

Article

Modeling the Potential Distribution of *Aulonemia queko*: Historical, Current, and Future Scenarios in Ecuador and Other Andean Countries

Hugo Cedillo ^{1,2,*}, Luis G. García-Montero ¹, Omar Cabrera ³ , Mélida Rocano ², Andrés Arciniegas ² and Oswaldo Jadán ^{2,*} 

¹ Centro para la Conservación de la Biodiversidad y el Desarrollo Sostenible (CBDS), E.T.S.I. Montes, Forestal y del Medio Natural, Universidad Politécnica de Madrid (UPM), 28040 Madrid, Spain; luisgonzaga.garcia@upm.es

² Grupo de Ecología Forestal, Agroecosistemas y Silvopasturas en Sistemas Ganaderos, Facultad de Ciencias Agropecuarias, Universidad de Cuenca, Cuenca 010114, Ecuador; melida.rocano@ucuenca.edu.ec (M.R.); andres.arciniegas@ucuenca.edu.ec (A.A.)

³ Department of Biological Sciences, Private Technical University of Loja, San Cayetano Alto s/n, Loja 1101608, Ecuador; hocabrera@utpl.edu.ec

* Correspondence: hugo.cedillo@ucuenca.edu.ec (H.C.); oswaldo.jadan@ucuenca.edu.ec (O.J.); Tel.: +34-664565997 (H.C.); +593-992245446 (O.J.)

Abstract: *Aulonemia queko* Goudot (Poaceae, Bambusoideae) is a species of great cultural importance that has been used as a non-timber forest product in Andean forests for centuries. Despite inhabiting montane forests vulnerable to deforestation, its distribution has not been thoroughly assessed for conservation. This study analyzes its potential distribution at the regional scale (the four countries where it is distributed) and locally (in greater detail within Ecuador), using presence records and climatic and land-use data. Maxent was identified as the best algorithm, achieving high values of AUC, TSS, sensitivity, and specificity. At a regional level, *A. queko* is estimated to occupy approximately 264,540 km², mostly in Peru, with small areas in Bolivia. In Ecuador, the historical scenario showed the widest distribution, while the current–near-future scenario (20–40–SSP126) presented a more stable model. Temperature and rainfall represented critical factors in defining suitable habitats, as *A. queko* is highly sensitive to seasonal moisture availability. Land-use changes have reduced potential habitats by more than 35%, underscoring an intensified threat of habitat loss in these biodiversity-rich regions. However, projected climate changes pose an even greater impact, significantly reducing potential distribution. Our findings highlight the compelling effects of both climate-change-driven and human-driven land-use change on the future persistence of *A. queko* and emphasize the urgent need for targeted conservation strategies to protect its core habitats.

Keywords: *Aulonemia queko*; azuay; molleturo; potential distribution; precipitation; temperature



Academic Editors: Qinglai Dang, Lei Wang and Ilona Mészáros

Received: 9 January 2025

Revised: 13 February 2025

Accepted: 14 February 2025

Published: 26 February 2025

Citation: Cedillo, H.; García-Montero, L.G.; Cabrera, O.; Rocano, M.; Arciniegas, A.; Jadán, O. Modeling the Potential Distribution of *Aulonemia queko*: Historical, Current, and Future Scenarios in Ecuador and Other Andean Countries. *Diversity* **2025**, *17*, 167. <https://doi.org/10.3390/d17030167>

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1. Introduction

Species distribution models reveal the areas with appropriate environmental conditions required by species or plant formation of interest, based on a set of their presence data as well as environmental variables [1]. These models take into account different topics related to ecology, biogeography, evolution, and climate change [2]. In the current context, there is a growing interest in species modeling, which supports the design of actions for

the management, control, and conservation of species within a given area [3,4]. When including future scenarios, spatial ecological modeling plays a crucial role in predicting the impacts of climate change on species distribution [5], considering future variations of climatic factors, but also the pressure of deforestation and biodiversity loss on native species, resulting in fragmented habitats [6]. In these scenarios, along with other key species, certain bamboo species must be considered due to their ecological and cultural significance at both regional and local levels.

Aulonemia queko Goudot (Poaceae, Bambusoideae) is a neotropical bamboo species found in the Andean regions of Colombia, Ecuador, Peru, and Bolivia [7]. Few studies have addressed its taxonomy, anatomy, and uses in these countries [8]. It thrives in forests facing deforestation pressures. *A. queko* holds ethnobotanical significance in Ecuador as a non-timber product [9]. Its long stems are used to craft musical instruments like flutes and blowpipes [10,11]. These stems also serve as structural elements for rural house roofs and are employed in making baskets and crafts [10,12–14]. Additionally, *A. queko* is used in floral arrangements, kitchen utensils, lamps, curtains, fishing rods, and hunting instruments [15]. Its leaves provide forage for livestock, including cattle, sheep, guinea pigs, and rabbits [16–18]. However, tropical habitats of the *Aulonemia* Goudot genus face threats from deforestation and human activities [10,19]. The future of *A. queko* is uncertain due to overexploitation and habitat loss from deforestation, mining, and land burning [20,21].

The ecology and potential distribution of Andean bamboo species, particularly of *A. queko*, are poorly known. Some noteworthy local studies are modeling the distribution of certain *Aulonemia* species for management and conservation purposes, such as those regarding the ecological niche of *A. herzogiana* (Henrard) McClure, *A. hirtula* (Pilg.) McClure, and *A. tremula* Renvoize, endemic to the Yungueño páramo of La Paz in Bolivia [19]. In northwestern Argentina, the distribution of native and introduced woody bamboo species was modeled, predicting the potential distribution into higher altitudes based on mean temperatures and precipitation [22]. However, the low research interest for the *Aulonemia* genus is likely due to its predominantly artisanal use in rural areas, where it serves as raw material for small-scale local production. Consequently, its reproduction, ecology, and current and future distribution for management and conservation purposes have not been studied, as has been conducted with other bamboo genera such as *Guadua* and *Bambusa* [16,23].

In this context, predictive spatial ecological modeling of *A. queko* could play a pivotal role in assessing this species' distribution, providing essential insights to guide effective management and conservation efforts. Various modeling methods are available to assess past, present, and future species distributions [24]. Maxent stands out for its effectiveness with limited distribution data, which is a typical situation for tropical ecosystems, as it integrates multiple environmental variables to improve predictive accuracy and identify potential conservation areas under climate change scenarios [25,26]. Generalized linear models (GLMs) are also widely used for their flexibility in handling diverse response data and multiple environmental factors, making them ideal for complex species–habitat relationships [27,28]. In tropical ecosystems, GLMs well capture the effects of variable environmental conditions on species distribution [29,30]. Similarly, random forest (RF) excels at managing large datasets with numerous variables, providing accurate predictions in complex contexts [31]. Random forest has proven effective in tropical biodiversity studies, aiding in the design of strategies to mitigate the effects of climate change [32,33].

As a pioneer study on a poorly known species and its contribution to its management and conservation, the primary aim of the present research was to evaluate the potential distribution and temporal changes of *A. queko*. The specific objectives were as follows: (1) Model the potential distribution of *A. queko* at a regional scale using presence

data from the Global Biodiversity Information Facility (GBIF) digital platform. (2) Model its distribution using historical and future climate data, focusing on the distribution of the species in natural habitats within Ecuador; we expected a significant decrease in areas of potential distribution from historical to future scenarios, with steeper declines under more severe climate change conditions. (3) Determine whether recent land-use changes have a more significant impact on the potential distribution of *A. queko* than projections based on future climate scenarios; we expected severe future climate change projections to have a more decisive impact on the species' potential distribution area. Additionally, we wanted to determine the environmental variables that most strongly influence the potential distribution across the different models. To achieve this, we tested various ecological modeling methods and metrics to identify the best-performing model.

2. Materials and Methods

2.1. Study Area

At a regional level, the study area spans across Colombia, Ecuador, Peru, and Bolivia (Figure 1A). The distribution of *A. queko* in these countries was documented using presence records from the GBIF, with an altitudinal range from 1100 m to 4004 m. To delineate this species' potential distribution with more precision, we defined a geographical area with an elevation range between 650 and 4500 m, incorporating a 500 m buffer beyond the species' recorded lower and upper elevation limits (Figure 1B). At a local level, we focused on continental Ecuador, where *A. queko* is particularly abundant in secondary cloud forests in the Western and Eastern Cordilleras, especially in the provinces of Azuay, Imbabura, Loja, and Napo, as documented by Aguirre [12].

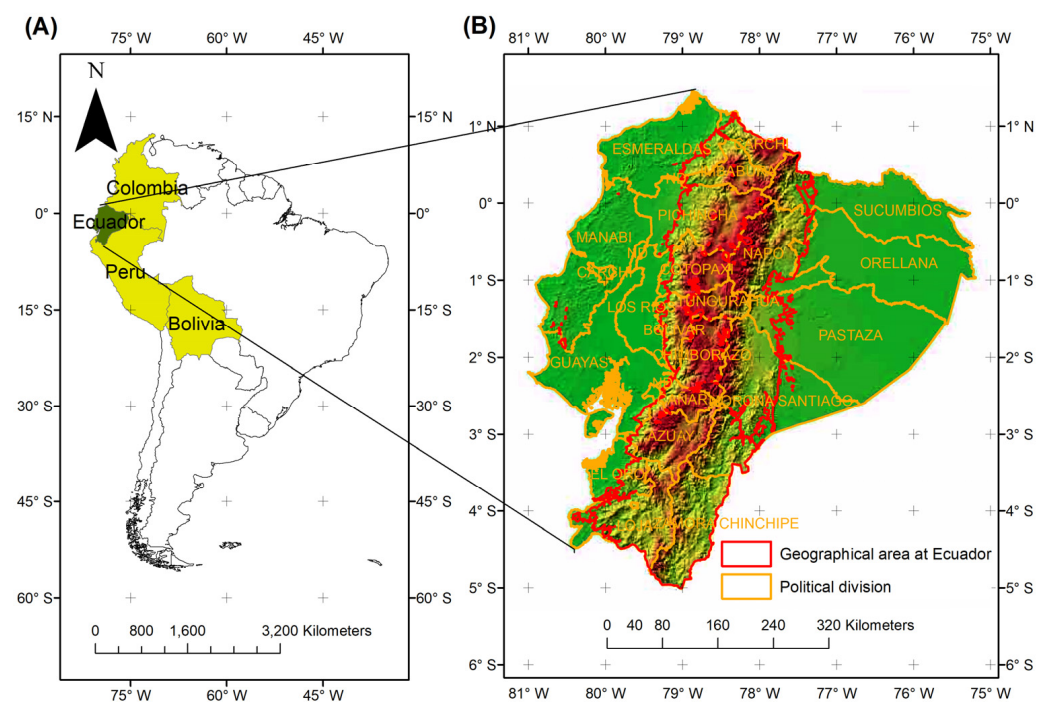


Figure 1. (A) Regional-scale map centered on Colombia, Ecuador, Peru, and Bolivia, the countries where there are presence records of *A. queko*. (B) Local-scale map of continental Ecuador showing its political division (provinces in orange) and its geographical area outlined in red.

2.2. Data Collection

To model the potential distribution of *A. queko* at the regional level, geographical presence data (x, y) were acquired from the Global Biodiversity Information Facility (GBIF) platform using the R package 'rgbif' [34]. These records of *A. queko* presence were concen-

trated in the inter-Andean zone across Colombia, Ecuador, Peru, and Bolivia. Subsequently, data cleaning was performed using the ‘CoordinateCleaner’ R package [35], which removed records lacking coordinates and addressed incomplete or inaccurate data. The resulting matrix depicting the species distribution in the four countries was based on their presence. The dataset included records reported between 1945 and 2010.

Nineteen historical climatic variables (climate averages for the years 1970–2000) with their continuous data were incorporated into the matrix, derived from georeferenced raster layers from the global climatic database WorldClim [36] (Appendix A). For this purpose, the presence records were used to extract the environmental variable values using the ‘extract’ function from the ‘raster’ package in R [37]. This comprehensive set of climatic variables facilitated a thorough analysis of the ecological niche and potential distribution of *A. queko* across the specified region (Table 1).

Table 1. Climatic variables used for modeling the potential distribution of *A. queko* at the regional (four South American countries) and local (Ecuador) levels.

Code	Variable—Unit	Range	Average
B1	Annual mean temperature (°C)	9.4–19.9	12.5
B2	Mean diurnal range (mean of monthly (max temp–min temp)) (°C)	9.0–11.6	10.3
B3	Isothermality (BIO2/BIO7) ($\times 100$) (%)	81.5–88	83.9
B4	Temperature seasonality (standard deviation $\times 100$) (°C)	20.4–65.3	42.9
B5	Max temperature of warmest month (°C)	15.5–24.9	18.7
B6	Min temperature of coldest month (°C)	3.5–14.6	6.5
B7	Temperature annual range (BIO5–BIO6) (°C)	10.3–13.6	12.2
B8	Mean temperature of wettest quarter (°C)	9.7–20.4	12.7
B9	Mean temperature of driest quarter (°C)	8.7–19.4	12.1
B10	Mean temperature of warmest quarter (°C)	9.9–20.4	12.9
B11	Mean temperature of coldest quarter (°C)	8.6–19.5	11.9
B12	Annual precipitation (mm)	717–1687	903.1
B13	Precipitation of wettest month (mm)	103–351	143
B14	Precipitation of driest month (mm)	1–79	27.1
B15	Precipitation seasonality (coefficient of variation) (%)	13.8–96.1	56.2
B16	Precipitation of wettest quarter (mm)	277–962	386.4
B17	Precipitation of driest quarter (mm)	12–263	97.5
B18	Precipitation of warmest quarter (mm)	147–782	309.5
B19	Precipitation of coldest quarter (mm)	12–346	120.4

This presence data matrix was also used to model Ecuador’s historical climate scenario (average from 1970–2000), including country-specific records. Additional models were created for present and future scenarios using shared socioeconomic pathways (SSPs), which provide projections of emissions and land-use changes [38]. We selected SSP126 (optimistic), SSP245 (moderate), and SSP585 (pessimistic) across two time periods: the present and near future (2020–2040), represented by 21–40–SSP126, 21–40–SSP245, and 21–40–SSP585, and the longer-term future (2041–2060), with 41–60–SSP126, 41–60–SSP245, and 41–60–SSP585. To assess the distribution of *A. queko* in Ecuador under these scenarios (historical, the near future, and longer-term future), we applied the same climate variables used at the regional level but also included slope data derived from digital models created using 40 m elevation contour lines.

2.3. Data Analysis

To analyze the impact of land-use change on the distribution of *A. queko*, we focused on the scenario showing the largest area of potential distribution across all analyzed scenarios. We used the 2020 vegetation cover and land use layer for continental Ecuador, provided

by the Ministry of Environment and Ecological Transition of Ecuador [39] on a shapefile format. This layer was intersected with the distribution areas identified through the optimal modeling approach (Maxent) and reclassified in ArcGIS. This analysis allowed us to assess whether land-use change has a more decisive influence in predicting the species' future distribution than the ecological modeling based on climate factors. Following these intersections, we further examined the areas with the highest potential for *A. queko* distribution, divided by province, within its natural distribution range in Ecuador.

2.4. Generation of Models

Using spatial distribution models, we generated maps depicting the distribution of *A. queko* based on presence records collected regionally and within continental Ecuador. At both regional and Ecuadorian scales, a correlation analysis was conducted to select non-correlated climatic variables ($r < 0.7$) (to avoid collinearity), using the 'caret' package in R [40].

We used three algorithms to model the potential distribution of *A. queko*: maximum entropy models (MaxEnt) [26,41], general linear models (GLMs) [42,43], and random forest (RF) [44,45], implemented in R using several specialized packages. The MaxEnt algorithm was executed via the 'dismo' package in R [46], which allows maximum entropy modeling based on presence data, using the maxent function. For the generalized linear model (GLM), the GLM function from R's base package [38] was employed, fitting the model with a binomial distribution suited for presence/absence data. The random forest model was implemented with the 'randomForest' package [47], using the 'randomForest' function to generate the model from training data. In addition to using the available presence points for each species, we generated random reference points by increasing the number of presence data fivefold, at both regional scale and within Ecuador. Although no strict rule exists for determining the number of random points, this proportion was selected to achieve a reasonable balance between the presence and absence of data. The dataset was then randomly divided into 70% training and 30% testing subsets, with 10 validation replicates to minimize uncertainty.

2.5. Accuracy and Predictive Ability of the Models

To assess the accuracy and predictive capacity of the models, three validation methods were applied, including metrics such as the area under the ROC curve (AUC), true skill statistic (TSS), sensitivity, and specificity. The AUC was calculated using the roc function from the 'pROC' package in R [48], which evaluates the models' ability to distinguish between species presence and absence; AUC values less than 0.7 were considered poor, values between 0.7 and 0.9 were considered moderate, and values greater than 0.9 were considered excellent [27,49]. True skill statistic was computed with the TSS function from the 'PresenceAbsence' package in R [50], a metric that accounts for both sensitivity and specificity. True skill statistic values less than 0.4 were considered "poor", values between 0.4 and 0.6 were classified as "moderate", and values between 0.6 and 1 were classified as "good" [27]. The TSS value is calculated as sensitivity plus specificity minus 1. Sensitivity (true positives) and specificity (true negatives) were determined using the sensitivity and specificity functions from the 'caret' package in R. Sensitivity reflects the probability of correctly predicting a presence, while specificity reflects the probability of correctly predicting an absence [27,51].

2.6. Assessment and Selection of the Best Model

The model with the highest AUC, TSS, sensitivity, and specificity values was selected as the best predictive model for the regional level and within Ecuador's historical scenario. A higher weight of 3 was assigned to the AUC metric due to its reliability in evaluating

model performance, particularly in cases of class imbalance. As the authors of [51] highlight, AUC is a robust measure of a model's ability to distinguish between presences and absences across various thresholds, making it especially useful for imbalanced datasets common in ecological modeling. Furthermore, Jiménez-Valverde [52] emphasizes that AUC is independent of species prevalence, providing a more universally applicable metric for model comparison. Although TSS is also valuable, its sensitivity to class prevalence, particularly when absence classes dominate, can lead to biased results, as noted by Al-louche [53]. Therefore, assigning a weight of 2 to TSS acknowledges its importance, while prioritizing AUC reflects its superior ability to assess discriminative power without being influenced by class imbalance. At the Ecuadorian level, the same selected model (historical) was applied to other scenarios, which allowed us to homogenize the comparison with the same model.

2.7. Model Classification and Area Calculation

The best models selected for both the regional and historical levels in Ecuador, in addition to the models for the current and future scenarios, were divided into two classifications: (1) two categories of distribution and absence (binary classification); and (2) four categories: absence, low distribution, medium distribution, and high distribution (detailed classification). These two classifications enable us to conduct general and exhaustive analyses, respectively, of the potential distribution of *A. queko* in various ecological modeling scenarios. The classification was performed using the ArcGIS Pro 10.8 software, applying the Jenks natural breaks classification method. To further explore the effects of environmental factors on species distribution, we calculated the percentage of contribution of each predictor variable to the best-fitting distribution model.

3. Results

3.1. Selection of the Best Model

Maxent recorded the highest AUC values, with 0.99 at the regional level and 0.95 at the Ecuadorian level, both considered excellent (Table 2). Similarly, TSS showed the highest values for Maxent, with 0.74 and 0.69 for the regional and Ecuadorian levels, classified as good and moderate, respectively. At the regional level, Maxent outperformed in both sensitivity and specificity, whereas at the Ecuadorian level, GLM had higher sensitivity and RF had higher specificity. Therefore, based on the final rating values for the three models (taking into account the previous weighting), Maxent achieved the highest overall scores and was selected as the best model for both the regional and Ecuadorian levels.

Table 2. Accuracy evaluation of the GLM, Maxent, and RF models to predict the potential distribution of *A. queko* at the regional and Ecuadorian levels.

Level	Methods	AUC	TSS	Sensitivity	Specificity	Score
Regional	Maxent	0.99	0.74	0.66	0.77	5.91
	GLM	0.59	−0.03	0.62	0.33	2.66
	RF	0.49	0	0	1	2.47
Ecuador (Historical)	Maxent	0.95	0.69	0.20	0.29	4.3
	GLM	0.87	−0.34	0.60	0.06	1.38
	RF	0.76	0.41	0.45	0.96	3.89

3.2. Potential Distribution of *A. queko* at the Regional Level

At the regional level, *A. queko* was found to have a potential distribution area of 264,540 km² across the four Andean countries (Figure 2A). Peru exhibited the largest area of potential distribution, while Bolivia recorded the smallest. A similar trend was observed in

the areas of high potential distribution (Figure 2B), with Bolivia's high-potential area being notably small, measuring just 693 km². Furthermore, when comparing the overall potential distribution to the area of the highest potential, there was a decrease of 41%, reducing the area to 110,381 km².

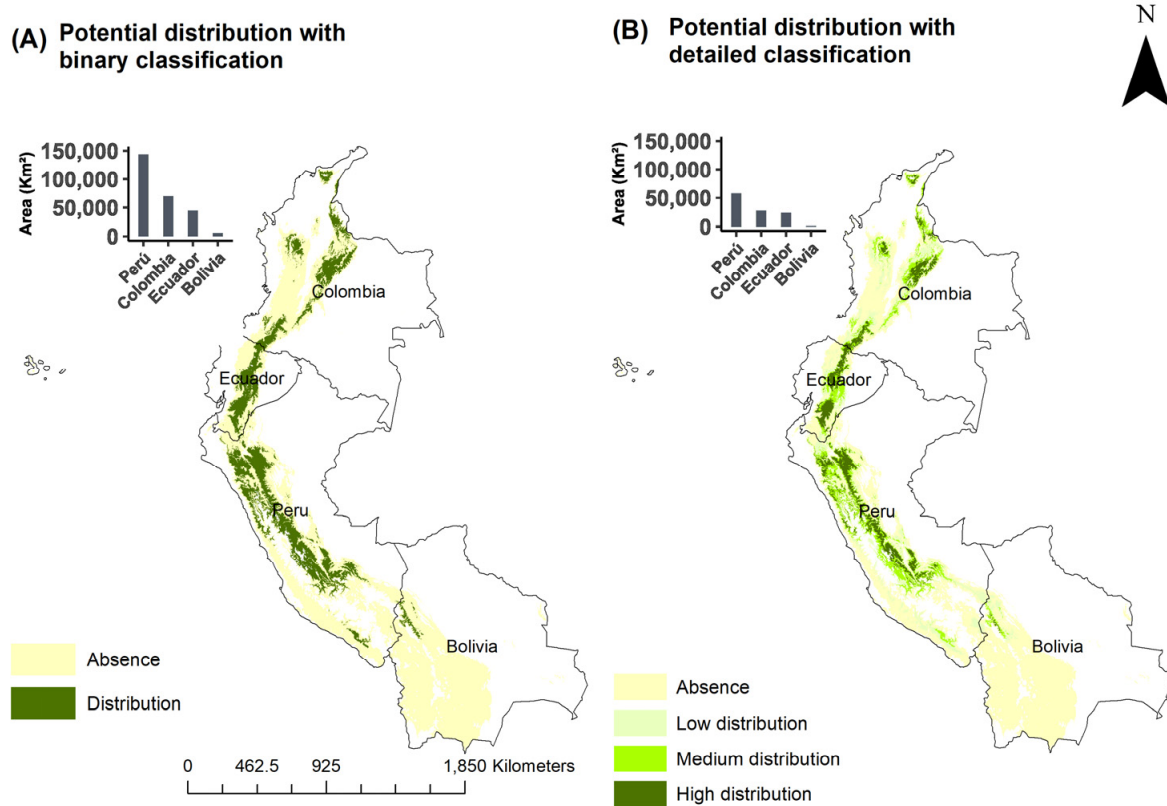


Figure 2. Potential distribution of *A. queko* at the regional level across Colombia, Ecuador, Peru, and Bolivia. (A) Binary classification. (B) Detailed classification.

3.3. Potential Distribution of *A. queko* at the Ecuadorian Level

Considering the minimum distribution threshold and its binary classification, the historical scenario exhibited the largest potential distribution area at 78,658 km², compared to the other scenarios (Figure 3A,H). The future scenarios for 2021–2040 and 2014–2060 showed minimal changes in potential distribution (Figure 3B–G,H). Among these, the 21–40–SPP126 scenario demonstrated the greatest potential for future distribution, covering 24,001 km² (Figure 3C,H). A similar pattern was evident in the detailed classification (Figure 4), where the area of high distribution was greater in the historical scenario, measuring 56,355 km² (Figure 4A,H). Over the studied period, no significant changes were observed in areas of high potential distribution (Figure 4B–G,H). Notably, the 41–60–SPP245 scenario exhibited the highest potential for future distribution (Figure 4F,H).

3.4. Potential Distribution with Land-Use Changes in Ecuador

The historical scenario, which showed the largest potential distribution area (Figure 5A–C), was intersected with the land-use change layer. After this intersection, the areas of distribution (binary classification) and the high distribution category (detailed classification) decreased by 37% and 35%, respectively (Figure 5A–C). Furthermore, the binary classification scenario indicated a larger potential surface area than the high distribution category of the detailed classification (Figure 5C). Nevertheless, the intersected results revealed that the potential distribution areas are larger than any of the analyzed future modeling scenarios (Figure 5C). Additionally, these results demonstrated that future

climate variables have a more definitive impact on reducing potential distribution areas than land-use changes recorded up to 2020.

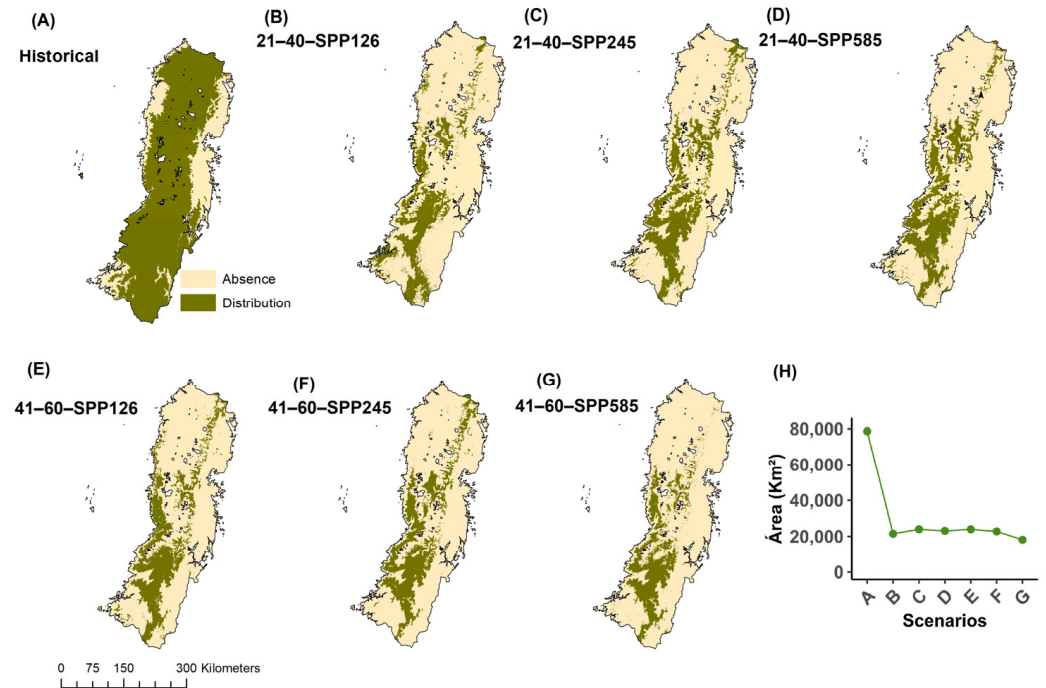


Figure 3. Binary classification maps illustrating the potential changes in the distribution of *A. queko*. (A) Historical scenario. (B–D) Current and near-future scenarios 2020–2040. (E–G) Future scenarios 2041–2060. (H) Area comparisons between scenarios. The letters up to G have the same meaning in (H).

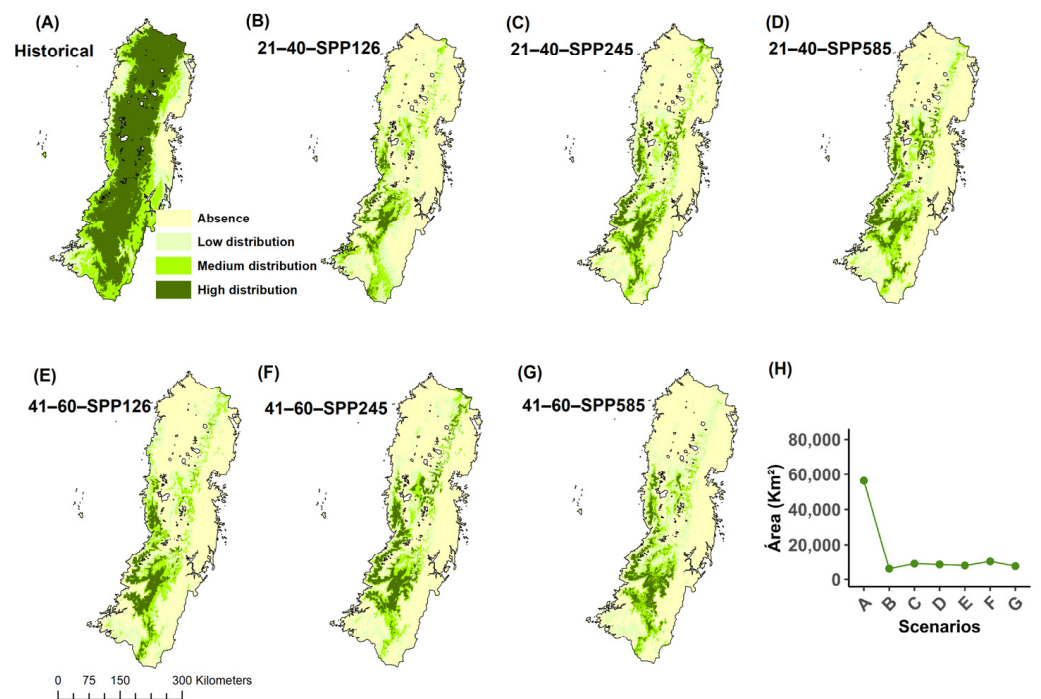


Figure 4. Detailed classification maps illustrating potential changes in the distribution of *A. queko*. (A) Historical scenario. (B–D) Current and near-future scenarios (2020–2040). (E–G) Future scenarios (2041–2060). (H) Area comparisons between scenarios. The letters up to G have the same meaning in (H).

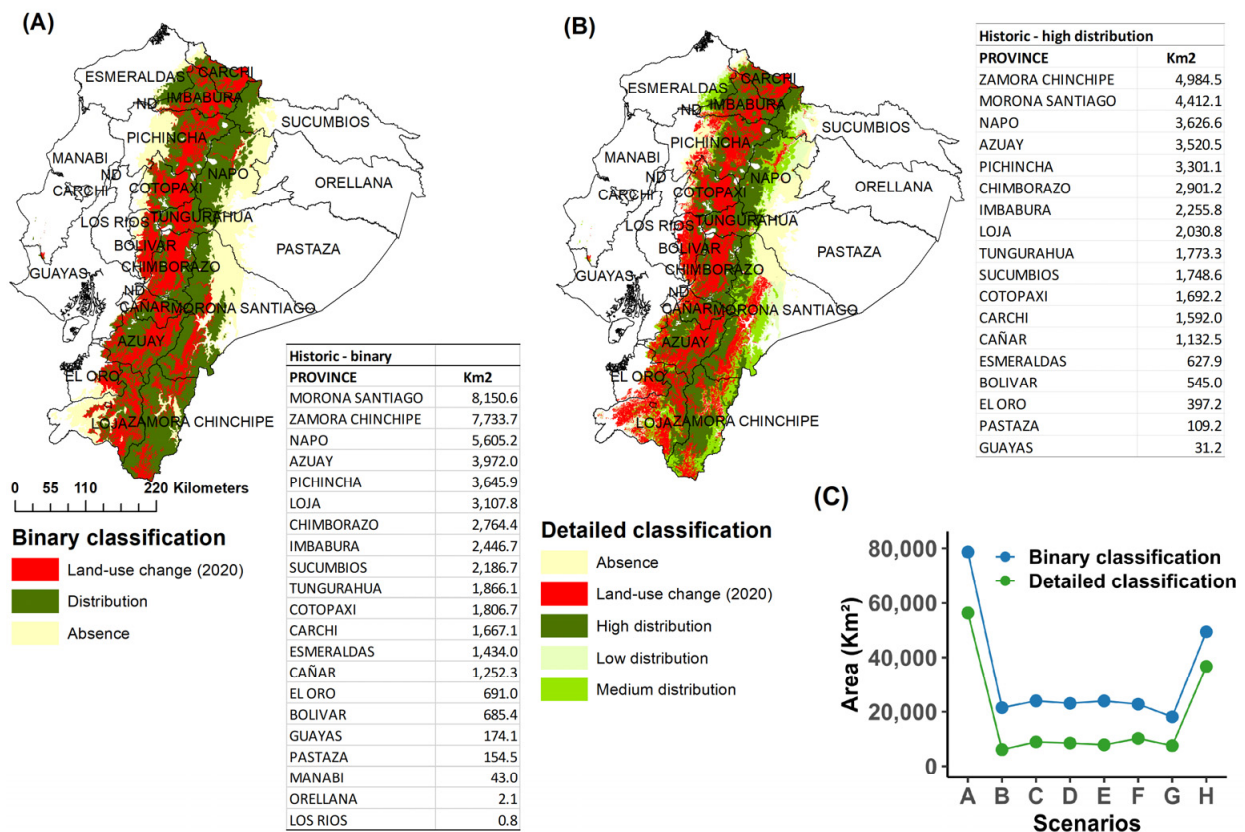


Figure 5. Distribution maps of *A. queko*, considering the historical scenario and changes in land use in Ecuador until 2020, illustrated through binary (A) and detailed (B) classifications. In (C), the distribution of *A. queko* across two categories is shown and the letters represent the following: (A)—historical scenario; (B–D)—current and near-future scenarios (2020–2040); (E–G)—future scenarios (2041–2060); H—historical scenario intercepted with a land-use change layer of Ecuador (2020).

In the historical scenario overlapped with land-use change, the provinces of Morona Santiago and Zamora Chinchipe showed a larger area of distribution in the binary classification, while Orellana and Los Ríos exhibited smaller surface areas (Figure 5A). Considering the widespread distribution of *A. queko* (Figure 5B), the provinces of Zamora Chinchipe and Morona Santiago exhibited larger areas of high distribution, in contrast to Pastaza and Guayas.

3.5. Environmental Variables and Their Influence on Potential Distribution Models

At the regional level, the uncorrelated predictor variables used in the model were B1, B2, B4, B15, and B18. Among these, only B4 had a >50% contribution to the model, while the remaining variables each contributed less than 50%. At the Ecuadorian level, the uncorrelated variables B2, B3, B4, B5, B14, B15, B18, and slope were used across all scenarios. Of these, B5 and B14 were the most significant in explaining the models for all scenarios of *A. queko* distribution. Additionally, in scenarios with a larger predicted area, such as the historical one (Figure 6A), B5, B3, and B14 were the most influential. In the current and near-future scenario named 21–40–SPP126 (Figure 6B), B5, B3, and B18 were the key contributors, while in the future scenario 41–60–SPP245 (Figure 6G), B18, B14, and B5 played the most important roles in the model.

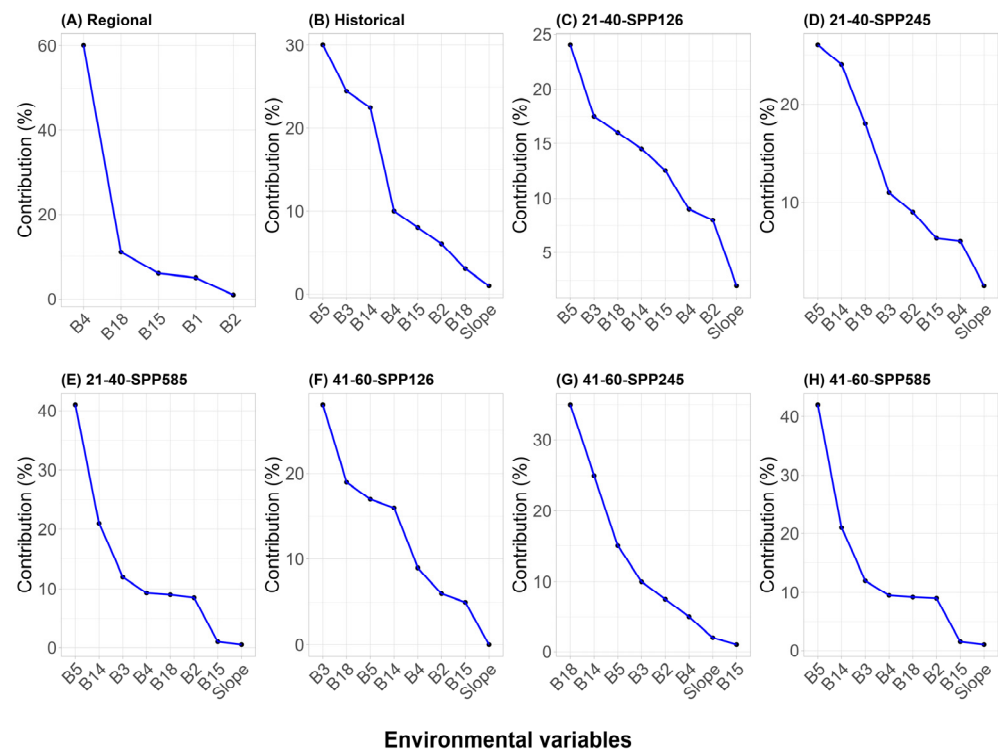


Figure 6. Uncorrelated environmental variables and their respective percentage of explanation in the models for the different scenarios (A–H) of the potential distribution of *A. queko* at the regional level and within Ecuador. The meaning of the constant climatic variables is given in Table 1.

4. Discussion

Before performing the analyses at regional and Ecuadorian scales, it is important to evaluate the data used in selecting the best model. The AUC values for GLM and RF highlight the influence of spatial scale on predictive accuracy. At the regional level, AUC values are lower (GLM: 0.59, RF: 0.49) compared to the national level (0.87 and 0.76, respectively), likely due to greater geographic extension and increased environmental heterogeneity, which complicates species distribution predictions [54]. In contrast, at the national scale, more homogeneous and detailed data improve model performance [55]. Additionally, environmental complexity particularly affects RF, which, despite its flexibility, requires well-structured data to achieve accurate predictions [56].

4.1. Potential Distribution of *A. queko* at a Regional Scale

In our research, we analyzed at two levels the potential distribution of *A. queko*, an emblematic species used for handicraft production. At the regional level, we assessed its distribution across four Andean countries in South America, using various species distribution algorithms and finding Maxent to be the best fit. This algorithm combines pre-processed environmental variables and presence records to model the species' ecological niche and create potential distribution maps. Previous studies confirm that a species' ecological niche can be quantitatively represented by integrating presence records with biotic and abiotic variables [57]. Zhang [58] used the Maxent model to predict the suitable habitats of *Cinnamomum camphora* at China under climate change scenarios, demonstrating its effectiveness in diverse environmental conditions. Their findings align with our results, where Maxent also proved to be the best algorithm for modeling the potential distribution of *A. queko* across in four countries at the Andean region.

At the regional level, the presence of *A. queko* showed potential distribution areas greater than 50% in Colombia and Peru, both in general and high distribution, compared to

smaller areas at Ecuador and, especially, Bolivia. This reflects the broad natural range of the species across the Andean territories. Seasonal temperature played a key role in defining the species' distribution limits by impacting its survival, reproduction, and resource availability, thus shaping the habitats where *A. queko* can thrive [59]. This variable may also influence certain ecological interactions and migration patterns [60]. Similar results were found by Perez-Suarez [61], who used the Maxent model to predict the distribution of *Pinus hartwegii* in Mexico, identifying temperature and precipitation as key factors shaping its habitat. Their findings, particularly regarding the impact of seasonal temperature variations, align with our results, reinforcing the critical role of climatic variables in defining the ecological niches of species across the Andean region.

4.2. Distribution of *A. queko* in Natural Habitats Within Ecuador

The study used both historical and projected climate scenarios to model the potential distribution of *A. queko* across Ecuador. We also analyzed distribution changes under three intensity scenarios in SSP—SSP126, SSP245, and SSP585—over two periods: the near future (2020–2040) and the longer-term future (2041–2060). In addition to climate data, the slope was incorporated to minimize uncertainty in distribution models of *A. queko* in Ecuador. Findings from the historical scenario indicated the largest potential distribution area, suggesting that *A. queko* currently occupies an optimal range in stable historical climates. The present and near-future projections showed slight reductions in the species' range, with SSP126 (optimistic) offering the greatest stability. This aligns with studies indicating that lower-emission scenarios are more favorable in maintaining species distribution [62,63]. In line with this, a study by Gonzales-Trujillo [64] investigated the distribution of Andean plant species under climate change and found that regions with lower emission scenarios (SSP126) were less prone to habitat loss, similar to our results for *A. queko*. Although high-potential areas for *A. queko* remained relatively stable across scenarios, the regional climate variability presents challenges for persistence. Core habitats for *A. queko* likely include the regions less affected by climate- and human-driven changes, providing stable conditions that support survival despite environmental shifts.

At Ecuador's historical context, the distribution of *A. queko* is primarily driven by three climate factors: the maximum temperature of the warmest month, isothermality, and precipitation during the driest month. High temperatures set an ecological limit, beyond which the species may experience stress or mortality, particularly in warmer regions. This is consistent with findings for other Andean species, such as *Puya raimondii*, where temperature increases have been linked to habitat contraction and higher mortality rates in the warmer parts of its range [65]. Isothermality plays a fundamental role in maintaining stable growth conditions, being particularly important for mountain species that depend on consistent thermal patterns to regulate their physiological processes. This concept aligns with the statement by Quintero [66] who argues that seasonal variation is a key factor explaining much of the differences in the climatic niche amplitudes among species, as greater thermal stability facilitates more efficient adaptation to environmental changes. Additionally, sufficient rainfall during the driest month is crucial for mitigating drought stress, highlighting water availability as a key factor in the persistence of species across diverse landscapes. The findings of Wang [67] reinforce this notion, demonstrating that precipitation during this critical period plays a fundamental role in determining the suitable areas for species distribution. The species in their study exhibited a strong correlation with the amount of rainfall received during the driest month, with limited precipitation during this period restricting their expansion into areas with inadequate water availability.

Under the most stable present and future scenario, i.e., 21–40 SSP126, the precipitation during the warmest quarter becomes an even more decisive factor for *A. queko*'s poten-

tial distribution, as this coincides with the period of highest environmental demand for moisture. During these months, *A. queko* likely experiences elevated evaporation and transpiration due to warmer temperatures, making water availability essential. Precipitation during the warmest quarter has been identified as a crucial factor for species distributions, particularly during times of high moisture demand, as observed in studies on *Magnolia sieboldii* and *Haloxylon ammodendron* [68,69]. These species rely heavily on water availability during this period, with insufficient rainfall restricting their distribution, particularly under changing climatic conditions. Similarly, for *A. queko*, the importance of precipitation during the warmest quarter is expected to intensify in future scenarios, as it coincides with the species' peak moisture demand, highlighting the critical role of water availability in shaping its potential range.

4.3. Distribution of *A. queko* in the Historical Scenario, Intersected with a Land-Use Change Layer for Ecuador (2020)

This study reveals a significant reduction in the species' potential distribution due to land-use changes and climate variability. While the historical scenario exhibited the largest distribution area, land-use changes led to a 37% decline in the binary classification, and the high-distribution category decreased by 35%. These results are consistent with findings from other Andean countries, where habitat loss and climate change are primary drivers of species distribution shifts [70,71]. Furthermore, the interaction between climate change and land-use transformations exacerbates habitat degradation, complicating conservation planning [72].

Although climate variables have a more significant impact on habitat reduction than land-use changes, driving shifts in species distributions and altering habitat suitability [72], some suggest that land-use change could ultimately have a more significant impact than climate change, given its long-standing nature and its likely limited connection to climate modification [73,74]. However, recent studies have documented a strong relationship between land-use change and climate variation, both contributing significantly to future habitat loss [75]. In Colombia, deforestation and agricultural expansion have dramatically reduced suitable habitats for endemic species [76], while in Peru, montane forests are threatened by climate-induced range shifts [77]. In Ecuador, regional variability across provinces emphasizes the need for targeted conservation efforts, with some areas acting as refuges and others requiring urgent intervention. Similarly, studies in Argentina project severe range reductions for historically widespread species in the future [78]. These findings highlight the need to integrate land-use policies with climate adaptation strategies for effective conservation planning.

5. Conclusions

Aulonemia queko occupies a substantial range across the Andes, predominantly in Peru, with smaller, less extensive areas in Bolivia. In Ecuador, however, it has notable coverage relative to its overall distribution in the Andes, with its range showing significant shifts from historical to current and projected future scenarios. The potential distribution of *A. queko* is heavily influenced by climatic variables, particularly temperature and precipitation, underscoring the species' sensitivity to seasonal changes in moisture availability. This highlights the critical need to incorporate climate projections into habitat conservation planning, especially in regions where the species naturally thrives. Land-use changes have reduced suitable habitats for *A. queko* by over 35%, directly threatening the species' ability to find resources, reproduce, and maintain viable populations, underscoring the severe impact of human activities on its long-term survival. Combined with climate-driven environmental shifts that further decrease potential distribution, these findings stress

the urgent need for conservation strategies to mitigate habitat loss in these biodiversity-rich areas.

Incentives for the conservation of natural cover, environmental education and awareness, the promotion of sustainable agricultural practices, economic alternatives for local communities, and the restoration of degraded areas represent challenging but viable alternatives to halt land-use change in Ecuador. These actions would contribute to reducing the loss of natural habitats, thus protecting the flora and fauna of a megadiverse country. By integrating these approaches, it is possible to create a more sustainable balance between development and conservation, ensuring the long-term survival of Ecuador's unique biodiversity.

Author Contributions: H.C.: Conceptualization, data curation, methodology, software, visualization, writing—original draft, writing—review and editing. L.G.G.-M.: Visualization, writing—original draft, writing—review and editing. O.C.: Methodology, software, supervision, validation. M.R. and A.A.: Investigation, methodology. O.J.: Funding acquisition, investigation, project administration, resources, conceptualization, data curation, methodology, software, visualization, writing—original draft, writing—review and editing. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: Data will be made available on request.

Acknowledgments: The authors express their gratitude to the Vice-Rectorate for Research of the University of Cuenca (Vicerrectorado de Investigación de la Universidad de Cuenca, VIUC, <https://www.ucuenca.edu.ec/investigacion-innovacion/>), Ecuador, accessed on 4 January 2024, for providing financial support for the research project “El Rol de los bosques andinos frente al cambio climático con base a la relación taxonómica y funcional de la vegetación leñosa con los stocks de carbono, Azuay—Ecuador”. The authors also thank VIUC for allocating part of our workload to the production of this paper. Omar Cabrera thanks the UTPL for their support in the culmination of the manuscript. The authors thank Diana Szekely for her help in the language revision. This research was conducted under permit No. 214-19-IC-FLO-DPAA/MA, granted by the Ministry of the Environment of Ecuador.

Conflicts of Interest: The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Abbreviations

AUC	Area under the curve
TSS	True skill statistic
GLMs	Generalized linear models
RF	Random forest
GBIF	Global Biodiversity Information Facility
SSPs	Shared socioeconomic pathways
MAATE	Ministry of Environment and Water and the Ecological Transition of Ecuador

Appendix A. Climatic Variables and Elevation Used to Generate Potential Distribution Models. The Meaning of the Variables and Their Units Can Be Found in Table 1 of the Main Text

Specie	Longitud	Latitude	B1	B2	B3	B4	B5	B6	B7	B8	B9	B10	B11	B12	B13	B14	B15	B16	B17	B18	B19	Elevation (m)
<i>Aulonemia queko</i>	−77.0	1.2	13.7	9.3	87.8	46.1	18.7	8.1	10.6	13.4	13.9	14.1	13.0	2088	235.6	129.5	19.9	661.6	418.0	572.0	533.4	2483
<i>Aulonemia queko</i>	−78.2	−1.0	11.6	10.0	83.1	53.3	17.9	5.9	12.0	11.3	11.9	12.1	10.9	1114	130.7	53.5	22.8	352.7	191.0	254.5	341.5	2925
<i>Aulonemia queko</i>	−75.0	−11.5	9.6	13.2	79.4	49.0	17.2	0.6	16.6	9.6	9.0	10.2	9.0	1020	160.5	16.0	60.9	451.0	66.0	309.3	66.0	4004
<i>Aulonemia queko</i>	−73.6	−11.6	18.8	12.4	82.0	61.6	26.0	10.9	15.1	18.7	18.1	19.6	18.1	1705	236.7	45.0	48.8	693.0	179.7	407.4	184.5	2039
<i>Aulonemia queko</i>	−79.4	−2.8	9.3	9.8	82.0	52.2	15.3	3.4	11.9	9.7	8.6	9.7	8.5	974	137.7	32.8	43.3	389.5	118.3	342.3	123.3	3310
<i>Aulonemia queko</i>	−79.5	−2.8	12.9	10.0	84.0	34.7	19.0	7.0	12.0	13.2	12.4	13.2	12.4	767	151.2	4.0	83.2	418.0	25.0	317.0	28.7	2649
<i>Aulonemia queko</i>	−79.4	−2.8	10.1	10.1	82.5	49.7	16.3	4.1	12.2	10.5	9.4	10.5	9.4	917	138.6	26.4	50.1	388.9	97.2	331.2	97.9	3155
<i>Aulonemia queko</i>	−78.1	−0.2	9.3	10.6	88.2	46.0	15.2	3.2	12.0	9.3	9.4	9.6	8.6	1212	118.7	78.5	13.5	353.0	263.0	273.5	320.2	3282
<i>Aulonemia queko</i>	−79.2	−3.9	16.9	10.3	81.5	40.4	23.7	11.0	12.7	17.1	17.1	17.3	16.3	834	113.0	46.0	28.8	282.0	146.4	158.8	203.2	2046
<i>Aulonemia queko</i>	−79.1	−1.8	14.1	10.1	82.7	32.9	20.4	8.2	12.2	14.4	13.7	14.4	13.7	856	177.3	5.5	88.0	495.3	37.0	399.0	37.0	2328
<i>Aulonemia queko</i>	−72.5	−12.5	18.3	13.1	81.6	64.7	26.2	10.1	16.1	18.3	17.5	19.1	17.5	1543	239.3	35.5	57.2	676.3	141.8	385.3	143.0	2248
<i>Aulonemia queko</i>	−79.2	−1.6	19.4	9.0	88.1	34.4	24.4	14.2	10.2	19.8	19.1	19.9	19.1	1674	342.5	8.7	92.5	944.8	51.5	771.3	65.5	1144
<i>Aulonemia queko</i>	−76.9	1.1	12.9	8.7	86.2	51.5	17.7	7.6	10.1	12.6	13.2	13.3	12.2	2474	338.0	135.0	32.1	900.7	424.0	664.0	782.5	2615
<i>Aulonemia queko</i>	−75.6	−10.4	14.3	12.3	79.9	62.4	21.1	5.8	15.4	14.4	13.4	14.9	13.4	858	127.8	18.8	58.5	376.1	68.7	269.5	68.7	2860
<i>Aulonemia queko</i>	−67.8	−16.3	13.7	12.6	75.9	107.1	21.2	4.6	16.6	14.6	12.3	14.7	12.3	889	183.3	16.0	71.6	454.5	63.0	373.5	63.0	2937
<i>Aulonemia queko</i>	−67.9	−16.3	14.6	12.5	76.3	99.4	21.9	5.5	16.4	15.4	13.2	15.5	13.2	934	192.0	15.0	72.5	479.8	61.3	393.3	61.3	2736
<i>Aulonemia queko</i>	−76.1	−9.8	17.5	13.2	81.8	50.1	25.1	8.9	16.2	17.3	17.0	18.2	17.0	643	102.8	11.3	64.7	287.3	40.0	161.3	40.0	2449
<i>Aulonemia queko</i>	−76.7	1.9	11.1	10.1	88.3	43.4	17.0	5.5	11.5	11.2	10.5	11.5	10.5	1837	219.3	99.9	29.7	626.8	321.8	522.9	324.7	2904
<i>Aulonemia queko</i>	−75.8	−9.5	19.8	12.4	83.8	47.7	26.8	12.0	14.8	19.5	19.4	20.4	19.4	828	116.2	27.3	50.0	330.5	83.5	203.2	83.5	2144
<i>Aulonemia queko</i>	−78.8	−2.9	15.6	11.6	85.3	47.6	22.7	9.2	13.6	15.9	15.9	16.0	14.9	873	101.8	57.1	19.4	276.6	178.5	244.0	215.7	2280

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