Trabajo

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Habitat loss and climate-induced distributional shifts on the Andean Red-spotted glassfrog (*Nymphargus grandisonae*)

Mateo A. Vega-Yánez[1,2,3], Daniela Franco-Mena[1], Juan M. Guayasamin[1], Evanna Jaramillo[2], Julián A. Velasco[4]

[1] Laboratorio de Biología Evolutiva, Global Research & Solutions Center, Colegio de Ciencias Biológicas y Ambientales COCIBA, Universidad San Francisco de Quito USFQ, Quito, Campus Cumbayá, Pichincha, Ecuador

[2] Universidad San Francisco de Quito USFQ, Colegio de Ciencias Biológicas y Ambientales COCIBA, Maestría en Ecología Tropical y Conservación, Quito, Ecuador

[3] Instituto Nacional de Biodiversidad, Quito, Ecuador

[4] Instituto de Ciencias de la Atmósfera y Cambio Climático, Universidad Nacional Autónoma de México, CP 04510, México City, México

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ABSTRACT

Climate change and habitat loss are two interrelated dimensions of the current global biodiversity crisis. The Red-spotted glassfrog (*Nymphargus grandisonae*) inhabits the northern Andes in Colombia and Ecuador. This study analyses time series of habitat loss within the species' current range, using remote sensing data collected between 1985 and 2022. We also report a new occurrence record in the western foothills of Ecuador. Furthermore, we evaluate potential changes to the climatic suitability of its habitat under a climate change scenario (SSP3-7.0) for the period 2061–2080, using an ecological niche modelling approach. Our results suggest that the species' range could, on average, contract by 45% and shift upwards in elevation by approximately 270 meters. Furthermore, the distribution patterns of the species in the Andean foothills show a high degree of fragmentation. Climate niche analysis shows that the species is highly dependent on humidity and sensitive to temperature fluctuations. In general, models project a decrease in precipitation in the future. Between 1985 and 2022, nearly 32,600 hectares of vegetation cover were lost within the species' range, with the highest rates of loss recorded in Ecuador. These findings highlight the urgent need for conservation strategies that integrate climate change adaptation and habitat protection to reduce the risk of potential extinction.

Key words: Climate change, Biodiversity, Tropical Andes, Amphibians, Habitat loss.

RESUMEN

El cambio climático y la pérdida de hábitat son dos dimensiones estrechamente relacionadas de la actual crisis global de biodiversidad. La rana de cristal de manchas rojas (*Nymphargus grandisonae*) habita en los Andes del norte en Colombia y Ecuador. Este estudio analiza series temporales de pérdida de hábitat dentro del rango actual de la especie, utilizando datos de percepción remota recolectados entre 1985 y 2022. También reportamos un nuevo registro de presencia en las estribaciones occidentales de Ecuador. Además, evaluamos los posibles cambios en la idoneidad climática de su hábitat bajo un escenario de cambio climático (SSP3-7.0) para el periodo 2061–2080, utilizando un enfoque de modelado de nicho ecológico. Nuestros resultados sugieren que el rango de la especie podría, en promedio, contraerse en un 45% y desplazarse hacia arriba en altitud aproximadamente 270 metros. Asimismo, los patrones de distribución de la especie en las estribaciones andinas muestran un alto grado de fragmentación. El análisis del nicho climático indica que la especie depende en gran medida de la humedad y es sensible a las fluctuaciones de temperatura. En general, los modelos proyectan una disminución en la

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Author for correspondence: mvegayanez183@gmail.com

precipitación en el futuro. Entre 1985 y 2022, se perdieron cerca de 32,600 hectáreas de cobertura vegetal dentro del rango de la especie, registrándo las tasas más altas de pérdida en Ecuador. Estos hallazgos resaltan la necesidad urgente de estrategias de conservación que integren la adaptación al cambio climático y la protección del hábitat para reducir el riesgo de una posible extinción.

Palabras claves: Cambio climático, Biodiversidad, Andes Tropicales, Anfibios, Pérdida de hábitat.

Introduction

Climate change and biodiversity loss are interlinked issues that humanity faces as part of a planetary crisis (Passarelli *et al.*, 2021). Biodiversity is threatened by habitat loss, fragmentation, overexploitation, invasive species, and climate change (Brook *et al.*, 2008; Bellard *et al.*, 2022). Anthropogenic climate change is already considered one of the most significant threats to biodiversity in the coming decades (Ripple *et al.*, 2025). The acceleration in warming rates has left notable consequences on the marine and terrestrial ecosystems (Burrows *et al.*, 2011). The impacts of climate change on biodiversity have been observed from gene to ecosystem levels (Scheffers *et al.*, 2016), with many species experiencing widespread population collapses (Roman-Palacios & Wiens 2020; Wiens 2016) and extensive distributional shifts (Lenoir *et al.*, 2020; Antão *et al.*, 2020).

Habitat loss and climate change often worsen biodiversity loss by increasing the susceptibility of populations to extinction (Jetz *et al.*, 2007; Mantyka-Pringle *et al.*, 2012). These combined human stressors are exacerbated in taxa with small population sizes and poor dispersal abilities, such as amphibians and reptiles (Newbold 2018). Amphibians are among the most threatened vertebrate groups, with habitat loss and climate change being the most critical extinction drivers (Luedtke *et al.*, 2023). However, it is unknown for many species how these threats act synergistically and can drive population declines across their geographical distribution. Even for many species, there is still a gap in distribution information, the so-called 'Wallacean shortfall', and new geographical records are continually emerging in the literature, mainly for Neotropical species.

In recent years, the Andes of Ecuador and Colombia have seen important rediscoveries of amphibian species, some of which had not been reported for a long time or were considered extinct. Moreover, range extensions have been documented. In the last year alone, several studies have reported these findings (Aponte-Gutiérrez *et al.*, 2024; Copete Mosquera *et al.*, 2024; Sánchez-Nivicela *et al.*, 2024; Vega-Yánez *et al.*, 2024). However, the rediscovery of these species is particularly challenging, given the rapid destruction of their habitats due to anthropogenic activities (Luedtke *et al.*, 2023). For instance, in Ecuador, where between 1990 and 2018, approximately 21,263 km^2 of forest area was lost, primarily due to its conversion into agricultural land (Rivas *et al.*, 2024). A similar phenomenon was observed in Colombia, where approximately 15,181 km^2 of tropical forest was lost between 2013 and 2018. The Amazon region was the most affected, followed by the Andean region, and this deforestation trend is projected to continue in the future (González-González *et al.*, 2021). When these effects are combined with the impacts of climate change, it is estimated that between 63.4% and 79.4% of suitable habitat for endemic anurans in the Colombian Andes could be lost (Agudelo-Hz *et al.*, 2019).

Among the group of anurans, the family Centrolenidae (Taylor, 1951) comprises a group of neotropical frogs characterized by their translucent ventral skin, which allows the observation of internal structures, an uncommon feature among amphibians (Guayasamin *et al.*, 2009). These frogs, commonly known as glassfrogs, are found exclusively in Central and South America, particularly in humid and mountainous ecosystems associated with water bodies (Castroviejo-Fisher *et al.*, 2014; Guayasamin *et al.*, 2009). Their evolutionary history shows that they diverged about 30 million years ago and have a diversity peak at intermediate altitudes in the Andes (Hutter *et al.*, 2013a; Castroviejo-Fisher *et al.*, 2014). Similarly, a relationship between rates of climatic niche evolution and altitudinal change has been identified, suggesting that many species maintain their environmental preferences over time (Hutter *et al.*, 2013b).

The Northern Andes house about half of the diversity of glassfrogs, with 83 species documented in this bioregion (Guayasamin *et al.*, 2020). Within this outstanding diversity, one of the most readily recognized species is Red-spotted glassfrog, *Nymphargus grandisonae* (Cochran & Goin, 1970). This taxon is distributed in the Andes of Colombia and Ecuador between 1,140 to 3,200 m (Guayasamin *et al.*, 2020, 2025; Frost, 2025).

The Red-spotted glassfrog is nocturnal, commonly found in primary, secondary forests, grasslands, in vegetation adjacent to streams or marshes (Hutter *et al.*, 2013b; Guayasamin *et al.*, 2020). Although this species is distributed in localities inside and outside private protected areas (Guayasamin *et al.*, 2020), and is tolerable to moderate habitat disturbance, it faces major threats such as deforestation and mining (Roy *et al.*, 2018). We selected this study species for the following reasons: (i) it is easily identifiable, (ii) it has abundant locality records in an area currently facing climate change and deforestation, and (iii) it represents a group of biphasic amphibians that rely on streams with riverine vegetation, thus, the results could be extrapolated to other taxa with similar characteristics.

In this study, we assess the potential impacts of habitat loss and future climate change on the distributional range of *N. grandisonae* in the northern Andes. We conduct a time-series analysis of potential habitat loss within the current distributional range of *N. grandisonae* using remote sensing data from 1985 to 2022. We also assess possible changes in the climatic suitability of *N. grandisonae* under a climate change scenario (SSP3-7.0) for 2061-2080, using an ecological niche modeling approach. These analyses allow us to evaluate potential scenarios for the species, and to guide conservation actions.

Materials and methods

Data collection

Occurrence records of *Nymphargus grandisonae* were compiled from various biodiversity databases, including the Global Biodiversity Information Facility (GBIF), Bioweb-Ecuador (QCAZ), the Base Nacional de Datos de Biodiversidad (BNDB-INABIO), Centro Jambatu, and the Instituto de Ciencias Naturales (ICN) of the Universidad Nacional of Colombia. We also include the new record obtained during field work in the Pululahua Geobotanical Reserve. The specimen was collected by Mateo A. Vega-Yánez and Marco Murminacho (member of the community of Pululahua) on 26 March 2025 at 21h51 in the Pululahua Geobotanical Reserve (0° 3′ 23.65″ N; 78° 30′ 27.21″ W, at 2,120 m. a.s.l.) on a leaf three meters above the ground in a stream next to a rock wall covered with moss and ferns. At the same site, the vocalizations of several males (more than five individuals) were heard more than five meters above the ground. The collection and field research were conducted under the permit MAATE-CMARG-2022-0575, issued by the Ministerio de Ambiente y Energía (MAE) de Ecuador. The specimen of the Pululahua Geobotanical Reserve was deposited at the Centro Jambatu (CJ), Quito, Ecuador. All records were validated, including the verification of geographic coordinates and associated metadata, and then integrated into a standardized database for subsequent analyses, ensuring a minimum distance of approximately 4.6 km between occurrence points.

Species distribution modeling

We downloaded bioclimatic variables from WorldClim v2.1 at a spatial resolution of 2.5 min (Fick & Hijmans, 2017). We selected the variables less autocorrelated using the variance inflation factor (VIF) with the vif function from the R package usdm (Naimi *et al.*, 2014) using a threshold of 0.7. According to this we used the following variables: bio18 = precipitation of the warmest quarter, bio19 = precipitation of the coldest quarter, bio2 = mean diurnal range (mean of monthly (max temp - min temp)), bio4 = temperature seasonality (standard deviation ×100), and bio9 = mean temperature of the driest quarter.

Models were fitted using a calibration area or “M" (Soberon & Peterson, 2005) using a 400 km buffer for each occurrence record of the species (this area encompassed the Andes of Ecuador and Colombia). In addition, the occurrence data were randomly divided into two sets: 70% for calibration and 30% for validation. Using the ecospat package (Broennimann *et al.*, 2014), we generated 1,000 pseudo-absences. We selected three modeling algorithms: support vector machine (SVM), random forest (RF), and boosted regression trees (BRT), and generated 10 replicates per model. Finally, each model was evaluated based on true skill statistics (TSS) and omission rate (Allouche, Tsoar & Kadmon, 2006; Li & Guo, 2013) to build a consensus ensemble model.

Future model projections

For future models, CMIP6 climate projections were used for the period 2061-2080, under the Shared Socio-economic Pathways scenario SSP3-7.0, at the same spatial resolution as the variables for the present models. Four global climate models (GCMs) were randomly selected: EC-Earth3-Veg, IPSL-CM6A-LR, GISS-E2-1-G, and MPI-ESM1-2-HR (Eyring *et al.*, 2016). We generated a series of model transfers for each GCM in a single high-emission climate change scenario (SSP3-7.0) to identify possible changes in distribution patterns throughout the Andean region, where the species is distributed. The previously obtained distribution models were transformed into binary presence/absence models to facilitate the corresponding analyses. A threshold of 0.9 in suitability values at occurrence sites was used to define suitable areas. Based on that, the potential future distribution area of the species was defined, which was subsequently used for the vegetation analysis.

Analysis of climatic variables and the spatio-temporal dynamics of vegetation

We converted the distribution models into binary presence–absence maps to simplify the analysis. Suitable areas were defined using a suitability threshold of 0.9 at the occurrence locations. To explore the similarity patterns between the global climate models (GCMs) as a function of these bioclimatic variables, a non-metric multidimensional scaling analysis was applied using the metaMDS function of the vegan package in R (Oksanen *et al.*, 2022). To ensure the stability of the solution and to avoid local optima, trymax = 1,000 was set, allowing up to 1,000 random optimization trials. Lastly, the surface predicted by the models was calculated, and univariate descriptive statistics were used to analyze the changes. The results were visualised using a series of graphs generated with the ggplot2 package.

The MapBiomas collection (available at https://amazonia.mapbiomas.org/proyecto/), which provides information at a spatial resolution of 30 meters based on supervised classification of satellite imagery, was used to analyze changes in vegetation cover. Land use cover was downloaded for the years 1985, 1990, 1995, 2000, 2005, 2010, 2015, 2020, and 2022. All vegetation covers were transformed to the WGS 1984 UTM Zone 17S (Ecuador) and 18S (Colombia) spatial reference systems to ensure correct overlap and comparison of geographic information. A temporal trend analysis was carried out, estimating the area of vegetation cover for each year, to quantify the loss of vegetation in the potential range of *N. grandisonae* in both space and time. From the values obtained, we estimated the rate of vegetation change and the average annual deforestation for each five-year interval, using the equations proposed by Puyravaud (2003). All analyses were carried out using R software (R Core Team, 2024).

Results

Occurrence and new record

Once the information obtained from biodiversity databases had been validated, 155 occurrence records of *Nymphargus grandisonae* were compiled and used in the distribution models. The new occurrence record (LBE1055) corresponds to a male with a snout-vent length (SVL) of 26.32 mm, which has thirteen distinctive red spots on the body: seven on the dorsum and six on the hind limbs, a diagnostic feature of the species (Fig. 1).

Species distribution model.

All the algorithms evaluated showed high prediction performance in estimating the distribution of *Nymphargus grandisonae*, especially Random Forest, which achieved the best overall score. This algorithm obtained the highest AUC value (0.99), indicating an adequate discriminative ability. In addition, it obtained the highest correlation (0.87), the highest TSS value (0.90), and the lowest Deviance (0.21), reflecting a lower prediction error. In contrast, both Boosted Regression Trees (BRT) and SVM also showed robust performance, with AUC values above 0.95 and TSS values above 0.85, suggesting that all the applied models were effective. The consensus ensemble model for the current distribution indicates that the species is primarily concentrated in the Andean foothills of northern Ecuador and Colombia, between 589 and 3,328 m elevation. A few scattered pixels also appear along the Colombia–Venezuela border, corresponding to marginal areas of the Eastern Cordillera. In Ecuador, the most suitable areas are located in the western foothills of the north, particularly in montane and piedmont forests, which narrow towards the south. Whereas in Colombia, the distribution is wider, with high

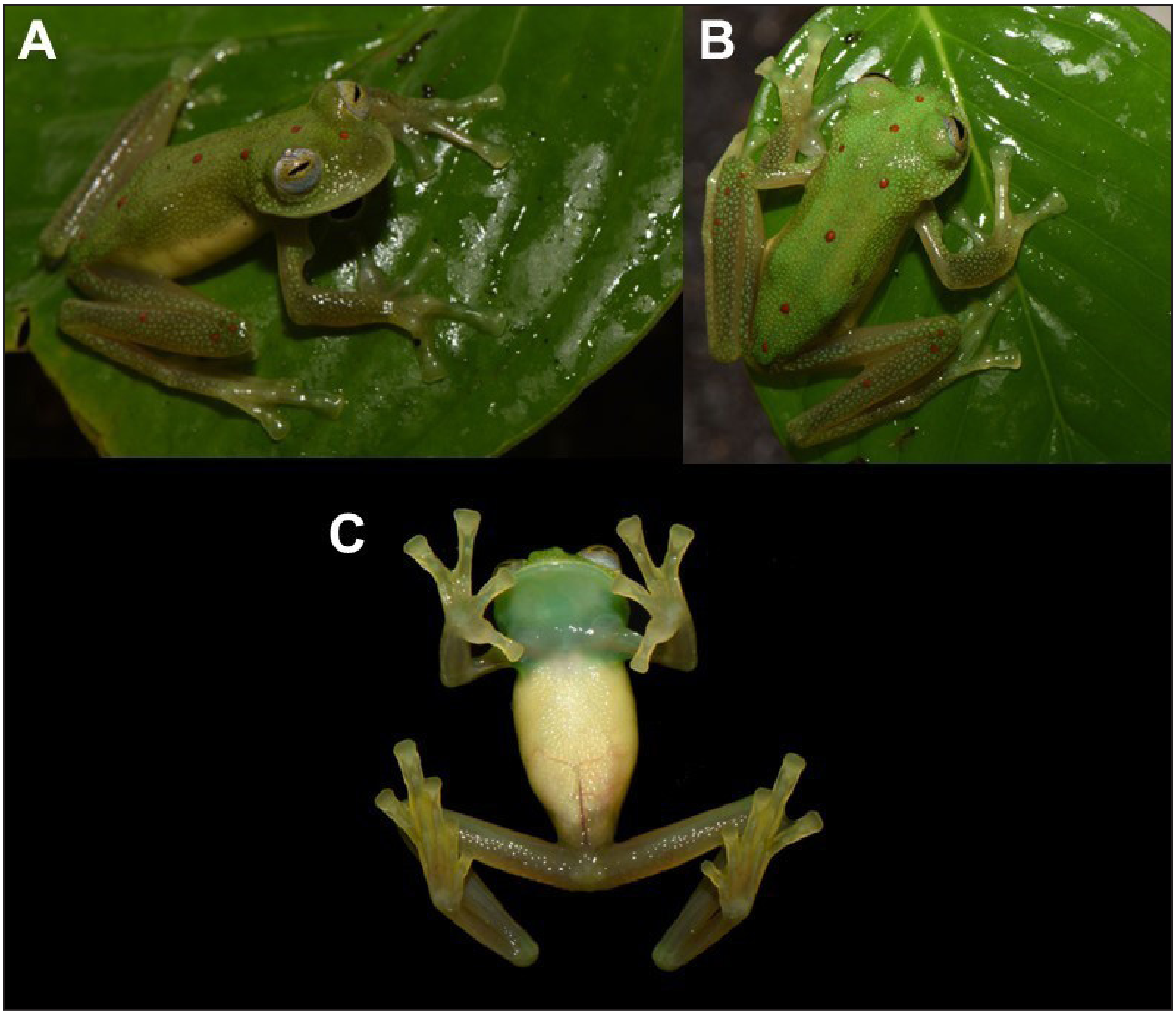

Figure 1. Photographs of the new occurrence record of *Nymphargus grandisonae* in Pululahua Geobotanical Reserve. **A.** lateral view, **B.** dorsal view, and **C.** ventral view. Photographs by: Mateo A. Vega-Yánez

suitability in the Central and Western cordillera, and important areas also in the Eastern cordillera.

Future model projections.

Distribution projections for the period 2061-2080 under the SSP370 scenario, based on four global climate models (EC-Earth3-Veg, GISS-E2-1-G, IPSL-CM6A-LR, and MPI-ESM1-2-HR), show heterogeneous patterns with areas of convergence (Fig. 2). The models project a fragmented distribution of the species in certain areas of the foothills of the Andes in Ecuador and Colombia. In addition, an average elevational shift of 270 m is projected throughout the range, with a higher increase of 312 m in Ecuador.

On the other hand, a significant reduction in the area projected by the different global climate models (GCMs) is observed in Colombia, Ecuador and throughout the full range of *N. grandisonae* (Table 1). The EC-Earth3-Veg model projects the highest total area loss (33,420 km^2), which is concentrated primarily in Colombia, and demonstrates the most significant contraction of the full range (57%). In contrast, the GISS-E2-1-G model projects the highest area gain (16,438 km^2), particularly in Colombia, and shows the lowest contraction in this country (23%). However, in Ecuador, this model estimates a significant loss of 6,667 km^2, the highest among all models for that country, with a contraction of 51%. The IPSL-CM6A-LR model is an intermediate projection, with a total loss of 31,069 km^2 and an overall contraction of 37%. In Colombia, the loss extends

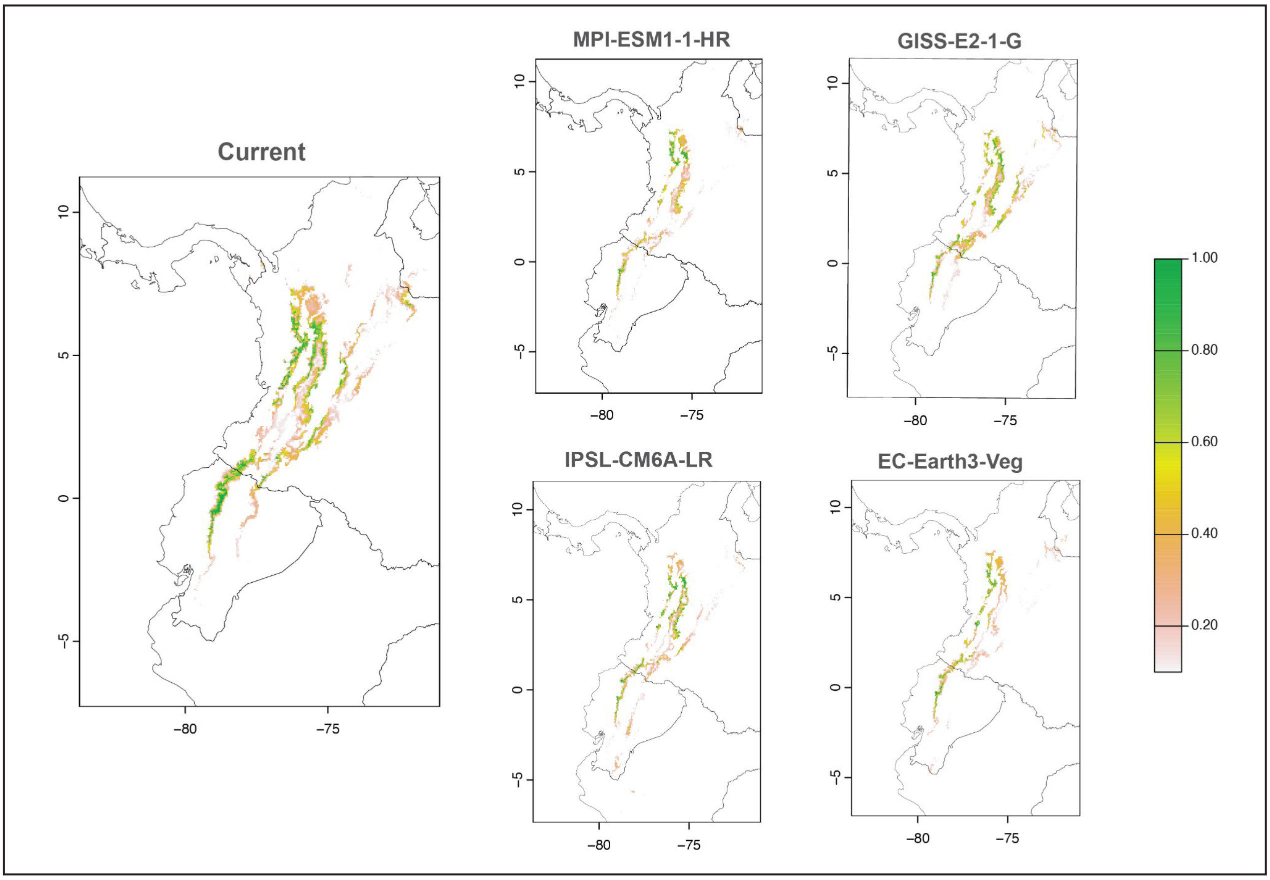

Figure 2. Geographical patterns of suitable habitat for *Nymphargus grandisonae* in the Northern Andes of South America and future models under four global climate models (GCMs) for the SSP3-7.0 scenario for the time-horizon 2061 - 2080.

to 26,583 km^2 (indicating a 50% contraction), while in Ecuador, the projected reduction is 47%. The MPI-ESM-2-HR model also projects a considerable loss (31,169 km^2) and a total range contraction of 52%. Despite Colombia maintaining its status as the most affected country in absolute terms (29,739 km^2 lost), Ecuador demonstrates the most significant percentage contraction (54%) among all models analyzed (Fig. 3).

Analysis of climatic variables.

The results of the Variance Inflation Factor (VIF) analysis indicate that five bioclimatic variables (bio2, bio4, bio9, bio18, and bio19) do not exhibit significant autocorrelation, so they can be considered independent of each other. The correlation coefficients between them vary from a minimum of -0.0418 (between bio9 and bio2) to a maximum of 0.4347 (between bio9 and bio19), indicating a low correlation. These variables help to explain, to a certain extent, the climatic niche of *N. grandisonae*. The species avoids areas of excessive heat and drought, and requires moisture even in winter. Its thermal tolerance varies according to the environment: in hot, dry climates it is adapted to water stress, while in regions with more stable temperatures it depends on permanently humid environments. It is particularly sensitive to variations in rainfall and temperature, with a strong dependence on rainfall in the warm season and humidity in the winter.

Analyzing the changes of these variables in the future (2061-2080) under Shared Socio-economic Pathways SSP3-7.0 as a function of the four global climate models (GCMs), it is observed that they have different climate projections (Fig. 4). However, there is a general trend towards an increase in the variables bio4 and bio9, while the variables bio2, bio18, and bio19 tend to decrease. In particular, the variables bio18 and bio19 (precipitation) show an increase only in the IPSL-CM6A-LR model compared to current conditions (Fig. 4A). The temperature variables, especially bio4, show a decrease in all models, with the GISS-E2-1-G model projecting the highest decrease compared to current conditions. An increase is projected for bio2 and bio9, although the IPSL-CM6A-LR model indicates a decrease for bio9 (Fig.

Table 1. Values of total area, loss, and potential area gain of *N. grandisonae* based on global climate models for Ecuador and its entire range. Negative values show loss of surface

		Full Range (km2)	**Colombia (km2)**	**Ecuador (km2)**
Current	Total area	49,466	40,512	8,953
EC-Earth3-Veg	Projected total area	21,137	16,203	4,934
	Gain Area	5,176	4,407	684
	Loss Area	33,420	29,596	5,363
	Absolute change	28,329	24,309	4,020
	Contraction area %	57	60	45
GISS-E2-1-G	Projected total area	37,366	32,952	4,413
	Gain Area	16,438	15,563	1,133
	Loss Area	28,495	25,441	6,667
	Absolute change	12,100	7,560	4,540
	Contraction area %	32	23	51
IPSL-CM6A-LR	Projected total area	24,815	20,055	4,760
	Gain Area	6,418	5,201	1,217
	Loss Area	31,069	26,583	6,966
	Absolute change	18,397	20,457	4,194
	Contraction area %	37	50	47
MPI-ESM-2-HR	Projected total area	23,923	19,782	4,141
	Gain Area	5,749	5,215	534
	Loss Area	31,169	29,739	7,051
	Absolute change	25,543	20,730	4,813
	Contraction area %	52	51	54

4B). Non-metric multidimensional scaling (NMDS) analysis showed that the Procrustes analysis showed a good fit between the configurations, with a low root mean square error (RMSE) (0.0453) and a moderate maximum residual (0.0819), indicating a high similarity between the compared structures. Moreover, the algorithm sufficiently complied with the convergence criteria and stopped at a sufficiently low stress level. In the reduced space (dimensions MDS1 and MDS2), clear patterns of similarity and difference between the climate models and the current conditions are observed (Fig. 4B). The EC-Earth3-Veg model is the closest to the present, suggesting a high structural similarity according to the variables analysed. In contrast, IPSL-CM6A-LR is the most distant model from the present model, indicating a higher divergence in terms of climate structure. Among the models, GISS-E2-1-G and MPI-ESM1-2-HR show the highest mutual proximity, that they share common features in multivariate space, although both are relatively far from the current. The IPSL-CM6A-LR model is not only far from the present, but also maintains a considerable distance from the other models, which positions it as the most isolated in terms of structural similarity.

Spatio-temporal dynamics of vegetation.

It is estimated that between 1985 and 2022, there was a net loss of approximately 32,600 hectares of vegetation cover within the potential range of *N. grandisonae* in the northern Andes of South America (Fig. 5). In Colombia, the loss is predominantly concentrated in the foothills of the Western, Central and Eastern Cordilleras. In Ecuador, deforestation is most severe along the western slopes of the Andes, including areas in close proximity to the new site where the species has been recorded (Pululahua Geobotanical Reserve). The analysis of rates of change and average deforestation values between 1985 and 2020 shows variations both at the full range level and in national contexts (Colombia and Ecuador) (Fig. 6; Table 2). Within the full range, the dynamics of vegetation cover loss have been marked by fluctuations, with negative deforestation rates observed in the majority of the periods analyzed. The 1995-2000 and 2015-2020 periods registered the highest average deforestation rates, with estimated losses of 13,060 ha/year (2.0%) and 9,800 ha/year (1.5%), respectively. In Colombia, the period 1985-1990 evidenced a net increase in forest cover, with an annual gain of 9,880 ha. However, between 1990 and 1995, there was a sharp decrease, with a nega-

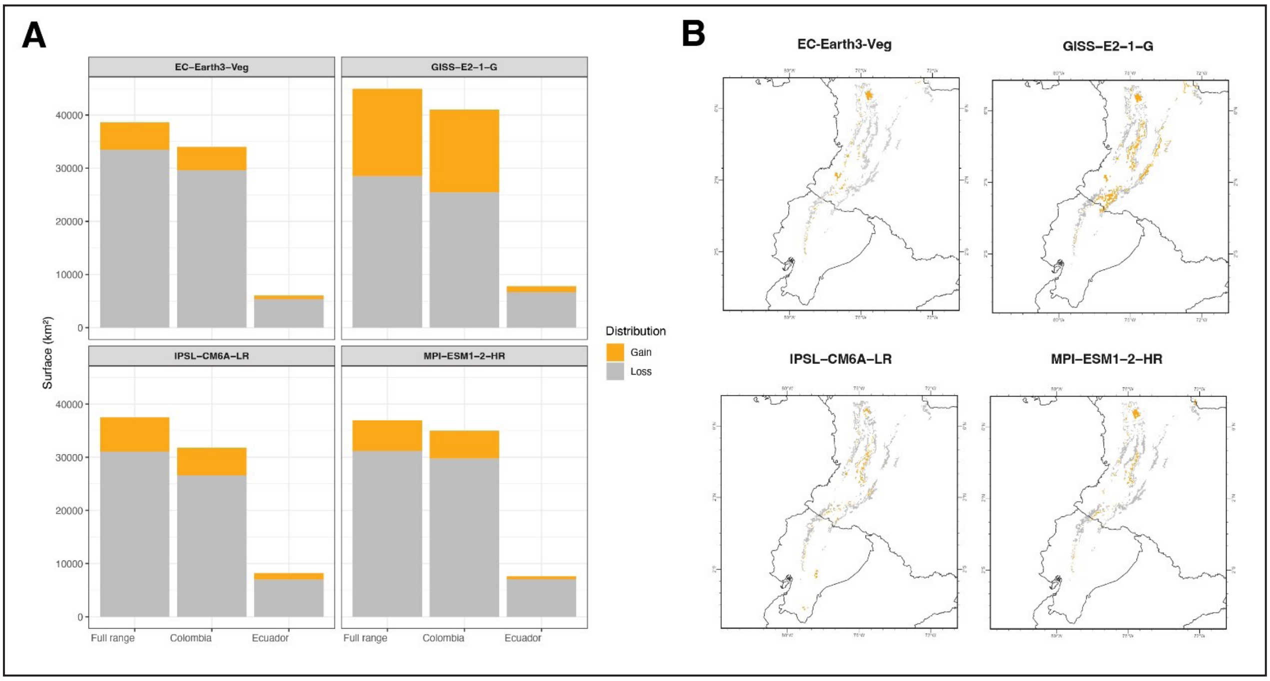

Figure 3. A. Surface area in square kilometers of gain and loss in the distribution of *Nymphargus grandisonae* according to the four global climate models (GCMs), compared to its current distribution. **B.** Maps of gain and loss in distribution according to the different models.

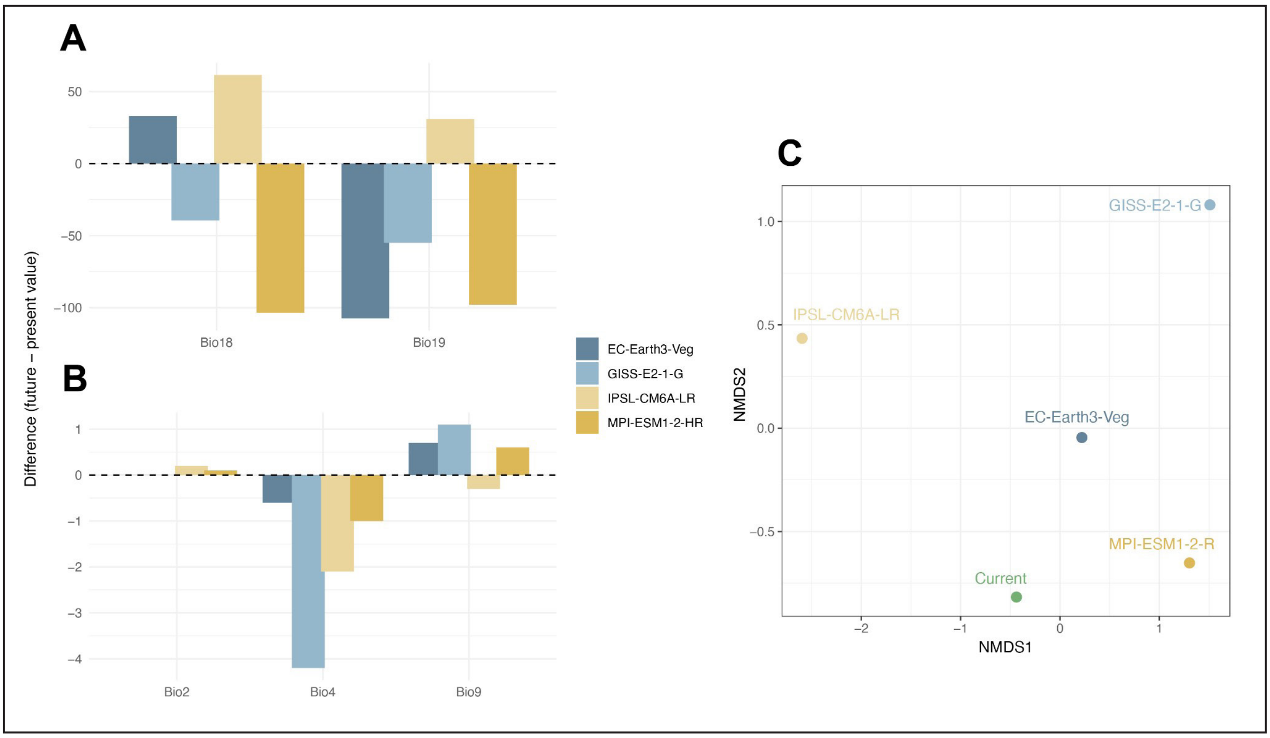

Figure 4. A. Difference between future and present values of precipitation variables (bio18 = Precipitation of Warmest Quarter and bio19 = Precipitation of Coldest Quarter) according to the four global climate models for the distribution of *N. grandisonae* in Ecuador. ***B***. Difference between future and present values of temperature variables (bio2 = Mean Diurnal Range, bio4 = Temperature Seasonality, and bio9 = Mean Temperature of Driest Quarter). **C**. Non-metric multidimensional scaling (NMDS) of temperature and precipitation variables grouped according to the four global climate models (GCMs) and current conditions.

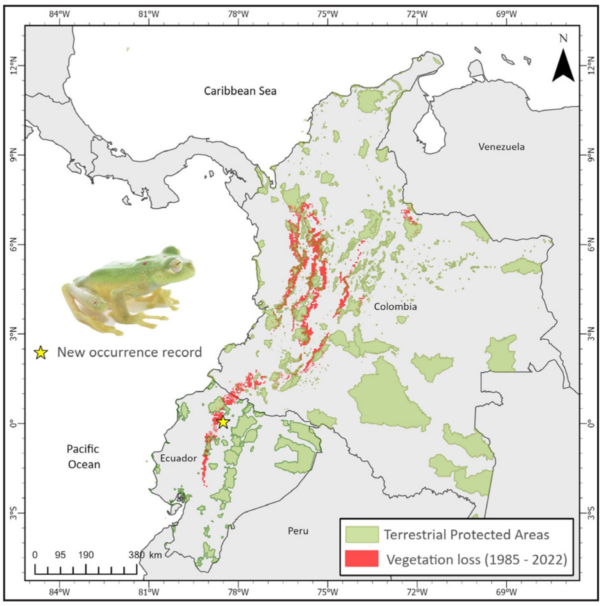

Figure 5. Map of gross vegetation loss in the distribution range of *N. grandisonae* and its new record in the Pululahua Geobotanical Reserve, Ecuador.

tive rate of change (-0.1436), a net loss of 3,720 ha/year and a percentage rate of deforestation of 0.72%. Subsequently, between 1995 and 2000, there was a considerable increase (15,140 ha/year), followed by a slight growth trend until reaching a significant loss again between 2015 and 2020 (8,980 ha/year). While in Ecuador exhibits a more persistent pattern of forest loss over time. The highest recorded rates were observed between 1995-2000 and 2000-2005, with averages of 2,080 ha/year (1.62%) and 1,880 ha/year (1.48%), correspondingly. In contrast to the Colombian case, Ecuador experienced a temporary recovery between 2005 and 2015, with net increases in vegetation cover during two consecutive periods. However, this trend underwent a reversal between 2015 and 2020, during which a loss of 820 ha/year was recorded (Table 2). Currently, across its entire range, the species covers approximately 49,466 km², of which 19,515 km² are within protected areas, equivalent to only 39.4% of its potential habitat under formal protection. Representation differs significantly between countries. In Ecuador, the species occupies 8,953 km², but only 2,833 km² are included in protected areas (31.6%). In Colombia, which has the largest proportion of the distribution (40,512 km²), around 16,681 km² are under protection (41.1%).

Table 2. Rate of vegetation change and average deforestation in the potential habitat of the *Nymphargus grandisonae*. Negative (-) values are related to deforestation, while positive (+) values represent gain in forest cover.

Period	**Rate of change**	**Average deforestation ha/year**	**Average deforestation rate (%)**
	Full range		
1985 - 1990	-0.0029	-9,300	1.46
1990 - 1995	0.0010	+3,360	-
1995 - 2000	-0.0040	-13,060	2.0
2000 - 2005	0.0005	+1,620	-
2005 - 2010	-0.001	-3,340	0.5
2010 - 2015	-0.0008	-2,500	0.38
2015 - 2020	-0.003	-9,800	1.50
	Colombia		
1985 - 1990	0.0038	+9,880	-
1990 - 1995	-0.1436	-3,720	0.72
1995 - 2000	0.0058	+15,140	-
2000 - 2005	0.0001	+240	-
2005 - 2010	0.0005	+1,240	-
2010 - 2015	0.0007	+1,900	-
2015 - 2020	-0.0034	-8,980	1.68
	Ecuador		
1985 - 1990	-0.0009	-580	0.45
1990 - 1995	0.0006	+360	-
1995 - 2000	-0.0033	-2,080	1.62

2000 - 2005	-0.0030	-1,880	1.48
2005 - 2010	0.0034	+2,140	-
2010 - 2015	0.0009	+580	-
2015 - 2020	-0.0013	820	0.64

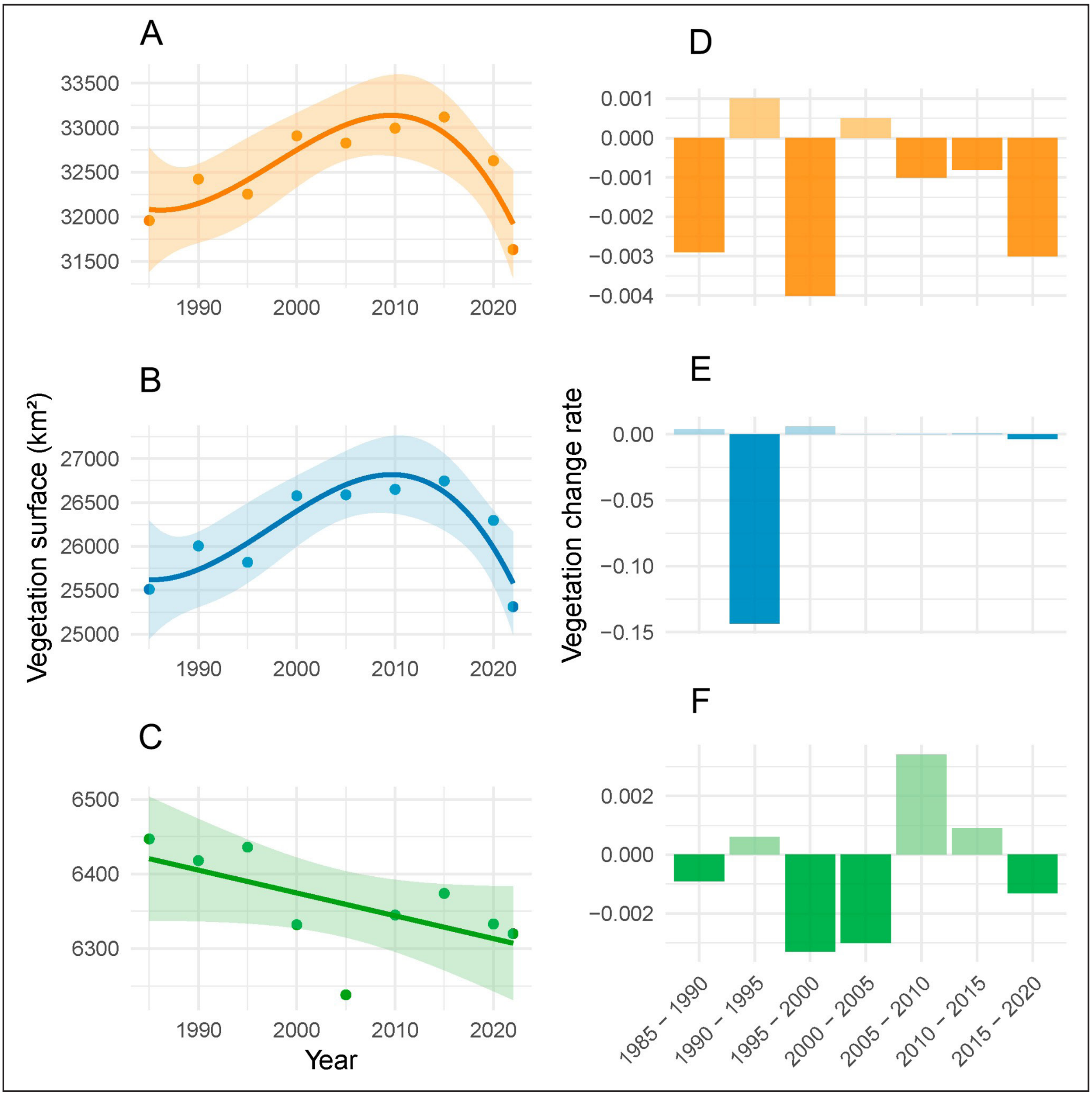

Figure 6. Changes in vegetation cover within the range of *N. grandisonae* between 1985 and 2022. **A**-**C**. Vegetation surface area (km²): **A**. full range, **B**. Colombia, and **C**. Ecuador. **D**-**F**. Rate of change vegetation cover: **D**. full range, **E**. Colombia, and F. Ecuador.

Discussion

Our study underscores the value of integrating ecological, climatic, and spatial evidence to refine the conservation status of *Nymphargus grandisonae*. Beyond documenting a new record for the species, our results show that accelerated habitat loss combined with projected climate change could reduce its suitable range by nearly half by the end of the century. Although currently listed as Least Concern (LC), the species shows marked sensitivity to declining humidity, temperature shifts, and increasing fragmentation. Because climate alone rarely captures the full extent of future pressures on amphibians, incorporating land-use dynamics is essential. Studies integrating climate and land-use scenarios have shown that while climate drives broad distributional trends, land-use trajectories can modulate or even redirect range shifts (Blank & Blaustein, 2012). Likewise, presence-only modeling in threatened amphibians demonstrates that accounting for fine-scale habitat attributes substantially improves the identification of priority conservation areas (Préau *et al.* 2019). Together, these insights highlight the importance of combining multiple modeling approaches and reinforce the urgency of conservation strategies that link habitat protection, land-use planning, and climate-change adaptation for the long-term persistence of *N. grandisonae*.

Regularly updating geographic distribution data remains fundamental for effective biodiversity assessment (Meyer *et al.*, 2015), particularly because species occurrence accuracy directly influences model performance. Likewise, future projections under climate change demand the incorporation of multiple global climate models (GCMs) to better capture the uncertainty surrounding potential species distributions. Although CMIP6 models share core physical foundations, they differ in methodological structure, component interactions, and the representation of processes such as carbon cycling, aerosols, and volcanic activity (Eyring *et al.*, 2016; Kim *et al.*, 2020). These differences can lead to contrasting outcomes, even under comparable emission scenarios. Our analyses indicate that IPSL-CM6A-LR is the only model projecting increases in wet-season (bio18) and dry-season (bio9) precipitation within the climatic niche of *N. grandisonae*, likely reflecting shifts or intensification of regional convergence zones and wind systems (Boucher *et al.*, 2020). Across scenarios, climate models predict an average 45% reduction in suitable range by 2061–2080, effectively erasing nearly half of the species range. Such contraction is expected to amplify fragmentation, elevate the risk of demographic bottlenecks, and erode genetic diversity (Beebee, 2005; Guan *et al.*, 2021). Restricted gene flow among isolated populations would further increase drift and inbreeding, reduce the capacity of the species to respond to environmental change, and raise the risk of local and even global extirpation.

Projections also indicate an upward shift in the species altitudinal distribution, emphasizing the need to safeguard potential refuge areas and limit human activities within them to ensure long term persistence. In Ecuador, *N. grandisonae* occupies a relatively small range and continues to experience vegetation loss, with degradation occurring even inside protected areas. This pattern shows that protected areas remain vulnerable to deforestation, degradation, fragmentation and fire. Between 1990 and 2018, about four percent of national cumulative deforestation took place within the Sistema Nacional de Áreas Protegidas (Kleeman *et al.*, 2022). These trends raise concerns about the effectiveness of protected area management and the broader capacity to conserve vegetation in Ecuador. Given the projected upslope shift of *N. grandisonae*, conservation strategies should prioritize maintaining elevational connectivity by protecting the remaining forest along altitudinal gradients and restoring degraded high elevation habitats. This continuity is essential for enabling populations to track suitable climatic conditions through time (Hannah *et al.*, 2007). In addition, streams and rivers, together with their riparian vegetation, should be recognized as key ecological corridors because they connect breeding sites, facilitate dispersal and provide stable microclimatic refuges for biphasic amphibians. Strengthening enforcement within protected areas is essential to curb illegal logging and limit further fragmentation. Restoring riparian buffers and safeguarding the integrity of headwater streams would improve habitat quality and connectivity while reducing sedimentation and hydrological disruption (Thieme *et al.*, 2023). Establishing ecological corridors between isolated populations would help maintain gene flow and reduce the risk of inbreeding. Implementing long term monitoring programmes that combine field surveys with remote sensing would support adaptive management and allow early detection of habitat change.

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Literature cited

Agudelo-Hz, W. J., Urbina-Cardona, N., & Armenteras-Pascual, D. (2019). Critical shifts on spatial traits and the risk of extinction of Andean anurans: an assessment of the combined effects of climate and land-use change in

Colombia. *Perspectives in Ecology and Conservation*, 17: 206-219.

Allouche, O., Tsoar, A., & Kadmon, R. (2006). Assessing the accuracy of species distribution models: prevalence, kappa and the true skill statistic (TSS). *Journal of Applied Ecology,* 43: 1223-1232.

Antão, L. H., Bates, A. E., Blowes, S. A., Waldock, C., Supp, S. R., Magurran, A. E., Dornelas, M., & Schipper, A. M. (2020). Temperature-related biodiversity change across temperate marine and terrestrial systems. *Nature Ecology & Evolution*, 4: 927-933.

Aponte-Gutiérrez, A. F., Arcila-Pérez, L. F., & Galeano, S. P. (2024). The first record of Amazophrynella siona Rojas-Zamora *et al.*, 2018 in Colombia, with notes on its natural history. *Herpetology Notes*, 17: 431-435. https://www.biotaxa.org/hn/article/view/83211

Blank, L., & Blaustein, L. (2012). Using ecological niche modeling to predict the distributions of two endangered amphibian species in aquatic breeding sites. *Hydrobiologia*, 693, 157–167.

Beebee, T. J. C. (2005). Conservation genetics of amphibians. *Heredity*, 95: 423-427.

Bellard, C., Marino, C., & Courchamp, F. (2022). Ranking threats to biodiversity and why it doesn't matter. *Nature Communications*, 13: 2616.

Boucher, O., Servonnat, J., Albright, A. L., Aumont, O., Balkanski, Y., Bastrikov, V., ... & Vuichard, N. (2020). Presentation and evaluation of the IPSL-CM6A-LR climate model. *Journal of Advances in Modeling Earth Systems*, 12: e2019MS002010.

Broennimann, O., Di Cola, V., Petitpierre, B., Breiner, F., Scherrer, D., Manuela, D., & Broennimann, M. O. (2014). Package 'ecospat'. [WWW document] URL https://cran.r-project.org/web/packages/ecospat/index.html

Brook, B. W., Sodhi, N. S., & Bradshaw, C. J. (2008). Synergies among extinction drivers under global change. Trends in Ecology & Evolution, 23: 453-460.

Burrows, M. T., Schoeman, D. S., Buckley, L. B., Moore, P., Poloczanska, E. S., Brander, K. M., Brown, C., Bruno, J. F., Duarte, C. M., Halpern, B. S., Holding, J., Kappel, C. V., Kiessling, W., O'Connor, M. I., Pandolfi, J. M., Parmesan, C., Schwing, F. B., Sydeman, W. J., & Richardson, A. J. (2011). The pace of shifting climate in marine and terrestrial ecosystems. *Science*, 334: 652-655.

Castroviejo-Fisher, S., Guayasamin, J. M., Gonzalez-Voyer, A., & Vilà, C. (2014). Neotropical diversification seen through glassfrogs. *Journal of Biogeography*, 41: 66-80.

Cochran, D. M., & Goin, C. J. (1970). Frogs of Colombia. Bulletin of the United States National Museum. Washington, D. C. 288: 1-655.

Copete Mosquera, L. A., Restrepo Montoya, J., & Sánchez Vialas, A. (2024). El registro más meridional del sapo picudo de Antioquia Rhinella tenrec (Anura: Bufonidae). *Revista Latinoamericana de Herpetología*, 7: e898 (58-62)

Eyring, V., Bony, S., Meehl, G. A., Senior, C. A., Stevens, B., Stouffer, R. J., & Taylor, K. E. (2016). Overview of the Coupled Model Intercomparison Project Phase 6 (CMIP6) experimental design and organization. *Geoscientific Model Development*, 9: 1937-1958.

Fick, S. E., & Hijmans, R. J. (2017). WorldClim 2: new 1km spatial resolution climate surfaces for global land areas. *International Journal of Climatology*, 37: 4302-4315.

Frost, D. R. (2025). Amphibian Species of the World: an Online Reference. Version 6.2 (1/07/2025). American Museum of Natural History. https://amphibiansoftheworld.amnh.org/index.php.

González-González, A., Villegas, J. C., Clerici, N., & Salazar, J. F. (2021). Spatial-temporal dynamics of deforestation and its drivers indicate need for locally-adapted environmental governance in Colombia. *Ecological Indicators*, 126: 107695.

Guan, B., Gao, J., Chen, W., Gong, X., & Ge, G. (2021). The effects of climate change on landscape connectivity and genetic clusters in a small subtropical and warm-temperate tree. *Frontiers in Plant Science*, 12: 671336.

Guayasamin, J. M., Castroviejo-Fisher, S., Trueb, L., Ayarzagüena, J., Rada, M., & Vila, C. (2009). Phylogenetic systematics of Glassfrogs (Amphibia: Centrolenidae) and their sister taxon Allophryne ruthveni. *Zootaxa*, 2100: 1-97.

Guayasamin, J. M., Cisneros-Heredia, D. F., McDiarmid, R. W., Peña, P., & Hutter, C. R. (2020). Glassfrogs of Ecuador: Diversity, Evolution, and Conservation. *Diversity,* 12: 222.

Hannah, L., Midgley, G., Andelman, S., Araújo, M. B., Hughes, G., Martínez-Meyer, E., Pearson, R. G., & Williams, P. (2007). Protected area needs in a changing climate. *Frontiers in Ecology and the Environment*, 5: 131-138.

Hutter, C. R., Esobar-Lasso, S., Rojas-Morales, J. A., Gutiérrez-Cárdenas, P. D. A., Imba, H., & Guayasamin, J. M. (2013a). The territoriality, vocalizations and aggressive interactions of the red-spotted glassfrog, Nymphargus grandisonae, Cochran and Goin, 1970 (Anura: Centrolenidae). *Journal of Natural History*, 47: 3011-3032.

Hutter, C. R., Guayasamin, J. M., & Wiens, J. J. (2013b). Explaining Andean megadiversity: the evolutionary and ecological causes of glassfrog elevational richness patterns. Ecology Letters, 16: 1135-1144.

Jetz, W., Wilcove, D. S., & Dobson, A. P. (2007). Projected Impacts of Climate and Land-Use Change on the Global Diversity of Birds. PLoS Biology, 5: e157.

Kim, Y. H., Min, S. K., Zhang, X., Sillmann, J., & Sandstad, M. (2020). Evaluation of the CMIP6 multi-model ensemble for climate extreme indices. Weather and Climate Extremes, 29, 100269.

Kleemann, J., Zamora, C., Villacis-Chiluisa, A. B., Cuenca, P., Koo, H., Noh, J. K., & Thiel, M. (2022). Deforestation in continental Ecuador with a focus on protected areas. *Land*, 11: 268.

Lenoir, J., Bertrand, R., Comte, L., Bourgeaud, L., Hattab, T., Murienne, J., & Grenouillet, G. (2020). Species better track climate warming in the oceans than on land. *Nature Ecology & Evolution*, 4: 1044-1059.

Li, W., & Guo, Q. (2013). How to assess the prediction accuracy of species presence–absence models without absence data? *Ecography*, 36: 788-799.

Luedtke, J. A., Chanson, J., Neam, K., *et al.* (2023). Ongoing declines for the world's amphibians in the face of emerging threats. *Nature*, 622, 308–314.

Mantyka-Pringle, C. S., Martin, T. G., & Rhodes, J. R. (2012). Interactions between Climate and Habitat Loss Effects on Biodiversity: A Systematic Review and Meta-Analysis. *Global Change Biology*, 18: 1239-1252.

MapBiomas Colombia Project. (2025). Colección 2.0 de mapas anuales de cobertura y uso del suelo de Colombia. Gaia Amazonas Foundation. https://colombia.mapbiomas.org

Meyer, C., Kreft, H., Guralnick, R., & Jetz, W. (2015). Global priorities for an effective information basis of biodiversity distributions. *Nature Communications*, 6: 1-8.

Naimi, B., Hamm, N. A., Groen, T. A., Skidmore, A. K., & Toxopeus, A. G. (2014). Where is positional uncertainty a problem for species distribution modelling? *Ecography*, 37: 191-203.

Newbold, T. (2018). Future effects of climate and land-use change on terrestrial vertebrate community diversity under different scenarios. Proceedings of the Royal Society B, 285: 20180792.

Oksanen, J., Simpson, G. L., Blanchet, F. G., Kindt, R., Legendre, P., Minchin, P. R., O'Hara, R. B., Solymos, P., Stevens, M. H. H., Szoecs, E., Wagner, H., Barbour, M., Bedward, M., Bolker, B., Borcard, D., Carvalho, G., Chirico, M., De Caceres, M., Durand, S., Weedon, J. (2022). vegan: Community Ecology Package (Version 2.6-4) [Software]. CRAN. https://CRAN.R-project.org/package=vegan

Passarelli, D., Denton, F., & Day, A. (2021). Beyond opportunism: The UN development system's response to the triple planetary crisis. United Nations University. https://i.unu.edu/media/cpr.unu.edu/attachment/4977/UNUTriplePlanetaryCrisis2021.pdf

Préau, C., Isselin-Nondedeu, F., Sellier, Y., Bertrand, R., & Grandjean, F. (2019). Predicting suitable habitats of four range margin amphibians under climate and land-use changes in southwestern France. *Regional Environmental Change*, 19: 27-38.

Puyravaud, J. P. (2003). Standardizing the calculation of the annual rate of deforestation. *Forest Ecology and Management*, 177: 593-596.

R Development Core Team. (2024). R: A language and environment for statistical computing. R Foundation for Statistical Computing. http://www.R-project.org

Ripple, W. J., Wolf, C., Gregg, J. W., & Torres-Romero, E. J. (2025). Climate change threats to Earth's wild animals. *BioScience*, biaf059.

Rivas, C. A., Guerrero-Casado, J., & Navarro-Cerrillo, R. M. (2024). Functional connectivity across dominant forest ecosystems in Ecuador: A major challenge for a country with a high deforestation rate. *Journal for Nature Conservation*, 78: 126549.

Román-Palacios, C., & Wiens, J. J. (2020). Recent responses to climate change reveal the drivers of species extinction and survival. *Proceedings of the National Academy of Sciences*, 117: 4211-4217.

Roy, B. A., Zorrilla, M., Endara, L., Thomas, D. C., Vandegrift, R., Rubenstein, J. M., & Read, M. (2018). New mining concessions could severely decrease biodiversity and ecosystem services in Ecuador. *Tropical Conservation Science*, 11: 1940082918780427.

Sánchez-Nivicela, J. C., Székely, D., Salagaje, M. L. A., Astudillo-Abad, N., Culebras, J., Ortiz, E. A., & Székely, P. (2024). One hundred years of solitude: The rediscovery of Pristimantis ruidus (Anura, Strabomantidae) in the southern Andes, Ecuador and its phylogenetic relationships. *Zoosystematics and Evolution*, 100: 1107-1120.

Scheffers, B. R., De Meester, L., Bridge, T. C. L., Hoffmann, A. A., Pandolfi, J. M., Corlett, R. T., Butchart, S. H. M., Pearce-Kelly, P., Kovacs, K. M., Dudgeon, D., Pacifici, M., Rondinini, C., Foden, W. B., Martin, T. G., Mora, C., Bickford, D., & Watson, J. E. M. (2016). The broad footprint of climate change from genes to biomes to people. *Science*, 354: aaf7671.

Soberon, J., & Peterson, A. T. (2005). Interpretation of models of fundamental ecological niches and species' distributional areas. Biodiversity Informatics, 2.

Taylor, E. H. (1951). Two new genera and a new family of tropical American frogs. Proceedings of the Biological Society of Washington, 64, 33–40. https://biostor.org/reference/65690

Thieme, M., Birnie-Gauvin, K., Opperman, J. J., Franklin, P. A., Richter, H., Baumgartner, L., Silva, L. G. M., & Cooke, S. J. (2023). Measures to safeguard and restore river connectivity. *Environmental Reviews, 32*: 366-386.

Vega-Yánez, M. A., Quezada-Riera, A. B., Rios-Touma, B., Vizcaíno-Barba, M. d. C., Millingalli, W., Ganzino, O., Coloma, L. A., Tapia, E. E., Dupérré, N., Páez-Vacas, M., Parra-Puente, D., Franco-Mena, D., Gavilanes, G., Salazar-Valenzuela, D., Valle, C. A., & Guayasamin, J. M. (2024). Path for recovery: an ecological overview of the Jambato Harlequin Toad (Bufonidae: Atelopus ignescens) in its last known locality, Angamarca Valley, Ecuador. PeerJ, 12: e17344.

Wiens, J. J. (2016). Climate-related local extinctions are already widespread among plant and animal species. *PLoS Biology*, 14: e2001104.