that fail" in traditional restoration, encountered the issue of "shifting goals," and have been subject to "escalation" as the topic became a lightning rod for debate. More broadly we suggest that relating emerging problems in ecosystem management with known patterns of system feedbacks and underlying causal loops may ease this process, helping to work toward more effective interventions that result in positive outcomes rather than surprising unintended consequences.

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LITERATURE CITED

Allen BL, Fleming PJS, Allen LR, Engeman RM, Ballard G, Leung LKP (2013) As clear as mud: a critical review of evidence for the ecological roles of Australian dingoes. Biological Conservation 159:158–174

Armitage DR, Plummer R, Berkes F, Arthur RI, Charles AT, Davidson-Hunt IJ, et al. (2009) Adaptive co-management for social-ecological complexity. Frontiers in Ecology and the Environment 7:95-102.

Boyd CS, Kerby JD, Svejcar TJ, Bates JD, Johnson DD, Davies KW (2017) The sage-grouse habitat mortgage: effective conifer management in space and time. Rangeland Ecology & Management 70:141–148

Burnett K, Kaiser B, Roumasset J (2007) Economic lessons from control efforts for an invasive species: *Miconia calvescens* in Hawaii. Journal of Forest Economics 13:151–167

Butterfield BJ, Copeland SM, Munson SM, Roybal CM, Wood TE (2017) Prestoration: using species in restoration that will persist now and into the future. Restoration Ecology 25:S155–S163

Cordell S, Ostertag R, Michaud J, Warman L (2016) Quandaries of a decade-long restoration experiment trying to reduce invasive species: beat them, join them, give up, or start over? Restoration Ecology 24:139–114

Davies KW, Boyd CS, Beck JL, Bates JD, Svejcar TJ, Gregg MA (2011) Saving the sagebrush sea: an ecosystem conservation plan for big sagebrush plant communities. Biological Conservation 144:2573–2584

Dittel JW, Sanchez D, Ellsworth LM, Morozumi CN, Mata-Gonzalez R (2018) Vegetation response to juniper reduction and grazing exclusion in sagebrush-steppe habitat in eastern Oregon. Rangeland Ecology & Management 71:213–219

Duboz R, Echaubard P, Promburom P, Kilvington M, Ross H, Allen W, Ward J, Deffuant G, de Garine-Wichatitsky M, Binot A (2018) Systems thinking in practice: participatory modeling as a foundation for integrated approaches to health. Frontiers in Veterinary Science 5:303

Enquist CA, Jackson ST, Garfin GM, Davis FW, Gerber LR, Littell JA, et al. (2017) Foundations of translational ecology. Frontiers in Ecology and the Environment 15:541–550

Evans MR, Bithell M, Cornell SJ, Dall SRX, Díaz S, Emmott S, et al. (2013) Predictive systems ecology. Proceedings of the Royal Society B: Biological Sciences 280:20131452

Fleming PA, Anderson H, Prendergast AS, Bretz MR, Valentine LE, Hardy GES (2014) Is the loss of Australian digging mammals contributing to a deterioration in ecosystem function? Mammal Review 44:94–108

Frederickson L (2017) Bio-invasions and bio-fixes: Mysis shrimp introductions in the twentieth century. Environment and History 23:285–320

Game ET, Meijaard E, Sheil D, McDonald-Madden E (2014) Conservation in a wicked complex world; challenges and solutions. Conservation Letters 7: 271–277

Gann GD, McDonald T, Aronson J, Dixon KW, Walder B, Hallett JG, et al. (2018) The SER standards: a globally relevant and inclusive tool for improving restoration practice—a reply to Higgs et al. Restoration Ecology 26:426–430

Gann GD, McDonald T, Walder B, Aronson J, Nelson CR, Jonson J, et al. (2019) International principles and standards for the practice of ecological restoration. Restoration Ecology 27:S1–S46

Gharajedaghi J (2011) Systems thinking, third edition: managing chaos and complexity: a platform for designing business architecture. Morgan Kauffmann, Burlington, Massachusetts

Head L, Larson BMH, Hobbs RJ, Atchison J, Gill N, Kull C, Rangan H (2015) Living with invasive plants in the Anthropocene: the importance of understanding practice and experience. Conservation and Society 13:311–318

Heap I (2014) Global perspective of herbicide-resistant weeds. Pest Management Science 70:1306–1315

Heller NE, Hobbs RJ (2014) Development of a natural practice to adapt conservation goals to global change. Conservation Biology 28:696–704

Higgs E, Harris J, Murphy S, Bowers K, Hobbs R, Jenkins W, et al. (2018) On principles and standards in ecological restoration. Restoration Ecology 26:399–403

Hobbs RJ (2018) Restoration Ecology's silver jubilee: innovation, debate, and creating a future for restoration ecology. Restoration Ecology 26:801–805

Hobbs RJ, Norton DA (1996) Towards a conceptual framework for restoration ecology. Restoration Ecology 4:93–110

Hobbs RJ, Higgs E, Harris JA (2009) Novel ecosystems: implications for conservation and restoration. Trends in Ecology and Evolution 24:599–605

Hobbs RJ, Hallett LM, Ehrlich PR, Mooney HA (2011) Intervention ecology: applying ecological science in the 21st century. Bioscience 61:442–450

Hobbs RJ, Higgs ES, Hall CA (2013) Novel ecosystems: intervening in the new ecological world order. Wiley-Blackwell, Oxford, United Kingdom

Holling CS (1978) Adaptive Environmental Assessment and Management. Wiley and Son, Chichester.

Johnson CN, Prior LD, Archibald S, Poulos HM, Barton AM, Williamson GJ, Bowman DMJS (2018) Can trophic rewilding reduce the impact of fire in a more flammable world? Philosophical Transactions of the Royal Society B: Biological Sciences 373:20170443

Karieva P, Silliman B, Marvier M (2017) Effective conservation science: data not dogma. Oxford University Press, Oxford, United Kingdom

Kerns BK, Tortorelli C, Day MA, Nietupski T, Barros AMG, Kim JB, Krawchuk MA (2020) Invasive grasses: a new perfect storm for forested ecosystems? Forest Ecology and Management 463:117985

Kettenring KM, Adams CR (2011) Lessons learned from invasive plant control experiments: a systematic review and meta-analysis. Journal of Applied Ecology 48:970–979

Kim DH (1993) Systems archetypes: diagnosing systemic issues and designing high leverage interventions. Pegasus Communications, Cambridge, Massachusetts

Kuussaari M, Bommarco R, Heikkinen RK, Helm A, Krauss J, Lindborg R, et al. (2009) Extinction debt: a challenge for biodiversity conservation. Trends in Ecology & Evolution 24:564–571

Larrosa C, Carrasco LR, Milner-Gulland EJ (2016) Unintended feedbacks: challenges and opportunities for improving conservation effectiveness. Conservation Letters 9:316–326

Lawler J, Watson J, Game E (2015) Conservation in the face of climate change: recent developments. F1000Research 4:1158

Leger EA (2008) The adaptive value of remnant native plants in invaded communities: an example from the Great Basin. Ecological Applications 18: 1226–1235

Leger EA, Baughman OW (2015) What seeds to plant in the Great Basin? Comparing traits prioritized in native plant cultivars and releases with those that promote survival in the field. Natural Areas Journal 35:54–68, 15

Leger EA, Espeland EK (2010) Coevolution between native and invasive plant competitors: implications for invasive species management: managing coevolution. Evolutionary Applications 3:169–178

Letnic M, Ritchie EG, Dickman CR (2012) Top predators as biodiversity regulators: the dingo *Canis lupus dingo* as a case study. Biological Reviews 87: 390–413

Lim FKS, Carrasco LR, McHardy J, Edwards DP (2017) Perverse market outcomes from biodiversity conservation interventions. Conservation Letters 10:506–516

Lindenmayer DB, Likens GE, Krebs CJ, Hobbs RJ (2010) Improved probability of detection of ecological “surprises”. Proceedings of the National Academy of Sciences 107:21957–21962

Mackovjak J (2010) Tongass timber: a history of logging and timber utilization in Southeast Alaska. Forest History Society, Durham, North Carolina

Margoluis R, Stem C, Swaminathan V, Brown M, Johnson A, Placci G, Salafsky N, Tilders I (2013) Results chains: a tool for conservation action design, management, and evaluation. Ecology and Society 18:Art22

McDonald T, Gann GD, J J, Dixon KW (2016) International standards for the practice of ecological restoration – including principles and key concepts. Society for Ecological Restoration, Washington D.C.

Meadows DH (1999) Leverage points places to intervene in a system. The Sustainability Institute, Hartland, Vermont

Meadows DH (2008) Thinking in systems – a primer. Chelsea Green Publishing, White River Junction, Vermont

Motta EVS, Raymann K, Moran NA (2018) Glyphosate perturbs the gut microbiota of honey bees. Proceedings of the National Academy of Sciences 115:10305–10310

Murcia C, Aronson J, Kattan GH, Moreno-Mateos D, Dixon K, Simberloff D (2014) A critique of the ‘novel ecosystem’ concept. Trends in Ecology & Evolution 29:548–553

Nimmo DG, Watson SJ, Forsyth DM, Bradshaw CJA (2015) FORUM: dingoes can help conserve wildlife and our methods can tell. Journal of Applied Ecology 52:281–285

Odum HT (1994) Ecological and general systems. an introduction to systems ecology. Revised edition. University Press of Colorado, Niwot, Colorado

Ostertag R, Cordell S, Michaud J, Cole TC, Schulten JR, Publico KM, Enoka JH (2009) Ecosystem and restoration consequences of invasive woody species removal in Hawaiian lowland wet forest. Ecosystems 12:503–515

Partelow S (2018) A review of the social-ecological systems framework: applications, methods, modifications, and challenges. Ecology and Society 23: Art36

Pollock D (2019) The wooleen way: renewing an Australian resource. Scribe Publications, Melbourne, Australia

Powles SB, Yu Q (2010) Evolution in action: plants resistant to herbicides. Annual Review of Plant Biology 61:317–347

Reynolds M, Holwell S (2010) Systems approaches to managing change: a practical guide. Springer, London, United Kingdom

Ross DA, Wade JP (2015) A definition of systems thinking: a systems approach. Procedia Computer Science 44:669–678

Sánchez-Bayo F, Goulson D, Pennacchio F, Nazzi F, Goka K, Desneux N (2016) Are bee diseases linked to pesticides?—a brief review. Environment International 89-90:7–11

Senge P (1990) The fifth discipline: the art and practice of the learning organisation. Century, London, United Kingdom

Shaner DL, Beckie HJ (2014) The future for weed control and technology. Pest Management Science 70:1329–1339

Stringer LC, Dougill Andrew J, Fraser Evan, Hubacek Klaus, Prell Christina, Reed Mark S (2006) Unpacking ‘participation’ in the adaptive management of social-ecological systems: a critical review. Ecology and Society 11:2

Valentine LE, Ruthrof KX, Fisher R, Hardy GESJ, Hobbs RJ, Fleming PA (2018) Bioturbation by bandicoots facilitates seedling growth by altering soil properties. Functional Ecology 32:2138–2148

Walters CJ, Hilborn R (1978) Ecological optimization and adaptive management. Annual Review of Ecology and Systematics 9:157-188.

Westgate MJ, Likens GE, Lindenmayer DB (2013) Adaptive management of biological systems: a review. Biological Conservation 158:128–139

Williams B, Hummelbrunner R (2011) Systems concepts in action: a practitioner’s toolkit. Stanford University Press, Stanford, California

Wittmer HU, Elbroch LM, Marshall AJ (2013) Good intentions gone wrong: did conservation management threaten endangered huemul deer *Hippocamelus bisulcus* in the future Patagonia National Park? Oryx 47:393–402

Zavaleta ES, Hobbs RJ, Mooney HA (2001) Viewing invasive species removal in a whole-ecosystem context. Trends in Ecology and Evolution 16:454–459

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