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Current and future effects of global change on a hotspot's freshwater diversity

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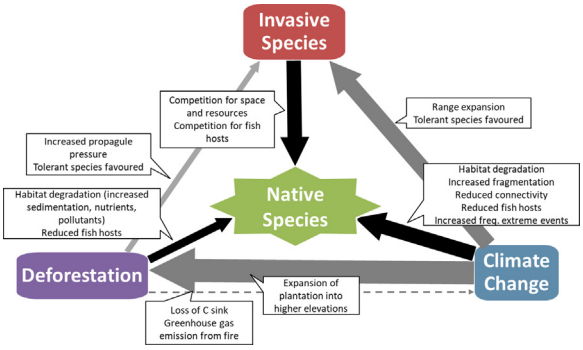
HIGHLIGHTS

- Drivers of freshwater biodiversity loss in the tropics are poorly understood.
- We investigated the effects of deforestation, climate change and invasive species.
- We evaluated multiple future scenarios using ensemble distribution models.
- By 2050, freshwater mussels may lose 20–30% of their current suitable habitat.
- Native mussels may compete with invasive mussels across 60% of their range.
- Our projections can guide future expeditions and measures to preserve biodiversity.

GRAPHICAL ABSTRACT

During the past decades, global deforestation for palm oil production has increased dramatically fuelled by growing demands, which, together with on-going climate changes and the unprecedented expansion of invasive species is expected to have catastrophic consequences for biodiversity conservation. Here we focus our attention on freshwater mussels, a vulnerable group facing global declines that provides compelling indications of overall freshwater biodiversity. Using Species Distribution Models based on field data from a recent expedition in the biodiversity hotspot Sundaland, we anticipate major range contractions of native freshwater fauna, and fragmentation of the remaining suitable habitat. Our projections can be used to guide future expeditions to monitor the conservation status of freshwater biodiversity, and potentially reveal populations of potentially extirpated endemic species.



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ABSTRACT

Deforestation, climate change and invasive species constitute three global threats to biodiversity that act synergistically. However, drivers and rates of loss of freshwater biodiversity now and in the future are poorly understood. Here we focus on the potential impacts of global change on freshwater mussels (Order Unionida) in Sundaland (SE Asia), a vulnerable group facing global declines and recognized indicators of overall freshwater biodiversity. We used an ensemble of distribution models to identify habitats potentially suitable for freshwater mussels and their change under a range of climate, deforestation and invasion scenarios. Our data and models revealed that, at present, Sundaland features 47 and 32 Mha of habitat that can be considered environmentally

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suitable for native and invasive freshwater mussels, respectively. We anticipate that by 2050, the area suitable for palm oil cultivation may expand between 8 and 44 Mha, representing an annual increase of 2–11%. This is expected to result in a 20% decrease in suitable habitat for native mussels, a drop that reaches 30% by 2050 when considering concomitant climate change. In contrast, the habitat potentially suitable for invasive mussels may increase by 44–56% under 2050 future scenarios. Consequently, native mussels may compete for habitat, food resources and fish hosts with invasive mussels across approximately 60% of their suitable range. Our projections can be used to guide future expeditions to monitor the conservation status of freshwater biodiversity, and potentially reveal populations of endemic species on the brink of extinction. Future conservation measures—most importantly the designation of nature reserves—should take into account trends in freshwater biodiversity generally, and particularly species such as freshwater mussels, vital to safeguard fundamental ecosystem services.

1. Introduction

Deforestation, climate change and invasive species constitute three major threats to biodiversity that are exacerbated by synergistic effects (Brook et al., 2008). Sundaland (encompassing Peninsular Malaysia, Borneo, Sumatra and Java) is a global biodiversity hotspot holding >80% of South-East Asia's remaining primary forest (Myers et al., 2000). At the same time, Sundaland produces >80% of all palm oil consumed globally (Fitzherbert et al., 2008). The consequence is one of the highest rates of deforestation in the world, with oil-palm expansion being the main driver of habitat degradation and biodiversity loss (Sodhi et al., 2004). Beyond terrestrial ecosystems, the expansion of palm plantations degrades freshwater habitats by severely increasing bank erosion and sediment yield, decreasing forest shading and forest litter, and altering water quality (Chellaiah and Yule, 2017; Douglas et al., 1992; Zieritz et al., 2016). Yet, the extraordinary freshwater biodiversity of Sundaland has received little attention. This is alarming, since the richness of endemic and threatened freshwater species is the highest in South-East Asia (Collen et al., 2014), where habitat loss will therefore affect a very significant part of the world's biodiversity (Dudgeon, 2003).

The effects of deforestation are reinforced by on-going climate changes that will further affect freshwater habitat availability and quality over large scales (Meyer et al., 1999). Climate change projections anticipate the warming of Sundaland, showing an increase in annual precipitation with large seasonal and spatial variability, and higher frequency of disturbance events (e.g. storms, floods, droughts) related to El Niño/La Niña cycles (IPCC, 2014). These changes are likely to affect the survival of native freshwater species (Hastie et al., 2003; Poff et al., 2012). Together, deforestation and climate change may also favour the expansion of aquatic invasive species that competitively may displace native populations (Didham et al., 2007). One example is the Chinese pond mussel (*Sinanodonta woodiana* Lea 1834) that is native to temperate and tropical eastern Asia, primarily the Amur and Yangtze river basins (Kraszewski and Zdanowski, 2007; Soroka, 2005). The species has spread considerably over the last decades in Asia, Europe and the Americas driven by intentional and unintentional introductions as a food source, for ornamental purposes and attached to their fish hosts, so that in Malaysia it is now considered the most widespread freshwater mussel species (Zieritz et al., 2018).

As a consequence of these interacting threats, the distribution of native freshwater mussels (Bivalvia: Unionida) has contracted considerably over recent decades in Sundaland, and will likely continue to do so in the future (Zieritz et al., 2016). Recent expeditions to Malaysian Borneo failed to confirm the presence of four of its five endemic species, which are possibly extinct (Zieritz et al., 2018). Since freshwater mussels are indicators of habitat quality and overall freshwater biodiversity (Aldridge et al., 2007), we may expect similar decreasing patterns for other freshwater taxa. Indeed, two whole orders of insects (Coleoptera and Hemiptera) were reported to be absent from streams flowing through oil palm plantations in Malaysia, in comparison to rainforest streams (Mercer et al., 2014). Likewise, fish biomass, richness and functional diversity declined markedly in streams that lost their riparian buffer due to deforestation (Giam et al., 2015), with 77% estimated loss of species in the future if current rates of deforestation are maintained (Giam et al., 2012). In spite of these figures, the effects of deforestation on freshwater biodiversity in Sundaland, and more generally tropical Asia, have received little attention (Dudgeon, 2003), let alone their synergistic interaction with other drivers of change.

For the first time, here we anticipate the collective consequences of oil-palm plantation expansion, climate change and invasive species on the distribution of native freshwater mussels and, by extension, freshwater biodiversity in Sundaland. In particular, this study aims to quantify the relative importance of major drivers of freshwater biodiversity loss in Sundaland, and to spatially identify regions of particular concern for freshwater mussel conservation under global change. Maps can be further used to direct future expeditions to monitor the conservation status of freshwater biodiversity, and potentially discover relict populations of endemic species. In the light of our results, we finally discuss the synergistic consequences of global change upon the conservation of freshwater biodiversity in a global hotspot where many species have recently become extremely rare, possibly extinct.

2. Material and methods

This study focuses on Sundaland, including Peninsular Malaysia, Borneo, Java and Sumatra. Sundaland is recognized as one of the most important global biodiversity hotspots (Myers et al., 2000). The region is also undergoing exceptional loss of habitat due to human activities (logging, slash-and-burn agriculture, oil-palm plantations), and retains only 8% of its primary forests (Myers et al., 2000). To investigate the potential consequences of oil-palm expansion, climate change and invasive species on the distribution of native freshwater mussels, we used Species Distribution Models (SDM). This technique uses as input the occurrence of species and the set of factors that might affect the likelihood of species establishment. Once calibrated, the model extrapolates the environmental preferences of the species onto the region of interest, identifying areas at continental or regional scale that are environmentally most similar to the current range of the species (Guisan and Thuiller, 2005).

2.1. Mussel occurrence

Data on the presence/absence of freshwater mussels in Malaysia (i.e. Peninsular Malaysia, and Sarawak and Sabah in northern Borneo) were collected in surveys conducted between 2014 and 2016 (Zieritz et al., 2016, 2018). A total of 227 sites were surveyed (155 in Peninsular Malaysia and 72 in Borneo), covering 35 river basins and a wide diversity of freshwater habitats: rivers, creeks, canals, rice-paddy run-offs, lakes, reservoirs and ponds (Fig. 1). After intensive sampling effort, nine native freshwater mussels were identified: *Contradens contradens* (Lea, 1838), *Hyriopsis bialata* (Simpson, 1900), *Physunio superbus* (Lea,