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Research article

Biological invasions, ecological resilience and adaptive governance

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ABSTRACT

In a world of increasing interconnections in global trade as well as rapid change in climate and land cover, the accelerating introduction and spread of invasive species is a critical concern due to associated negative social and ecological impacts, both real and perceived. Much of the societal response to invasive species to date has been associated with negative economic consequences of invasions. This response has shaped a war-like approach to addressing invasions, one with an agenda of eradications and intense ecological restoration efforts towards prior or more desirable ecological regimes. This trajectory often ignores the concept of ecological resilience and associated approaches of resilience-based governance. We argue that the relationship between ecological resilience and invasive species has been understudied to the detriment of attempts to govern invasions, and that most management actions fail, primarily because they do not incorporate adaptive, learning-based approaches. Invasive species can decrease resilience by reducing the biodiversity that underpins ecological functions and processes, making ecosystems more prone to regime shifts. However, invasions do not always result in a shift to an alternative regime; invasions can also increase resilience by introducing novelty, replacing lost ecological functions or adding redundancy that strengthens already existing structures and processes in an ecosystem. This paper examines the potential impacts of species invasions on the resilience of ecosystems and suggests that resilience-based approaches can inform policy by linking the governance of biological invasions to the negotiation of tradeoffs between ecosystem services.

1. Introduction

Biological invasions are a common, inescapable part of a globalized world that is continuously modified. Human activity intentionally and unintentionally influences species distributions, introducing species to new environments including degraded and modified environments susceptible to biological reorganization (Rahel and Olden, 2008). Invasive species—non-native species that geographically spread and increase in abundance following initial

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establishment (Lodge et al., 2006)—by affecting ecological processes (Gandhi and Herms, 2010), engineering ecosystem structure (Crooks, 2002) or affecting community dynamics (Yurkonis et al., 2005), can significantly alter ecosystem structure and function that may result in a significant alteration in the provision of ecosystem services. Although there has been a recent shift toward prevention of invasions (Cook et al., 2010; Simberloff, 2013), traditional approaches to managing invasions have been largely reactionary in nature, with a focus on control through mitigation and eradication (Keller et al., 2007; Foxcroft and McGeoch, 2011). This control approach grew out of a dominant narrative that invasions are ecologically, economically and culturally undesirable, and has been reinforced by many documented cases of detrimental, and often highly visible, impacts (Keller et al., 2007).

This traditional view of invasions and associated approaches to management have become increasingly contested as economically inefficient, ecologically (and evolutionarily) ineffective and potentially undesirable in many cases (Angeler et al., 2012; Allen et al., 2013; Lotz and Allen, 2013). Some invasions may have neutral or positive outcomes (both real and perceived) (e.g., Sax et al., 2002), because they either reinforce specific ecosystem functions or provide economic benefit (e.g., Thomsen, 2010; Wallach et al., 2015; Weigel et al., 2016). Failed invasions or those with neutral ecological outcomes may in fact be more common than what has been reported, because invasions with detrimental ecological or economic effects are more likely to be published than studies reporting non-significant effects (Levine and D'Antonio, 2003). Even some invasions initially labeled as socially undesirable may be beneficial to some degree because they provide opportunity to gain a deeper understanding of complex system dynamics (e.g., Bertness and Cloverdale, 2013). Though scientific understanding and technological innovation has and will advance to further support a "detect and eradicate" approach for some invasive species (Simberloff, 2013), new conceptual frameworks for managing invasions are required to address the complexity of invasions (Ricciardi and Atkinson, 2004) especially given the rapid increase in ecological and socioeconomic uncertainties associated with global change.

The concept of ecological resilience, defined as the capacity of a system to withstand change while maintaining processes and structures (Holling, 1973), offers a rich theoretical frame for understanding invasions. In addition, ecological resilience and related concepts can serve as a bridge to new approaches to invasive species management with a focus on understanding ecosystem dynamics as opposed to controlling a single species (Angeler et al., 2015a). Resilience—as a property of complex systems—has inspired a series of theoretical advancements in approaches to governing interactions between society and biophysical systems (Gunderson et al., 2005; Folke, 2006). In this context, 'governance' describes the "social and political process of defining goals for the management of [social-ecological systems] and resolving tradeoffs, and management is defined as the actions taken to achieve these goals and includes monitoring and implementation" (Biggs et al., 2012 citing Pahl-Wostl, 2009). Gaining an understanding of biological invasions in terms of ecological resilience allows for the deliberate engagement with resilience-based approaches to governance (Garmestani and Benson, 2013) that can coordinate the management of invasive species at scales relevant to ecosystems, ecosystem function and the provision of ecosystem services, instead of at anthropocentric scales such as political and jurisdictional boundaries.

In this paper we highlight the potential of adaptive governance, a resilience-based approach that shifts the focus of governance and management actions from reactions toward a single species invasion to a more holistic view of the functional role of invasions in ecosystems. We frame adaptive governance as an approach to managing tradeoffs between ecosystem services, recognizing that the role of invasions in these complex processes may not always be spatially or temporally apparent. Our goal is that this synthesis of scholarship will be a bridge to policy to inform both future empirical research on biological invasions as well as practical applications of resilience-based governance approaches to managing invasive species and associated effects on ecosystem services and human wellbeing.

2. Ecological resilience and biological invasions

The concept of ecological resilience emphasizes non-linear change in ecological systems, more specifically, the existence of alternative regimes (Holling, 1973). Once a disturbance threshold is passed, a system can undergo a shift characterized by a relatively abrupt change in structuring processes, reorganizing into a new regime dominated by a different set of processes, structures, functions and feedbacks (represented in the adaptive cycle of complex systems (Holling, 1986); Fig. 1). Undergoing such a regime shift may be unlikely if the system is resilient to the influence of disturbance events (i.e., structuring processes are reinforced by social-ecological feedbacks and cross-scale interactions) (Nyström et al., 2012). However, system-reinforcing feedbacks can be weakened with the addition of novel species, such is the case with biological invasions. Biological invasions can influence ecosystem resilience and threshold dynamics, potentially triggering regime shifts.

In this section we review biological invasions from an ecological resilience perspective, paying particular attention to literature that highlights the importance of scale, invasion success and the role of invasions in building and eroding the resilience of ecosystem regimes.

2.1. Scale

Explicit to the concepts of ecological resilience is a cross-scale view of ecosystem structure and dynamics (Garmestani et al., 2009). Scale-specific interactions between patterns and processes and biotic-abiotic feedbacks provide systems with their

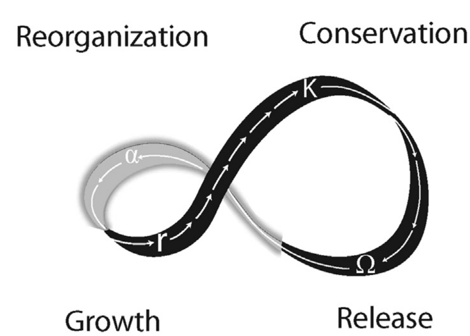

Fig. 1. A representation of an adaptive cycle. The arrows indicate the speed of the cycle where short, closely spaced arrows indicate a slowly changing state and long arrows indicate a rapidly changing state. The cycle reflects changes in two properties: (1) Y axis—the potential that is inherent in the accumulated resources of biomass and nutrients; (2) X axis—the degree of connectedness among controlling variables. Low connectedness is associated with diffuse elements loosely connected to each other whose behavior is dominated by outward relations and affected by outside variability. High connectedness is associated with aggregated elements whose behavior is dominated by inward relations among elements of the aggregates, relations that control or mediate the influence of external variability. Opportunities for invasion are heightened as the cycle transitions from the Omega phase into the onset of the Alpha phase (shown in lighter coloration). Adapted from *Panarchy: Understanding Transformations in Human and Natural Systems*, L.H. Gunderson and C.S. Holling, eds. Copyright © 2002 by Island Press.