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Assessing the aggregated risk of invasive crayfish and climate change to freshwater crabs: A Southeast Asian case study

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ABSTRACT

Primary freshwater crabs represent a culturally and ecologically significant component of freshwater habitats globally that has a high percentage of threatened species. Invasive species (especially non-indigenous crayfish) and climate change are not only important standalone threats, but are also expected to compound existing threats (e.g., habitat loss/modification, pollution) and challenge the long-term survival of these decapod crustaceans. This study illustrates the importance of considering these two emerging and growing threats in conservation or management strategies by quantifying (via species distribution models) the individual and aggregated risks of these threats in Southeast Asia, a region with the highest diversity of primary freshwater crabs and a high proportion of imperiled species. Results predicted that most species of crabs (82.1%) will co-occur (and hence interact) with invasive crayfish to a moderate to high degree, and most species (69.2%) will also experience a reduction in suitable climate conditions in the future. In terms of aggregated risk, the results also predict an increased overlap between invasive crayfish and native crabs for three out of the seven species analyzed (namely *Procambarus virginalis*, *Cherax destructor* and *Orconectes rusticus*). Findings from this study provide a quantitatively derived rationale for the development of adaptive regulations and conservation plans in the region to minimize the risk of invasive species in a cost-effective way, thereby enabling the protection of Southeast Asia's natural heritage and its vital ecosystem services.

1. Introduction

Primary freshwater crabs represent a significant yet often understudied component of aquatic biodiversity that is particularly at risk to global change (Collen et al., 2014; Cumberlidge et al., 2009; Yeo et al., 2014). With over 1300 species described to date, this diverse group of brachyuran crabs (belonging to the families Gecarcinucidae, Potamidae, Potamonautidae, Pseudothelphusidae and Trichodactylidae) is largely circum-tropically distributed (Cumberlidge et al., 2009; Tsang et al., 2014; Yeo et al., 2008). They complete their entire lifecycle independent of a marine phase (Cumberlidge & Ng, 2009; Yeo et al., 2008), and play prominent ecological and cultural roles within their native range (Cumberlidge et al., 2009; Dobson et al., 2007; Yeo et al., 2008). Their ability to feed across multiple trophic levels makes them vital to the maintenance of the local food web assemblages (Dobson et al., 2007; Dudgeon & Cheung, 1990; Kasai & Naruse, 2003; Maitland, 2003), and their burrowing capabilities enables regulation of water levels in habitats (Dobson, 2004; Ng, 1989; Stahl et al., 2014). The cultural importance of freshwater crabs is reflected in their widespread consumption by with local groups in Asia and South America for food and medicinal purposes (Dai, 1999; Finkers, 1986; Ng, 1988; Yeo & Ng, 1998; Yeo et al., 2008).

Despite their significance, research efforts towards these decapods have been severely lacking (Cumberlidge et al., 2009). As a result, almost 50% of the freshwater crab species assessed in the 2008 International Union for Conservation of Nature (IUCN) Red List of threatened species were found to be data deficient (e.g., lacking sufficient population or distribution data) for determination of extinction risk (Cumberlidge et al., 2009). Existing threats to these crabs, however, are notable. Among the species with sufficient data for assessment, a relatively large proportion (34.8%) of freshwater crabs are near threatened or threatened (Cumberlidge et al., 2009). This level stems from both high levels of species endemism, as well as habitat change and pollution (Cumberlidge et al., 2009; Esser & Cumberlidge, 2008a; Esser & Cumberlidge, 2008b; Ng & Yeo, 2007). Specifically, agriculture and deforestation have been implicated as threats for a large number of threatened freshwater crab species in parts of Southeast Asia and Sri Lanka (Bahir, Ng, Crandall, & Pethiyagoda, 2005; Cumberlidge et al., 2009; Ng & Yeo, 2007; Pethiyagoda, 1994). As few conservation plans or efforts exist to safeguard threatened populations (Cumberlidge et al.,

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2009; Ng et al., 2014; Yeo et al., 2016), many species could face extinction in the near future, especially in light of their vulnerability to invasive species and climate change (Cumberlidge et al., 2009).

Biological invasions are known to have extensive ecological impacts especially within fresh waters (Beisel, 2001; Lodge et al., 1998). These impacts are typically pronounced for species such as freshwater crabs owing to their limited distribution (Cumberlidge et al., 2009; Ogada, 2006). One group of invaders that poses a notable threat to freshwater crabs is the non-indigenous crayfish species (NICS) (Foster & Harper, 2007; Ogada, 2006; Savvides et al., 2015). These mostly temperate decapod species, similar to freshwater crabs, complete their entire lifecycle in fresh waters, and affect habitats through their feeding and burrowing behavior (Crandall & Buhay, 2008; Larson & Olden, 2010; Reynolds et al., 2013). As a result, crayfish have a tendency to co-occur and directly interact with native crabs when released into tropical regions—an event that has received scientific attention, but is increasing in frequency and likelihood (Ahyong & Yeo, 2007; Hobbs et al., 1989; Lodge et al., 2012). For instance, the North American red swamp crayfish *Procambarus clarkii* has been shown to agonistically interact with and outcompete native freshwater crabs (Ogada, 2006; Savvides et al., 2015), with its competitive superiority linked to the decline of native crab populations following their invasion of rivers in Western Kenya (Cumberlidge et al., 2009; Foster & Harper, 2007; Ogada, 2006).

Such negative impacts are also likely to be affected by climate change. While human-induced climate change is forecast to cause alterations to ecosystem processes and increases in prevalence of human diseases (Sala et al., 2000; Thomas et al., 2004), many studies also predict its ability to cause biodiversity loss (Alamgir et al., 2015; IPCC, 2013; Poesch et al., 2016; Thomas et al., 2004). Species such as freshwater crabs (Cumberlidge et al., 2009; Woodward et al., 2010) are expected to face reductions in suitable habitat conditions (e.g., (Alamgir et al., 2015; Poesch et al., 2016)), and magnifications of other threats (Hellmann et al., 2008). For example, the vulnerability of native decapods in Europe to invasive impacts can be intensified because of the future range shifts and expansion of NICS (Capinha et al., 2013).

The combined threat of climate change and invasive species is of particular concern in Southeast Asia where 11 nations hold 20–25% of the world's native plant and animal biodiversity in roughly 4% of its land area (Sodhi et al., 2004; Woodruff, 2010). This region, with its rapidly growing human populations and economies, is already experiencing impacts associated with the growing number of invasive species (Nghiem et al., 2013). Specifically, the increasing introduction and establishment of NICS in the region (e.g., (Ahyong & Yeo, 2007; Patoka et al., 2016; Wanjit & Chaichana, 2013)) puts many freshwater crab species at risk (Lodge et al., 2012). This is likely to be further compounded by the effects of climate change that are predicted to cause losses of coastal systems, increased temperatures (up to 6 °C), and potentially drastic changes in climatic patterns in Southeast Asia (IPCC, 2007; IPCC, 2013). These emerging threats, together with the high levels of endemism and species richness of freshwater crabs (containing 30% of all extant species), mean that this region represents an important target for conservation research efforts (Cumberlidge et al., 2009; Yeo et al., 2016).

Consequently, this study focuses on Southeast Asian freshwater crabs, with the aim of assessing the aggregated risk of these two emerging and understudied threats. Here we quantify the vulnerability of freshwater crabs, through the use of species distribution modeling (SDM) of the seven most high-risk NICS and all native freshwater crabs in the region (under both current and future climate scenarios), to: 1) the (Grinnellian niche) overlap and co-occurrence with NICS; 2) projected future climate conditions (and their effects on availability of suitable habitat); and 3) shifts in risk of overlap resulting from climate change.

2. Methods

2.1. Study area, focal species and occurrence data

This study focused on countries in Southeast Asia (11°S–28°N and 92–141°E), a tropical region characterized by a warm and humid climate with monsoon seasonality (e.g., (Choi et al., 2009; Chotamonsak et al., 2011)). While the region is known to have a high number of endemic freshwater crabs (Cumberlidge et al., 2009; Yeo et al., 2008), Southeast Asia has almost no native crayfish (apart from Indonesian West Papua, part of the Australasian biogeographical region) (e.g., (Lukhaup, 2015)). However, NICS have been recorded from multiple locations within Southeast Asia, including Singapore (Belle et al., 2011), Malaysia (Awangku et al., 2016), Indonesia (Patoka et al., 2016), and Thailand (Wanjit & Chaichana, 2013), with unconfirmed reports from Philippines (Cagauan, 2007; Hentonnen & Huner, 1999).

This study focuses on seven NICS in two families as focal species—*Cherax destructor* and *C. quadricarinatus* (Parastacidae), and *Orconectes immunis*, *O. rusticus*, *O. virilis*, *Procambarus clarkii* and *P. virginalis* [Marmorkrebs] (Cambaridae). Although not all seven species have established populations within Southeast Asia, they represent those that are commonly traded internationally for food and as ornamental species (Chucholl & Wendler, 2017; Lodge et al., 2012; Zeng et al., 2015). They have long histories of introduction (Zeng et al., 2015), possess established populations within tropical, subtropical and temperate climates (e.g., (Feria & Faulkes, 2011; Zeng et al., 2016)), and have known negative impacts on recipient ecosystems (e.g., (Gherardi, 2007; Lodge et al., 2012)). Although a recent update of crayfish taxonomy classifies all three *Orconectes* species under the genus *Faxonius* (Crandall & De Grave, 2017), this study retains the use of *Orconectes*, which is widely used in invasion biology literature (e.g., (Larson et al., 2017)). Locality information for these crayfishes was gathered from a variety of sources including recent sampling efforts within the region (Singapore and Malaysia), museum records (e.g., Lee Kong Chian Natural History Museum, Singapore; Smithsonian National Museum of Natural History, USA), online databases (e.g., Global Biodiversity Information Facility (http://www.gbif.org); The IUCN Red List of Threatened Species (http://www.iucnredlist.org)), and published literature (e.g., (Feria & Faulkes, 2011; Kawai et al., 2009; Zeng et al., 2016)) (Appendix S1).

The location data for all 396 species of freshwater crabs within Southeast Asia (as of 2012; (Freitag, 2012; Yeo et al., 2008)) was also gathered from similar data sources—recent sampling efforts, museum records, onlxine databases, and published literature (Appendix S1). Localities of these crab species (which belong to the families Potamidae and Gecarcinucidae) were then plotted onto the map of Southeast Asia, at a resolution of 2.5 arc min (~25 km^2), and duplicates within each cell were removed. Crab species with more than four occurrence points were selected for SDMs (n = 39).

2.2. Forming SDMs, and projecting current and future climate scenarios

This study used Maxent (version 3.3.3 k) to model species distributions (Phillips et al., 2006) because of its ability to handle presence-only data and small sample sizes (n = 4–7), while producing highly accurate predictions (Hernandez et al., 2006; Rhoden et al., 2017; Wisz et al., 2008). Set within a machine-learning framework, Maxent allows users to project a species' likely distribution over temporal and spatial scales based on the relationship between environmental variables and locality information (Phillips et al., 2006). It also allows for adjustments within the tool, catering to species-specific situations, and improving the accuracy of SDMs (see (Muscarella et al., 2014)).

While only the native range of crabs was considered during SDM formation (to approximate the native realized Grinnellian niche), the full range (both native and alien) of each crayfish species was used to