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Shifting Paradigms in the Field of Invasion Ecology

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Historically, introductions of species outside their native geographic ranges have been considered to be among the greatest of all threats to native ecosystems [1-4]. Prior to human advancement across the globe, unique assemblages of organisms evolved on geographically separated continents, and came to be easily distinguishable (*i.e.*, "Wallace's Realms"). As humans and technology advance, however, there is a growing homogenization of these assemblages throughout the world, often with detrimental consequences to the evolved community structure and function [3,5]. Although recognized earlier [6], the pioneering and most influential work on the topic was Charles Elton's book, *The Ecology of Invasions by Animals and Plants* [1]. Based on a series of radio interviews and short literary publications, this comprehensive work (at the time) provided a description of many species invasions (termed "ecological explosions"), as well as an attempt to generalize characteristics of species and ecosystems prone to successful invasion. Aimed at the public sector, this work raised concern about the future of native biota worldwide. As such, Elton was instrumental in promoting the development of theory, management principles, and inspiring research in the field. With Elton's work, the field of invasion ecology was established.

The progression and development of the field of invasion ecology since Charles Elton has been rapid, now with significant expenditures dedicated to research and management efforts. Interested researchers must also battle to keep up with current research in a litany of publications and numerous journals dedicated solely to the study of invasion ecology/biology. Perhaps it is due to the rapid evolution of this growing discipline that seemingly erroneous generalities and assumptions regarding non-native species expansions have been made. Here, I focus on the growing realization that, despite the demonstrated negative impacts of some non-native species, generalities in the field of invasion ecology have been difficult to come by and assessments of species introductions need to be made on an ecosystem- and species-specific basis.

The term "invasive species" is typically used to refer to organisms that detrimentally impact native species as they expand their geographic range. The terminology and jargon associated with non-native species introductions is oftentimes confusing and misleading, and may be one reason invasive species have been generally regarded as negative additions to ecosystems. For example, if a particular species has been identified as negatively impacting native species and becomes labeled as an invasive, it may become universally viewed as "invasive" across all parts of its introduced range, whether or not any negative impacts occur. This seems to be the case with Eurasian milfoil (*Myriophyllum spicatum*), a species of submerged aquatic vegetation that is frequently considered one of the most detrimental of all aquatic plants, competitively excluding native species and reducing species diversity [7]. While this may be true in some areas, recent research has failed to confirm the widespread validity of milfoil's negative impacts across spatially-separated ecosystems [8,9].

Additionally, authors have recently began to publish and cite an increasing number of studies demonstrating a lack of strong negative impacts of invasions on native ecosystems, assertions that challenge many of Elton's predictions and the paradigm status these invasion principles have acquired [10,11]. For every introduced species that does wreak havoc in the invaded ecosystem (and the examples are numerous), there may be dozens which do not, rather simply adding to the species richness in the inoculated ecosystem. This has generated some animosity in the recent literature, with one author asserting that "*much of the field's conventional wisdom is wrong,* [and] *that biologists are more swayed by their emotions about invasive species than they care to admit, and that invasion biology as a field should be disbanded*" [12,13]. General concepts such as invasion resistance are challenged by this work [13], and the work of many others [11,14-18]. Indeed, the "good-versus-evil" view of native and invasive species clearly leads to some anthropomorphism and perhaps even some unintended bias by many researchers, environmental managers, and media. Still, it is difficult to discount the advancements made to the larger field of ecology by the study of invasive species. As noted by Pysek and Hulme [19], the field has yielded much insight in regards to ecosystem functioning [20-22], population dynamics [23], and evolution of communities [24]. Even if reabsorbed into general ecology as suggested by Davis [13], it is likely that studies of invasive species will continue to provide important insights into the nature by which native ecosystems function.

As researchers continue to develop new methods and technology to detect invasive species and determine their impacts, there does appear to be one emerging theme in the field of invasion ecology. The addition of higher trophic level invaders may have the most severe impact on ecosystems [11,25]. This should come as no surprise, as consumer control, as well as the indirect effects of the presence of predators (referred to collectively as "top down effects"), has often been shown as a strong, structuring influence in the regulation of many ecosystems [26-31]. Since ecosystems respond strongly to native consumers, it can also be predicted that the invaders demonstrating the strongest impacts would be consumers. Sax and Gaines [11] demonstrated that consumer effects facilitate native species extinction on islands by over 66%, while plants alone accounted for less than 20%. Evidence to date has seemed supportive of this notion, with strong negative effects occurring as a result of other invading consumers [25,32,33]. Still, additional research and evidence is needed to support this broad conclusion. As the field of invasion ecology/biology continues to grow and evolve, it is imperative we keep in mind the dangers of generalizing the impacts of introduced species, avoid emotional involvement, and continue to promote science-driven assessments of introduced species.

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