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Laevicaulis haroldi (Veronicellidae: Gastropoda), a potential future invader to India

Biswa Bhusana Mahapatra[1,2] and N. A. Aravind[1,3,*]

[1]Ashoka Trust for Research in Ecology and the Environment (ATREE), Royal Enclave, Srirampura, Jakkur, Bengaluru 560 064, India
[2]Manipal Academy of Higher Education, Manipal 576 104, India
[3]Yenepoya Research Centre, Yenepoya (Deemed to be University), University Road, Derlakatte, Mangalore 575 018, India

Invasive alien species are considered one of the greatest threats to biodiversity, ecosystem services, economy and human health. Global climate change will only exacerbate the impact of several invasive species in the introduced range. Hence the control and management of invasive species is crucial. Spatial tools such as GIS/RS and ecological niche models can help understand the potential region where the species might invade and predict invasive spread under different climate change scenarios. This study explores if the newly introduced slug from South Africa, *Laevicaulis haroldi* (Purcell's hunter slug or caterpillar slug) will become invasive in India under current as well as future climate scenarios. Our result suggests that most parts of western and Peninsular India are vulnerable to the invasion, and suitable regions will only increase

*For correspondence. (e-mail: aravind@atree.org)

under both climate change scenarios. It calls for the early detection and management of this potential invader to India.

Keywords: Climate change scenarios, economic loss, invasive alien species, *Laevicaulis haroldi*, niche modelling.

INVASIVE alien species (IAS) are plants or animals that are introduced by humans outside of their natural geographic range into an area where they are not naturally present[1]. They are introduced accidentally or intentionally. IAS are introduced accidentally through trade, such as via ships or transportation and intentionally through pet trade, ornamental plants or for research. In a newly invaded region, invasive species follow the stages from introduction to establishment and dispersal to a large area[2]. IAS are among the greatest threats to biodiversity, ecosystem services, human health and economy, after habitat destruction[3]. Globally, IAS cause economic loss to the tune of $120 billion per year in USA and around €20 billion in Europe[4,5]. A number of studies have reported that IAS are responsible for the extinction of native and endemic species[1].

Since introduced species usually occur at low densities, early detection is difficult[6–8]. Predicting which species will become invasive in a particular area is also a challenging task[9]. However, with the advent of spatial tools such as geographical information system and remote sensing (GIS/RS) and ecological niche modelling (ENM) or species distribution modelling (SDM), one can predict the distribution of species purely based on the environmental variables and transfer the model to a new region or time (spatial and temporal)[10]. ENM is used widely in various applications ranging from taxonomy to conservation biology to biogeography[10]. These models are valuable tools in predicting the potential spread of invasive species, both spatially and temporally[11]. In this study, we aim to assess if the newly introduced slug *Laevicaulis haroldi* (Veronicellidae) has a suitable niche in India using the ENM approach and, if so, which are the regions it can spread in the future.

L. haroldi (Veronicellidae), commonly known as Purcell's hunter slug or caterpillar slug, is native to South Africa and was described in 1980 (ref. 12). It is a rare species with limited distribution in South Africa[13]. According to the International Union for Conservation of Nature (IUCN), it is an Endangered species due to severely fragmented populations and continuing decline of mature individuals in the native range[14]. Very little is known of its ecology, though it is reported to be associated with marshland and waterside vegetation[13]. According to recent literature, *L. haroldi* was introduced to India from South Africa by international trade into Mumbai around 2010–2012 (ref. 15). Even though it is listed as an endangered species, *L. haroldi* has become a pest in certain parts of India[16]. It was first reported in 2015 from Aurangabad, Paithan and Gangapur, Aurangabad district, Maharashtra[16]. Later it was reported from several places in that State[17]. Since then, there have been more than 60 records from all over India[15,18].

Niche modelling was carried out for *L. haroldi* using georeferenced data downloaded from India Biodiversity Portal and iNaturalist, and collated from the published literature[16–18]. The 76 georeferenced occurrence points from both the native (68 records) and introduced ranges (eight records; see Supplementary Table 1) were used for species distribution modelling using MaxEnt (ver. 3.4.4)[19]. We downloaded environmental data for the current climatic scenario from Worldclim ver. 2 database (www.worldclim.org) and for future climate change scenarios RCP 2.6 and RCP 8.5 from the Intergovernmental Panel on Climate Change (IPCC)[20]. We extracted BioClim data for each occurrence point and tested for collinearity. We excluded all layers with a correlation of |>0.70|. Finally, only five variables, namely Bio 1, Bio 4, Bio 12, Bio 14 and Bio 19 were used for niche modelling (see Supplementary Table 2). We used the default feature in MaxEnt ver. 3.4.4 to run the model and project two future climate scenarios (details of the method used are provided in the Supplementary Information). We calculated the true skill statistic (TSS) to assess model accuracy[21]. Binary maps were developed using 10 percentile training threshold to assess the changes in the area between future and current scenarios. Climatic niche overlap was computed to assess if there is a potential niche shift between native and introduced ranges using the Humboldt package in R (ref. 22).

The niche modelling results suggest that the model performance is very good (TSS: 0.926 and AUC: 0.982). Currently, *L. haroldi* is reported from Karnataka, Maharashtra, Tamil Nadu, Gujarat, Uttar Pradesh, Rajasthan and West Bengal (Figure 1 *a*), distributed within an altitudinal range from 2 to 900 m amsl, temperature range from 24°C to 29°C (26.8°C ± 1.6°C) and rainfall between 536 and 3200 mm (1372 ± 763 mm). Maximum reporting is from July to October (75% of all records) throughout its introduced range (Figure 1 *c*), which coincides with the monsoon season in India. Niche modelling results show that there is high suitability in the western and south eastern parts of the country. Most parts of Andhra Pradesh, Karnataka, Gujarat, western Maharashtra and West Bengal are highly suitable. The southern parts of Telangana, northeast Tamil Nadu, coastal Odisha and some parts of Assam and Meghalaya are also highly suitable for *L. haroldi* invasion. Under future climate change scenarios (RCP 2.6 and RCP 8.5), the species will have more area under high suitability in Karnataka, Maharashtra, Odisha, West Bengal, Bihar, Uttar Pradesh and some states in North East India (Figure 2). This increase in area is around 13.60% under RCP 2.6 and 23% under RCP 8.5 (Figure 2 *d*). PCAenv result shows significant difference

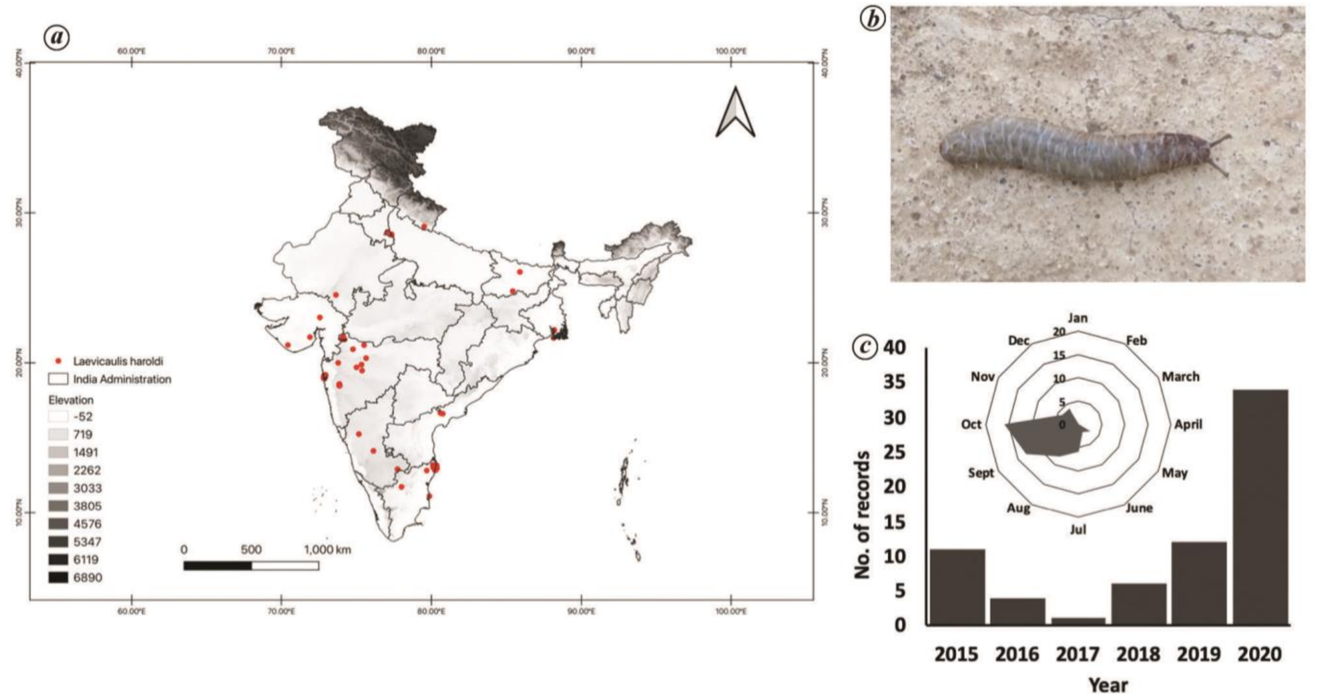

Figure 1. ***a***, Distribution of *Laevicaulis haroldi* in India. ***b***, An adult individual of *L. haroldi*. ***c***, Number of reports since 2015 and monthly reporting of *L. haroldi* in India from various sources. (Inset: See Supplementary information.)

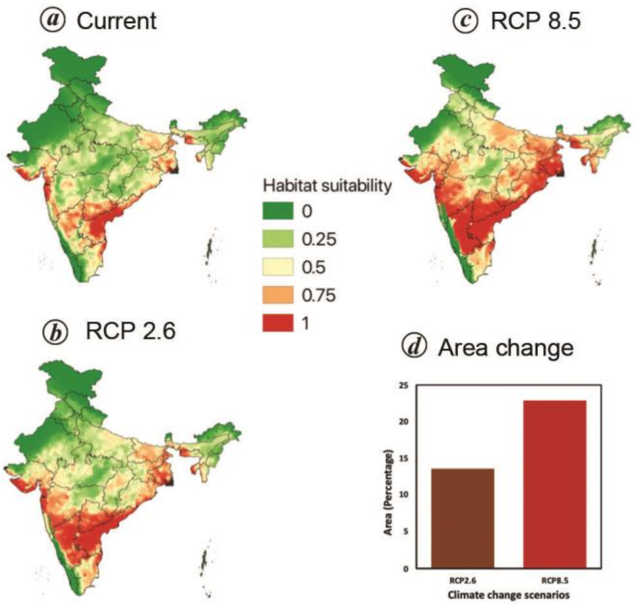

Figure 2. Ecological niche modelling predictions for *L. haroldi* under (***a***) current climate, (***b***) RCP 2.6, (***c***) RCP 8.5. (***d***) Change in suitability area from current to future climatic scenarios.

in the climatic conditions between native and introduced ranges (Figure 3), indicating a niche shift in the introduced range. Among environmental variables, BIO 12 (annual precipitation, 29.7%), BIO 1 (annual mean temperature, 22.6%), and BIO 14 (precipitation of driest month, 22%) contributed more than 75% to the model. This indicates that precipitation influences the invasion to a significant extent.

When a species is introduced to a new area, the introduced population often experience a 'lag phase' before establishing a viable population[23]; thus, limiting its early detection in the introduced region. *L. haroldi* was probably introduced to India a decade back, but its occurrence has been reported only recently (in 2013). In the recent literature, it has been suggested that this species was introduced in 2005, but without any proof for it[24]. Hence, this record has to be considered with caution. Though the species was reported from Aurangabad district in 2013, it was a wrong identification[15]. Our modelling results indicate that there are highly suitable areas in western and southern India for *L. haroldi*. This species might colonize these regions if it is not managed in a timely manner. The climate change modelling for two scenarios shows there is a significant increase in the suitable areas, indicating that the species might spread to a much larger area in the future. In addition, the niche of *L. haroldi* is entirely different in its native range compared to its introduced range in India. This shows that the species has shifted its realized niche, thus occupying novel climatic condition in India. This will have implications for its future spread in the country. With more data from native and invaded ranges, the climatic niche shift model will be more robust.

The introduction of *L. haroldi* into India has been most likely through the import of agricultural and horticultural produce. India's import from South Africa has increased

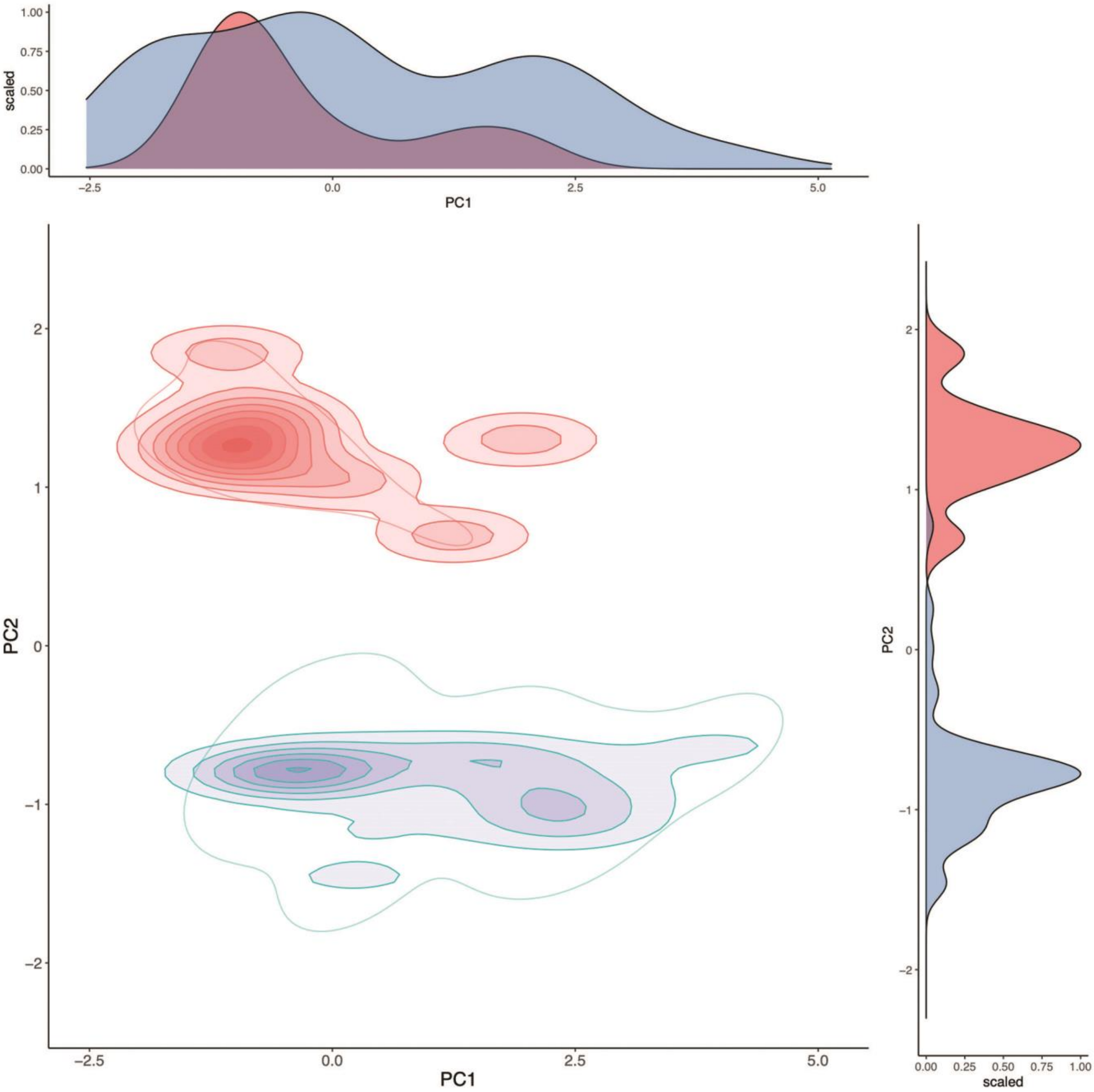

Figure 3. Native (red) and introduced climatic space (blue) for *L. haroldi*. Multivariate climatic space was calculated using the environmental principal components analysis (PCAenv) for climatic conditions in native (South Africa) and introduced regions (India). The histogram represents density of principal component in environmental space.

significantly since 2006, which includes fruits and vegetables apart from minerals[25]. The slug *L. haroldi* probably reached the Indian coast through these agricultural/horticultural imports to Mumbai through ships. From there, it probably dispersed to other regions through local transport of fruits and vegetables. Haplotype network analysis from various populations across India and from the native range will give us better insight into its introduction history[26].

Slugs and snails are known to be one of the most significant threats to agricultural and horticultural plants[27]. Species such as *Lissachatina fulica* (Giant African Snail) and *Pomacea canaliculata* (golden apple snail) have a severe impact on the local economy[27]. They feed on a variety of native plants, decaying plant matter, and agricultural and horticultural crops. *L. haroldi* was reported to feed on leaves and bark of the mulberry plants and chew off the succulent parts, thus reducing their nutritive value[16]. It was also seen on several other plants in the introduced areas, such as *Carica papaya*, *Calotropis gigantea*, *Parthenium hysterophorus*, *Azadirachta indica*, etc.[17]. A detailed study is required to assess the reproductive ecology, population structure, environmental and economic impact of *L. haroldi*. One of the major concerns is its year-round occurrence; this invasion could be even more catastrophic in irrigated farms as the species prefers high moisture areas[13]. Given the shift in the niche and adaption to a new climatic regime and no predator, this species might become a serious invader impacting native species and economy.

Early detection and control are key for managing newly introduced species before they become invasive[28]. Existing reports suggest that *L. haroldi* occurs in large numbers; for example, Magare[17] found more than 56 individuals in 3 m^2 area around Vanyavihir, Taloda district, Maharashtra[17]. Hence monitoring and control is the key to the successful management of this invader. We need to capitalize on citizen scientists' potential in locating hitherto unrecorded populations in a short period with limited resources. Awareness needs to be created among the forest managers, agriculturists, horticulturists and farmers to detect, manage and control this newly introduced species. Non-toxic methods of controlling this pest need to be developed. Also, a strict quarantine in the ports should be in place to avoid further introductions.

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