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Using simulation modeling to inform management of invasive species: A case study of eastern brook trout suppression and eradication

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ABSTRACT

Ecosystem impacts due to invasive species continue to attract significant conservation effort worldwide. In aquatic ecosystems, physical interventions such as suppression and eradication of non-native species are typically expensive, long-term commitments, with few examples of lasting success in the absence of significant ongoing effort. Control of non-native species is a major conservation and restoration challenge, as a species' demographic resilience and connectivity within networks can limit the ability of suppression or eradication efforts to influence populations. Simulation tools can provide valuable insights for the management of these systems - from evaluation of tradeoffs between time and effort to prediction of relative success rates of alternative strategies in changing environments. In the Pacific Northwest region of the U.S., the eastern brook trout (EBT; *Salvelinus fontinalis*) is a non-native invasive species that competes with native fish species across a wide spatial scale due to extensive human-mediated introduction starting in the early 20th century. The goal of this study was to simulate the individual movement and demographics of EBT before, during, and following implementation of control efforts in tributaries within the Pend Oreille River watershed. The ultimate purpose of the model was to inform mitigation decisions through the investigation of alternative management actions in an adaptive management framework. Our results indicate that eradication of EBT is improbable in large systems via electrofishing, but suppression is a viable alternative given sustained management efforts. Changes to scheduling, effort, and length of electrofishing suppression treatments had minimal effects on EBT population recovery times. We reproduced the effects of compensatory responses to control treatments, including increases in juvenile survival and emigration rates, and demonstrated that these mechanisms are likely drivers of recovery following treatment. Our study highlights the many benefits of incorporating spatially explicit, individual-based models into management plans for the control of invasive species.

1. Introduction

Invasive species are increasingly threatening native ecosystems. In the United States, damages from these species have been estimated to cost between 121 and 220 billion USD annually (Pimentel et al., 2005; Marbuah et al., 2014), and have been identified as a major cause of past species extinctions (Clavero and García-Berthou, 2005). Invasive species can negatively impact ecosystem services that are beneficial to industries such as agriculture, water, tourism, and recreation (Charles and Dukes, 2008). In response to the damage caused, tremendous effort is spent on preventing the establishment of new invasions, as well as mitigating existing invasions, though results of such programs are rarely documented (Marbuah et al., 2014). Approaches to control of invasive species range from prevention via economic incentives, policy instruments, and preventive monitoring, to on-the-ground management and in some cases, direct action against the invasive species via various methods (Genovesi and Shine, 2004; e.g., mechanical harvest, biological control, genetic manipulation, and systematic eradication).

Eradication (i.e., complete removal of a species) and suppression (i.e., reduction of species abundance/density) are approaches commonly taken to control invasive species. Some eradication programs have been successful as eradications of diverse taxa have been reported across the globe (e.g., rodent eradications from islands, Howald et al., 2007; plant eradications resulting in restored ecological function,

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Kennedy et al., 2005, Holsman et al., 2010; and insect eradications, Klassen and Curtis, 2005). A review of attempted eradications in Europe reported 37 successful eradications of mammals, but noted limited success among plant and invertebrate species (Genovesi, 2005). Other programs may fail at eradication but are successful at suppressing abundance of invasive species to low densities. The ecological consequences of suppression and whether it is functionally equivalent to eradication remains unclear (Simberloff, 2009). Given the environmental, economic, and social ramifications of eradication and suppression programs, it is vital to strike a balance between effort, financial cost, ecosystem integrity, monitoring, and prevention (Fraser et al., 2006; Mehta et al., 2007; Bogich et al., 2008; Lampert et al., 2014).

Ecological modeling is one approach to the management of invasive species that can be implemented at relatively low cost in terms of money, effort, and ecosystem function. Models can be developed and evaluated prior to and after manipulation of the natural system. Examples include models that have evaluated the cost of eradication versus suppression (Baxter et al., 2008), predicted probable invasion locations (Schmidt et al., 2010), and examined risks posed by potential invaders through distributional niche modeling (Jiménez-Valverde et al., 2011). Spatially-explicit individual-based models (SIBM) are a type of ecological model becoming more common as tools used for understanding mechanisms driving invasion dynamics (Pyšek and Hulme, 2005; Anderson and Dragićević, 2015; Fraser et al., 2015). A spatially-explicit model can allow for landscape configuration to affect model processes, and thus, for testing of alternative landscapes under different scenarios of management or land use. A model that is individual-based produces broad-scale patterns that emerge from the interactions of individual agents; a powerful approach to understanding mechanistic drivers of population-level processes (Grimm and Railsback, 2005). Invasions are inherently population-level processes (Peterson et al., 2004a), and therefore, modeling those processes from the bottom-up may reveal insights as to how invaders are successful and what strategies may succeed in the management of invasive species.

We developed a SIBM to understand the processes driving the persistence of eastern brook trout (hereafter EBT; *Salvelinus fontinalis*) invasions of streams in the northwestern United States, and to evaluate alternative management strategies for the control of EBT. EBT are native to the eastern United States, but have been repeatedly and intentionally introduced to western stream systems for recreational purposes (Fuller et al., 1999; Dunham et al., 2002). These introductions, and subsequent colonizations of contiguous habitat have been identified as a substantial threat to the persistence or recovery of native salmonids through interbreeding or competition for habitat and food resources (Andonaegui, 2003). In the Pacific Northwest, EBT are often implicated for having negative effects on native species such as Westslope Cutthroat Trout (*Oncorhynchus clarkii lewisi*; Dunham et al., 2002, Scoppettone et al., 2012), Bull Trout (*Salvelinus confluentus*; Gunckel et al., 2002) and Redband Rainbow Trout (*Oncorhynchus mykiss gairdnerii*; Miller et al., 2014).

Eradication and suppression programs are a common management tool used in response to EBT invasion and establishment, and are often undertaken with the goal of restoring native trout populations. Results from such programs have been mixed. Eradication has occasionally been successful in smaller systems, but in larger systems suppression may serve as a manageable substitute to aid in the restoration of native species (Shepard et al., 2002; Meyer et al., 2006; Carmona-Catot et al., 2010). One factor affecting the success of these programs is compensatory responses, or the ability of EBT to compensate for the additional mortality of control treatments via increased survival or immigration rates (Peterson et al., 2008). SIBMs are an ideal tool for evaluating eradication and suppression programs, investigating compensatory mechanisms, and preventing the loss of money and time due to failed efforts. Such models can then be implemented in an adaptive management framework, adjusting the model based on feedback from empirical data collected during field operations, with concomitant improvement of applied management actions over time (Starfield and Bleloch, 1986; Walters, 1986).

The broad objective of our simulation study was to produce a model that would simulate the bottom-up mechanisms driving EBT demographics (e.g., movement, mortality, growth) that could then be used to answer questions about how EBT respond to control treatments. Specific objectives were to (1) evaluate and compare alternative management strategies for EBT control, and (2) investigate the role of compensatory responses to control efforts by EBT. We examined the effect of the following factors on EBT suppression, recovery (i.e., return of population size to pre-suppression levels), and compensatory responses: suppression schedule, effort, landscape configuration (i.e., stream barriers), and stray rates (i.e., dispersal rates). Our results will be used to inform an active adaptive EBT management program taking place in the study area. Our results and methodology will also serve as a template for simulating the management of invasive aquatic species, particularly in the context of conservation of threatened species and ecosystems. Finally, our results demonstrate the value of applying SIBMs to landscape-level problems and the ability to test alternative mechanisms driving system processes.

2. Methods

2.1. Study system

We modeled the manual and chemical control of non-native EBT in north-eastern Washington, USA (Fig. 1) in the lower Pend Oreille River and nearby tributaries. The study area on the lower Pend Oreille River extends from Box Canyon Dam (RM 34.5) to Boundary Dam (RM 16.0) located on the US-Canada border. Major tributaries on this river stretch include Flume, Slate, Sullivan, and Sweet Creeks. The Pend Oreille River originates in Montana and Idaho, USA, and flows through the Okanogan Highlands in Washington, USA, the western portion of the Rocky Mountains, and enters the Columbia River a few miles north of the border between Washington and British Columbia, CA. Where native fish once moved freely, dams, culverts, and warm impounded waters have restricted fish travel or allowed only one-way passage out of tributaries. Stocked non-native fish (e.g., EBT) have interacted both ecologically (e.g., competition of resources) and biologically (e.g., interbreeding) with their native counterparts. EBT were cultivated and stocked widely throughout the Western US during the 20th century (Fuller et al., 1999), primarily from state operated hatcheries to promote fishing opportunities for recreation and subsistence. Within the region of interest to this study approximately 665,000 EBT were stocked into many local tributaries over the period of record from 1933 to 1981 (Kloempken, 1996) leading to extensive naturalization, range expansion and attendant impacts on native fauna. EBT currently tend to occupy the lower reaches of tributaries where they are sympatric with native Westslope Cutthroat trout and Bull Trout (*Salvelinus confluentus*) that are listed under the Endangered Species Act. Also within the study area are two hydropower dams regulated by the Federal Energy Regulatory Commission that have recently received new operating licenses containing requirements to develop and implement management plans to address the impacts of continued presence of EBT (FERC, 2005, 2013).

2.2. Model overview

We used CDMetaPOP v1.0 (for a full model description see Landguth et al., 2017) to simulate the proposed EBT management plan (SCL, 2010). CDMetaPOP is a riverscape-level, spatially-explicit, and individual-based eco-genetic model of meta-population dynamics. CDMetaPOP simulates demographic (and genetic) processes of a metapopulation comprising a number of populations inhabiting individual patches. Patches are populated with individuals and regulate carrying capacity, habitat suitability, temperature, capture probability, and