Climate change has no significant negative effects on the suitable habitats for granular poison frog (*Oophaga granulifera*) according to species distribution modeling

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Abstract

Almost half of amphibian species globally are experiencing population declines. Future climate change effects, such as prolonged droughts and increased temperatures, are expected to contribute to the decline of these species. The *Oophaga granulifera* (granular poison frog) located in Costa Rica in particular is an endangered frog species that is experiencing such declines. The *O. granulifera* controls the populations of small invertebrates, such as ants and mites, as their predators and are used as biodiversity indicators due to their sensitivity toward environmental changes. This study aims to determine potential distribution and habitat suitability of the *O. granulifera* by developing a species distribution model (SDM) to analyze the effects of climate change on the species between the present and the future (years 2061-2080). I collected occurrence records of *O. granulifera* from the Global Diversity Information Facility (GBIF) database and 19 climatic variables from the WorldClim database to produce a generalized linear model (GLM)—the model aimed to predict the effects of present and future climatic variables on the species distribution of *O. granulifera.* The SDM showed increased areas of suitable habitat from the present to the future, indicating that climate change may have no significant negative effects on the species distribution. Conservationists aiming to increase the *O. granulifera* population should focus on other factors that may contribute to their endangerment, such as habitat loss and diseases, since gradual climate change proved to not be a significant threats to population decline.

Keywords

Oophaga granulifera
Granular poison frog
Climate change
Species distribution modeling
Suitable habitat
Temperature

Introduction

A large proportion (43%) of amphibian species are experiencing population declines globally which only continue to worsen (Wake & Koo, 2018). Factors that have led to this population declines include habitat destruction, drainage of wetlands, the rise of urbanization, and a pathogenic chytrid fungus called *Batrachochytrium dendrobatidis* (Bd). Bd was discovered in the late 20th century and is the forefront of the investigation for determining amphibian decline (Wake & Koo, 2018). The fungus invades the amphibian's permeable skin and disrupts their osmotic balance, therefore inducing heart failure and killing the organism infected (Wake & Koo, 2018). Climate change causes frogs to be more susceptible to Bd. Bd shows significantly higher infection rates during cool-dry season than during the warm-wet season (Longo & Zamudio, 2016). This seasonal trend shows that certain environmental conditions are more favorable to the pathogen than others. Bd maintains a strong threat to amphibian species but especially frogs.

Future climate change is predicted to worsen the situation (Corn, 2005). With their sensitivity to temperature and precipitation, amphibians are expected to suffer under future climate change conditions such as reduced soil moisture which could reduce prey species and eliminate habitat (Corn, 2005). Reduced snowfall and increased summer evaporation also poses an issue as it may affect the occurrence of seasonal wetlands, a crucial and popular habitat for amphibians (Corn, 2005). Prolonged droughts caused by increased temperatures, for example, can significantly reduce the number of wetlands therefore eliminating the habitats available for amphibians (Walls et al., 2013). Extreme climate change effects like droughts contribute to amphibian habitat loss, consequently leading to lower rates of survival and population decrease.

Despite their decline, amphibians are essential to ecosystems and are the most abundant vertebrate species (Wake & Koo, 2018). One of the most well-known amphibians are frogs. Frogs play vital roles in wet and dry ecosystems as they are both prey and predators to several organisms, affecting the food chains in many ecosystems (Dorcas & Gibbons, 2011). They are also bioindicators–indicators of an ecosystems' health–because of their heightened sensitivity to environmental problems and changes (Dorcas & Gibbons, 2011). Their permeable skin makes them more susceptible to toxins in their environment (Dorcas & Gibbons, 2011). Frogs are found in terrestrial and freshwater aquatic habitats including, but not limited to, areas in and around lakes, ponds, swamps, wetlands, and mountain streams (Dorcas & Gibbons, 2011). Lakes, in particular, are increasing in temperature due to climate change. Lake warming decreases the population of zooplankton in the body of water, limiting the food supply of frogs' prey and disrupting the food web (Havens & Jeppesen, 2018). Climate change effects on aquatic areas therefore affect their ability to thrive in their habitat.

One frog species in particular that is listed as a vulnerable species on the IUCN Red List is the *Oophaga granulifera*, also known as the granular poison frog. The granular poison frog is common in the Pacific portion of Costa Rica and is declining due to changes in their habitats (IUCN, 2020). This species specifically is threatened by expanding agriculture through plantations of oil palm, banana, and pineapple and the spraying of pesticides and fungicides, and is usually found in small streams within humid lowland forests (IUCN, 2020). The granular poison frog is a species of dart frog that control the populations of small invertebrates as their predators, and are used as biodiversity indicators due to their sensitivity toward environmental changes (McGugan et al., 2016).

To determine the habitat suitability and potential distribution for the *O. granulifera*, I developed a species distribution model (SDM) for the species. My objectives are as follows: (a) to identify the environmental factors in Costa Rica associated with Granular Poison Frogs; (b) to predict present and future habitat distribution for Granular Poison Frogs using available occurrence records and literature records.

Methods

Data collections

I obtained occurrence records of the *O. granulifera* from Global Biodiversity Information Facility (GBIF) GBIF.org (13 June 2024) GBIF Occurrence Download https://doi.org/10.15468/dl.bvfdgq. The GBIF is a database and data infrastructure supported by multiple national governments, aimed at providing open-access biodiversity data for the public and the science community. The total number of occurrences for *O. granulifera* downloaded is 434. These occurrences are found mainly in Costa Rica. The timeline of the sightings for this species ranges from 1958 to 2024. I filtered to keep only occurrence with coordinates. The latitudes range from 8 to 10 and longitudes range from -84 to -83.

Environmental Variables

I acquired environmental variables representing the current climatic conditions from the WorldClim database (Fick and Hijmans, 2017) at the resolution of 2.5 arc min. The environmental variables included: Bio1 = Annual mean temperature, Bio2 = Mean diurnal range (max temp – min temp) (monthly average), Bio3 = Isothermality (Bio1/Bio7) * 100, Bio4 = Temperature Seasonality (Coefficient of Variation), Bio5 = Max Temperature of Warmest Month, Bio6 = Min Temperature of Coldest Month, Bio7 = Temperature Annual Range (Bio5-Bio6), Bio8 = Mean Temperature of Wettest Quarter, Bio9 = Mean Temperature of Driest Quarter, Bio10 = Mean Temperature of Warmest Quarter, Bio11 = Mean Temperature of Coldest Quarter, Bio12 = Annual Precipitation, Bio13 = Precipitation of Wettest Month, Bio14 = Precipitation of Driest Month, Bio15 = Precipitation Seasonality (Coefficient of Variation), Bio16 = Precipitation of Wettest Quarter, Bio17 = Precipitation of Driest Quarter, Bio18 = Precipitation of Warmest Quarter, and Bio19 = Precipitation of Coldest Quarter. Using R software (R Core Team, 2023) and raster package (Hijmans, 2024), I trimmed the environmental variables so that the geographic range of environmental variables was contained with 0 and 15 degree latitudes and -90 and -75 degree longitudes. The extent of the environmental variables covers and extends beyond the latitudinal and longitudinal ranges of *O. granulifera*.

In addition, to project species future suitable areas, I acquired environmental variables representing future climatic conditions for the years 2061- 2080 under the model MPI-ESM1-2-HR and CMIP6 (Gutjahr et al., 2019) The future climatic raster layers were also trimmed using the sampling extent mentioned above.

Modeling Strategy

To investigate the suitable habitat areas of *O. granulifera*, we performed multivariate generalized linear model (GLM). I randomly selected 10,000 pseudo-absence, or “background” points, within the range of the environmental variables (see section above). The number of 10,000 pseudo-absence points followed the recommendation by Barbet-Massin et al. (2012). After running the GLM model, I converted the continuous probability of habitat suitability to a binary response output (suitable = TRUE or FALSE). The suitability cut-off was equal to the threshold at which the sum of the model sensitivity (true positive rate) and specificity (true negative rate) is highest (Field et al. 1997; Liu et al. 2011). I then used five-fold cross validation to evaluate the trained GLM; in each cross validation, 80% of the occurrence data were training data, leaving the remaining 20% as testing data. We evaluated the performance of GLM by calculating the Area Under the ROC Curve (AUC). We then projected future suitable habitat areas for *O. granulifera* in 2061-2080.

Results

The final GBIF dataset of *O. granulifera* contains 310 records with coordinates. The GLM species distribution model shows an AUC value of 0.995, which indicates that it is an accurate classifier between positive and negative cases (Figure 1). The GLM model output shows that Bio2, 5, 9, 10, 12, 13, and 14 show significant positive correlation to predicting species presence, and Bio1, 3, 4, 6, 7, 8, 11, 15, 16, 17, 18 and 19 show significant negative correlation to species presence (Table 1). The comparison between current and future suitable habitat area reveals that areas of suitable habitat will increase (Figure 2).

Figure 1 ROC (Area under the receiver operator) curve, demonstrates the accuracy of the SDM model of the *O. granulifera* in distinguishing positive and negative cases.

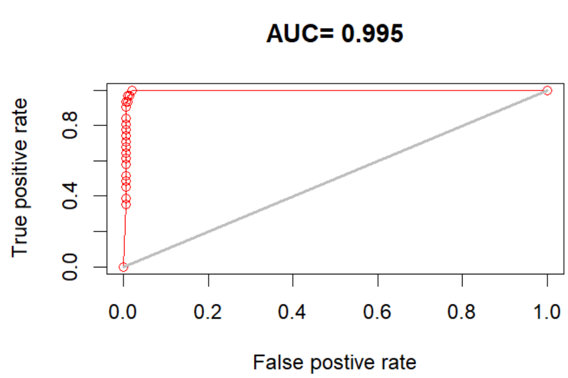
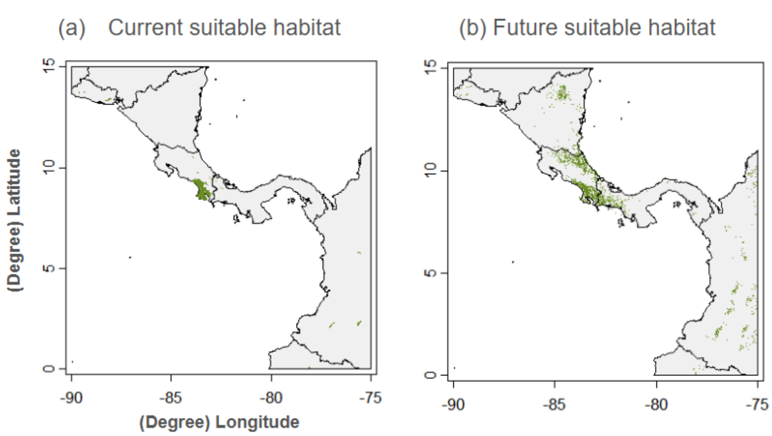


Table 1 Generalized linear model (GLM) output for predicting the effects of climatic variables on *O. granulifera* species presence.

	A	B	C	D	E
1		Estimate	Std. Error	z value	Pr(>|z|)
2	(Intercept)	396.3851614	473.658128	0.8368591986	0.4026717172
3	wc2.1_2.5m_bio_1	-13.42437703	57.50620962	-0.2334422163	0.8154180347
4	wc2.1_2.5m_bio_2	55.4760911	47.26674846	1.173681138	0.2405227683
5	wc2.1_2.5m_bio_3	-5.998591978	6.417186444	-0.9347697827	0.3499069553
6	wc2.1_2.5m_bio_4	-5.701797404	2.156438478	-2.644080721	0.008191311908
7	wc2.1_2.5m_bio_5	5204128.875	19113545.5	0.2722743865	0.7854110491
8	wc2.1_2.5m_bio_6	-5204178.003	19113546.59	-0.2722769413	0.7854090848
9	wc2.1_2.5m_bio_7	-5204189.975	19113545.76	-0.2722775794	0.7854085942
10	wc2.1_2.5m_bio_8	-4.86143251	5.646544412	-0.8609571014	0.3892616705
11	wc2.1_2.5m_bio_9	13.68535267	8.437673933	1.621934289	0.1048174188
12	wc2.1_2.5m_bio_10	257.563234	101.6243421	2.534463976	0.01126195059
13	wc2.1_2.5m_bio_11	-203.15815	78.70152695	-2.581374947	0.009840763672
14	wc2.1_2.5m_bio_12	0.002185796422	0.01037139306	0.2107524427	0.8330804502
15	wc2.1_2.5m_bio_13	0.0651730897	0.02826818403	2.305527996	0.02113702066
16	wc2.1_2.5m_bio_14	0.06191391796	0.07696465055	0.8044461648	0.4211393488
17	wc2.1_2.5m_bio_15	-0.7876855141	0.3895930154	-2.021816313	0.04319533182
18	wc2.1_2.5m_bio_16	-0.004888443441	0.02467677844	-0.1980989315	0.8429676608
19	wc2.1_2.5m_bio_17	-0.07243906509	0.04330722282	-1.672678606	0.09439058309
20	wc2.1_2.5m_bio_18	-0.0001678410036	0.01568032944	-0.01070392075	0.99145967
21	wc2.1_2.5m_bio_19	-0.011689906	0.009897980848	-1.181039464	0.2375870463

Figure 2 Species Distribution Model (SDM) for showing areas of current and future suitable habitat for the *O. granulifera* species.



Discussion

The Generalized Linear Model (GLM) showed that bioclimatic variables 2, 5, 9, 10, 12, 13, and 14 had a significant positive correlation with the distribution of *O. granulifera.* Variables 2, 5, 9, and 10 correspond to temperature being mean diurnal range, max temperature of warmest month, mean temperature of driest quarter, and mean temperature of warmest quarter, respectively. As these factors increase, so does habitat suitability for the species. Because they are directly proportional, if the factors decrease so does habitat suitability. This shows that overall higher temperatures make areas more environmentally advantageous for the species and will therefore lead to more areas of suitable habitat. These variables have a positive correlation to species distribution because granular poison frogs are already adapted to warmer temperatures due to their location close to the equator in Costa Rica. Increased temperatures are therefore not a threat to the species but can help the frogs maintain their optimal body temperature and enhance their activity and breeding behavior. The GLM also showed that bioclimatic variables 1, 3, 4, 6, 7, 8, 11, 15, 16, 17, 18, and 19 had a significant negative correlation with the distribution of *O. granulifera.* Variables 1, 3, 4, 6, 7, 8, and 11 correspond to temperature being annual mean temperature, isothermality, temperature seasonality, min temperature of coldest month, temperature annual range, mean temperature of wettest quarter, and mean temperature of coldest quarter, respectively. Variables 15, 16, 17, 18, and 19 correspond to precipitation being precipitation seasonality, precipitation of wettest quarter, precipitation of warmest quarter, and precipitation of coldest quarter, respectively. The SDM model is fairly accurate but it is important to recognize its limitations. It is difficult to interpret the variables of a species distribution model (SDM) because of collinearity of the predictor variables. Because environmental variables like temperature and precipitation are highly correlated, it is difficult to distinguish their individual effects on the species distribution and compare their importances.

In the species distribution model, the area of suitable habitats for the *O. granulifera* in Costa Rica from present day to the years 2061-2080 increased. Based on these results, climate change does not negatively impact habitat suitability and is therefore not a threat towards the species nor contributing to their endangered state. However, it is essential to recognize that although the model demonstrates an increase in suitable habitat for the species, the model only accounts for variables that correspond to climate change, not any other factors. So although climate change is not a disadvantage for this species, it doesn't mean that the number of suitable habitats won't decrease or their endangered state won't worsen in the future due to other factors that weren't accounted for through these results. The SDM model is also based on variables that account for gradual climate change. Gradual environmental changes like a slow increase in temperature may not affect the species since they can most likely adapt over time to warmer climates. More extreme and rapid environmental effects caused by climate change are not accounted for by the SDM, however, these are factors that would potentially impact suitable habitats.

Other studies have shown that future climate change is a strong threat to amphibian species (Corn, 2005). Prolonged droughts caused by a rise in temperatures, for example, can significantly reduce the number of wetlands therefore eliminating the habitats available for amphibians (Walls et al., 2013). Droughts caused by El Nino, a more extreme and short term climate change, also cause breeding ponds to dry, killing the eggs and tadpoles of anurans (Corn, 2005). However, the data collected from the SDM shows otherwise. Bioclimatic variables

2, 5, 9, and 10 have a direct relationship with species distribution of *O. granulifera* which demonstrates that as temperatures increase, so does habitat suitability. While it was determined through other studies that increased temperatures reduce the number of suitable habitats for amphibians, the SDM proves the opposite for this specific amphibian species. It is important to recognize that the other study is analyzing amphibian species as a whole instead of one specific species through the SDM, which may explain the conflicting results. It was also determined by other studies that lake warming caused by higher temperatures from climate change kills the Zooplankton population which would serve as food for frogs (Havens & Jeppesen, 2018). Lake warming caused by climate change would therefore decrease the number of habitats suitable for frogs. However, variables of temperature in the SDM showed positive correlation with species distribution, showing that increasing temperature actually increases the number of suitable habitats. It is important to note that the study only focuses on frog species in general while the SDM is analyzing only one specific frog species. The conflicting results between the study and SDM results may also be explained by the fact that lake warming primarily affects aquatic frog species while the granular poison frog in Costa Rica is more terrestrial. The *O. granulifera* forages for food on land instead and is more likely to feed on invertebrates such as ants or mites (McGugan et al., 2016).

The SDM results showed an increased habitat suitability from the present to 50 years in future which suggests that climate change has no significant negative effect on the *O. granulifera*. Gradual trends of climate change may have even contributed to the increase in areas of suitable habitat. It is important to recognize, however, that the SDM only accounts for bioclimatic variables associated with climate change. While gradual climate change proved to not be a threat to the *O. granulifera*, there are several other factors not taken into account that are the reason for endangering the species. Therefore, species conservation for the granular poison frog should put its efforts more on prevalent issues and factors that actually contribute to its endangerment, such as extreme climate events, the rise of urbanization, the spread of pathogenic fungi such as *Bd,* and the spraying of pesticides and fungicides, instead of focusing on gradual climate change.

References

1. Corn, P. S. (2005). Climate change and Amphibians. *Animal Biodiversity and Conservation*, *28*(1), 59–67. https://doi.org/10.32800/abc.2005.28.0059
2. Dorcas, M. E., & Gibbons, W. (2011). *Frogs: The animal answer guide*. Johns Hopkins University Press.
3. Havens, K., & Jeppesen, E. (2018). Ecological responses of Lakes to climate change. *Water*, *10*(7), 917. https://doi.org/10.3390/w10070917
4. IUCN. (2020). *Oophaga granulifera.* In *IUCN Red List of Threatened Species.* International Union for Conservation of Nature. https://www.iucnredlist.org/species/55186/3025447
5. Longo, A. V., & Zamudio, K. R. (2016). Environmental fluctuations and host skin bacteria shift survival advantage between frogs and their fungal pathogen. *The ISME Journal*, *11*(2), 349–361. https://doi.org/10.1038/ismej.2016.138
6. McGugan, J. R., Byrd, G. D., Roland, A. B., Caty, S. N., Kabir, N., Tapia, E. E., Trauger, S. A., Coloma, L. A., & O'Connell, L. A. (2016). Ant and Mite Diversity Drives Toxin Variation in the Little Devil Poison Frog. *Journal of Chemical Ecology*, *42*(6), 537–551. https://doi.org/10.1007/s10886-016-0715-x
7. Wake, D. B., & Koo, M. S. (2018). Amphibians. *Current Biology*, *28*(21). https://doi.org/10.1016/j.cub.2018.09.028
8. Walls, S., Barichivich, W., & Brown, M. (2013). Drought, deluge and declines: The impact of precipitation extremes on amphibians in a changing climate. *Biology*, *2*(1), 399–418. https://doi.org/10.3390/biology2010399