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ORIGINAL ARTICLE

Ecology and conservation of *Pseudolestes mirabilis* (Odonata: Zygoptera), a damselfly endemic to Hainan Island of China

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Abstract

Although some efforts have addressed oriental dragonfly conservation, knowledge on the ecology and geographic distribution of such dragonflies remains scant. The phoenix damselfly *Pseudolestes mirabilis* Kirby, 1900 is the single species in the family Pseudolestidae that is endemic to Hainan Island of China. This damselfly was recommended by the International Union for the Conservation of Nature to be of priority for further study and conservation. In this work, we use ecological niche modeling techniques to estimate the dimensions of the realized niches of this damselfly and to predict its potential distribution. Our findings suggest that the phoenix damselfly possessed a small climate space characterized by low temperature and high precipitation. Highly suitable areas are mainly distributed in the low-altitude regions of southern central tree-covered mountains in Hainan. Caution is warranted when considering the potential habitat loss attributed to human activity and climate change.

Key words: ecological niche modeling, Odonata conservation, Oriental Region, Pseudolestidae.

INTRODUCTION

The Oriental Region has the largest number of endemic dragonfly species that face risks of extinction in the world and is characterized by the highest diversity of Odonata (Kalkman *et al.* 2008; Clausnitzer *et al.* 2009). However, the ecology and geographic distribution of these dragonflies have been poorly studied and have received scant attention for conservation action. In 1997, the International Union for the Conservation of Nature (IUCN) released a Dragonfly Action Plan to address the threatened dragonflies in the Oriental Region and listed 44 dragonflies as priority species for further study and conservation (Moore 1997). Among these species, *Pseudolestes mirabilis* Kirby 1900, a unique damselfly endemic to Hainan Island of southern China, is worthy of focus for research on conservation.

Pseudolestes mirabilis was listed for its beautiful appearance, unique behavior and pendent phylogenetic position. The species has a striking blue face and reduced colorful hind wings, which are golden and black above and silvery white and black underneath (Fig. 1a). In territorial fighting, two males can hover face-to-face for approximately four minutes, keeping their position as if they are locked. Its charming appearance and unique behavior has caused *P. mirabilis* to gain the beautiful common name "phoenix damselfly" (Reels 2008). *Pseudolestes mirabilis* was originally placed in the monotypic subfamily (i.e. Pseudolestinae, Kirby 1900). Fraser (1957) later proposed the family Pseudolestidae to house the genus *Pseudolestes* and several other genera, followed by Davies and Tobin (1984). Bybee *et al.* (2008) suggested that this species belongs to Megapodagrionidae. Yu and Bu (2011) suggested that *P. mirabilis* is close to Amphipterygidae and thus deserves a family status based its extraordinary larva characteristics.

The distribution of a species is an expression of its fundamental niche in geographic space, which is limited by the interactions between biotic and abiotic factors, as well as dispersal capability (Soberón & Peterson 2011). By using occurrence-associated environmental variables, ecological niche modeling (ENM) seeks to characterize the realized niche of species and then identifies where their distribution lies in the geographic space (Pearson 2007). Biotic factors may either be implicitly

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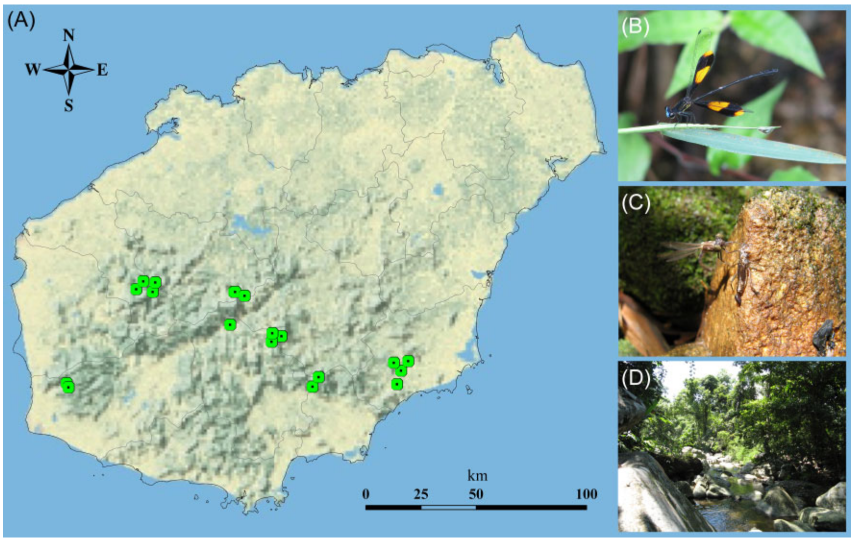

Figure 1 (A) Map of the occurrence records of *Pseudolestes mirabilis* in Hainan Island. (B) Adult, (C) larva and (D) representative habitat.

represented in the model because they strongly correlate with abiotic factors or disappear for such fine-scale interactions that would be overlooked in large-scale analysis (Soberón & Nakamura 2009). Nonetheless, ENM has been increasingly used for characterizing the ecological requirements of species (e.g., Owens *et al.* 2012), conservation priority setting (e.g. Irfan-Ullah *et al.* 2006) and other aspects of ecology and evolution (Raxworthy *et al.* 2007; Zhu *et al.* 2012, 2013).

In this study, we used ENM to estimate the dimensions of the realized niche of the phoenix damselfly, as well as to predict its potential distribution in Hainan. The ecological niche of a species in this work can be defined as a set of environmental conditions under which such a species is able to maintain populations without immigrational subsidy (Grinnell 1917, 1924). Vulnerable areas that might suffer from habitat loss because of human activity and climate change, along with the potential areas where the phoenix damselfly might be found, were unveiled for conservation action. This study highlights the ENM correlative approach for the biodiversity conservation of dragonflies in the Oriental Region, particularly for localized endemic species.

MATERIALS AND METHODS

Input data

Hainan was intensively surveyed under the support of Biological Resources Survey of Hainan Island and Xisha Archipelago Program (2007–2011) to provide a sketch of the geographic distribution of the phoenix damselfly in Hainan. The specimens were collected by using a sweep net and then deposited in the Institute of Entomology at Nankai University. Geographic coordinates were recorded for each specimen by using a GPS unit during field collection. Two additional occurrence records were obtained from the literature (Wilson & Reels 2001; Kadoorie Farm and Botanic Garden 2002). Eighteen distributional records were prepared (Table 1).

Environmental dimensions by which to characterize the ecological requirement of *P. mirabilis* were selected, considering climate, topography and habitats that might potentially affect the geographic distribution of the phoenix damselfly. Although climate variables represented by "bioclimatic variables" are believed to be biologically meaningful (Hijmans *et al.* 2005), highly correlative variables were excluded from this study. Bioclimatic variables such as annual mean temperature, mean temperature diurnal range, maximum temperature of the warmest month, minimum temperature of the coldest month, annual precipitation, precipitation of the wettest month, and precipitation of the driest month derived from the WorldClim (http://www.worldclim.org/ Hijmans *et al.* 2005) were used. Topography variables represented by elevation, slope, aspect and compound topographic index were derived from the HYDRO1k Elevation Derivative Database of the US Geological Survey (USGS 2001). The habitat variable was represented by land cover type derived from the GLC 2000 database (http://bioval.jrc.ec.europa.eu). All dimensions were set at 1-km spatial resolution for analysis.

Modeling approach

A wide range of methods had been explored for ENM. Among these methods, the maximum entropy algorithm implemented in the Maxent program (Phillips *et al.*

Table 1 Occurrence records for *Pseudolestes mirabilis*†

Longitude	Latitude	Reciprocal prediction	Jackknife LPT	Full model suitability	Jackknife success
108.8417	18.7000	0.0863	0.3611	0.6549	Y
108.8491	18.6828	0.1074	0.3455	0.6949	Y
109.1250	19.0833	0.1945	0.2982	0.4769	Y
109.1540	19.1156	0.6145	0.3297	0.6310	Y
109.1925	19.0725	0.6912	0.3085	0.7602	Y
109.2025	19.1111	0.4120	0.2540	0.5383	Y
109.5075	18.9383	0.1797	0.3438	0.2908	N
109.5242	19.0725	0.2938	0.2457	0.6747	Y
109.5666	19.0568	0.4374	0.2286	0.7509	Y
109.6767	18.8692	0.5669	0.2493	0.7645	Y
109.6797	18.9039	0.6679	0.2194	0.7972	Y
109.7167	18.8917	0.6673	0.2919	0.7399	Y
109.8435	18.6860	0.3226	0.3183	0.7018	Y
109.8683	18.7250	0.6291	0.2774	0.5445	Y
110.1750	18.7833	0.1455	0.3057	0.5926	Y
110.1878	18.6958	0.0007	0.2278	0.3652	Y
110.2042	18.7511	0.0381	0.1843	0.5416	Y
110.2333	18.7903	0.0349	0.2816	0.3772	Y

†Suitability score of each point in Maxent model reciprocal predictions, lowest presence threshold (LPT) and model success in predicting the excluded point in question, as well as the suitability score trained by using all records are shown.

2004, 2006) generally outperforms other algorithms (Phillips *et al.* 2006). Maxent follows the principle of maximum entropy and spreads out probability as uniformly as possible, but is subject to the caveat that the variables must match empirical information, such as the known presence occurrence record (Phillips *et al.* 2004, 2006). Maxent is not very sensitive to sample size (Wisz *et al.* 2008) and can be applied to sample sizes as small as five (Pearson *et al.* 2007). The default convergence threshold (10^{-5}), maximum number of iterations (500) and logistic output were used. To visualize niches in ecological dimensions, environmental grids and the final prediction were combined in ArcGIS 10 (ESRI 2006). The attribute tables associated with these combined grids were imported into SPSS 19 to reduce data density by randomly selecting 10% of the data. These reduced tables were then exported to Sigmplot 11, where scatter plots were prepared for visualization (see methods in Kambhampati & Peterson 2007; Donalisio & Peterson 2011).

For model evaluation, the occurrence records were equally partitioned into training and testing data. We reciprocally evaluated the mode by selecting 50% of occurrence data with their longitude > (or <) the mean longitude of all records to test models trained using the remaining 50%. A modified jackknife approach specifically designed for a small sample size was also used (Pearson *et al.* 2007). In the latter method, independent Maxent models were generated iteratively, excluding one locality in each turn, and then the lowest suitability score of a presence point or lowest presence threshold (LPT) for each model was used to determine areas of predicted presence. The proportion of the training area predicted as present and the failure or success of the model to predict jackknifed points were used to calculate the probability of the observed degree of coincidence (Pearson *et al.* 2007). Finally, all the records were used to calibrate the niche model for visualization.

RESULTS

In reciprocal predictions, the suitability ranged from 0.08 to 0.7 and from 0.0005 to 0.70 for each half of the occurrence records when models were trained by using the other half (Table 1). Five or eight out of nine points were identified with high suitability in the reciprocal predictions (Table 1, Fig. 2). The records that were used to validate niche models were completely independent of the model training records, suggesting good model performance. In the Pearson jackknife-based test, the success rate was 94.4% and was significantly better than random expectations ($P < 0.01$). The suitability of each point ranged from 0.29 to 0.80 when the model was trained by using all records (Table 1). High suitability areas identified by Maxent were distributed mainly in central and southern Hainan (Fig. 3) and mostly belonged to the montane areas (Fig. 1).

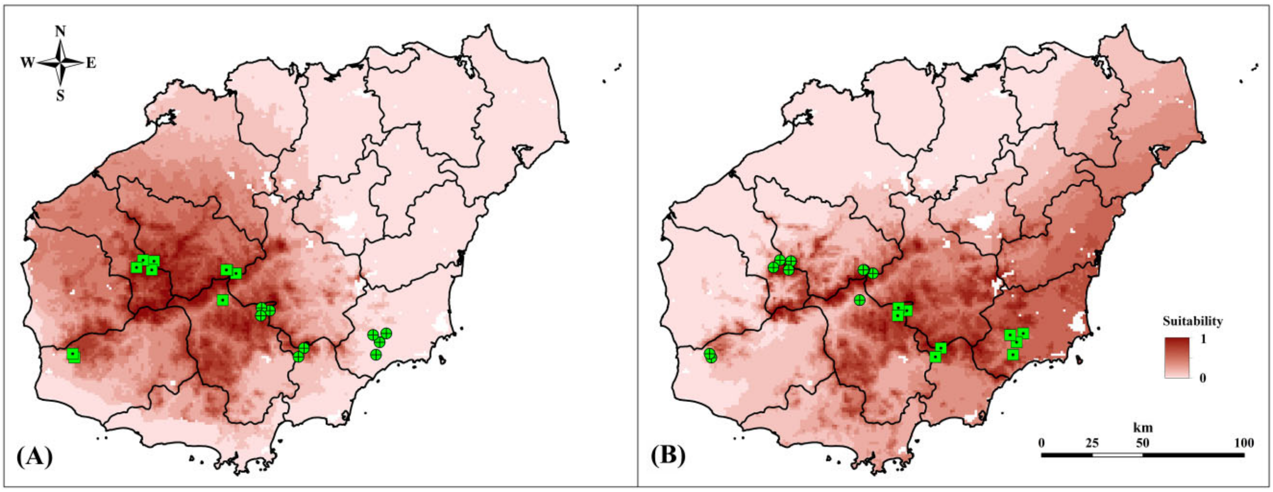

Figure 2 Reciprocal predictions of niche models based on half of the occurrence records using Maxent. Square dots indicate the records used for model calibration, and circle dots indicate the testing records.

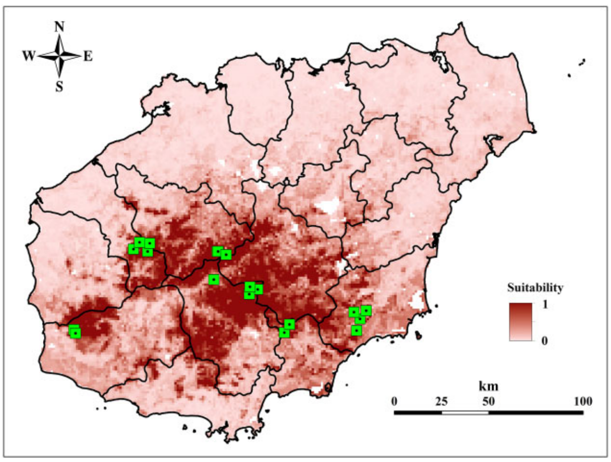

Figure 3 Niche model based on all occurrence records using Maxent. Square dots indicate the records used for model calibration.

These identified areas can be tentatively classified into four subareas (i.e. the north-western, eastern, south-central and disjunct south-western subareas), which were also supported in reciprocal predictions (Figs 2,3). Although no records were available for niche model calibration in the south-central subarea, this area showed high suitability. Some areas appeared in places of strong human activity, including south of the north-western subarea, central part of the eastern subarea, and most parts of the south-western subarea. These areas were usually characterized by intense tree farms or tourism activities in Hainan. In terms of ecological dimensions, the phoenix damselfly possessed a small climate space, and highly suitable areas usually appeared in dimensions of low temperature, high precipitation and low altitude (<950 m), as well as in tree-covered mountains (GLC value <11) (Fig. 4).

DISCUSSION

Limitations on the materials and methodology employed in this study have to be addressed here. Thoroughly exploring the environmental factors that limit the distribution of the phoenix damselfly by using 18 occurrence records is unreasonable. The ecology of the phoenix damselfly was poorly studied, and only some brief descriptions of the habitats are currently available (Reels 2010). Such descriptions include "common on small shady and open montane streams with stony substrates" and "some even occurred in very small 'puddles' covered with dense vegetation formed by discontinuous streams (Reels 2008; Yu & Bu 2011)". The ecology and geographic distribution of the phoenix damselfly have not been explicitly studied. In this study, we correlatively revealed the ecological dimension and potential distribution of the phoenix damselfly by using ENM. Although expecting ENM to explore the fundamental niche of the phoenix damselfly is unreasonable (Soberón & Peterson 2011), ENM did identify regions that had similar environmental conditions to areas where the species was known to occur, thus offering valuable information for the phoenix damselfly's conservation (Pearson *et al.* 2007; Peterson *et al.* 2011). The south-central area showed high suitability although no record

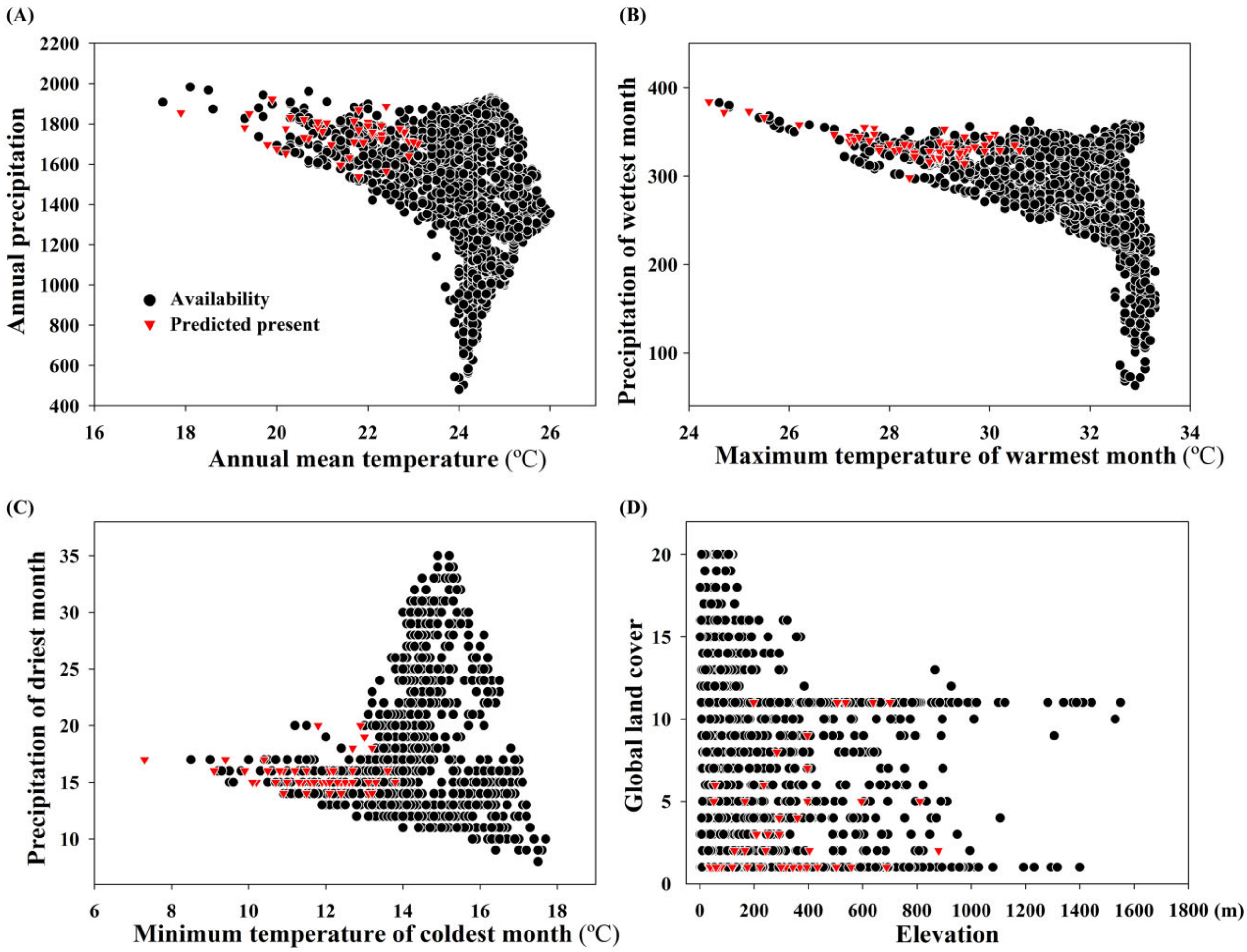

Figure 4 Two-dimensional visualization of the ecological dimension of *Pseudolestes mirabilis*. Modeled suitability is accorded to the combinations of the final prediction and the environmental grids of (A) annual mean temperature and annual precipitation, (B) maximum temperature of warmest month and precipitation of wettest month, (C) minimum temperature of coldest month and precipitation of driest month, and (D) global land cover.

was available for niche modeling. Future field surveys might determine either the real distribution or the potential distribution of the phoenix damselfly in this area (Pearson 2007).

Pseudolestes mirabilis is a forest-dependent species, it is usually observed on small, forested streams (Reels 2010). In this study, the highly suitable areas were mainly distributed in the low-altitude and tree-covered montane areas (GLC value <11). These areas usually were distributed in the foot of the mountain, which are easily accessible to humans and are thus affected by human activities. The ever-increasing tree farms, dams, tourism and other human activities are threatening suitable habitats of *P. mirabilis*, despite the establishment of 11 nature reserves in Hainan. In addition, future climate change might compel the phoenix damselfly to an even more restricted area. Species with small range sizes, such as the phoenix damselfly, tend to occur in climatically diverse regions where they might have been buffered from extinction in the past; the coincidence of climate and species rarity pose high risks to small-range species from climate change (Ohlemüller *et al*. 2008).

Although some efforts have addressed the threatened dragonflies in the Oriental Region (Moore 1997), our knowledge, let alone conservation action, on their ecology and distribution remain scarce. The Oriental Region encapsulated two biodiversity hotspots (i.e., Indo–Burma and South-Central China) (Myers *et al*. 2000). Species in hotspots tend to be scarce within their range, thus increasing the probability of their extinction, particularly for island-endemic species (Brown 1984; Gaston 1994; Clausnitzer *et al*. 2009). Our study first used ENM to unveil the ecological dimension and potential distribution of damselfly in the Oriental Region. This approach will shed light on the phoenix damselfly's conservation and can also be applied elsewhere for other IUCN-listed dragonflies. More research and attention are therefore required to ensure conservation for this special organism.

CONCLUSIONS

The ecological dimensions and potential distribution of the unique phoenix damselfly were explicitly studied by using the ecological niche modeling approach. Our findings suggest the phoenix damselfly possessed a small climate space, which is characterized by low temperature and high precipitation. Highly suitable areas are distributed mainly in the low-altitude areas of southern tree-covered mountains in Hainan, where care should be taken to prevent the potential habitat loss attributed to human activity and climate change. More ecological niche modeling approaches are required to address dragonfly conservation in the Oriental Region.

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