Modeling Earth Systems and Environment (2022) 8:3059–3072
https://doi.org/10.1007/s40808-021-01284-4

ORIGINAL ARTICLE

Consequences of climate change in allopatric speciation and endemism: modeling the biogeography of *Dravidogecko*

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Received: 16 June 2021 / Accepted: 7 September 2021 / Published online: 25 September 2021

Abstract

Western Ghats landscape is unique in habitat diversity and endemism, predicted to undergo massive global warming changes. After the Pleistocene, particular micro-climatic conditions prevailed in the Western Ghats, leading to allopatric speciation and endemism. We evaluated this hypothesis by modeling the distribution patterns of endemic ancient reptilian genera, the *Dravidogecko* using various environmental variables under past, present, and future climate scenarios. We surveyed 58 heterogeneous locations for one year in the Nilgiris (Southern Western Ghats), where the species records are not there. We used environmental variables like diurnal range, isothermality, altitude, precipitation, canopy height, and density to predict the current distribution model. The paleoclimate modeling indicates the presence of species extant throughout the Southern Western Ghats in the Pleistocene. The geographical isolation due to the redress of cooler weather from the lower reaches enclosed the climatic specialist, *Dravidogecko,* to the upper reaches leading to allopatric speciation. We conclude that climate-oriented speciation is under threat as it may lose all the suitable habitats due to global warming and climate change. We also nominate a new species named *Dravidogecko coonoorenis* and predict more species of this genus from the Western Ghats.

Keywords Paleoclimate · Western Ghats · Range reduction · Extinction · Isolation · New species

Introduction

The speciation event depends on isolation, habitat conditions, inter-specific interactions, and climate change, limiting its distribution to a specified geographical range. Knowledge about biogeography, speciation events, isolation patterns, and isolating mechanisms is essential for their conservation and understanding of natural history and ecology (Franklin 2010; Kim et al. 2020). The changing climate and the resultant isolation govern the distribution or isolate the population into small fragments leading to allopatric speciation. The speciation of isolated meta-populations in local habitat depends on ecological conditions. Such events of allopatric speciation and the influence of climate in speciation events have been reported previously throughout the Western Ghats (WG), and most of them are endemic species (Dutta et al. 2004; Gupta 2010; Biju et al. 2011; Robin et al. 2015; Bose 2016; Chaitanya et al. 2019; Raman et al. 2020a). The spatial–temporal conjunctions on species distribution were found significant in recent years (Shameer et al. 2021), and this is important to understand the threats like plummeting population, habitat fragmentation, deterioration, changing climate, and invasive species (Gibbons et al. 2000; Thomas et al. 2004; Todd et al. 2010; Urban 2015). Reptiles are poikilothermic vertebrates occupying diverse habitats and rely on the environment for thriving, as their physiology and metabolism fluctuate with environmental conditions (Huey and Stevenson 1979; Avery 1979; Pough 1980; Heatwole and Taylor 1987; Du et al. 2010). The temperature has a potential role in restricting the distribution of reptiles. The reptiles determine their distribution towards high altitudes where cold conditions are prevailing. When the temperature varies spatially, the maintenance of optimal temperature makes poikilotherms survive, and the temperature variations induce thermal shifting of the species

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(Adolph and Porter 1993; Stenseth et al. 2002; Huey et al. 2009; Huey et al. 2012; Bestion et al. 2015; Rutschmann et al. 2016; Piantoni et al. 2019). Shifting reshapes their original ranges and forces them to survive in a more fragile habitat, and any minor variations in climate lead to extinction (Ferro et al. 2014; Lemes et al. 2014; Fitzgerald et al. 2018; Powers and Jetz 2019; Vicente et al. 2019).

Geckos are one of the least understood vertebrate communities. Its taxonomical progression in recent years defined many new species through revision, omissions, inclusion, and consolidation (Mirza 2010; Venugopal 2010a, b; Palot 2015; Aengals et al. 2018; Chaitanya et al. 2019). *Dravidogecko*, by its etymology, is an ancient gecko genus endemic to southern WG (Smith 1935; Boulenger 1885; Murthy 1993; Johnsingh 2001; Cyriac et al. 2011). For the first time, a single specimen of this species was observed from the Anamalai hills of WG by Günther (1875) and described as *Gecko anamallensis*. In the initial stages of identification, the genus assignment for the species was a taxonomical complexity. Boulenger (1885) described the species as *Hoplodactylus* due to its similarity to the New Zealand and Bengal specimens. Smith (1933, 1935) clarified the discrepancy of Bengal specimen and placed this under a new genera *Dravidogecko,* and commented that the similarities to *Hoplodactylus* are due to parallel evolution. The species is placed under the genus *Hemidactylus* by Bauer and Russell (1995) as *Hemidactylus anamallensis*. Bansal and Karanth (2013), based on molecular evidence, re-classified it as *Dravidogecko anamallensis*. Chaitanya et al. (2019) identified the various meta-population as separate species. They named it as *Dravidogecko septentrionalis*, *Dravidogecko meghamalaiensis*, *Draviodogecko douglhasadamsii*, *Dravidogecko smithi*, *Dravidogecko tholpalli*, and *Dravidogecko janakiae* as it has considerable genetic divergence. The *Dravidogecko* is noted for its adaptation to the colder climate and is an old stock of reptiles seen only at the higher altitude. The separation of this cryptic genera may have occurred during Eocene in the drifting Indian Plate (Bansal and Karanth 2013; Agarwal et al. 2014; Chaitanya et al. 2019).

Occurrence data of species with environmental data inclusion help precisely map the distribution in a feasible habitat (Soberón 2010). Species distribution modeling (SDM), otherwise called Environmental Niche Modeling (ENM) (Peterson 2006), resolves the range assessment and preferable habitat prediction, thereby helps in the conservation of less known species (Whittaker et al. 2005; Stuart et al. 2010; Warren and Seifert 2011; Fourcade et al. 2014). MaxEnt (Phillips et al. 2006) models the ecological niche of various taxa covering both flora and fauna based on the presence data (Raman et al. 2020a, b). The machine language of the MaxEnt has proven the ability to forecast the geographical distribution, preferable habitat, and niche suitability for data-deficient species even for more minor data (Phillips et al. 2006; Elith et al. 2011). Species distribution modeling of reptiles in India is rare, and only a few literatures are available (Srinivasulu and Srinivasulu 2016; Javed et al. 2017; Srikanthan et al. 2018, Srinivasulu et al. 2021). Distributional models will offer in-depth knowledge about the habitat, which will inform us about the needs and needless factors acting around the environment of a species that scores high for a management plan.

The WG is an old mountain chain situated in southwestern peninsular India and separates the coastline tracts with the Deccan plateau (Pascal et al. 2004). This mountain chain existed even before the collision of the Indian plate with the Laurasia, is a hot spot of endemism (Vijayakumar et al. 2001; Roelants et al. 2004; Dutta et al. 2004; Biju et al. 2010, 2011; Bhupathy et al. 2012; Bhupathy and Sathishkumar 2013; Ganesh et al. 2013; Palot 2015; Chaitanya et al. 2018). Most of the endemic species are climate specialists, and the distribution is solely in high altitudes. The climatic shift in the ancient geological periods modulated the species distribution and accounted for the endemism (Warshall 1995; Wikramanayake et al. 2002; Robin et al. 2010; Chaitanya et al. 2019; Raman et al. 2020a, b). The endemic reptiles may have a limited tolerance range and get rapidly influenced by global warming than the endemic mammals and birds (Taylor and Kumar 2016). The WG is facing massive transformation due to climate change (Sony et al. 2018; Raman et al. 2020a, b), habitat fragmentation (Qureshi 2014), urbanization, invasion of alien species (Mungi et al. 2020), and other anthropogenic influences (Cincotta et al. 2000; Bawa et al. 2007; Feeley et al. 2013). The predictive models based on the endangered mammalian species (Raman et al. 2020b) and plants (Sen et al. 2016; Priti et al. 2016) suggest a significant impact on the ecosystem due to climate change resulting in range reduction.

Dravidogecko is a nocturnal species that can tolerate and live only in the cold high altitude climatic conditions, unlike many other geckos reported so far. Even the slightest variations in the prevailing climate can have an impact on these poikilothermic animals. The cumulative minor changes in temperature in the long-term view can have a drastic effect, which can even be fatal to these endemic populations. Chaitanya et al. (2019) observed that each of the existing meta-populations presently is acclimatized to that specific pockets and diverged as separate species. Robin et al. (2015) demonstrated the divergence of laughing thrush meta-population to different WG species. Birds are homeothermic animals, which can withstand the fluctuations to a possible degree, unlike poikilotherms. The species divergence is an indication of struggle towards existence in isolated patches having optimum climatic conditions. It is urgent to identify and map all the suitable habitats in the WG landscape under the present climatic scenario, which helps to ascertain the unidentified isolated populations and its ecology. Predicting suitable habitats under various emission scenarios may help us identify the potential habits under threat. Hence, based on the occurrence data, the present study attempts to predict the WG's suitable habitats in current and future scenarios for the *Dravidogecko* genera. As an ancient gecko species, we try to model the range of distribution in the Pleistocene climate, after which the species postulated to have diverged. The study attempted to evaluate the hypothesis that the climatic change after the Pleistocene causes allopatric speciation. We also assess the habitat suitability in the global warming scenario and predict and possibilities of extinction.

Methods

The Western Ghats

The WG landscape in peninsular India is a long stretch of mountain chains extending ~1600 km through Gujarat, Maharashtra, Goa, Kerala, Karnataka, and Tamil Nadu in India. The WG is the faulted ridges of an upraised plateau and is not a real mountain (Bhat 2017). The mountain chain formed around 120–130 mya by volcanic eruptions, when the Indian subcontinent drifted near Reunion Island. Many reptiles, including the dinosaurs, became extinct during this phase as a result of volcanoes. The 2000 mya old rocks found in the Southern WG are evidence of dormal uplift erecting the WG (Radhakrishna et al. 2019). Peninsular India broke, and the faulting resulted in the uplift of the eastern side. The Eocene changes (40–45 mya) in peninsular India changed the faunal distribution and geography (Karanth 2006). The high rates of the uplifts caused high altitudes, slopes, and gorges, which caused the various climate conditions to become the cradle of speciation of different life forms causing the present level of endemism. This hilly undulating terrain with diversified landscape and vegetation profoundly influences the climate prevailing in peninsular India (Gunnell 1997). This terrain accounts for half of the Indian reptiles (Islam and Rahmani 2004) and highly diverse amphibian fauna.

Dravidogecko—diagnostic features

The body is grayish brown and marbled with dark brown patches. The tail is thick, and at the base, it is cross barred with dark brown streaks and covered with small scales. The head is compressed and covered with small granular scales. The body is dorso-ventrally compressed and elongated with small rounded granules throughout the body. The rostral is without a median groove, and the nasal is in contact with the rostral and the first labial. Digits are moderately short long-clawed terminal phalanges that are curved and arise angularly from the lamellar pad's distal portion. This species is easily differentiated from the *Hemidactylus* by undivided scansors on the toes (Bauer and Russell 1995; Chaitanya et al. 2019).

Field survey

We surveyed the bushy regions, abandoned buildings, orchards, cowsheds, creeks, concrete retaining walls, and tea estates in Coonoor, Kundha, and Kotagiri regions in the Nilgiri Hills (Southern WG) for the presence of *Dravidogecko* from August 2018 to May 2019. We sampled 58 heterogeneous sampling sites for three hours a night per sampling site (7.00 pm to 8.00 pm, 11.00 pm to 12.00 am, and 5.00 am to 6.00 am) with the aid of torchlight. We recorded the geo-coordinates of the species occurring sites and sampled them repeatedly to confirm their presence. The genera is easily recognizable, and we identified the species in the study location itself without capturing them based on morphology. We confirmed the genus by analysing DNA from the gecko's shed tail piece after it was disturbed. We charachterised mitochondrial (mt) cytochrome oxidase I subunit (COX1) region and the nuclear recombination activation factor 1 (RAG1) gene. As the COX1 region of the genera is not charachterised previously, we used the RAG1 region for species identification.

Based on the available literature (Günther 1876; Boulenger 1885; Smith 1935; Murthy 1993; Cherian et al. 2000; Johnsingh 2001; Ishwar et al. 2001; Agosti and Egloff 2009; Chandramouli and Ganesh 2011; Bansal and Karanth 2013; Chaitanya et al. 2018; Chaitanya et al. 2019), we georeferenced the points of occurrence using Google Earth. We also collected the available occurrence points (geo-coordinates) from the databases like *i*Naturalist, GBIF, and Hiveminer. We collected 52 locations from the literature and the databases and nineteen sites directly from the Nilgiris. We compiled the direct records and literature records and obtained 71 locations of *Dravidogecko* for WG. To reduce the bias and over prediction, spatially close forms (~ within 4 km) were removed for modeling by thinning using the package 'spThin' (Aiello-Lammens et al. 2015). After spatial thinning, we obtained a total of 41 records for modeling.

DNA analysis

We initially digested the tail sample with ATL buffer (Qiagen) for 48 h (Nittu et al. 2021) and done the extraction of DNA from the digest using Qiagen DNeasy Blood and Tissue DNA Extraction kit (Cat No. /ID: 69504). We amplified the COX1 region using the universal LCO 1490—HCO 2198 primers (Folmer et al. 1994) using the amplification conditions standardized in our lab (Thunnisa et al. 2021). We used the same method as Chaitanya et al. (2019) to amplify the

RAG1 regions of the Dravidogecko. We examined the PCR products in a 2% agarose gel and cleaned the amplified products with a Qiagen PCR purification kit (Cat No. 28104). The purified products were sequenced bidirectionally in the ABI 3730 Genetic Analyzer using the Sanger dideoxy method after the 'snapchill' protocol (Nittu et al. 2021). We used the NCBI BLAST platform to look for sequence similarities. Using the phangorn 2.5.5 package, we built the maximum likelihood tree in R studio (Schliep 2011; Schliep et al. 2017). According to Felsenstein (1981), we calculated the maximum likelihood with 1000 bootstraps. We used the 'HKY' evolutionary model to optimize the branch lengths based on the Bayesian Index Criterion (BIC) values. We included NCBI accessions MN520274.1 to MN520279.1 for tree construction and visualised in FigTree v1.4.3 software.

Environmental constraints

We used environmental constraints like forest canopy height (Simard et al. 2011), tree density (Crowther et al. 2015), elevation, and nineteen bio-climatic variables (Fick and Hijmans 2017) for current distribution modeling. First, we downloaded the 'elevation' layer from the National Oceanic and Atmospheric Administration, US Department of Commerce website. Then, we used the Worldclim database's data for the 19 bio-climatic predictor variables labeled as bio 1 to 19 (Fick and Hijmans 2017). First, we performed a collinearity test, and we discarded the highly correlated variables from the modeling. We have produced an optimum distribution model after reducing the masking effect (De Bin et al. 2016). Next, we selected the variables based on the variance inflation factors (VIFs) using 'usdm' package (Naimi 2013) in the R platform. We discarded the variables having scores greater than 5 (VIFs > 5) from the final modeling. Finally, we considered eight variables after accounting for collinearity for predicting the ecological niche of *Dravidogecko* in the WG. The selected variables are the bio 3 (isothermality), bio 14 (precipitation of driest month), bio 18 (precipitation of warmest quarter), and the bio 19 (precipitation of coldest quarter) and one topographic layer (elevation), forest canopy height, and tree density.

Distribution modeling

We have done the Habitat Suitability Modeling (HSM) of *Dravidogecko* using the MaxEnt software Version 3.3.3 k (Phillips et al. 2006). MaxEnt is a widely accepted software for predicting the species distribution models with considerable predictive accuracy and simplicity (Merow et al. 2013). The species distribution model of *Dravidogecko* was run in MaxEnt with 41 replicates using auto features, default regularization multiplier (= 1),with 10,000 background points and maximum iterations of 5,000 by a subsampling procedure. We used approximately 20% of iterations for training and the remaining (80%) for modeling. Other settings were kept in the default mode as this approach is considered to obtain maximum accuracy across multiple models without individual configuration (Phillips et al. 2006).We also created a bias file (locations having confirmed absence based on our survey) to reduce the sampling bias using the R package "KernSmooth" (Wand 1994).The contribution of all the selected seven bio-climatic variables was estimated using the Jackknife protocol. We viewed the output files in R using the "raster" package and prepared the distribution maps. We used GeoCAT software (http://geocat.kew.org) for calculating the EOO (extent of occurrence) and the DIVA-GIS (https://www.diva-gis.org) tools for estimating the change of suitable habitats between past, present, and future climatic scenarios.

Habitat prediction under Pleistocene and in climate-changing scenario

We modeled the Pleistocene period using the 'Pleistocene: Last Glacial Maximum (ca. 21 ka), v1.2b data' (21,000 years ago) from the PaleoClim website (www. paleoclim. org). We used the CHELSA data (Brown et al. 2018) in 30 arc seconds (~ 1 km) based on PMIP3 data. Data use the paleoDEM with an interpolation of global glacier cover to better represent precipitation and temperature values. We projected the future climatic scenario in three representative Concentration Pathways 4.5 (RCP 4.5), 6.0 (RCP 6.0), and 8.5 (RCP 8.5) using bio-climatic variables. We followed the Hadley Global Environment Model 2-Atmosphere Ocean (HADGEM2-AO) of 30 arc-second (~ 1 km) spatial resolution for climatic projections. We followed the fifth assessment report (AR5) of the Intergovernmental Panel for Climate Change (IPCC 2014). RCP 4.5 represents an optimistic emission scenario, where emissions will peak around 2040 and then decline. RCP 6.0 is also a stabilizing emission scenario where the emission will stabilize after the 2060s. RCP 8.5 assumes increased greenhouse gas emissions throughout the twenty-first century (Sharma et al. 2017). Projections were made up to 2070 in the WG region downloaded from the Consultative Group on International Agricultural Research (CGIAR) Research Program on Climate Change, Agriculture and Food Security (CCAFS) climate data archive (https://www.ccafs-climate.org/data). This analysis omitted the topographic features and dynamic non-climatic variables expected to change in the past and the future.

Appraisal of the model

We estimated two metrics to appraise the data: the Area under Receiver Operating Characteristic Curve (AUC) and the True Skill Statistics (TSS). The evaluation based on the

AUC alone is valid (Austin 2007; Lobo et al. 2008), as this alone may not reflect the model information properly, TSS is also considered. The AUC is a threshold-independent metric that estimates the model's ability to differentiate random and background points for model evaluation. The TSS scores are a threshold-dependent accuracy measure and were calculated based on the sensitivity + specificity − 1 formula. The probability threshold measured the sensitivity and specificity functions following Allouche et al. (2006).

Results

General observations

Dravidogecko, as reported earlier, is observed as a nocturnal lizard (Fig. 1) and seems to be predominantly active during early night hours to midnight. We watched them frequently in the stunted trees with berries or mostly in pear, apple, and custard apple orchards. They are also present in abandoned buildings, rocky and human-made crevices near forest or plantation areas. We also observed that they hide inside the rocky, wooden, and cemented crevices during the day start emerging out immediately after dusk. They seem to be highly sensitive to light, avoid artificial lights, and prefer to stay away from the light when introduced. They try to wriggle and coil the tail when disturbed with light, and during the defecation, the tail tip shedding is rare. We also observed these geckos as solitary and infrequently in groups ranging from 3 to 15 in the same locality. We never found the species crawling on the ground but observed in the branches of trees or walls and maintained a height of 3–7 ft from the ground. On continuous observations, we found they prefer mostly the formicids and small insects. The attempt to identify the poops of this lizard for prey analysis was not successful. We discovered their constant movements through the cable lines where formicids are present. We noted the co-occurrence of *Cnemaspis* in the same habitat where *Dravidogecko* also is seen. The solitary individual is chiefly to be males, and the preliminary observations assume the breeding period corresponds from January to April, and we observed the hatchlings in May.

Fig. 1 The *Dravidogecko* species observed from the study area. The banding pattern of the species differ from the reported six species suggesting the possibility of becoming a new species

Molecular identification

The sequences of COX1 and the RAG1 were deposited in NCBI genbank with accession numbers OK172084 and OK181856. The folmer region of the *Dravidogecko* is not previously reported, hence the comparison using this region was not possible. However, the sequence shows maximum similarity with related gecko species.The BLAST comparison using the RAG1 confirmed that the specimen is *Dravidogecko* itself. The phylogenetic analysis using RAG1 genes, placed the species in the *Dravidogecko* cluster as a separate node (Fig. 2).

Model performance

The area under the curve and the value of the receiver-operated curve indicate the model is highly informative. Any score above 0.75 is informative (Chunco et al. 2013). The true skill statistics (TSS) holds equal weight on the sensitivity and specificity between − 1 and + 1 (TSS = sensitivity + specificity − 1). Sensitivity estimates the exactly classified presence, and specificity is the estimate of the real absences. The TSS value and the overall accuracy is 0.81, and sensitivity is 1, the specificity is 0.81, the kappa value is 0.02, and the kappa max value is 0.44. The values indicate the accuracy of model prediction in current and future scenarios of gecko distribution in WG.

Top environmental variables

The most contributed variables (Fig. 3) of geckos habitat suitability are bio14 (65.2%), alt (10.3%) bio2 (5.8), bio18 (5.2%), tree density (5.2%), bio 19(3%), canopy height (2.7%) and the bio3 (2.6%). Variables indicate the importance of precipitation, altitude, diurnal range, temperature, density, and vegetation type in predicting habitat suitability. The variables of more permutation importance are bio 2 (52%), bio14 (24.4%), and the alt (10.1) (see supplementary material S1 for more details). The Jackknife test for variables' importance to predict gecko habitat shows the contribution of significant variables. The altitude response curve shows the optimum altitude the animal prefers is around 1500MSL, after which the curve remains flattened. We also observed the presence of gecko between 1000 and 1600 MSL in the Nilgiris. The bio2 variable (mean diurnal range) response is negative, indicating the preference for shorter days. The bio14 is the rain in the wettest month, and bio 18 is the driest quarter corresponds to northeast monsoon in the WG. The bio19, precipitation of the coldest quarter, shows a negative response in the species distribution. The canopy

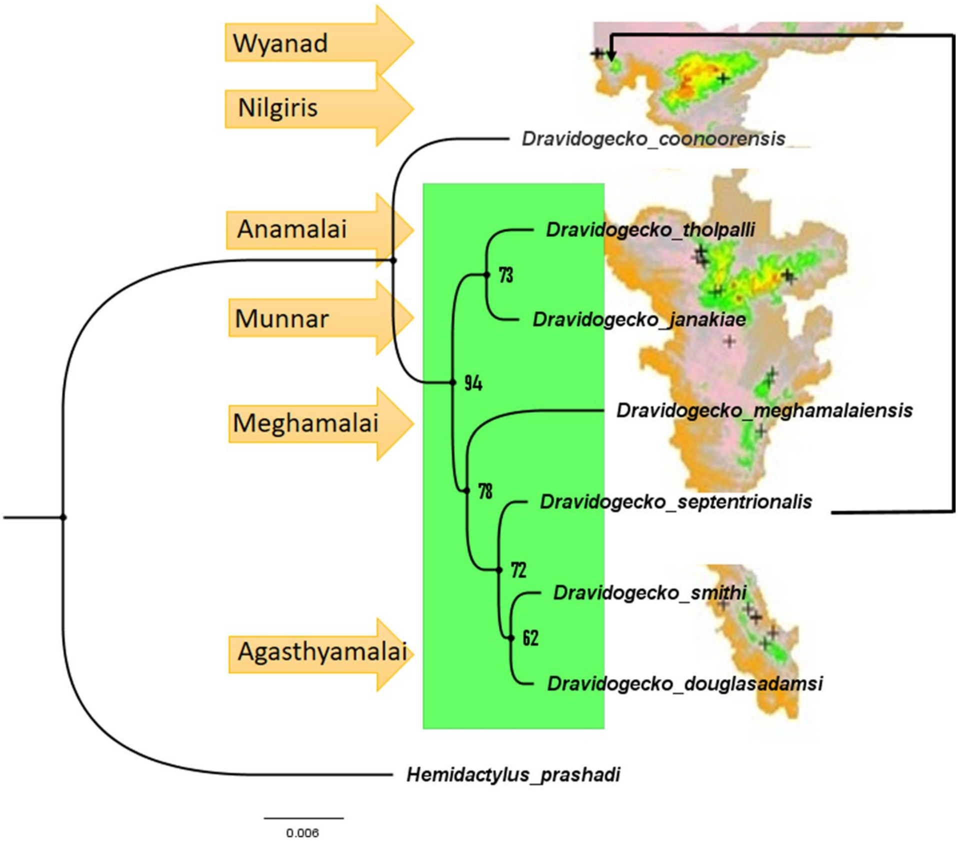

Fig. 2 Phylogenetic analysis of *Dravidogecko* observed from the Nilgiris. The green colour represents previously described species of Dravidogecko, and the Nilgiri specimen, which falls outside this cluster, could be an ancient stock with more ancestral similarities. Molecular analysis indicates the specimen is a new species and, we nominate it as *Dravidogecko coonoorensis*

height variable's response indicates that the species prefer to stay on trees with minimum height (supplementary material S2). The *Dravidogecko* shows a positive response towards the vegetation density, suggesting its preference for stunted bushy vegetation like shola.

Current suitable habitat

Our model predicted the patchy distribution of habitat suitability of gecko towards the southern WG. The habitat suitability index (HSI 0.25–1.0) of gecko in WG is estimated to be 21,452 km^2, is slightly lower than the extent of occurrence (EOO) (24,231.847 km^2). On the other hand, the HSI was greater than area of occurrence (AOO), 92, 27, 320, and 648 Km^2 for the cell sizes of 1, 2, 4, and 6 Km^2, respectively. The high suitability area possesses 31.5% of the total HSI index. Based on the SDM, we propose seven meta-populations, they are the Silent Valley- Mukkurthi-Nilgiri, the Siruvani-Veliangiri, the Valparai-Anamalai-Palani Hills, the Meghamalai, the Wagmon-Poonjar- Elappally, and the Shendurny-Agasthyamalai. The core distribution belongs to Agathyamalai-Pondmudy-Shendurny, Valparai-Anamalai-Palani Hills, and the Nilgiris-Silent Valley.

Modeling under paleoclimate and future emission scenarios

The distribution of *Dravidogecko* in the Pleistocene climatic conditions predicts its continuous distribution in the entire Southern WG. The prediction indicates a constant stretch of population existed in the region, North and South of the Palghat gap, and the present patchy distribution is primarily climate modulated one. Figure 4 shows HSM predicted for the Pleistocene, current, and future climatic conditions under three emission scenarios. The model estimate shows the TSS value is 0.88, and the overall accuracy is 0.95, sensitivity is 0.96, specificity is 0.91, kappa value is 0.06, and the kappa max is 0.50, indicating model accuracy. The future bio-climatic variable response shows that bio3 and bio14 have a positive relationship, while bio2 negatively responds. The alt, bio18, and bio19 have mixed reactions with an optimum range of positive interaction (supplementary material S3). The habitat prediction models show that only 2226 km^2 (0.014% of WG's total area) forms a highly suitable habitat for the *Dravidogecko*. There will be a reduction of highly suitable habitat under the RCP 4.5 (46.19%), RCP 6.0 (57.1%), and RCP 8.5 (71.08%) emission scenarios (Fig. 5). Other than the Silent Valley-Mukkurthi-Nilgiri and the Agasthyamalai population, all the other identified meta-populations are at high

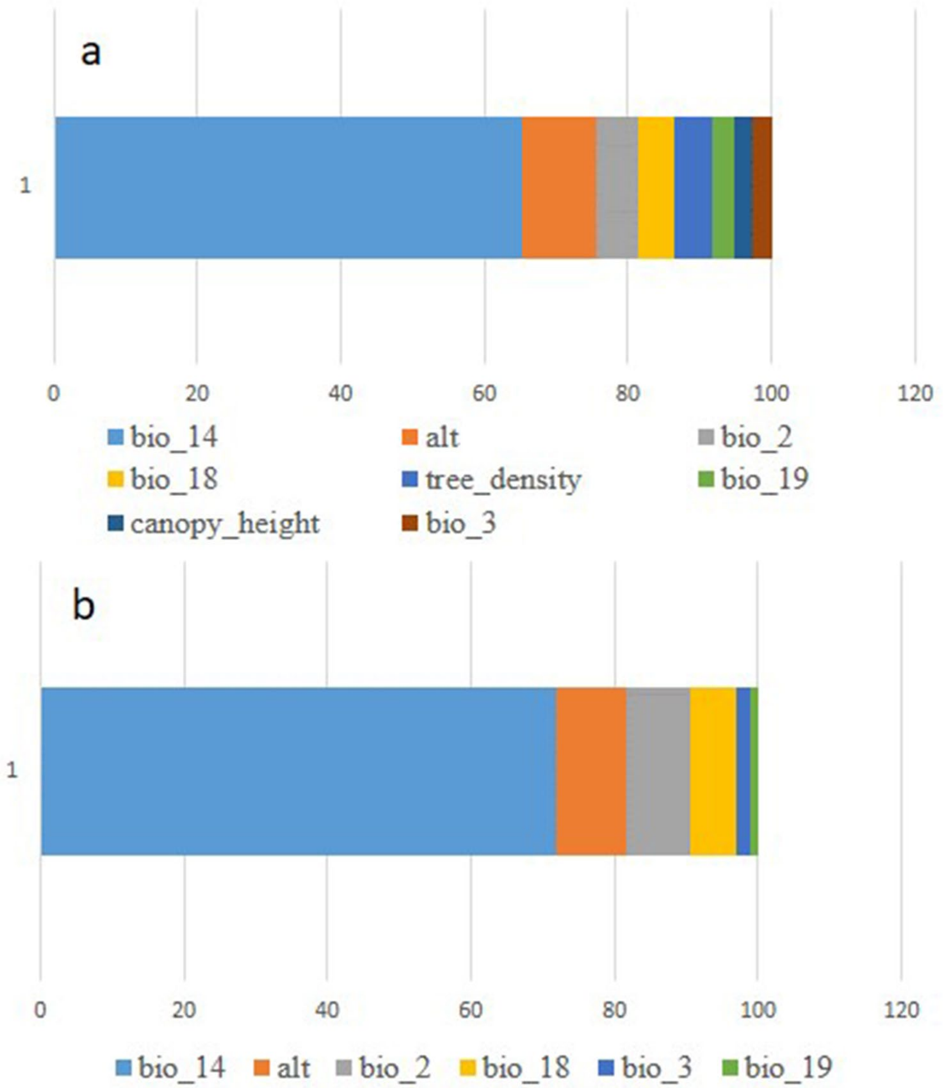

Fig. 3 Percentage contribution of the highly influential variables under current (**a**) and future (**b**) climatic scenario

risk of extinction. On evaluating the gain and loss, it is clear that there is a significant loss of the core (very highly suitable) habitat in all emission scenarios. On the contrary, there are a minor gain of moderately and suitable habitats under various emission scenarios, corresponding to the loss of crucial (very highly suitable) habitat.

Discussion

The quaternary climate change accounts for the changes in their distributional range of endemic species to present geographic patterns (Hewitt 2000, 2004; Bose 2016; Ray et al. 2018). During this period, there was a contraction in the existing ranges owing to the climatic change resulting in the divergence of isolated meta-population into new species (Willis and Niklas 2004; Hewitt 2004; Provan and Bennett 2008; Stewart et al. 2010; Bose 2016). The evolution and speciation of the *Dravidogecko* happened during the Eocene period in the drifting Indian plate (Chaitanya et al. 2019). Gupta (2010) reported various species colonized in the WG in the late Miocene to early Quaternary when the paleoclimate was comparatively favorable. Studies based on the phylogeography and paleo-niche modeling (Robin et al. 2010; Ray et al. 2018) provided vital insights into the ice age, and the continuous precipitation in the WG made these regions quite acceptable for colonization (Kim et al. 2008; Farooqui et al. 2014). According to the paleoclimate hypothesis, the dry glacial period in the interglacial caused speciation events. Studies also postulated the divide of deep and wide valleys in WGs caused species diversification (Robin et al. 2015; Vijayakumar et al. 2016). There is enough evidence to show that climate changes during the glacial and interglacial period influenced forests and grasslands in the high mountain ranges. There may be a species expansion during the ice age and a retreat during the interglacial period. The

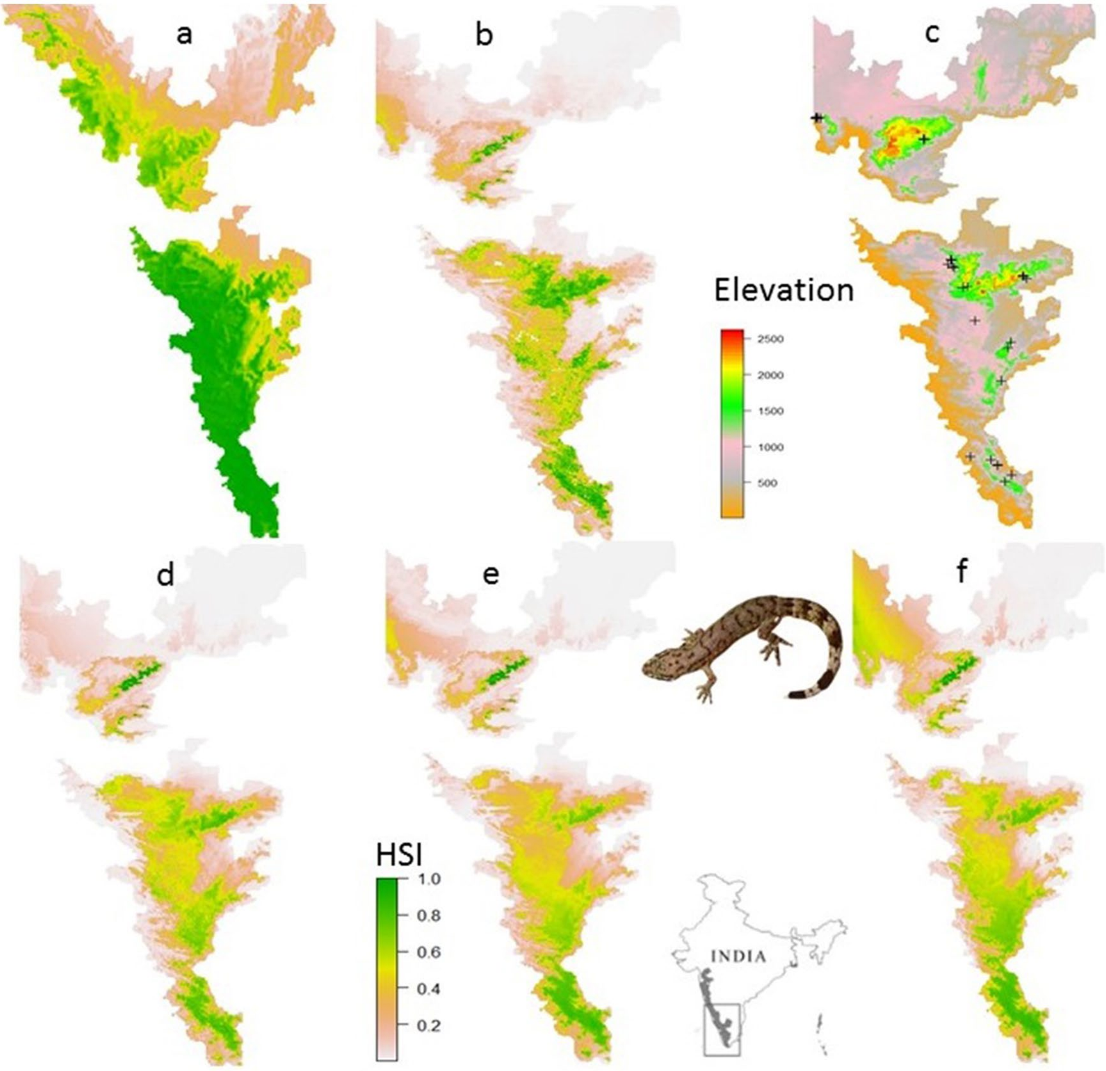

Fig. 4 Habitat suitability model of *Dravidogecko*. **a** HSM under Pleistocene Climate, **b** HSM under current climate, **c** occurrence points on the elevation map of the WG, **d** HSM under RCP 4.5, **e** HSM under RCP 6, **f** HSM under RCP 8.5

recent epoch (or Anthropocene) is in such an interglacial period. The prediction analysis for the near future indicates the withdrawal may more in a short span, leading to loss of suitable habitat and extinction. The climatic change may lead the *Dravidogecko* to isolated populations followed by allopatric speciation, as discussed in previous studies (refer above). Most of these allopatric splits had occurred around 2.6 mya, in the Quaternary period, which is right in the case of *Dravidogecko* also (Chaitanya et al. 2019). The MaxEnt-based analysis also predicts the temperature, precipitation, and altitude are the most influential factors in the species distribution. The rainfall is speculated as an essential factor and can limit species dispersal (Sekar and Karanth 2013). Evaluating another school of thought, the rise and fall of the sea level stand the reason for primary isolation and endemism in the WG (Hallam 1984). The temperature and precipitation play a significant role in the distribution and further divergence of this ancient poikilothermic lizard. The distribution of the *Dravidogecko* seems highly influenced by the bio2, bio3, bio14, bio18, and bio19 variables, indicating the influence of precipitation.

The lizards are highly sensitive poikilotherms towards temperature and elevation (Roll et al. 2017; Berriozabal-Islas et al. 2018). Diversification of reptiles in an area mainly relies on the elevation, temperature, and precipitation (McCain 2010; Boieiro et al. 2013). The altitudinal gradients appeared as the reason for the biogeography and macroecology of endemic species. The concepts with a base in evolution and conservation can attribute to developing a suitable spatial model (Kent 2005; Beck et al. 2012). WG being a discontinuous mountain, due to geographic barriers, the environmental parameters would change to a higher degree,

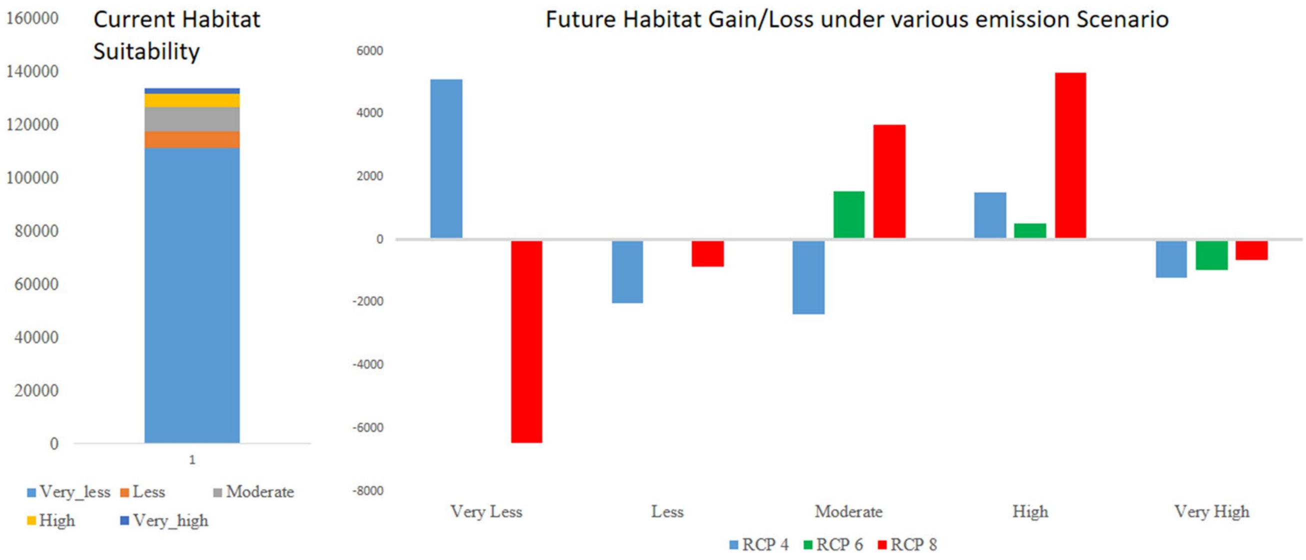

Fig. 5 Comparison of habitat gain and loss in the current and future emission scenarios. The figure shows the highly suitable habitats (Core habitats) will get vanished for the genera. The depletion corresponds to a minor increase of suitable habitats or buffers in some emission criteria. This suggests the range shift due to retreat and finally may lead to extinction

hampering similarity even in the same biome. Environmental variables could be a factor that offers niche dissimilarity, otherwise called uniqueness, where speciation occurs. The species richness may even differ within significantly smaller ranges (Fischer and Lindermayer 2005). Climate change is visible today with heavy thunderstorms and prolonged drought with temperature in the zenith. These alterations can affect an endemic species like *Dravidogecko* from the present surviving pockets in the high altitude. *Dravidogecko* is reported to be present in the wet—deciduous—evergreen forests and is even tricky to sight, being strictly nocturnal (Johnsingh 2001; Chaitanya et al. 2019). We recorded the presence of this ancient gecko from abandoned buildings near dense vegetation and orchards. There was a loss of forest at a rate of 0.57% annually in the last century (Menon and Bawa 1998), and the Southern WG experienced a drastic change in the land use pattern (Menon and Bawa 1997). The satellite imagery studies showed a loss of 2729 km^2 of forests in the WG, among which the dense forest shrink by 19.5% and open forest by 33.2% (Jha et al. 2000). The forest loss in the WG is around 35.3% in the last 100 years, notably the wet evergreen forest (30.6%), and the moist deciduous forest (24.8%) (Reddy et al. 2016). The present prediction identifies that the habitat loss will be 14.68–66.89% under various emission scenarios. The rainfall, deforestation, and altered land use pattern accelerate the weathering leading to landslides, impacting the native biota (Sajinkumar et al. 2011).

The distribution models serve a significant role in predicting the climate change and range shift of a data-deficient species (Franklin 2013; El-Gabbas and Dormann 2018). Providing insights into climate change and its impacts on biodiversity help to classify risk-prone areas (Srivastava et al. 2019). The species distribution presently shows seven meta-populations from the distributional range. Based on molecular studies we assume, the species we observed from upper altitide of the Nilgiris may be a different one and an older stock of the *Dravidogecko* species. The banding pattern also differed from the already reported six *Dravidogecko* species. Hence, we propose it may be a new species of *Dravidogecko* and we nominate this as *Dravidogecko coonoorenis*. However, more studies are suggested on the morphology and genetics to confirm species entity. Most of the identified meta-populations are new allopatric species (Chaitanya et al. 2019), with only one species towards the North of the Palghat gap. The distribution map shows the species distribution is less towards the North of the Palghat gap than towards the south, which can be due to the more threat factors prevailing in this region (Raman et al. 2020a, b). The distribution further shows to face severe threat soon, under various RCP, this may be more profound towards the North of Shenkotai to Palakkad gap, with the extinction of at least one or two *Dravidogecko* species. The genera have a high negative correlation to the bio2 variable (the diurnal range), designating the gecko as a strict nocturnal one. Kearney and Predavec (2000) studied the thermoregulatory mechanism in nocturnal gecko species. They observed that the nocturnal geckos regulate the body temperature to an extent like the diurnal lizards. The same concept may stand for the nocturnal *Dravidogecko*, but extend of regulation, reasons for nocturnal, and sympatric species interaction are unknown.

Climate change is one of the most significant threats in the Anthropocene (Thomas et al. 2004; Solomon et al. 2009; Karl et al. 2009; Pereira et al. 2010; Field and Barros 2014), which has impacts in various taxa leading to extinction by range shift (Guisan and Zimmermann 2000; Bellard et al. 2012). Range shifts may prompt the *Dravidogecko* to migrate to more upper altitude or small pockets, creating an uncomfortable zone slowly. Results indicate the 'highly suitable' (core) habitats decrease in different climate scenarios, and the suitable (buffer) habitat seems to be increasing. Hence, we postulate that animal range shifts towards high altitude (above the present optimum) by shrinking the present 'highly suitable' habitats due to the climate change and global warming, leading to the population decline. The SDM in endemic and endangered animal species and plants from the Nilgiris indicates similar results (Sen et al. 2016; Sony et al. 2018; Raman et al. 2020a, b). Geckos are distributed globally, especially in the warmer belts, where the situation is cozy, making their survival fit. *Dravidogecko* is specially adapted to the cooler high altitude and can be the relic of an ancient lineage, which thrived in the colder climate and restricted its range to an adaptable habitat in the WG during the climate change. The SDM works best to understand a rarity (McCune 2016), primarily related to climate change and habitat degradation (Ksiksi et al. 2019). Therefore, the environmental factors existing in the core habitat of the *Dravidogecko* is of high relevance. The disturbance of this unique set of ecological factors that structured endemic genera may have huge impacts on them, which may be more pronounced in lizards than the other taxa.

Conclusion

The present study suggested the possibility of a new species of *Dravidogecko* and showed patchy distributions of suitable isolated habitats of *Dravidogecko,* indicating more speciation events. We assess the genera cannot thrive in the climatic extremes, instead only in the ecotones or the moderate altitudes (< 1600MSL) where environmental factors are suitable. The habitat of *Dravidogecko* are delicate ecosystems, and even a minute change may upset the entire equilibrium leading to the extinction of habitat specialist prokaryotes. The small vertebrates like *Dravidogecko* are indicators of the ecosystem and reflect the changes in the landscape they live. The increased anthropogenic stress impacts the WG leading to increased greenhouse gas emissions and lesser carbon dioxide assimilation. These small-bodied cryptic nocturnal species may have a key role in the ecosystem they live. Conservation initiatives may be undertaken to preserve habitat of this species, which principally lies on climate change mitigation. Hence, we conclude, if global warming continues as anticipated, there will be massive changes in the WG, which backlashes with the extinction of native flora and fauna.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s40808-021-01284-4.

Acknowledgements The authors sincerely acknowledge the Tamil Nadu Forest Department and Dr. S. Suresh for providing information and support. We recognize the support of Mr. Abinesh Anbazhagan during the fieldwork.

Funding No funding was received for conducting this study.

Data availability The data used in the publication are acknowledged appropriately and other collected information are following the regulations of the authority.

Code availability All the software used in the present study are open-source software and downloaded accordingly.

Declarations

Conflict of interest The authors have no conflicts of interest to declare that are relevant to the content of this article.

Ethical approval The study does not include entry to a reserve area or handling a live animal hence, necessary permissions or approval of ethics committee is not necessary.

Consent for publication Consent for publication is not required in the present study.

Consent to participate Consent to participate is not required in the present study.

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