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Introduction

Biological invasions in the 21st century: Ecological impacts, predictions, and management across land and sea

In recent years, invasive species have been recognized as a major component of human-mediated impacts on natural systems (Pimentel et al., 2005). Along with global climate change and habitat destruction, the spread of invasive species are a chief signature and consequence of the Anthropocene. Biological invasions have been on the rise in modern times, however, due to enhanced human transport mechanisms, such as oceanic and continental shipping, which unintentionally transport hitchhiking species; while intentional movements of species for agriculture, aquaculture, pets, and ornamentals may also result in species' establishments in novel regions (Ruiz et al., 2000; Nentwig, 2007; Rilov and Crooks, 2009). This anthropogenic spread across natural barriers homogenizes the world's biota, resulting in global (and often disjunct) distributions of many terrestrial and aquatic species (Carlton, 2009; Rilov and Crooks, 2009). Biological invasions have thus been the focus of theoretical and empirical research dating to Darwin's own observations in the nineteenth century (Darwin, 1859). It is clear that well-developed investigations of species invasions are needed urgently to fully understand how community composition, biodiversity, and habitat are affected by the addition of species to natural communities. However, many of these issues remain only partially understood; e.g., the mechanisms of how invasive species appear, the conditions under which they thrive, and the impacts of invaders on native environments. Moreover, the prediction, prevention, and management of biological invasions are challenges being addressed across the globe, from regions at the forefront of management strategies (e.g., the contribution here by Campbell from New Zealand), to regions in which exotic species management is in its infancy (e.g., the contribution here by Khuroo et al. from India).

The aim of this special issue of *Environmental Research* is to feature the work of researchers investigating ecological, evolutionary, theoretical, and management aspects of invasive species in terrestrial and aquatic environments. By showcasing results from a diverse group of systems and approaches, we hope to promote understanding of the causes and impacts of invaders, as well as identify strategies to mitigate their effects on natural systems. The 13 papers included here represent cutting-edge research on new invasions, older invasions, and proposed management frameworks for controlling the spread of invasive species within and among political boundaries. This issue represents a truly international and global endeavor with author contributions spanning five continents (Asia, Australia, Europe, North America, and South America); nine countries (Argentina, Australia, Estonia, Germany, India, Mexico, New Zealand, Portugal, and USA); and research performed in numerous terrestrial and aquatic habitats around the world (alpine, grassland, lake, river, estuary, coast, and sea). Here, we take a broad definition of the words "invasion", "biological invasion", and "invasive species." With these terms we refer to biota that establish and are successful in areas where they have no prior evolutionary history. Several of these species can have 'invasive' qualities, whereby they spread quickly and may have negative competitive and/or predatory influences on native biota. In some cases, even native species may take on invasive qualities, as is discussed in the paper in this issue by Tong et al. We have organized the issue into four major themes: (1) ecological impacts of invaders on natural species and habitats; (2) environmental stress and invasive species; (3) understanding and predicting invasive species spread and distributions; and (4) invasion monitoring, risk, and management. The papers presented in these themes cover many of the diverse aspects of invasion biology research, including ecology, evolution, molecular genetics, conservation biology, biodiversity, biogeography, management, and economics.

Papers in the first theme, *Ecological impacts of invaders on natural species and habitats*, represent a mix of empirical and conceptual studies that focus on the consequences of invasive species when they invade new locations. The definition of invasion impact and what it means in context is explored by both Young and Larson and Thomsen et al. in their contributions. In particular, Young and Larson surveyed reviewers of articles for the journal *Biological Invasions* to understand, in the present-day, how invasion biologists perceive foundational issues regarding invasion terminology and the causes and consequences of invasive species. In their contribution, Thomsen et al. present a broad framework to help explain and understand variation in invasion impact among aquatic-based studies, separating drivers of impacts into universal and unique attributes, and finding that both the abundance and the taxonomic identity of the invader significantly influence invasion outcomes. In their contributions, Tong et al. and Arias-González et al. provide experimental evidence of invasion impact in two very different aquatic systems. In the Min River estuary of southeast China, Tong et al. document the impacts of a non-indigenous invasive (*Spartina alterniflora*) and a native aggressive (*Phragmites australis*) on habitats of the native matgrass (*Cyperus malaccensis*), finding that the recent invasion of *S. alterniflora* has altered much of the nutrient cycle of the ecosystem previously dominated by *C. malaccensis*. Arias-González et al. explore the effects of the invasive lionfish (*Pterois volitans*) on native food webs in the Caribbean Sea, finding that this famous invader is among the most relevant keystone species

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in the ecosystem and has also had significant ecological impacts there.

Papers in the second theme, *Environmental stress in invasive species*, explore the effects of environmental variability and stress on invasive species, at the individual level (as in McKenzie et al.) and at the group level (as in Ojaveer et al. and Lenz et al.). In the experimental study performed by McKenzie et al. in Australia, the authors examined tolerance to copper by the invasive bryozoan, *Watersipora subtorquata*, finding significant variation in copper tolerance between colonies and considerable potential for adaptation to high copper concentrations. In the study by Ojaveer et al., alien and native species from the Baltic Sea were investigated and compared to determine temporal variability in species distribution and size of populations in relation to environmental change; the authors found that inter-annual dynamics were not largely different between natives and invasives, though natives tended to exhibit more diverse variability patterns. Finally, Lenz et al. conducted a global comparison of marine invertebrates to test whether non-native species were more tolerant to stress than natives, finding consistent global patterns of less pronounced deviations of respiration rates and higher survival in non-natives versus their native counterparts.

Due to centuries of anthropogenic dispersal overlaid on millions of years of natural dispersal, many organisms present complex biogeographic patterns. Papers addressing this theme, *Understanding /predicting invasive species spread and distributions*, explore biogeographic patterns and processes of invasions, including their spread and distribution, as well as species richness and abundance of invaders in novel landscapes. Villalobos et al. take advantage of a long-term exclosure of large herbivores from an Andean grassland to show how invasive pine seedlings are impacted by feral horses. Santos et al. use a novel statistical approach to combine economic data with herbarium and literature data to predict areas of Portugal likely to experience further invasion by exotic plant species. Finally, Khuroo et al. document how native and exotic species richness and life forms are distributed differently along the large altitudinal gradient of the Himalayas, presenting a possible refuge from invasion for native communities at high elevation.

Finally, papers addressing the theme, *Invasion monitoring, risk, and management*, explore management issues related to species invasions in multiple contexts: from improving monitoring techniques using genetics tools (Darling and Mahon) to detailed risk assessment of non-indigenous species (Campbell) to establishing a framework for managing invasive species in the developing world where such regulations are not yet instituted (Khuroo et al.). In particular, Darling and Mahon review the utility of genetic tools in monitoring and understanding invasions in aquatic environments, using the recent introduction of Asian carp to the Midwest USA as a case study; Campbell provides a comprehensive biosecurity risk assessment protocol for species being imported into New Zealand; and Khuroo et al. review management frameworks from regions around the world, applying them to India in order to develop an integrated research framework and policy agenda for biological invasions in that country, as well as recommendations for management across political boundaries in Asia.

Together, the manuscripts included in this special issue present novel and integral data regarding the impact and spread of invasive species in natural environments, as well as the effects of environmental variability and stress on established invasive species, and how invaders can be monitored and managed. The four themes provide a broad overview of the issues related to biological invasions and underscore the importance of continued focus on this critical environmental issue. Finally, the questions and concerns evoked by the contributions here can serve as further impetus for researchers across the globe and political boundaries to investigate the many areas of biological invasions that still need to be explored and learned.

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April M.H. Blakeslee *
Smithsonian Environmental Research Center (SERC), Edgewater, MD, USA

Biology Department, University of Long Island, CW Post, Brookville, NY, USA
E-mail address: April.Blakeslee@liu.edu

João Canning-Clode
Smithsonian Environmental Research Center (SERC), Edgewater, MD, USA

CIMAR/CIIMAR—Centre of Marine and Environmental Research, Porto, Portugal

Eric M. Lind
Smithsonian Environmental Research Center (SERC), Edgewater, MD, USA

Department of Ecology, Evolution and Behavior, University of Minnesota, St. Paul, MN, USA

Gemma Quilez-Badia
World Wildlife Fund for Nature's Mediterranean Programme Office, Barcelona, Spain

* Corresponding author at: Long Island University, CW Post Campus, Brookville, NY, USA.