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Effects of future climate change and habitat loss in the distribution of frog species in the Ecuadorian Andes

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1. ABSTRACT

The biodiversity of the tropical Andes is threatened by climate change and habitat loss. Many studies have focused in the future effects of climate change on species distribution and conservation but few have included the effects habitat loss in their predictive studies. In this study we evaluated the combined effects of these two threats in the future distributions of endemic frogs species of the Ecuadorian Andes to the year 2050. We used ecological niche models to predict the distribution of 68 frog species using a combination of four Representative Concentration Pathway scenarios of future climate and four scenarios of dispersal capabilities. We constructed a predictive model of natural vegetation loss in Ecuador by 2050 using the Multi-Layer Perceptron neural network and Markov Chain analysis algorithms. We also explored how changes in frogs species richness resulting from climate change and habitat loss correlate with altitude and magnitude of climate change. Our results show climate change had a positive effect on the future distribution area of ~60% of the frogs species, and a negative effect in ~40%. Dispersal capabilities greatly influenced the effect of climate change and habitat loss on distribution areas. Change in species richness due to climate change show positive correlations mainly with altitude, temperature and precipitation. Future habitat loss will exacerbate the negative effects of climate change and will limit its positive effects on frogs species' distributions. Our results suggest that, under a limited dispersal scenario, most Andean frogs species will be unable to effectively colonize new suitable habitat as result of habitat loss. Conversely, under dispersal scenarios of 5 km per year or more, climate change could have a positive effect in the area of distribution of most species. There are no specific studies on the dispersal capabilities of Andean frogs. Our study, illustrates the role of dispersal in the future effects of climate change and habitat loss.

2. RESUMEN

La biodiversidad de los Andes tropicales está siendo amenazada por el cambio climático y la pérdida de hábitat. Varios estudios se han enfocado en los efectos futuros del cambio climático en la distribución de las especies pero pocos han incluido los efectos de la perdida de hábitat en sus predicciones. En este estudio evaluamos los efectos combinados de estas dos amenazas en las distribuciones futuras de las especies endémicas de ranas de los Andes ecuatorianos para el año 2050. Utilizamos modelos de idoneidad de hábitat para predecir la distribución de 68 especies de ranas con una combinación de cuatro escenarios *Representative Concentration Pathways* de clima futuro y cuatro escenarios de capacidad de dispersión. Hicimos un modelo predictivo de cambio de la vegetación natural en el Ecuador para el 2050 usando los algoritmos *Multi-Layer Perceptron neural network* y el análisis de cadenas de Markov. También exploramos como los cambios en la riqueza de especies de anfibios resultantes del cambio climático y la perdida de hábitat se correlacionan con la altura y la magnitud del cambio climático. Nuestros resultados muestran que el cambio climático tuvo un efecto positivo en el área de distribución futura para ~ 60% de especies de ranas, y un efecto negativo para ~ 40%. Las capacidades de dispersión influenciaron enormemente en el efecto del cambio climático y la perdida de hábitat en las áreas de distribución. Cambios en la riqueza de las especies muestran correlaciones positivas principalmente con la altura, temperatura, y precipitación. La futura perdida de hábitat exacerbará los efectos negativos del cambio climático y limitará sus efectos positivos en la distribución de las especies de anfibios. Nuestros resultados sugieren que, bajo escenarios de dispersión limitados, la mayor parte de anfibios de los Andes serán incapaces de colonizar efectivamente nuevos hábitats idóneos como resultado del cambio climático y la pérdida de hábitat. En contraste, bajo escenarios de dispersión de 5 km por año o más, el cambio climático pudiera tener un efecto beneficioso en el área de distribución de la mayoría de especies. No existen estudios específicos sobre las capacidades de dispersión de los anfibios en los Andes. Nuestro estudio, ilustra el rol de la dispersión en el efecto futuro del cambio climático y la pérdida de hábitat.

3. INTRODUCTION

The Tropical Andes house an enormous biological richness with high levels of endemism (Gentry, 1982; Myers *et al.* 2000; Mittermeier *et al.* 2004; Killeen *et al.* 2007; Young and León 2007; Sarkar *et al.* 2008; Young, 2011). Yet, the tropical Andes are one of the most endangered biodiversity hotspots in the planet because of threats imposed by habitat loss and anthropogenic climate change (Myers *et al.* 2000; Mittermeier *et al.* 2004; Herzog *et al.* 2011). Habitat loss in the Andes is severe as its land cover has been transformed into “humanized landscapes” for millennia (Rodríguez-Mahecha *et al.* 2004; Young, 2009; Suárez *et al.* 2011; Cuesta *et al.* 2012). Moreover, climate change in the tropical Andes has already caused changes in temperature and humidity patterns, and several studies estimate the Andes will be one of the most affected regions in the world (Bradley *et al.* 2006; Young, 2009; Feeley and Silman 2010; Anderson *et al.* 2011, Cuesta *et al.* 2012). Therefore, research and opportune conservation measures are vital to protect the biodiversity of the tropical Andes.

The tropical Andes hotspot has the greatest amphibian diversity in the world (Mittermeier *et al.* 2004). Unfortunately, Andean frogs are at risk because they are highly vulnerable to habitat loss and climate change (B. E. Young *et al.* 2004; Stuart *et al.* 2004; Stuart *et al.* 2008). Amphibians have relatively low dispersal capabilities, difficulty to cross anthropic barriers, tight habitat tolerance, and narrow thermal tolerances (i.e. tropical species of ectotherms) (Duellman, 1999; Corn, 2005; Cushman, 2006; Parmesan, 2006; Stuart *et al.* 2008; Tewksbury *et al.* 2008). These characteristics reduce their tolerance to shifts in temperature and their ability to follow geographical shifts of their climatic envelope (Parmesan, 2006). In addition, studies suggest that synergetic effects between climate change, disease (e.g. Pounds *et al.* 2006), and environmental stress (Alford *et al.*

2007) have caused amphibian declines even in pristine environments of the Tropical Andes (Ron *et al.* 2003; Merino-Viteri *et al.* 2005). Moreover, the Andes hold the highest endemism of amphibian species in South America (Duellman, 1999). Andean endemic species tend to be restricted to small and specific habitats which tend to be isolated, topographically irregular, have specific key elements for survival, and climatic stable conditions (Larsen *et al.* 2011; Duellman, 1999). These features put Andean endemic species of frogs at an even higher risk from habitat loss and climate change.

Ecuador is the third most amphibian-diverse country in the world (Chanson *et al.* 2008; Ron *et al.* 2014), and most of the country's endemic amphibian species occur in the Andean montane forests (Ron *et al.* 2011). The Ecuadorian Andes are not exempt from habitat loss and climate change pressures. This region of Ecuador has suffered important changes in its original land cover (Sierra and Stallings 1998; Sierra, 2013) with mean annual mean deforestation ranging from 32,209 to 85,686 ha between 1990–2000 and 2000–2008 (Ministerio del Ambiente, 2012). Moreover, climate in the Ecuadorian Andes has suffered a temperature increment of approximately 0.1°Celsius per decade between 1939 and 2006 (Bradley *et al.*, 2006; Vuille, 2008). Both habitat loss and climate change are predicted to continue their current trends in the future (Bradley *et al.* 2006; Vuille, 2008; Sierra, 2013). It is necessary to study the effects of climate change in amphibian climatic envelops along a parallel process of land cover change to elaborate conservation plans which allow the survival of frogs in the long-term (Mittermeier *et al.* 2004; Ron, 2008; Young, 2009).

Our study includes a novel approach to understand the effects of climate change in the Andes. We predict the effect of climate change on species distributions using recently released climate change scenarios. We combine those predictions with models of habitat loss based on predictive future scenarios, rather than applying present habitat loss maps to future climate change projections (e.g. Ron *et al.* 2011; Ortega-Andrade *et al.* 2013). In our present study we address the effects of climate change and habitat loss simultaneously in the distribution of endemic frogs species of the Ecuadorian Andes for the year 2050. Our aim was: 1) to determine the effects of climate change using RCP and dispersal scenarios; 2) to measure the combined effects of climate change and habitat loss; 3) to explore spatial patterns from climate change and habitat loss of frogs species richness in the Andes; and, 4) to give a conservation category in 2050 for each frog species based on the IUCN red list (IUCN, 2012).

4. MATERIALS AND METHODS

4.1 EFFECTS OF CLIMATE CHANGE IN SPECIES DISTRIBUTIONS

4.1.1 SPECIES SAMPLING

Our study focused on endemic species of frogs of the Ecuadorian Andes. Amphibians have been successfully used as models to study environmental changes (Hopkins, 2007). We considered endemic species because it ensures their whole distribution is included in the analyses. Ecuador is an ideal region to study the effects of climate change and habitat loss in the Andean frog biodiversity. The unique geographical features of the country have promoted high diversity and endemism (Gentry, 1982). The Ecuadorian Andes possess 165 endemic frogs, and amphibians in general have been exhaustively sampled in the country (Ron *et al*. 2014). In this study, we used georeferenced occurrence records from the amphibian data base collection in AmphibiaWebEcuador (www.zoologia.puce.edu.ec) which holds ~ 70,000 amphibian specimens from Ecuador. This database renders a sampling density of ~ 0.247 records per squared kilometer, which is suitable considering the MZUSP museum of the University of Sao Paulo collection (biton.uspnet.usp.br/mz/), which holds the largest amphibian collection in South America with ~140,000 specimens, and a sampling density of ~0.016 records per squared kilometer. This provides an adequate data source of both number and records of species for the present study.

Our study follows AmphibiaWeb (www.amphibiaweb.org) taxonomy except for *Pristimantis matidiktyo* which is considered junior synonym of *Pristimantis librarius* (M. Ortega-Andrade, personal communication).We considered frogs species that are endemic to Ecuador, and whose distribution is completely or partially contained in the Andes according to Ron *et al.* (2014). We excluded species known to inhabit disturbed areas since they may not be affected by habitat loss. Moreover, only endemic frogs species with ten or more locality records were considered to increase niche model accuracy (Hernandez *et al.* 2006; Wisz *et al.* 2008). To reduce spatial auto-correlation, we removed localities less than 2 km apart from each other (Hernandez *et al.* 2006; Hijmans 2012; Boria *et al.* 2014; Radosavljevic and Anderson 2014). A total of 1,659 records and 68 endemic frogs species were included in the analyses, which represents ~41% of the endemic amphibian species of the Ecuadorian Andes described to date (Ron *et al.* 2014).

4.1.2 SPECIES CURRENT DISTRIBUTIONS

We used species records to generate ecological niche models for the endemic frogs species of the Ecuadorian Andes. We used the maximum entropy algorithm implemented in Maxent 3.3.3k (Phillips *et al.* 2006), as it is the best option to model species environmental niches with presence-only occurrence data (Elith, Graham *et al.* 2006; Hernandez *et al.* 2006; Wisz *et al.* 2008). For the model we used climatic variables from WorldClim 1.4 database at a 30 arc-second resolution or ~1km^2 (Hijmans *et al.* 2005) as predictive variables. We eliminated highly correlated variables as suggested by Merow *et al.* (2013) by correlating the values of the 19 WorldClim variables from collection points of all endemic frogs species included in the model (Hernandez *et al.* 2006; Merow *et al.* 2013). Correlation groups were formed where Pearson correlation indexes between variables were higher than $r = 0.8$. Within each correlation group, variables correlated with fewer variables and with a lower mean correlation index were included. Seven climatic variables were thus, selected: isothermality (bio3), temperature seasonality (bio4), maximum temperature of warmest month (bio5), temperature annual range (bio7), precipitation seasonality (bio15), precipitation of warmest quarter (bio18), and precipitation of coldest quarter (bio19).

We constructed the models using the ENMeval package (Muscarella *et al.* 2014) in R software version 3.2.1 (R Core Team 2014). For model evaluation we followed Shcheglovitova and Anderson (2013) and Pearson *et al.* (2007). For endemic frogs species with less than 25 occurrence records, we used a jacknife k-fold cross-validation using the same number of bins as collection points. For species with more than 25 occurrence records, we used the block partitioning method, which is recommended for climate change studies (Muscarella *et al.* 2014). Feature class and regularization multiplier combinations were tested for model construction as recommended by Merow *et al.* (2013), and Radosavljevic and Anderson (2014). Models were constructed using combinations of regularization multipliers of 0.5 to 4 with 0.5 increments with feature combinations L, LQ, LP, LQH, LQP, LQHP, H, QH, HP, HQP, and LQHP (where L = linear, Q = quadratic, H = hinge, and P = product) (Muscarella *et al.* 2014; Radosavljevic and Anderson 2014). Combinations produced 88 models per endemic frog species. For each species we chose the model with lowest “minimum training presence” omission rate (OR_{MTP}) among models and with delta of Akaike’s information criterion (ΔAIC) lower than two (Burnham and Anderson 2004; Muscarella *et al.* 2014; Radosavljevic and Anderson 2014).

To determine the current ecological niche model, we used as presence-absence threshold the “maximum training plus specificity” (Liu *et al.* 2005, Liu *et al.* 2013; Syfert *et al.* 2014). Resulting models were used to analyze climate change effects on species future ecological niche (see section 4.1.4). Moreover, current ecological niche models were modified by expert criteria mainly based on historical records to obtain species current distribution. As an example, according to distribution records *Hyloxalus italoi* is distributed in the eastern foothill forest and in the tropical rain forest of Ecuador (Páez-Vacas *et al* 2010). However, the species ecological niche model also predicted the species in the northwest Ecuador. Very few species are distributed in low lands both at the east and west of the Andes because of geographical isolation (dos Santos *et al.* 2015). Hence, predicted distribution in the western Andes was eliminated. Another example is *Telmatobius niger* whose ecological niche model predicts the species in a wide latitudinal range over the Andes. Yet, the species has only been recorded in the central Andes (Merino-Viteri *et al.* 2005) despite extensive sampling in the northern Andes (Ron *et al*. 2014). As a result, the species current ecological niche was cropped accordingly. Such analyses were applied for all species. The resulting polygons were used as estimates of the current distribution of each species.

4.1.3 SPECIES DISTRIBUTIONS UNDER CLIMATE CHANGE

For each analyzed species of endemic frogs of the Ecuadorian Andes, we projected ecological niche models using predicted climatic variables for the year 2050. The general circulation model (GCM) was HadGEM2-ES of the Met Office from the Hadley Center (HadGEM2 Development Team, 2011) as it is considered stable and realistic (Collins *et al.* 2011; Jones *et al.* 2011; HadGEM2 Development Team *et al.* 2011), and performs well in the tropics (Martin et al. 2011). HadGEM2-ES was evaluated using Representative Concentration Pathways (RCPs) which are a new generation of climate scenarios which incorporate the latest economic, technological, and environmental global information to represent future climate conditions (Moss *et al.* 2010b; Jones *et al*. 2011). RCPs were selected as the best models in the Coupled Model Intercomparison Project 5 (Jones *et al.* 2011) and were released for the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (Collins *et al.* 2011; Jones *et al.* 2011).

We used RCPs 2.6, 4.5, 6.0, and 8.5 as climate change scenarios (Ramirez-Villegas and Jarvis 2010). Projected ecological niche models used the same feature class and regularization multiplier combination as the best model selected in the corresponding current ecological niche model. Future climatic variables were the same as those selected for the current ecological niche models. The "maximum training plus specificity" threshold was applied to the projected niche models, and the resulting polygon was considered as the geographic distribution in year 2050.

Projected niche models for future climate change were cut according to four dispersal scenarios. Scenarios included: no-dispersal, 1 km per year, 5 km per year, and universal dispersal. These scenarios were selected based on expert criteria and the literature (reviewed in Wells, 2007). The maximum dispersal distance recorded for an amphibian is 55 km per year (*Rhinella marina*, B. L. Phillips *et al.* 2007) and was originally considered as a dispersal scenario; but, was eliminated as it did not differentiated from the universal dispersal scenario when applied to the analyzed distributions of frogs. The 1 km and 5 km dispersal scenarios were calculated as the Euclidean distance from the limits of the current distribution to the closet suitable area in the future scenario using the software R (R Core Team, 2015). Under the universal-dispersal scenario the future ecological niche model was not cut. The other scenarios restricted the future ecological niche model depending on the scenario of the distance covered per year. Resulting polygons were assumed as scenarios of future distributions for each endemic frogs species of the Ecuadorian Andes.

4.1.4 EFFECTS OF CLIMATE CHANGE IN SPECIES DISTRIBUTIONS DATA ANALYSIS

For each species, we calculated the proportion of change in area between current and future climate conditions with ecological niche modeling. We obtained the proportions by dividing future area of suitable habitat by current area, for each species. These proportions were used to test differences of the effects of RCP and dispersal scenarios on species distribution. We compared the proportions between RCP scenarios under a single dispersal scenario (i.e. universal dispersal) using Wilcoxon test. We only considered the universal dispersal scenarios because they show the pure effect of climate change under all RCP scenarios. Also, we compared proportions between dispersal scenarios under all RCP scenarios using Wilcoxon tests.

4.2 EFFECTS OF CLIMATE CHANGE AND HABITAT LOSS IN SPECIES DISTRIBUTIONS

4.2.1 PREDICTIVE MODEL OF HABITAT LOSS

We modeled future habitat loss for the year 2050 for mainland Ecuador using the Land Change Modeler for Ecological Sustainability (Eastman, 2012) as implemented in the software IDRISI Selva v17.02 (Clark Labs, Worcester, MA, USA). This modeling strategy has high performance to predict land cover change (Mas *et al.* 2014). To construct the model, we identified historic trends of habitat loss driven by predictor variables, validated these trends, and extrapolated them to predict future habitat loss (Clark Labs, 2009; Eastman, 2012). We constructed separated models for Coast, Andean, and Amazonian regions of Ecuador because their driving factors for habitat loss are different (Sierra, 2013). We followed Peralvo and Delgado (2010) geographical limits of the Ecuadorian regions. Besides, geographical partitioning is suggested to increase model transparency (Robinson, 2008). We constructed the models based on maps of habitat loss of Ecuador for the years 1990, 2000, and 2008 (Ministerio del Ambiente, 2012). Habitat loss maps had two habitat categories: presence of natural vegetation (e.g. native forest, shrubs, and herbaceous vegetation; Ministerio del Ambiente 2012b) and absence of natural vegetation (e.g. crops, pasture, urban areas, water, and glaciers). Historical changes in land cover were measured by identifying changes in categories between 1990 and 2000 (Eastman *et al.* 2005).

We aimed to identify variables that explain the loss and gain of natural habitat. An initial model included the following variables (based on Eastman, 2012 and Sierra, 2013):

altitude, slope, proximity to roads, proximity to settlements, proximity to rivers, proximity to disturbance, population density, and agricultural suitability. See Appendix 1 for details on data source and preparation of predictor variables. We tested the level of association between variables and land cover transitions using Cramer's *V* analysis; variables with coefficients under 0.15 were eliminated from the model (Eastman, 2012). We calculated transition potential maps based on the interaction of the predictor variables and the gain and loss of natural habitat (Eastman, 2012). Transition potential maps show the susceptibility of habitat categories to change between each other as the effect of predictor variables (Eastman, 2012). Estimates were based on the Multi-Layer Perceptron (MLP) method of neural networks (Bishop, 1995; Lek and Guégan, 1999). This method's products have been shown as highly accurate when modeling predictive land cover change (Pérez-Vega et al. 2012). MLP calculations were based on 10,000 pixels half of which were used for testing and half for training, over 10,000 interactions. Modelling parameters were set to default values as recommended by Eastman (2012).

Transition potential maps were used to model a single predictive scenario of susceptibility of natural habitat to change (i.e., soft model, Eastman, 2012) for the year 2008 using the Markov Chain analysis (Burnham, 1973). Modeling considered the Ecuadorian system of protected areas and planned additions to the national road network as planning variables (Appendix 1). We validated the 2008 soft model by calculating the area under the receiver operating characteristic curve (AUC; Swets, 1986) by comparing the estimated and the observed habitat loss in 2008. Validation demonstrated reliability in our predictor variables and modeling configurations (see the results, section 5.2). Finally, we predicted a land cover scenario for the year 2050 (i.e., hard model, Eastman, 2012) based on land cover transitions between 2000 and 2008 land cover maps, using our validated modeling parameters and predictor variables for 2000 and 2008 (Appendix 1). The 2050 land cover scenario was resampled to a 30 arc-second resolution (i.e. ~1 km^2) using the Nearest Neighbor resampling method as the best option for categorical data (Parker *et al.* 1983).

4.2.2 SPECIES DISTRIBUTIONS UNDER CLIMATE CHANGE AND HABITAT LOSS

We estimated the current species distributions under habitat loss by removing all the areas with absence of natural vegetation in 2008 from the species current distribution. We also removed water body areas because none of our modeled species are aquatic. To obtain the species distributions under climate change and habitat loss in 2050, we calculated new dispersal scenarios from the current species distributions under habitat loss; then, we removed all the areas with absence of natural vegetation in the 2050 per dispersal scenario. Then, we calculated the proportion of change in area of species distribution under habitat loss for each dispersal scenario. We obtained the proportions by dividing the distribution area under climate change and habitat loss in 2050 by the current distribution areas.

We estimated the proportion of remaining areas of natural vegetation in Ecuador for the years 2008 and 2050 dividing the calculated area of natural vegetation by the total surface of mainland Ecuador. We performed map algebra in the software ArcGIS 10.2 ESRI (Redlands CA, USA) to obtain persistence, loss, and regeneration of natural vegetation. Persistence was assumed as the unchanging natural vegetation in 2008 and 2050. Loss was assumed as the areas which had natural vegetation in 2008 and not in 2050; and, regeneration as the areas which did not have natural vegetation in 2008 and had it in 2050. We followed the same process to perform the Andean natural vegetation estimations.

4.3 SPATIAL PATTERNS IN THE EFFECT OF CLIMATE CHANGE UNDER HABITAT LOSS IN SPECIES DISTRIBUTIONS

The current distributions of all endemic frogs species were added into a single map to generate a map of species richness. The same map was generated for future distributions under each RCP scenario under the universal-dispersal scenario. Future maps of species richness were divided by the current map of species richness to obtain maps showing the proportion of change in species richness. Future maps of species richness were also subtracted from the current map to obtain maps showing the change in absolute species richness. Similarly, we calculated the proportion of change between current climate and the 2050 climate for annual mean temperature (bio1), maximum temperature of warmest month (bio 5), minimum temperature of coldest month (bio 6), annual precipitation (bio 12), and precipitation of driest month (bio 14) for each RCP scenario. Elevation data (SRTM; Ferr *et al.* 2007) was also considered for the spatial pattern analysis. Spatial resolution of the elevation data was resampled from its original 90 m. into the spatial resolution of the climatic variables used for the ecological niche modeling (~1km^2). We removed the habitat loss in 2050 from the maps of proportion of change in species richness, change in absolute species richness, proportion of change in climate, and the elevation. All maps and operations were performed using the Raster package (Hijmans, 2015) in the software R (R Core Team, 2015).

We obtained a matrix with the values per pixel of the proportion of change in species richness, the change in absolute species richness, the proportion of change between current and 2050 climate, and elevation with the software ArcGIS 10.2 ESRI (Redlands CA, USA). Then, we tested the correlation between the extracted values of the maps with Spearman’s correlations. To avoid spatial autocorrelation, we ran the analyses with a random sample of 500 pixels. All correlation analyses were performed using Hmisc package (Harrell, 2015) in the software R (R Core Team 2015).

4.4 CHANGES IN CONSERVATION STATUS AS A RESULT OF CLIMATE CHANGE AND HABITAT LOSS IN 2050

We selected the minimum area of species distribution among RCP scenarios in the no-dispersal scenario; and the maximum area for each species distribution among RCP scenarios in the universal dispersal scenario under 2050 habitat loss. We evaluated the Red List category on each scenario based on the B1 criterion of the IUCN Red List for threatened species (IUCN, 2012). Based on our study’s results, each species was also evaluated using the same criterion but for its current distribution under habitat loss in 2008.

5. RESULTS

5.1 EFFECTS OF CLIMATE CHANGE IN SPECIES DISTRIBUTIONS

Under the universal dispersal scenario, climate change caused an average 60% of endemic frogs species of the Ecuadorian Andes to increase their area of ecological niche (Figure 1). The effects of climate change were significantly different only between RCP scenarios 2.6 and 8.5, where RCP 8.5 showed smaller proportions of the current ecological niche of species compared to RCP 2.6 (Z = -3.074, P = 0.002) (Figure 2). On the other hand, dispersal scenarios showed significant differences in the proportion of change in the area of distribution under all RCP scenarios (Figure 3, Table 1).

5.2 EFFECTS OF CLIMATE CHANGE AND HABITAT LOSS IN SPECIES DITRIBUTIONS

Selected predictor variables to model the habitat loss in the year 2050 were specific in Coastal, Andean, and Amazonian Ecuador and are summarized in Appendix 1. The validations of predicted models in 2008 per region were accepted, showing the following results: Coast AUC = 0.904; Andes AUC = 0.926, Amazonia AUC = 0.858.

Currently, 62.59% of Ecuador’s natural vegetation remains. Endemic frogs species of the Ecuadorian Andes have an average of 64.39% ± 18.37% of remaining natural vegetation within their current distribution ranges (Figure 4). Our model of future land cover predicts 59.25% of Ecuador’s natural vegetation will remain in 2050, representing a net loss of 3.34% considering Ecuador’s mainland surface. Considering the area of natural vegetation in 2008, 18.27% is lost and 12.93% will be regrown by 2050 (Figure 5, Table 2). In the Ecuadorian Andes, 63.98% of natural vegetation remains at present, while 60.85% of vegetation will remain in 2050, where 17.57% of present remaining vegetation will be lost and 12.68% will be regrown (Figure 5, Table 2).

The combined effects of climate change and habitat loss on frogs species are highly dependent on the dispersal scenario. Under a non-dispersal scenario, average proportion of change in distribution range is 0.379 ± 0.162 of the current distribution; under a 1 km dispersal it is 0.674 ± 0.318; under a 5 km dispersal it is 0.970 ± 0.872; and, under universal dispersal scenario, average proportion of change in distribution range is 1.03 ± 0.935 (Figure 6).

5.3 SPATIAL PATTERNS IN THE EFFECT OF CLIMATE CHANGE UNDER HABITAT LOSS IN SPECIES DISTRIBUTIONS

The proportion of change in species richness of endemic frogs of the Ecuadorian Andes in 2050 under climate change increased with mean annual temperature and precipitation of the driest month under all RCP scenarios (Table 3). Altitude and maximum temperature of the warmest month were also associated with increase in species richness proportion under the scenarios RCP 2.6, RCP 4.5, and RCP 6.0, and annual precipitation under the scenarios RCP 2.6 and RCP 8.5. Spatial pattern of proportion of change in species richness with habitat loss in 2050 is shown in Figure 7.

Change in absolute species richness increased with altitude under the scenarios RCP 2.6, RCP 4.5, and RCP 6.0 (Table 4). Mean annual temperature, maximum temperature of the warmest month, and precipitation on the driest month were also associated with increase in species richness under the scenarios RCP 4.5 and RCP 6.0 (Table 4). The variable minimum temperature of coldest month and annual precipitation only showed associations with species richness under the RCP scenario 8.5 (Table 4). Spatial pattern of change in absolute species richness with habitat loss in 2050 is shown in Figure 8.

5.4 CHANGES IN CONSERVATION STATUS AS A RESULT OF CLIMATE CHANGE AND HABITAT LOSS IN 2050

According to the estimates of current distribution, six (8.82%) of the frogs species are Endangered, 46 (67.74%) are Vulnerable, and 16 (23.52%) are of Least Concern (Table 4). Under the minimum area of distribution among RCP scenarios in the no-dispersal scenario, the number of Endangered species rises to 24 (35.29%), Vulnerable species rises to 34 (51.47%) while Least Concern is reduced to 8 (13.23%) (Table 5). In the case of the maximum area distribution among RCP scenarios in the universal dispersal scenario, Endangered species reduced to 1(1.47%), 34 (50%) are vulnerable, and Least Concern rises to 33 (48.52%) (Table 5). None of the species will become extinct in 2050.

6. DISCUSION

6.1 EFFECTS OF CLIMATE CHANGE AND HABITAT LOSS IN SPECIES DITRIBUTIONS

Many studies have addressed the effects of climate change in future species distributions (e.g. Peterson *et al.,* 2002 ; Araújo *et al.,* 2006; Lawler *et al.,* 2009; Freeman *et al.,* 2013) and the effects of habitat loss in biodiversity (e.g. Brooks *et al.,* 2002; Sangermano, *et al.,* 2012; Estavillo *et al.,* 2013). However, none of them have considered the effect of both threats simultaneously, and therefore provide a partial view of the conservation future of species. In this study we combined scenarios of climate change and habitat loss to provide more reliable predictions of the conservation future of species. This integrative approach should better guide conservation efforts to ameliorate the effects of climate change and habitat loss.

Our results showed that the effect of climate change will potentially benefit the majority of frogs species while future change in natural vegetation cover varies with location but has an overall negative effect. Climate change could benefit ~60% of the analyzed species by potentially increasing their area of distribution 65%. However, the combined effects of climate change and habitat loss will limit the potential gain of distribution area to ~3%.

In our analyses, dispersal is the main factor influencing the intensity of the effects of climate change and habitat loss. The reduction in the distribution area under the no-dispersal scenario and the increment of distribution area under the universal dispersal scenario is evidence of spatial shifts in the species suitable climate due to climate change. In addition, our model of 2050 land cover shows important habitat losses, as well as gains because of regeneration, a tendency that is consistent with the models of Sierra (2013). Regenerated areas will provide new suitable habitat for colonization. Yet colonization depends on the dispersal abilities of each species (Cushman, 2006). As a result, dispersal will strongly influence the ability of frogs to follow shifts in their climate envelope and colonize new areas of regenerated habitat. Dispersal will allow species whose distributions are reduced by climate change and habitat loss to atenuate such negative effect, and species whose distribution areas are increased by these phenomena to seize the oportunity to colonize new areas.

At present, there are no studies showing the dispersal capabilities of Andean frogs. This limits our hability to identify the most probable dispersal scenario in our study based on factual data. In our study dispersal scenarios were based on Euclidean distances. We did not considered topographic barriers, climatic barriers, and habitat fragmentation, which are important factors limiting dispersal. Distance measurements considering topography do not differ significantly from Euclidean distance (G. Galarza, personal communication). Yet, barriers related to fragmentation (e.g. cities, roads, farmland) should exert great limitations on the ability of Andean frogs to disperse (Cushman, 2006). In general, frogs do not tend to migrate as much as other vertebrates (Wells, 2007). Hence, dispersal under climate change and habitat loss might be more closely reflected by our limited dispersal scenarios.

However, frogs do migrate when ecological pressures exist (Wells, 2007). For instance, changes in weather forced an amphibian population in Europe to travel 15 km from a hibernation site to a breeding site (Tunner and Kárpatí, 1997). *Hoplobatrachus occipitalis* (Anura, Dicroglossidae) in Africa was able to travel 6 km at a rate of 1 km per night in nature (Tunner, 1992; Spieler and Linsemair, 1998). Twitty *et al.* (1964) showed that under experimental conditions *Taricha rivularis* (Caudata, Salamandridae) was able to move many kilometers in an approximate two-year period crossing topographical barriers. The effects of climate change and habitat loss are important ecological pressures. Dispersal capabilities should depend greatly on species size and habits, rendering smaller and less active species to be more vulnerable to climate change and habitat loss (Bowler and Benton, 2005). Studies of dispersal capabilities of specific frog species of the Andes should further elucidate this matter. As a result, despite the general trend in amphibians is to show reduced dispersal, studies show amphibian species could show great dispersal capabilities under the right ecological circumstances. It is crucial to perform specific studies on Andean frog's dispersal capabilities that could elucidate their aptitude to cope with climate change and habitat loss.

6.2 SPATIAL PATTERNS IN THE EFFECT OF CLIMATE CHANGE UNDER HABITAT LOSS IN SPECIES DISTRIBUTIONS

It has been stated that climate change will cause mountain species to follow suitable climate by migrating uphill, fleeing from warming climate (Walther *et al.* 2002; Parmesan, 2006; Colwell *et al.* 2008; Sekercioglu *et al.* 2008; Lawler *et al.* 2009; Feeley and Silman 2010). Our results suggest that the proportion of change in species richness and absolute change in species richness will increase with altitude. This suggests endemic frog species in the Ecuadorian Andes will respond as expected and tend to migrate uphill. Proportion of change of species richness increased in areas with increased mean annual temperature and precipitation on the driest month. This concurs with the physiological preference of amphibians for warm environments due to ecotothermality, and preference for wet areas because of their sensitiveness to dissecation (Wells, 2007).

The maps of change in species richness (Figures 7, 8) show geographically specific patterns such as species gain in regions of high altitude, species loss in regions of intermediate altitude in the eastern slopes of the Andes, and species gain in regions of intermediate altitude in the western slopes. Our results show that the effect of climate change on species richness depends on the side of the Andes, altitude, and latitude, which probably responds to the high spatial heterogeneity of the Andean climate (Gentry, 1982; Killeen *et al.* 2007; Young and León 2007). Such effects of climate change have been shown to be complex (Garcia *et al.* 2014). Other metrics of evaluation on specific regions could further elucidate the nature of the effect of climate change in spatial shifting of species climate envelopes (e.g. specific gain and loss of species, orientation on envelope shifting) (Garcia *et al.* 2014; Cuesta *et al.*, 2015).

6.3 EFFECTS OF CLIMATE CHANGE IN SPECIES DISTRIBUTIONS

RCPs were designed to represent scenarios of climate change that increase in intensity from the RCP 2.6 (i.e. the less drastic scenario) to the RCP 8.5 (i.e. the most drastic scenario) (Moss *et al.* 2010a; Vuuren *et al.* 2011). Therefore, RCPs 2.6 and 8.5 are the most differentiated climate change scenarios. Accordingly, our results showed difference in the effects of climate change only between RCP scenarios 2.6 and 8.5. The effects of RCP 8.5 showed smaller proportions of the original ecological niche for the majority of species compared to the effects of RCP 2.6. This suggests that more drastic climate change scenarios tend to limit ecological niche expansion for the species that were positively affected by climate change, and further reduce ecological niche area for the species that were negatively affected.

6.4 CHANGES IN CONSERVATION STATUS AS RESULT OF CLIMATE CHANGE AND HABITAT LOSS IN 2050

It is possible that our results underestimate the threat of species of Andean frogs in 2050. For instance, we set the conservation status of *Hyloxalus jacobuspetersi* as vulnerable based on its current distribution with habitat loss, and maintain the category based on the effects of climate change and habitat loss in 2050. However, specific evaluation of the conservation situation of *H. jacobuspetersi* at present reveals the species is critically endangered provided only a single population is known to persist (Coloma *et al.* 2012). Nevertheless, specific evaluations of the conservation situation of most species are lacking. Our results give insights on the present conservation status of these species, and are an effort to understand their conservation situation in the future by integrating climate change and future habitat loss.

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8. FIGURES

Figure 1. Frequency distribution of the proportion of change in the area of the current ecological niche of endemic frogs species in the Ecuadorian Andes by 2050. Four Representative Concentration Pathway scenarios of climate change are shown. Values < 1 indicate net loss in area; values > 1 indicate net gain.

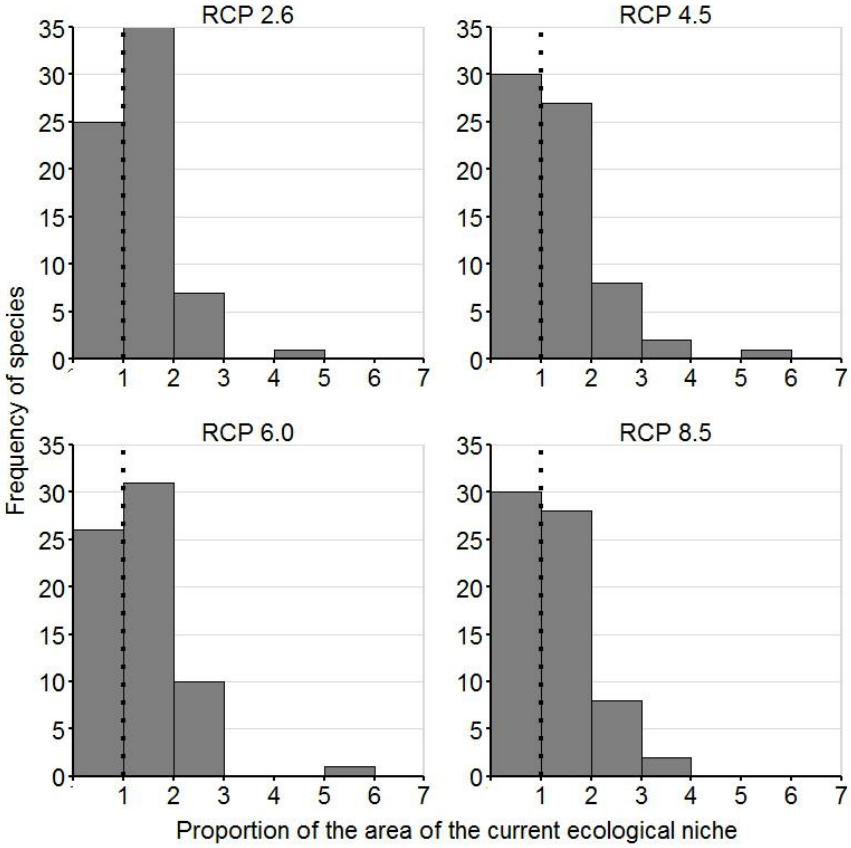

Figure 2. Net difference in the effects of Representative Concentration Pathway 2.6 and Representative Concentration Pathway 8.5 (effects of Representative Concentration Pathway 8.5 – effects of Representative Concentration Pathway 2.6) in the proportion of the area of current ecological niche of endemic frogs species in the Ecuadorian Andes by 2050. Values < 0 show reduced proportions of the area of current ecological niche in Representative Concentration Pathway 8.5 compared to Representative Concentration Pathway 2.5; values > 0 show increased area proportions of Representative Concentration Pathway 8.5 compared to Representative Concentration Pathway 2.6

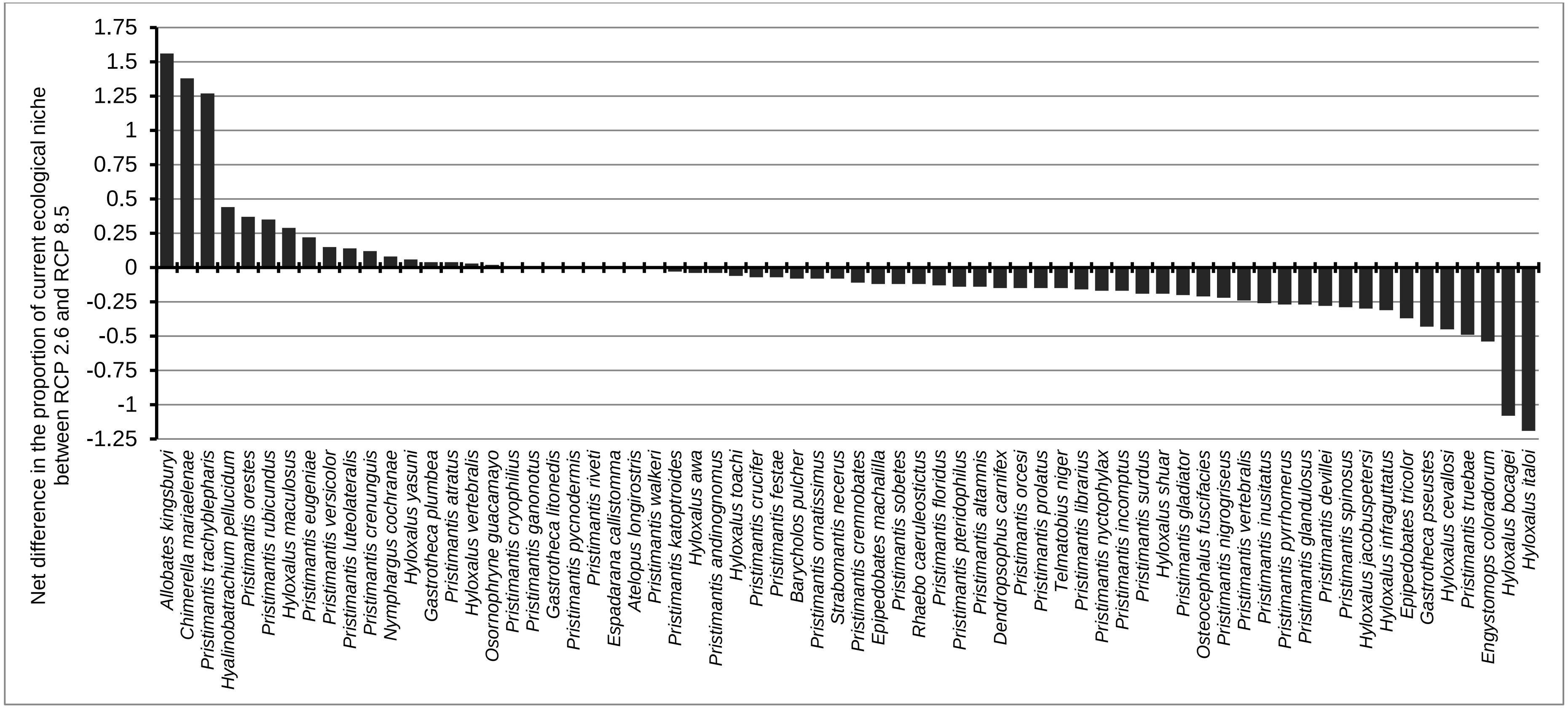

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Figure 3. Proportions of change in the area of current distribution of endemic frogs species of the Ecuadorian Andes by 2050. Four dispersal scenarios and four climate change scenarios are shown. Whiskers represent the first and the fourth quartile; boxes represent the second and third quartile. Boxes' middle line represents the median. Values < 1 indicate net loss in area; values > 1 indicate net gain.

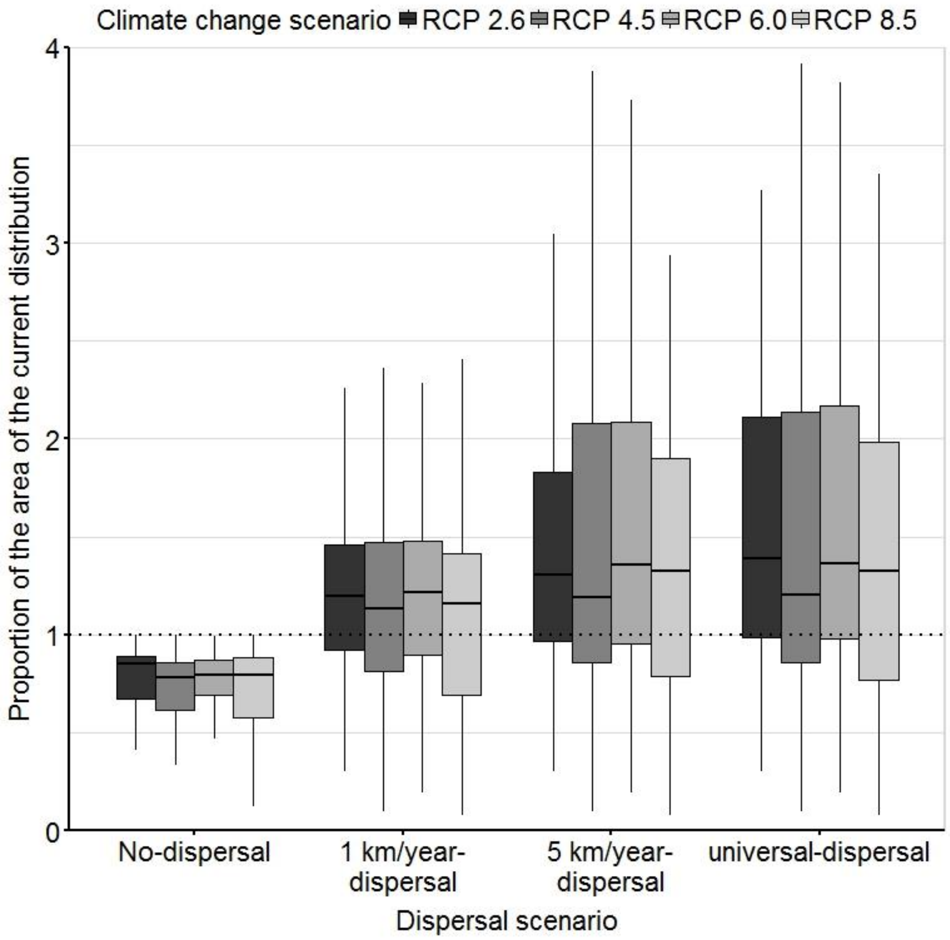


Figure 4. Frequency of endemic frogs species current distribution under habitat loss in the year 2008 in the Ecuadorian Andes.

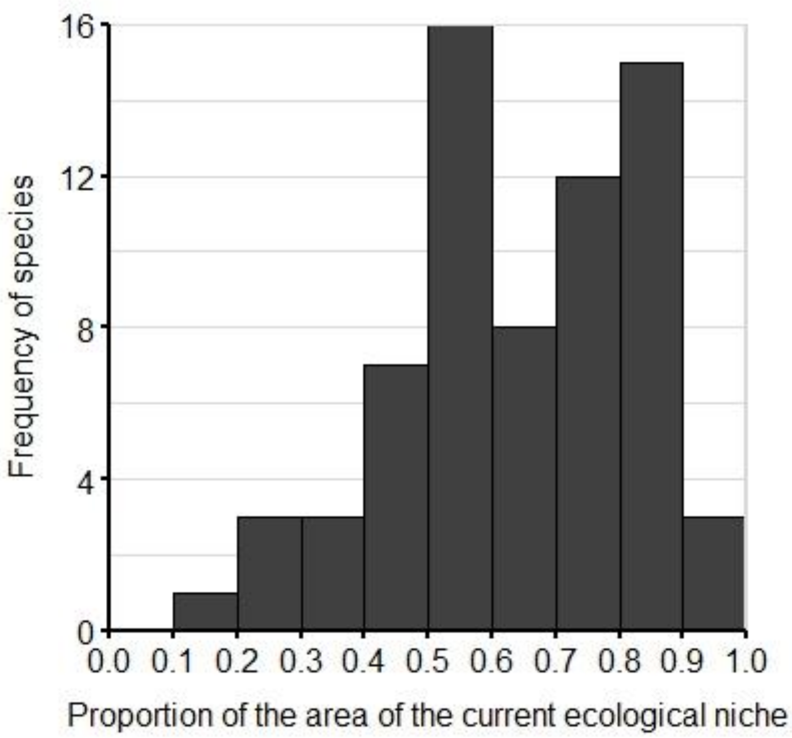


Figure 5. Change in habitat loss by the year 2050 in Ecuador based on the land cover changes in the year 2000 and 2008 (Ministerio del Ambiente, 2012). Ecuadorian Andes limits based on Peralvo y Delgado (2010).

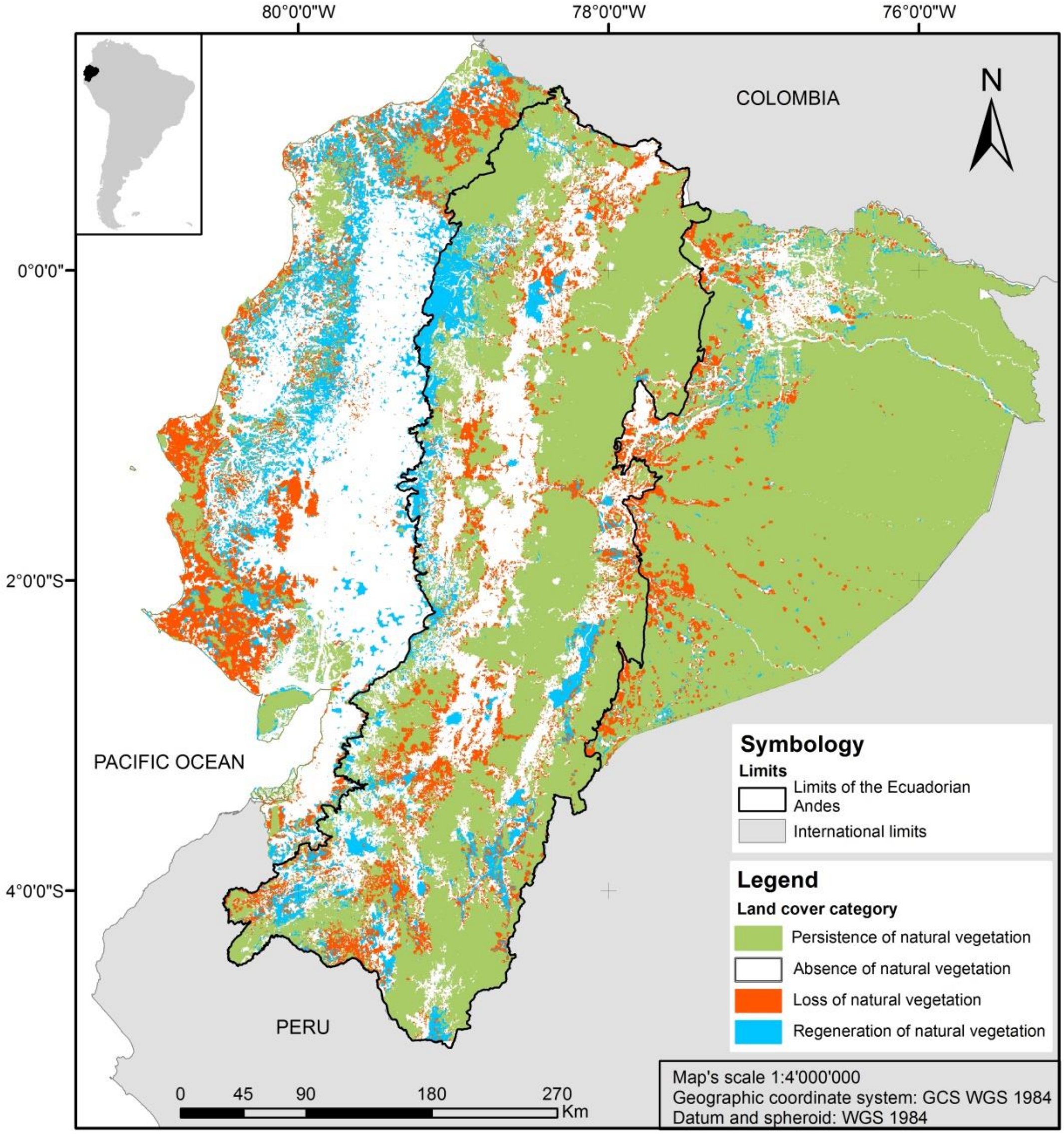


Figure 6. Proportions of change in the area of current distribution of endemic frogs species of the Ecuadorian Andes by 2050. No-dispersal scenario and universal scenario under Representative Concentration Pathway 2.6 and Representative Concentration Pathway 8.5 with and without habitat loss are shown. Whiskers represent the first and the fourth quartile; boxes represent the second and third quartile. Boxes' middle line represents the median. Values < 1 indicate net loss in area; values > 1 indicate net gain.

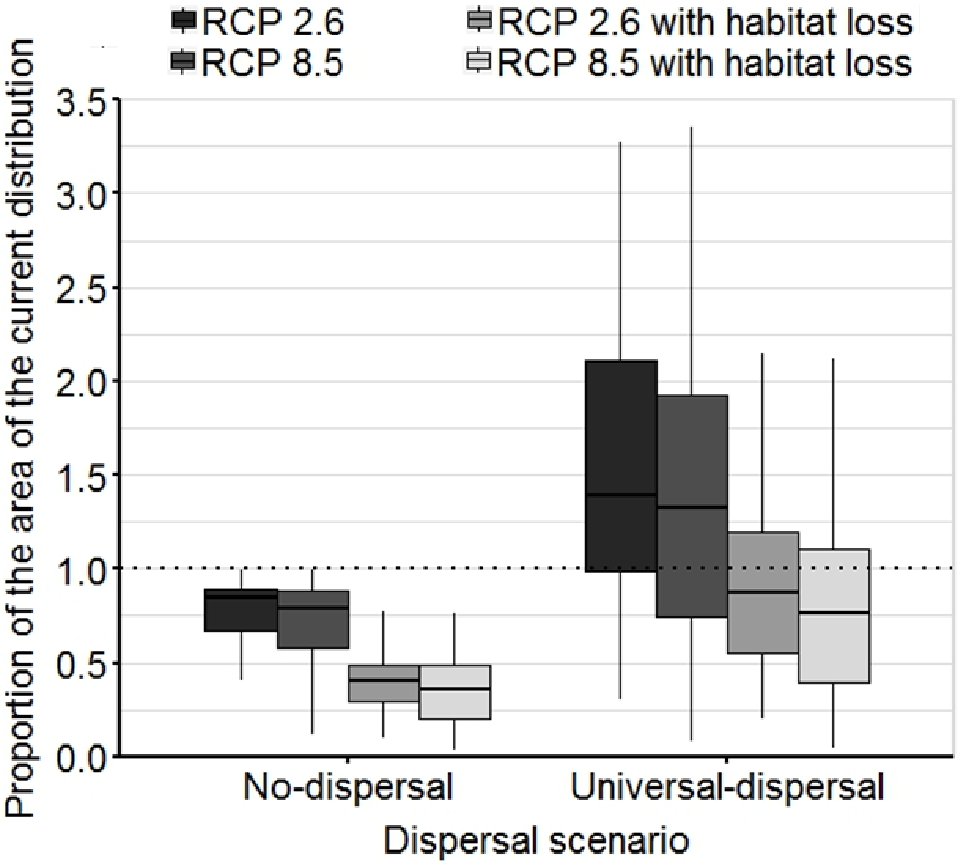


Figure 7. Proportion of change in species richness of endemic frogs species in the Ecuadorian Andes by 2050. Four Representative Concentration Pathway scenarios of climate change are shown assuming universal dispersal of the species. Dark grey represents habitat loss extracted by 2050.

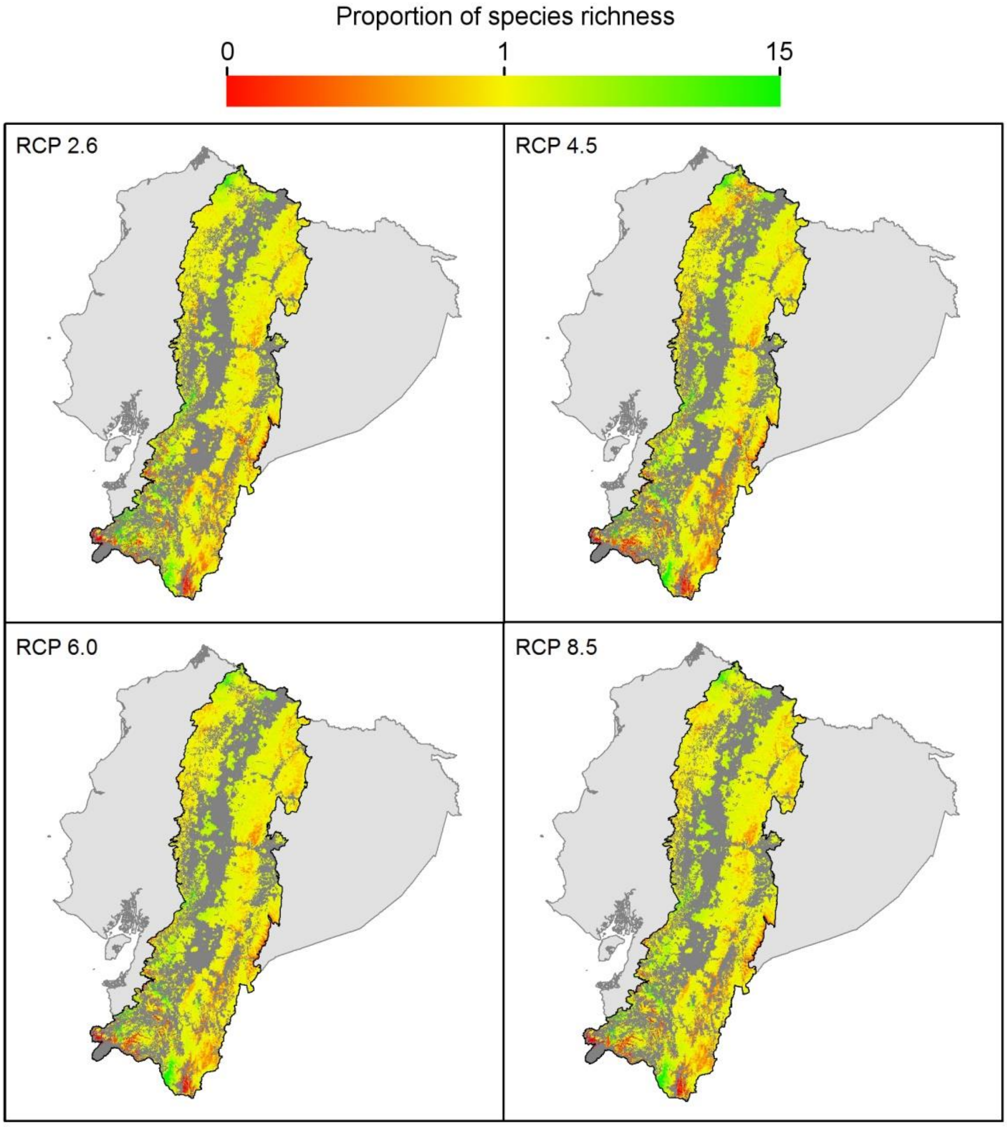
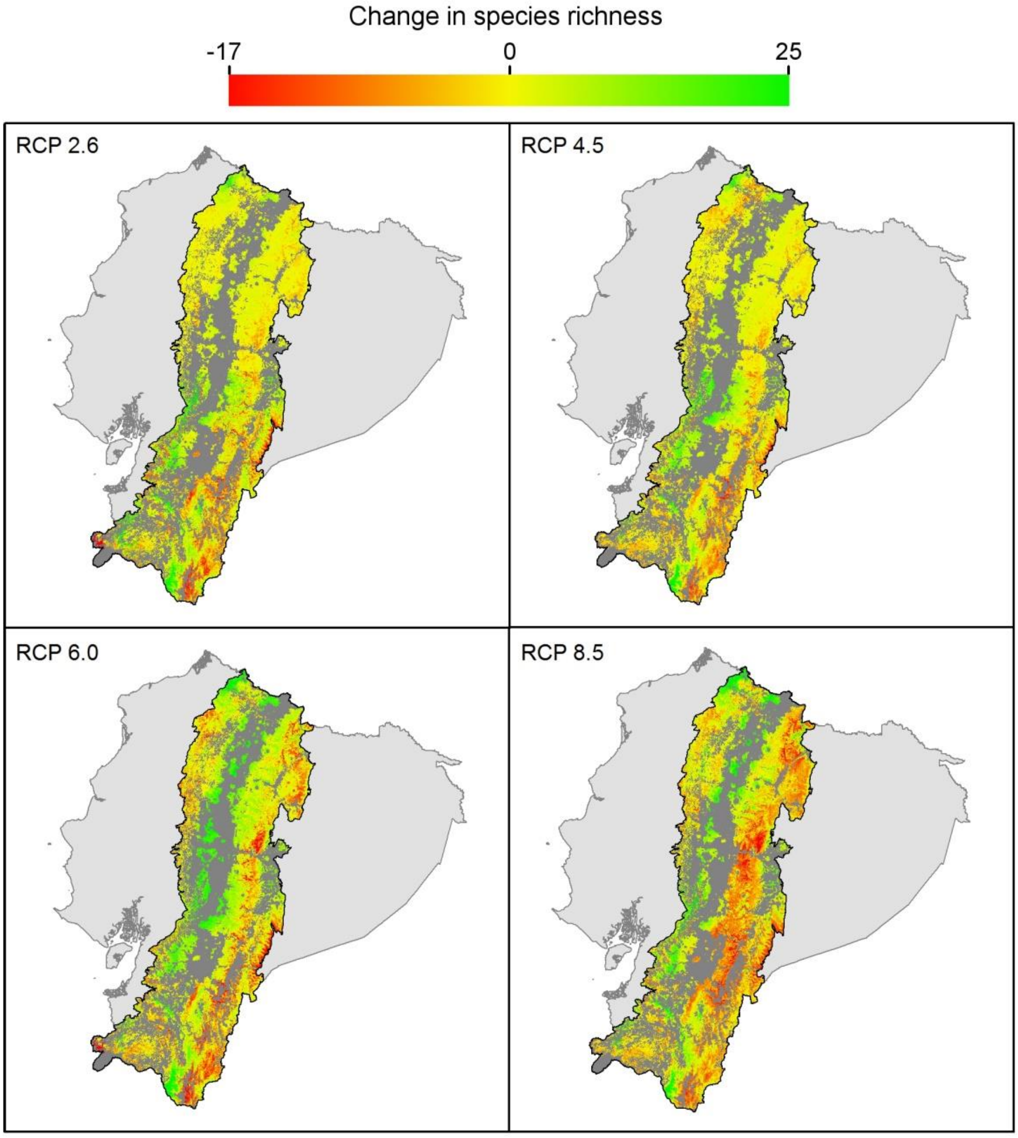


Figure 8. Change in absolute species richness of endemic frogs species in the Ecuadorian Andes by 2050. Four Representative Concentration Pathway scenarios of climate change are shown assuming universal dispersal of the species. Dark grey represents habitat loss extracted by 2050.



9. TABLES

Table 1. Wilcoxon tests analysis of the proportion of change (current species distribution ÷ future ecological niche model under climate change and dispersal scenarios) in the distribution area of endemic frogs species in the Ecuadorian Andes by 2050 under Representative Concentration Pathways and dispersal scenarios. Significant P values denoted by *.

Representative Concentration Pathway	Dispersal scenario	No-dispersal	1 km per year	5 km per year
2.6	1 km per year	$Z = -7.167$, $P < 0.001$*		
	5 km per year	$Z = -7.167$, $P < 0.001$*	$Z = -6.955$, $P < 0.001$*	
	Universal dispersal	$Z = -7.167$, $P < 0.001$*	$Z = -6.955$, $P < 0.001$*	$Z = -5.777$, $P < 0.001$*
4.5	1 km per year	$Z = -7.167$, $P < 0.001$*		
	5 km per year	$Z = -7.167$, $P < 0.001$*	$Z = -7.009$, $P < 0.001$*	
	Universal dispersal	$Z = -7.167$, $P < 0.001$*	$Z = -7.009$, $P < 0.001$*	$Z = -5.645$, $P < 0.001$*
6.0	1 km per year	$Z = -7.167$, $P < 0.001$*		
	5 km per year	$Z = -7.167$, $P < 0.001$*	$Z = -7.062$, $P < 0.001$*	
	Universal dispersal	$Z = -7.167$, $P < 0.001$*	$Z = -7.062$, $P < 0.001$*	$Z = -5.905$, $P < 0.001$*
8.5	1 km per year	$Z = -7.167$, $P < 0.001$*		
	5 km per year	$Z = -7.167$, $P < 0.001$*	$Z = -7.062$, $P < 0.001$*	
	Universal dispersal	$Z = -7.167$, $P < 0.001$*	$Z = -7.062$, $P < 0.001$*	$Z = -5.711$, $P < 0.001$*

Table 2. Land cover categories of the habitat loss map by the year 2050 in Ecuador and the Ecuadorian Andes. Areas shown in squared kilometers.

Land cover category	Area in Ecuador (km^2)	Area in the Ecuadorian Andes (km^2)
Persistence of natural vegetation	127,759	55,823
Absence of natural vegetation	73,193	29,539
Loss of natural vegetation	28,569	11,901
Regeneration of natural vegetation	20,222	8,589

Table 3. Spearman correlations between the proportion of change in species richness of endemic frogs of the Ecuadorian Andes and bioclimatic variables under climate change and habitat loss in 2050. Samples were taken from 500 randomly generated localities throughout the Ecuadorian Andes. Significant correlations denoted by *.

Environmental variable	Representative Concentration Pathway scenario			
	2.6	4.5	6.0	8.5
N=500				
Altitude	$P < 0.001$*	$P < 0.001$*	$P < 0.001$*	$P = 0.232$
	$r_s = 0.151$	$r_s = 0.332$	$r_s = 0.316$	$r_s = 0.053$
Annual mean temperature	$P < 0.001$*	$P < 0.001$*	$P < 0.001$*	$P < 0.001$*
	$r_s = 0.143$	$r_s = 0.214$	$r_s = 0.217$	$r_s = 0.091$
Maximum temperature of warmest month	$P < 0.001$*	$P < 0.001$*	$P < 0.001$*	$P = 0.063$
	$r_s = 0.152$	$r_s = 0.179$	$r_s = 0.198$	$r_s = 0.0831$
Minimum temperature of coldest month	$P = 287$	$P = 0.064$	$P = 0.055$	$P = 0.274$
	$r_s = 0.047$	$r_s = 0.082$	$r_s = 0.085$	$r_s = -0.048$
Annual precipitation	$P < 0.001$*	$P = 0.182$	$P = 0.189$	$P < 0.001$*
	$r_s = 0.96$	$r_s = 0.059$	$r_s = 0.058$	$r_s = 0.218$
Precipitation of driest month	$P < 0.001$*	$P < 0.001$*	$P < 0.001$*	$P < 0.001$*
	$r_s = 0.143$	$r_s = 0.225$	$r_s = 0.253$	$r_s = 0.221$

Table 4. Spearman correlations between change in number of species of endemic frogs of the Ecuadorian Andes and bioclimatic variables under climate change and habitat loss in 2050. Samples were taken from 500 randomly generated localities throughout Ecuadorian Andes. Significant correlations denoted by *.

Environmental variable	Representative Concentration Pathway scenario			
	2.6	4.5	6.0	8.5
N=500				
Altitude	$P < 0.001$*	$P < 0.001$*	$P < 0.001$*	$P = 0.201$
	r_s= 0.242	r_s= 0.353	r_s=0.421	r_s= 0.057
Annual mean temperature	$P = 0.171$	$P < 0.001$*	$P < 0.001$*	$P = 0.448$
	r_s= 0.061	r_s=0.158	r_s= 0.211	r_s= 0.033
Maximum temperature of warmest month	$P = 0.111$	$P < 0.001$*	$P < 0.001$*	$P = 0.206$
	r_s= 0.071	r_s= 0.155	r_s= 0.202	r_s= 0.056
Minimum temperature of coldest month	$P = 0.313$	$P = 0.859$	$P = 0.258$	$P < 0.001$*
	r_s= -0.045	r_s= 0.007	r_s= 0.051	r_s= -0.151
Annual precipitation	$P = 0.761$	$P = 0.148$	$P = 0.191$	$P < 0.001$*
	r_s= 0.0136	r_s=0.064	r_s= -0.058	r_s= 0.179
Precipitation of driest month	$P = 0.630$	$P < 0.001$*	$P < 0.001$*	$P = 0.057$
	r_s= 0.021	r_s= 0.225	r_s= 0.169	r_s= 0.085

Table 5. Categories of conservation status based on the B1 criterion of the IUCN Red List (UICN, 2012) of endemic amphibian species of the Ecuadorian Andes. Analysis based on current distributions and 2050 distributions according to predictions of climate change and habitat loss. Minimum area distribution represents the smallest distribution area among representative concentration pathway scenarios in the no-dispersal scenario, whereas maximum area distribution represents the largest distribution area among representative concentration pathway scenarios in the universal dispersal scenario Proportions calculated as a function of the area of the current distributions under 2008 habitat loss (* area of species distributions under climate change and habitat loss in 2050 ÷ current species distributions without 2008 habitat loss).

Family / Species	Current distribution under habitat loss		Minimum area distribution			Maximum area distribution		
	Area (km^2)	Conservation status	Area (km^2)	Area Proportion*	Conservation status	Area (km^2)	Area Proportion*	Conservation status
Aromobatidae								
Allobates kingsburyi	16765	Vulnerable	10169	0.607	Vulnerable	81018	4.833	Least concern
Bufonidae								
Atelopus longirostris	13623	Vulnerable	8216	0.603	Vulnerable	20440	1.500	Least concern
Osornophryne guacamayo	56761	Least Concern	50001	0.881	Least concern	74959	1.321	Least concern
Rhaebo caeruleostictus	33283	Least Concern	18842	0.566	Vulnerable	42095	1.265	Least concern
Centrolenidae								
Chimerella mariaelenae	17647	Vulnerable	11780	0.668	Vulnerable	71059	4.027	Least concern
Espadarana callistomma	5537	Vulnerable	2989	0.540	Endangered	16767	3.028	Vulnerable
Hyalinobatrachium pellucidum	26674	Least Concern	5928	0.222	Vulnerable	58234	2.183	Least concern
Nymphargus cochranae	39350	Least Concern	24699	0.628	Least concern	76170	1.936	Least concern
Craugastoridae								
Barycholos pulcher	12849	Vulnerable	4349	0.338	Endangered	20264	1.577	Least concern
Pristimantis altamnis	41903	Least Concern	7838	0.187	Vulnerable	18031	0.430	Vulnerable
P. andinognomus	8898	Vulnerable	5526	0.621	Vulnerable	25799	2.900	Least concern
P. atratus	31673	Least Concern	23528	0.743	Least concern	39406	1.244	Least concern
P. cremnobates	36959	Least Concern	23227	0.628	Least concern	44866	1.214	Least concern
P. crenunguis	9126	Vulnerable	5010	0.549	Vulnerable	14031	1.538	Vulnerable
P. crucifer	8621	Vulnerable	5087	0.590	Vulnerable	10872	1.261	Vulnerable
P. cryophilius	34208	Least Concern	24648	0.721	Least concern	32859	0.961	Least concern
P. devillei	17020	Vulnerable	1158	0.068	Endangered	14211	0.835	Vulnerable
P. eugeniae	4041	Endangered	2212	0.547	Endangered	6468	1.601	Vulnerable
P. festae	11194	Vulnerable	7873	0.703	Vulnerable	24369	2.177	Least concern
P. floridus	15260	Vulnerable	10207	0.669	Vulnerable	27473	1.800	Least concern
P. ganonotus	16564	Vulnerable	9478	0.572	Vulnerable	13467	0.813	Vulnerable
P. gladiator	18709	Vulnerable	855	0.046	Endangered	12485	0.667	Vulnerable
P. glandulosus	35705	Least Concern	5567	0.156	Vulnerable	21353	0.598	Least concern
P. incomptus	26534	Least Concern	11624	0.438	Vulnerable	17571	0.662	Vulnerable
P. inusitatus	14800	Vulnerable	2644	0.179	Endangered	19867	1.342	Vulnerable
P. katoptroides	21445	Least Concern	11410	0.532	Vulnerable	51382	2.396	Least concern
P. librarius	63519	Least Concern	48373	0.762	Least concern	65335	1.029	Least concern
P. luteolateralis	4926	Endangered	2844	0.577	Endangered	9340	1.896	Vulnerable

Table 5. Continued

Family / Species	Current distribution under habitat loss		Minimum area distribution			Maximum area distribution		
	Area (km^2)	Conservation status	Area (km^2)	Area Proportion*	Conservation status	Area (km^2)	Area Proportion*	Conservation status
P. nyctophylax	8632	Vulnerable	4700	0.544	Endangered	15122	1.752	Vulnerable
P. orcesi	17430	Vulnerable	11525	0.661	Vulnerable	15761	0.904	Vulnerable
P. orestes	12763	Vulnerable	8248	0.646	Vulnerable	31468	2.466	Least concern
P. ornatissimus	12054	Vulnerable	7101	0.589	Vulnerable	18696	1.551	Vulnerable
P. prolatus	7192	Vulnerable	3479	0.484	Endangered	5800	0.806	Vulnerable
P. pteridophilus	7632	Vulnerable	5033	0.659	Vulnerable	13156	1.724	Vulnerable
Craugastoridae								
Pristimantis pycnodermis	13137	Vulnerable	9295	0.708	Vulnerable	35635	2.713	Least concern
P. pyrrhomerus	8296	Vulnerable	3211	0.387	Endangered	9184	1.107	Vulnerable
P. riveti	16162	Vulnerable	8711	0.539	Vulnerable	24358	1.507	Least concern
P. rubicundus	38823	Least concern	28896	0.744	Least concern	105490	2.717	Least concern
P. sobetes	4372	Endangered	2180	0.499	Endangered	6477	1.482	Vulnerable
P. spinosus	17479	Vulnerable	8644	0.495	Vulnerable	29377	1.681	Least concern
P. surdus	5471	Vulnerable	2797	0.511	Endangered	15516	2.836	Vulnerable
P. trachyblepharis	23673	Least concern	12793	0.540	Vulnerable	81184	3.429	Least concern
P. truebae	10909	Vulnerable	4367	0.400	Endangered	16357	1.499	Vulnerable
P. versicolor	17336	Vulnerable	12784	0.737	Vulnerable	37788	2.180	Least concern
P. vertebralis	16107	Vulnerable	6883	0.427	Vulnerable	16207	1.006	Vulnerable
P. walkeri	17637	Vulnerable	9912	0.562	Vulnerable	25919	1.470	Least concern
Strabomantis necerus	12566	Vulnerable	7185	0.572	Vulnerable	20611	1.640	Least concern
Dendrobatidae								
Epipedobates machalilla	15837	Vulnerable	5869	0.371	Vulnerable	16650	1.051	Vulnerable
E. tricolor	2210	Endangered	612	0.277	Endangered	3505	1.586	Endangered
Hyloxalus awa	13582	Vulnerable	7712	0.568	Vulnerable	17916	1.319	Vulnerable
H. bocagei	11720	Vulnerable	5906	0.504	Vulnerable	35408	3.021	Least concern
H. cevallosi	12019	Vulnerable	4475	0.372	Endangered	48624	4.045	Least concern
H. infraguttatus	19024	Vulnerable	2006	0.105	Endangered	10469	0.550	Vulnerable
H. italoi	12266	Vulnerable	957	0.078	Endangered	29073	2.370	Least concern
H. jacobuspetersi	16862	Vulnerable	8583	0.509	Vulnerable	16763	0.994	Vulnerable
H. maculosus	7776	Vulnerable	3839	0.494	Endangered	70509	9.067	Least concern
H. shuar	19958	Vulnerable	2297	0.115	Endangered	8208	0.411	Vulnerable
H. toachi	8005	Vulnerable	5284	0.660	Vulnerable	15792	1.973	Vulnerable
H. vertebralis	5434	Vulnerable	2150	0.396	Endangered	6856	1.262	Vulnerable
H. yasuni	22352	Least concern	20346	0.910	Least concern	75296	3.369	Least concern
Hemiphractidae								
Gastrotheca litonedis	4383	Endangered	1493	0.341	Endangered	10488	2.393	Vulnerable
G. plumbea	7353	Vulnerable	5148	0.700	Vulnerable	14427	1.962	Vulnerable
G. pseustes	15729	Vulnerable	1250	0.079	Endangered	9915	0.630	Vulnerable
Hylidae								
Dendropsophus carnifex	7909	Vulnerable	6003	0.759	Vulnerable	15318	1.937	Vulnerable
Osteocephalus fuscifacies	16791	Vulnerable	3578	0.213	Endangered	15199	0.905	Vulnerable
Leptodactylidae								
Engystomops coloradorum	980	Endangered	461	0.471	Endangered	7976	8.140	Vulnerable
Telmatobiidae								
Telmatobius niger	12507	Vulnerable	8491	0.679	Vulnerable	26221	2.097	Least concern

10. APPENDIX

Appendix 1. Variable data source and application in the modeling of the predictive scenario of land cover of Ecuador for the year 2050. Where X represents the specific use of the variables in the model of Ecuadorian regions.

Variable's name	Predictor variable	Role in modeling[A]	Region			Modeling period	
			Coast	Andes	Amazonia	1990-2000	2000-2008
Elevation data layer	Altitude[B]	Static		X	X	SRTM, Farr et al.2007	SRTM, Farr et al.2007
Elevation data layer	Slope[B, C]	Static	X	X		SRTM, Farr et al.2007	SRTM, Farr et al.2007
Roads	Proximity to roads[D]	Dynamic	X	X	X	Larrea, 1999	PROMSA et al. 2001d
Settlements	Proximity to settlements[D, E]	Dynamic	X	X	X	Larrea 1999[F]	PROMSA et al. 2001a[F]; Instituto Ecuatoriano de Estadísticas y Censos, 2010[F, G]
Rivers	Proximity to rivers[D]	Dynamic	X			PROMSA et al. 2001b	PROMSA et al. 2001b
Ecuador's land cover	Proximity to disturbance[D, H]	Dynamic	X	X	X	Ministerio del Ambiente 2012	Ministerio del Ambiente 2012
Image of nocturnal lights	Population density[I]	Dynamic		X	X	Earth Observation Group, 1992	Earth Observation Group, 2000
	Agricultural suitability	Static	X	X	X	Ministerio de Agricultura, Ganadería y Pesca, 2002	Ministerio de Agricultura, Ganadería y Pesca, 2002
	National system of Protected areas of Ecuador	Planning	X	X	X	PROMSA et al. 2001c	Ministerio del Ambiente, 2014
Projected roads to the years 2020, 2028, 2037	Road extension[J]	Planning	X	X	X	Ministerio de Transporte y Obras Públicas, 2013a	Ministerio de Transporte y Obras Públicas,2013b

A. Dynamic variables change in a time frame while static variables do not change.
B. Original elevation layer with 90 meters resolution were transformed into climatic variables resolution (i.e. ~ 1km^2).
C. Slope was built using the altitude layer SRTM.
D. Proximity variables were calculated using Euclidean distance (Danielsson,1980) based on layers cited in data sources.
E. Includes urban and rural areas.
F. Layers were double checked to reduce information inconsistencies because of different detail levels of information sources.
G. We used Larrea (1999) and PROMSA et al. (2001a) to double check information and obtain a layer consistent with the information in Larrea (1999).
H. For the modeling period 1990-2000 we calculated the layer based on year 1990, and for the period 2000-2008 we based on the year 2000.
Euclidean distance calculation between previously deforested areas per pixel.
I. I. Sierra (2013b) shows night light intensity is a reflection of population density. For modeling based on the 1990-2000 period we used the year 1992 lights, and on the 2000-2008 period the year 2000 lights.
J. Road extensions are first order segments of roads planned to be built in the future.