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Habitat Suitability Distribution of Genus *Gynoxys* Cass. (Asteraceae): An Approach to Conservation and Ecological Restoration of the Andean Flora in Peru

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Abstract: In this research, species distribution prediction models (i.e., MaxEnt) were applied to analyze the suitability of the ecological environment among the clades of the genus *Gynoxys* in Peru. Bioclimatic, edaphic, and topographic variables were integrated to predict the areas with the most significant potential for optimal development of this genus. These data were combined to generate potential distribution maps, taking into account the most relevant variables for each clade. The validation of the MaxEnt model showed an outstanding performance, reaching AUC indices above 0.9, reflecting the high accuracy of the predictions. The results reveal that the key variables influencing the selection of the clade occurrence areas are: mintempwarmest (47.70% contribution) in the *Discoide* clade, topowet (33.20%) in the *Gynoxys* clade, and monthcountbytemp10 (33.30%) in the *Praegynoxys* clade. The potential distribution areas of these clades were 132,594 km^2 for *Discoide*, 168,574 km^2 for *Gynoxys*, and 37,392 km^2 for *Praegynoxys*. The areas with the highest probability of presence of the genus were found in the Andean regions of northern and central Peru. However, a significant proportion of these areas were threatened by habitat fragmentation and land degradation. In terms of conservation, it was found that 32.05, 35.46, and 61.02% of the potential distribution areas of the discoid, *Gynoxys*, and *Praegynoxys* clades, respectively, are conserved, which could be a relevant factor for the preservation of this genus. These findings underscore the relevance of safeguarding key areas for conserving *Gynoxys* and montane ecosystems in Peru, emphasizing the need for protection strategies that guarantee the long-term sustainability of these species and their associated habitats.

Keywords: Peruvian Andes; potential distribution; sustainability; gynoxoide; maxent; *Praegynoxys*

1. Introduction

The genus *Gynoxys* Cass is part of the family Asteraceae, tribe Senecioneae, subtribe Tussilagininae [1], Gynoxyoid group [2] with about 131 species [2–4], divided into three sections or clades that (i) characterize with leaves, stems of young shoots, glabrous involucres with simple or stellate hairs and discoid capitula (*Discoide* clade), (ii) with radiate capitula, pubescence with stellate hairs and external phyllaries present (*Paragynoxys* clade), and (iii) with radiate capitula with simple hairs and yellow flowers (*Gynoxys* clade) [2]. The clade includes trees, shrubs, and, to a lesser extent, liana that generally grow in the Andes. Biogeographically, *Gynoxys* is distributed in Bolivia, Colombia, Ecuador, Peru, and Venezuela [1] in addition to being represented by a single species in northern Argentina [5], and mostly its species are distinctive elements of the cloud forests or shrubs and solitary trees of the jalcas [3]. *Gynoxys* stands out as one of the most diverse plant lineages in terms of number of species within the Andean region, which contributes significantly to the remarkable species diversity and high rates of endemism in the Andes, one of the areas globally recognized as biodiversity hotspots [6,7].

In particular, Peru is a biodiversity hotspot for this genus, harboring a rich diversity of species distributed across different altitudinal ranges and habitat types [3]. The richness and diversity of *Gynoxys* in Peru reflect the ecological complexity of the Andes, where environmental conditions vary considerably as a function of elevation and geography [3,8–11]. These species contribute to regional biodiversity and play critical ecological roles, including pollination and ecosystem structure [12,13]. However, most *Gynoxys* species have limited geographic distributions and inhabit ecosystems that are being altered or degraded by human activities and climate change. Therefore, their conservation should be a priority [9,14–16].

Given increasing concerns about global warming and habitat degradation, knowing the genus's current and potential distribution is crucial for developing effective conservation strategies. In this context, species distribution modeling emerges as an indispensable tool. Among the available methodologies, the maximum entropy model, known as MaxEnt, has stood out for its high efficiency and flexibility in predicting the potential areas of species presence, using both environmental and occurrence data [17–19]. MaxEnt uses a statistical approach that maximizes the entropy of predicted distributions, allowing the identification of areas with a high probability of occurrence and helping to project how species might respond to changes in future environmental conditions [20,21].

This research is oriented to applying the MaxEnt model to determine the suitable distribution areas of the genus *Gynoxys* in Peru. Through this research, we seek not only to delineate the current and potential distribution areas but also to provide insight into how inappropriate land use practices influence the degradation of these species' habitats. The information generated will provide robust support for developing biodiversity conservation and sustainability management strategies, which are crucial for the preservation of the natural wealth of the Peruvian Andes.

2. Materials and Methods

2.1. Study Area

This work covers Peru, a country with an area of about 1.3 Mkm^2, which makes it the third largest territory in South America. Geographically, Peru is located between coordinates 0°03′00″ and 18°30′00″ south latitude and between meridians 68°30′00″ and 81°30′00″ west longitude. The country is bordered to the north by Ecuador and Colombia, to the east by Brazil, to the southeast by Bolivia, to the south by Chile, and to the west by the Pacific Ocean (Figure 1). Its extensive elevation range varies from sea level in the north to 6800 m asl at Mount Mataraju [22]. The country's varied geography results in a rich landscape diversity, translating into a wide range of natural resources and agroecosystems [23]. Peru stands out for its exceptional biodiversity, harboring around 19,147 vascular plant species and approximately 20,533 plant species [24,25]. This biological diversity is attributed to its strategic location in the western region of South America [26]. Since 1995, the country has adopted various conservation strategies, primarily by creating conservation areas.

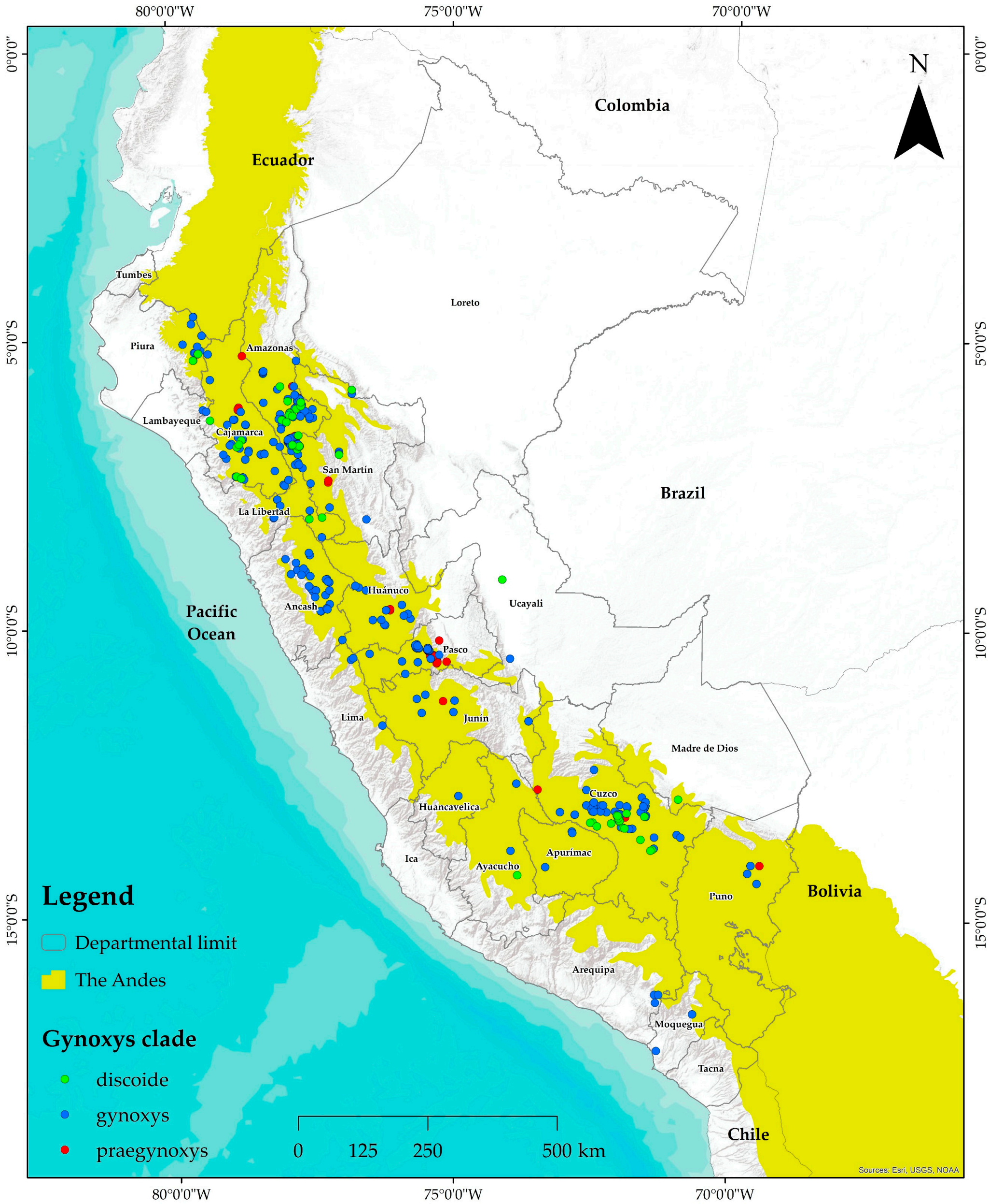

Figure 1. Location of the research area and analysis of the distribution of the genus *Gynoxys* in Peru.

Currently, there are 76 natural protected areas (NPAs), which are part of the National System of Natural Areas Protected by the Peruvian State [27]. Despite all this, between 1985 and 2021, more than 3 million hectares of forest have been lost at the national scale, including 2,600,400 hectares in the Amazon and more than 1 million in the Andean Mountains. Mining is the main threat in the Amazon, while agriculture poses the greatest risk in the Andes. Nevertheless, mining has increased by more than 3500% in the Andes, causing losses of 4.3% of Andean forests and 6.7% of wetlands in the last 37 years [28].

2.2. Records of Presence

Since 2018, records of the genus *Gynoxys* in Peru have been collected. These records were obtained through field trips in June 2018 and May 2024 aimed at collecting botanical samples (Figure 2). In addition, an exhaustive review of specimens preserved in the herbaria CPUN, CSP, F, HAO, HOXA, HSP, USM, and MOL, as well as photographs of botanical samples corresponding to the international herbaria B, GH, K, LSU, MO, NY, P, and US [29] was carried out. Previously selected occurrence data from the Global Biodiversity Information Facility (GBIF) [30] were incorporated to enrich the analysis. In total, 318 records of the genus *Gynoxys* were compiled for Peru, including 45 from the *Discoide* clade, 247 from the *Gynoxys* clade, and 26 from the *Praegynoxys* clade (Figure 2, Table S1).

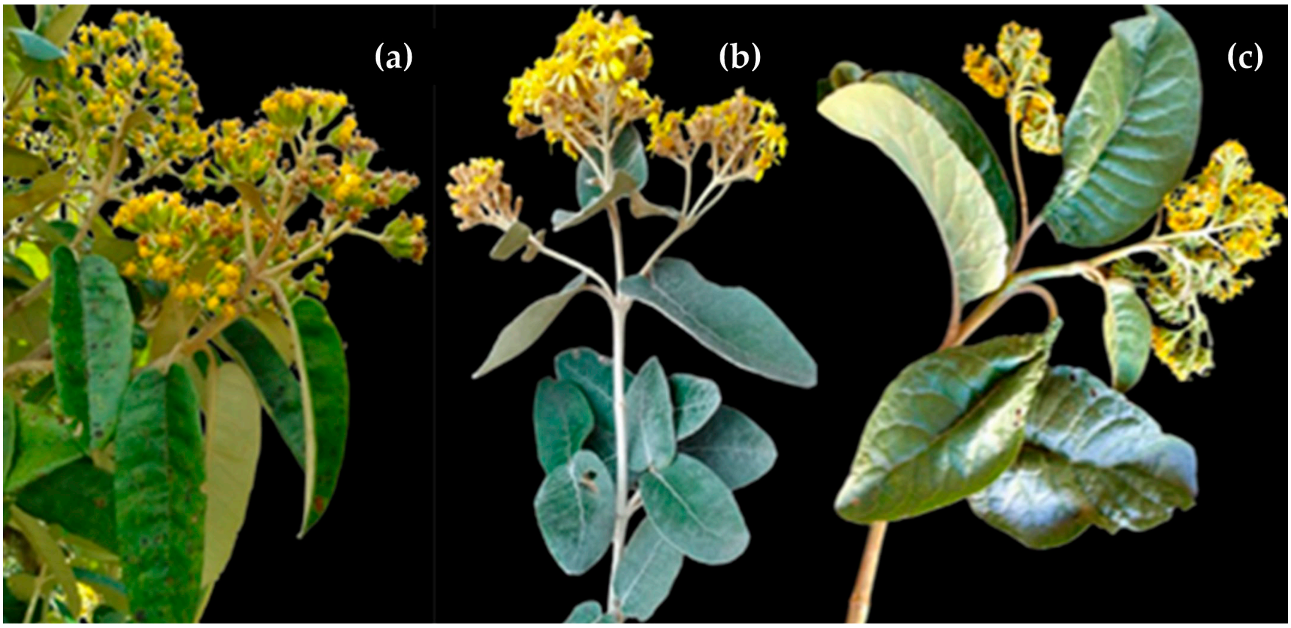

Figure 2. Botanical samples were collected from clades of the genus *Gynoxys* in Peru, where (**a**) *Discoide* clade, (**b**) *Gynoxys* clade, and (**c**) *Praegynoxys* clade.

2.3. Bioclimatic, Topographic, and Soil Factors

Distribution models mainly employ bioclimatic variables, radiation, and topographic factors [31,32]. However, since this study focuses on plants, edaphic variables are also incorporated [22,23,33–35]. Soil physicochemical parameters, such as texture, pH, organic matter, and nutrients, are key factors in analyzing the distribution of plant species in different geographical areas [36]. This aspect is especially relevant for the Asteraceae and Gynoxyoid groups [37]. This study selected 37 bioclimatic variables [38], three topographic variables, and nine edaphic variables for modeling [19]. Bioclimatic variables were obtained from WorldClim version 2, which provides data with a resolution of 30 s (~1 km) (http://www.worldclim.org/, accessed on 22 September 2024) [39] and from ENVIREM (https://envirem.github.io/, accessed on 22 September 2024) [40] (Table 1).

Current bioclimatic and environmental layers, corresponding to the average of 1970–2000, were used because of their public accessibility, broad geographic coverage, and high data resolution [41]. Topographic variables were derived from the Digital Elevation Model (DEM) with a resolution of 250 m, available through the CGIAR Consortium for Spatial Information portal (http://srtm.csi.cgiar.org/, accessed on 22 September 2024). Edaphic variables were extracted from the Soil Grids database (https://soilgrids.org/, accessed on 22 September 2024) with a spatial resolution of 250 m. Subsequently, all layers were resampled to a resolution of 250 m, resulting in 49 thematic layers, which were then transformed to ASCII format [42].

Table 1. Variables were used to model the distribution for each clade of the genus *Gynoxys* in Peruvian territory.

Variable	Symbol	Clade [1]
1. Bioclimatic variables		
Annual Mean Temperature	bio01	
Mean Diurnal Range	bio02	b; c
Isothermality	bio03	b; c
Temperature Seasonality	bio04	a
Max Temperature of Warmest Month	bio05	
Min Temperature of Warmest Month	bio06	
Annual Temperature Range	bio07	
Mean Temperature of Wettest Quarter	bio08	
Mean Temperature of Driest Quarter	bio09	
Mean Temperature of Warmest Quarter	bio10	
Mean Temperature of Coldest Quarter	bio11	
Annual Precipitation	bio12	
Precipitation of Wettest Month	bio13	a; b; c
Precipitation of Driest Month	bio14	b
Precipitation Seasonality	bio15	
Precipitation of Wettest Quarter	bio16	
Precipitation of Driest Quarter	bio17	
Precipitation of Warmest Quarter	bio18	a; b; c
Precipitation of Coldest Quarter	bio19	
Annual potential evapotranspiration: a measure of the ability of the atmosphere to remove water through evapotranspiration processes, given unlimited moisture	Annual pet	
Thornthwaite aridity index: Index of the degree of water deficit below water need	Aridity indexthornthwaite	a; b; c
A metric of relative wetness and aridity	Climatic moisture index	
Average temp. of the warmest month—average temp. of the coldest month	continentality	b; c
Emberger's pluviothermic quotient: a metric that was designed to differentiate among Mediterranean-type climates	embergerq	
The sum of the mean monthly temperature for months with a mean temperature greater than 0 °C multiplied by the number of days	growingdegdays0	
The sum of the mean monthly temperature for months with a mean temperature greater than 5 °C multiplied by the number of days	growingdegdays5	
Max. temp. of the coldest month	maxtempcoldestmonth	
Min. temp. of the warmest month	mintempwarmestmonth	a
Count the number of months with mean temp greater than 10 °C	monthcountbytemp10	a; b; c
Mean monthly PET of coldest quarter	eco quartier	

Table 1. *Cont.*

Variable	Symbol	Clade [1]
1. Bioclimatic variables		
Mean monthly PET of driest quarter	petdriestquarter	b
Monthly variability in potential evapotranspiration	pet-seasonality	b
Mean monthly PET of warmest quarter	petwarmestquarter	a
Mean monthly PET of wettest quarter	pet wettest quarter	
Compensated thermicity index: sum of mean annual temp., min. temp. of the coldest month, max. temp. of the coldest month, x 10, with compensations for better comparability across the globe	the mind	
Terrain roughness index	tri	a; b; c
SAGA-GIS topographic wetness index	to power	a; b; c
2. Topographic variables		
Elevation above mean sea level	dem	c
Cardinal orientation of the slope	aspect	a; b; c
Terrain tilt	slope	a; b; c
3. Edaphic variables		
The bulk density of the fine earth fraction	bdod	b; c
The proportion of clay particles (<0.002 mm) in the fine earth fraction	clay	b;c
Volumetric fraction of coarse fragments	Coarse	a; b; c
The proportion of sand particles (>0.05 mm) in the fine earth fraction	sand	a; b; c
The proportion of silt particles (≥0.002 mm and ≤0.05 mm) in the fine earth fraction	silt	a; b; c
Cation exchange capacity	cec	
Total nitrogen (N)	nitrog	a; b; c
Soil organic carbon content in the fine earth fraction	soc	b; c
Soil pH	phh2o	a; b; c

[1] a: *Discoide*, b: *Gynoxys* and c: *Praegynoxys*.

2.4. Selecting Variables

The high correlation between variables in distribution models can reduce the reliability of predictions, as the contributions of two or more similar variables may overlap [41,43]. To address multicollinearity, the 'removeCollinearity' function of the 'virtualspecies' package in R 3.6 was used [44]. This process consisted of three steps: (i) calculating Pearson correlation coefficients between variables, (ii) generating a distance matrix based on these coefficients, and (iii) constructing a dendrogram using hierarchical cluster analysis. To avoid multicollinearity in the models, a correlation threshold of $r \geq 0.7$ was defined as an acceptable limit [39,45]. Subsequently, a representative variable was selected from each group of correlated variables using a preliminary MaxEnt model, which employed all available variables. The final selection was based on the performance of each variable in the Jackknife test [23,46], where the training gains of a model with all variables were compared against a model with a single variable of interest [23,33]. In this way, 13 bioclimatic, eight edaphological, and three topographical variables were selected for inclusion in the final models' spatial distribution modeling of the genus *Gynoxys*.

2.5. Potential Distribution Modeling

Modeling of the potential distribution was performed using the Maximum Entropy algorithm [17], implemented in MaxEnt version 3.4.4 (https://biodiversityinformatics.amnh.org/open_source/maxent/, accessed on 12 December 2024), a tool known for its effectiveness in predicting distribution areas based on presence data and environmental variables. For this analysis, georeferenced data were randomly divided into two groups: one for model training, 75% of the records, and one for validation, with the remaining 25%. Ten replicates were performed for each species using the bootstrap method, with a maximum of 1000 iterations per replicate, to increase the accuracy of the predictions generated by the algorithm [47]. A convergence threshold of 0.00001 was set, indicating that the algorithm would continue to run until the difference between successive iterations was less than this value. In addition, a limit of 10,000 background points was set for the modeling process [48]. The default model settings were kept unchanged, taking advantage of MaxEnt's ability to automatically select the most appropriate function based on available data, which optimizes the model's performance [47].

Model validation was carried out using the area under the curve (AUC) method, which is obtained from the receiver operating characteristic (ROC) curve [49]. This method assigns a score that indicates the predictive ability of the model, i.e., how well the model can predict the presence or absence of the species in the evaluated areas. The AUC values obtained were classified into five performance levels: "excellent" for AUC above 0.9, "good" for values between 0.8 and 0.9, "acceptable" for values between 0.7 and 0.8, "poor" for values between 0.6 and 0.7, and "invalid" for AUC below 0.6 [50]. This classification allows an objective evaluation of the quality of the model, avoiding the imposition of subjective thresholds in interpreting the results [51].

The results were presented using the logistic format [20], which made it possible to generate maps representing continuous probability values, ranging from 0 to 1, for the potential distribution areas of the species. These probability values were grouped into four distribution categories: "high" for values greater than 0.6, "moderate" for values between 0.4 and 0.6, "low" for values between 0.2 and 0.4, and "no potential distribution" for values less than 0.2 [20,33]. To better illustrate the distribution, three different maps were produced, each representing the distribution of the three clades or subgroups within the genus *Gynoxys* (*Discoide*, *Gynoxys*, and *Praegynoxys*). In addition, a bar chart was generated to examine how these clades are distributed at the departmental level, which allowed the identification of the areas with the highest probability of presence of the genus in the country.

2.6. Associating Potential Distribution with Elevation and Ecoregions

A spatial overlap analysis was carried out using the potential distribution maps of the different clades of the genus *Gynoxys* in Peru. For this analysis, two geospatial datasets were used: the altitude shapefile, obtained from the digital elevation model (DEM), and the shapefile of the ecoregions of Peru, developed by the Ministry of Environment [52], based on the work of Antonio Brack Egg. The potential species distribution was graphically visualized considering the Peruvian territory's altitudinal range and various ecoregions. In addition, a multiple correspondence analysis (MCA) [53,54] was used to explore the relationship between the potential distribution areas of the clades of the genus and their different altitudinal ranges and ecoregions. This approach allowed the association of each clade with a specific altitudinal range and the types of ecoregions that predominate in the country, facilitating the understanding of the spatial distribution of the species. For this purpose, a categorical data matrix was structured with information on the presence of the clades in different altitudinal ranges and ecoregions, which was analyzed using the FactoMineR package in R. The results were visualized using biplots, where the clades were grouped according to their environmental similarities, making it possible to identify differentiated ecological patterns.

2.7. Determination of Key Areas for Research, Protection, and Restoration

An overlay of the potential distribution maps of the clades of the genus *Gynoxys* was carried out with the Shapefile corresponding to the System of Natural Protected Areas of Peru, available in the SERNANP geoserver (https://geo.sernanp.gob.pe/visorsernanp/#, accessed on 10 October 2024). The main objective of this analysis was to identify the areas within Peru with a high potential for harboring species of the genus, with special emphasis on those found within protected areas under different conservation modalities. These modalities include natural protected areas (ANP), reserved areas (ZR), buffer zones (ZA), biosphere reserves (BR), regional conservation areas (ACR), and private conservation areas (ACP) [27]. In addition, the layers representing the potential distribution of *Gynoxys* were superimposed with the map of degraded areas of Peru (2001–2021) (https://geoservidor.minam.gob.pe/recursos/intercambio-de-datos/, accessed on 22 September 2024). This map shows the estimated partial or total loss of key ecosystem components, such as water, soil, and biodiversity, negatively affecting their structure, functionality, and capacity to provide ecosystem services (LDN) [55].

This analysis facilitated the identification of areas in Peru with favorable conditions for the presence of *Gynoxys* but are currently affected by degradation processes caused by human activities [28]. Based on this finding, areas with the potential to be restored were identified, considering their capacity to recover their natural aptitude. In addition, this study highlighted other areas of potential distribution of the genus that are free of degradation, suggesting that these areas could be considered for future conservation and long-term protection strategies [22].

3. Results

3.1. Contribution of Variables

The bioclimatic variables and data obtained through the Jackknife test revealed that the most influential variables in determining habitat suitability for the three clades of the genus *Gynoxys* in Peru were the following: for the *Discoide* clade, the most important variables were tmintempwarmest, nitrogen, month-countbytemp10, aridityindexthornthwaite and bio18, which explained 82.90% of the variance in the model; for the *Gynoxys* clade, the key variables were topowet, petseasonality, petdriestquarter, petdriestquarter and nitrogen, with a contribution to the model of 71.50%; finally, for the *Praegynoxys* clade, the determining variables were monthcountbytemp10, elevation, bdod, phh2o and topowet, which contributed 79.30% to the total model (Table 2).

Table 2. Variables with the greatest contribution to the Maxent modeling of the three clades of the genus *Gynoxys* in Peru.

Clade	Variable 1 (%)	Variable 2 (%)	Variable 3 (%)	Variable 4 (%)	Variable 5 (%)	Total Contribution
Discoide	mintempwarmes-tmonth (47.70%)	nitrogen (11.30%)	monthcountby-temp10 (9.00%)	Aridity index Thornthwaite (7.90%)	bio18 (7.00%)	82.90%
Gynoxys	to power (33.20%)	pet-seasonality (17.60%)	petdriestquarter (6.90%)	Pet driest quarter (6.90%)	nitrogen (6.90%)	71.50%
Praegynoxys	monthcountby-temp10 (33.30%)	elevation (30.00%)	bdod (7.60%)	phh2o (4.50%)	to power (3.90%)	793%

3.2. Distribution Model Performance

Distribution models were developed for the clades of the genus *Gynoxys* in Peru, and each of these models showed excellent predictive performances, with areas under the curve (AUC) greater than 0.900. The AUC values obtained for each clade were 0.990 for *Praegynoxys*, 0.973 for discoid, and 0.953 for *Gynoxys*. Overall, the overall mean AUC value for all clades was 0.972, indicating a high level of accuracy in the predictions made by the models.

3.3. Current Potential Distribution

Under current edaphoclimatic conditions, total climatic suitability, which includes potential habitats classified as "high", "moderate", and "low", indicates a potential distribution of *Gynoxys* in Peru of 132,594.5 km^2 for the *Discoide* clade, 168,574.3 km^2 for *Gynoxys* clade and 38,119.3 km^2 for *Praegynoxys* clade (Figure 3).

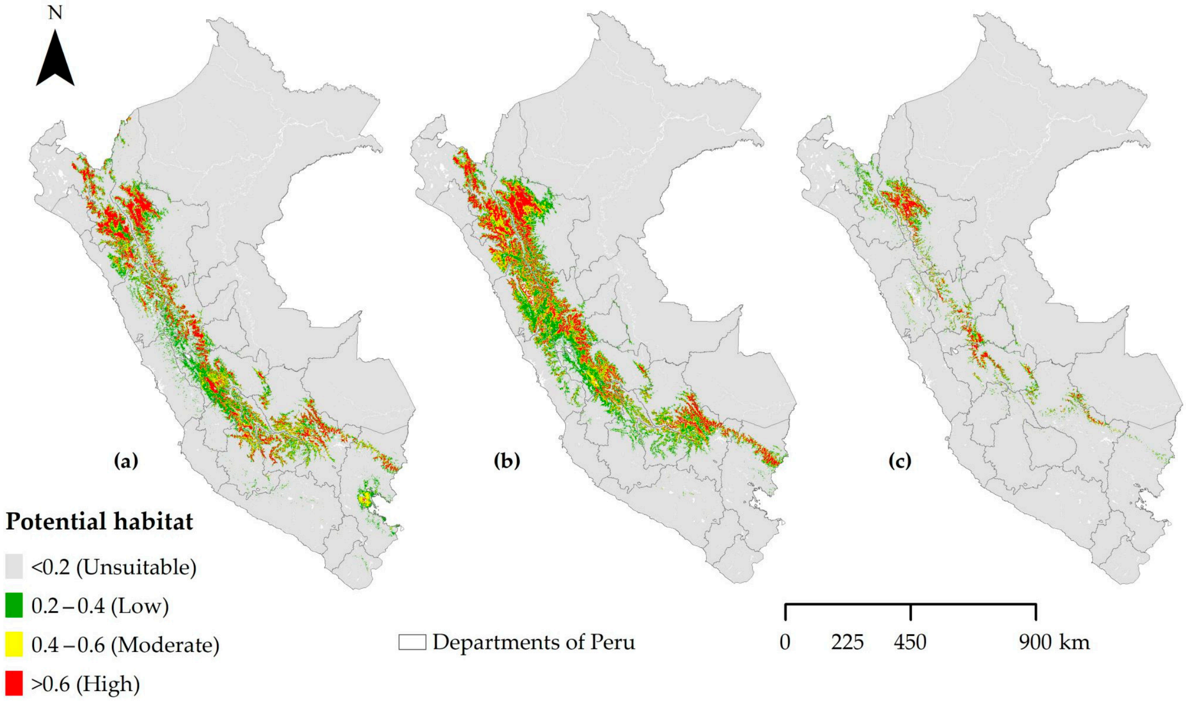

Figure 3. Distribution of potential areas of the genus *Gynoxys* in the Peruvian territory. Where the potential distribution of each clade is represented in (**a**) *Discoide* clade, (**b**) *Gynoxys* clade, and (**c**) *Praegynoxys* clade.

A comparison between the geographic distribution of the genus *Gynoxys* and its distribution at the departmental level in Peru shows that this genus is predominantly concentrated in the departments along the Andes Mountain range. Specifically, its highest density of presence is found in the northern and central macro-regions of the country, where a more significant distribution is observed in terms of number of records. In contrast, its presence is minimal or absent in the departments that comprise the coastal and Amazonian ecosystems Table 3). The potential distribution of the *Discoide* clade is particularly remarkable in the departments of Cajamarca (16,511.26 km^2), Cusco (15,923.24 km^2), Junín (15,245.67 km^2), Amazonas (11,421.72 km^2), and Huánuco (10,311.94 km^2). Among these, Cajamarca, Cusco, and Amazonas stand out as having the largest areas of suitable *Discoide* habitat, with areas of high and moderate potential totaling 10,553.16 km^2, 9532.10 km^2, and 7838.01 km^2, respectively (Table 3).

As for the *Gynoxys* clade, its potential distribution is even more extensive, standing out in the departments of Cusco (19,411.27 km^2), Ancash (18,711.60 km^2), Cajamarca (18,228.26 km^2), Junín (17,298.35 km^2), and Huánuco (15,851.53 km^2). The departments of Cajamarca, Cusco, and Ancash stand out for the large extension of areas suitable for *Gynoxys*, with areas of high and moderate potential reaching 13,552.28 km^2, 10,793.68 km^2 and 9624.73 km^2, respectively. Finally, the *Praegynoxys* clade has the most restricted distribution within the Peruvian territory, with a predominant concentration in the north and central part of the country. The departments with the most significant potential distribution for this clade are Amazonas (9648.68 km^2), Junín (4944.79 km^2), San Martín (4774.47 km^2), Huánuco (4373.61 km^2), and Cajamarca (4023.73 km^2). Among these, Amazonas, Junín, and San Martín stand out as having the most extensive areas suitable for *Praegynoxys*, with high and moderate potential areas of 6582.49 km^2, 2664.57 km^2, and 2287.80 km^2, respectively.

Table 3. Analysis of the potential distribution of the *Gynoxys* about the departments of Peru.

Macroregion	Department	*Discoide*				*Gynoxys*				*Praegynoxys*			
		Potential Areas (km^2)											
		Low	**Moderate**	**High**	**Total**	**Low**	**Moderate**	**High**	**Total**	**Low**	**Moderate**	**High**	**Total**
North	Amazonas	3583.71	2202.48	5635.53	11,421.72	2668.05	3102.96	6482.29	12,253.30	3066.19	2559.67	4022.82	9648.68
	Ancash	4492.13	1459.70	1152.57	7104.40	9086.87	5925.46	3699.27	18,711.60	813.31	243.60	75.42	1132.33
	Cajamarca	5958.10	3889.73	6663.43	16,511.26	4675.98	5484.37	8067.91	18,228.26	2990.86	771.00	261.87	4023.73
	La Libertad	3806.58	1964.48	1746.81	7517.87	4208.25	4174.79	3253.46	11,636.50	305.18	97.78	54.28	457.24
	Lambayeque	137.55	139.19	308.10	584.84	153.57	127.63	412.11	693.31	102.00	24.39	1.09	127.48
	Loreto	205.84	9.30	0.00	215.14	135.93	0.00	0.00	135.93	33.56	0.00	0.00	33.56
	Piura	1015.39	635.22	1366.36	3016.97	1322.27	1159.95	2029.53	4511.75	593.94	69.01	11.76	674.71
	San Martín	3235.75	1725.64	1949.80	6911.19	6545.40	3139.00	2642.90	12,327.30	2486.67	1182.50	1105.30	4774.47
	Subtotal	22,435.05	12,025.74	18,822.60	53,283.39	28,796.32	23,114.16	26,587.47	78,497.95	10,391.71	4,947.95	5,532.54	20,872.20
Center	Huánuco	4976.62	2070.00	3265.32	10,311.94	6540.23	4653.80	4657.50	15,851.53	2449.91	1057.61	866.09	4373.61
	Huancavelica	3939.85	1481.97	1185.58	6607.40	3487.70	1701.07	1,188.52	6377.29	170.03	37.70	14.72	222.45
	Junín	9266.65	3887.67	2091.35	15,245.67	9011.87	4875.72	3410.76	17,298.35	2280.22	1253.56	1411.01	4944.79
	Lima	1058.10	44.13	1.02	1103.25	4553.80	1659.20	722.30	6935.30	12.49	0.00	0.00	12.49
	Pasco	2907.55	603.29	1121.39	4632.23	3935.69	1652.34	1537.91	7125.94	1326.24	691.04	926.28	2943.56
	Ucayali	37.05	0.00	0.00	37.05	197.07	0.00	0.00	197.07	257.29	40.45	12.91	310.65
	Subtotal	22,185.82	8087.06	7664.66	37,937.54	27,726.36	14,542.13	11,516.99	53,785.48	6496.18	3080.36	3231.01	12,807.55
South	Apurímac	3503.55	2233.82	2003.85	7741.22	3927.12	1178.42	241.69	5347.23	32.50	3.05	0.06	35.61
	Arequipa	272.25	0.00	0.00	272.25	92.59	29.35	3.26	125.20	0.00	0.00	0.00	0.00
	Ayacucho	4363.92	2769.13	2197.91	9330.96	3577.55	1218.40	410.79	5206.74	124.29	24.31	6.49	155.09
	Cusco	6391.14	4614.20	4917.90	15,923.24	8617.59	5299.08	5494.60	19,411.27	1831.27	830.75	634.51	3296.53
	Madre de Dios	138.99	77.09	83.64	299.72	160.69	82.78	178.74	422.21	262.84	124.53	70.66	458.03
	Moquegua	0.00	0.00	0.00	0.00	43.50	0.00	0.00	43.50	0.00	0.00	0.00	0.00
	Puno	4625.50	2100.60	941.90	7668.00	2421.53	1464.20	1848.97	5734.70	400.73	79.24	14.36	494.33
	Tacna	138.16	0.00	0.00	138.16	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Subtotal	19,433.51	11,794.84	10,145.20	41,373.55	18,840.57	9272.23	8178.05	36,290.85	2,651.63	1061.88	726.08	4439.59
	Total	64,054.38	31,907.64	36,632.46	132,594.48	75,363.25	46,928.52	46,282.51	168,574.28	19,539.52	9090.19	9489.63	38,119.34

3.4. Relationship with Elevation and Ecoregions

Figure 4 shows a detailed analysis of the potential distribution of *Gynoxys* clades concerning elevation and ecoregion in Peru. In the case of the *Discoide* clade, it was found that 72,633.27 km^2 of its potential distribution is between 3001 and 4000 masl, 34,481.15 km^2 in the range of 4001 to 5000 masl, 17,879.03 km^2 between 2001 and 3000 masl, and 2750.60 km^2 above 5000 masl. On the other hand, no presence of this clade was observed below 2000 masl (Figure 4a). For the gynoxys clade, 76,553.97 km^2 of its potential distribution was found in the range of 3001–4000 masl, 42,792.20 km^2 between 2001 and 3000 masl, 39,447.16 km^2 between 4001 and 5000 masl and 9940.55 km^2 below 2000 masl. However, its presence above 5000 masl is minimal, with only 238.40 km^2 recorded in this range (Figure 4b). The *Praegynoxys* clade has a potential distribution of 21,837.83 km^2 between 2001 and 3000 masl, 10,632.90 km^2 between 3001 and 4000 masl, and 5596.67 km^2 in the 1001–2000 masl range. No distribution of this clade was observed below 1000 masl or above 4000 masl (Figure 4c). In addition, a multiple correlation analysis was performed to associate the potential distribution levels of the *Gynoxys* clades with their respective elevation ranges. The *Discoide* and *Praegynoxys* clades show an association between the moderate and high distribution levels with elevations of 2000 and 4000 masl, mainly.

The following information shows the potential distribution of the clades of the genus *Gynoxys* with the ecoregions of Peru. For the *Discoide* clade, it was found that 76,263.12 km^2 of its potential distribution area is in the puna, 49,949.63 km^2 in the high jungle (Yunga), 3034.04 km^2 in the steppe highlands, 1540.20 km^2 in the páramo, 1337.12 km^2 in the equatorial dry forest and 470.40 km^2 in the Amazon rainforest. In other ecoregions, the distribution of this clade is zero (Figure 4d). For the *Gynoxys* clade, it was determined that 90,282.59 km^2 of its potential distribution is in the puna, 63,510.99 km^2 in the high forest (Yunga), 10,663.58 km^2

in the steppe highlands, 1,701.37 km^2 in the equatorial dry forest, 1,672.43 km^2 in the paramo and 733.94 km^2 in the Amazon rainforest. Similar to the *Discoide* clade, it is not found in other ecoregions (Figure 4e). On the other hand, the *Praegynoxys* clade has a potential distribution of 27,195.93 km^2 in the high forest, 9177.25 km^2 in the puna, 531.20 km^2 in the Amazon rainforest, 500.95 km^2 in the equatorial dry forest, 393.70 km^2 in the steppe highlands, and 319.10 km^2 in the Amazon rainforest, with no presence in other ecoregions (Figure 4f).

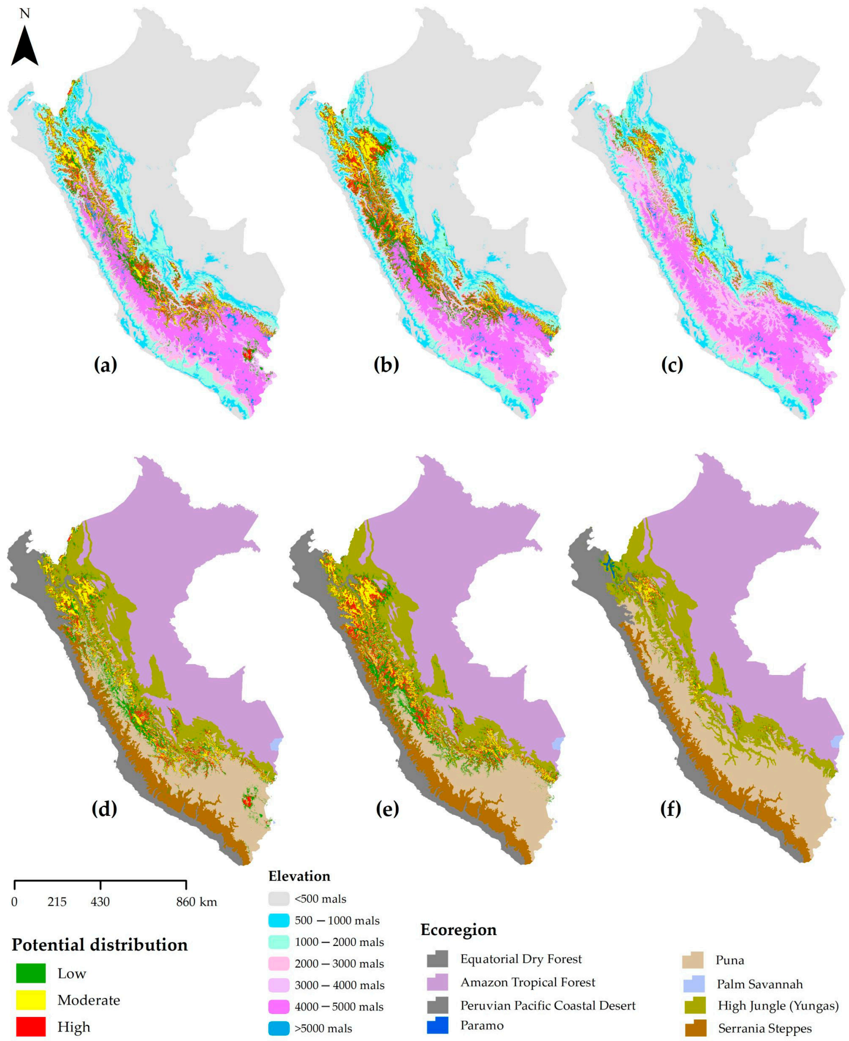

Figure 4. Association between the potential distribution of the genus *Gynoxys* with elevation and the ecoregions of Peru. Where (**a**–**c**) represent the association of the suitable areas of the *Discoide* clade, *Gynocys*, and *Praegynoxys* with altitude, and (**d**–**f**) shows the association of the potential distribution of the clades with ecoregions.

The MCA between the potential distribution of the genus *Gynoxys* with elevation and the ecoregions of Peru is shown in Figure 5. The low distribution level of the *Discoide* clade is also associated with higher elevations, while the low level of *Praegynoxys* is associated with lower elevations (1000–2000 masl). In contrast, the potential distribution of the *Gynoxys* clade spans a broader range of elevations, between 2000 and 5000 masl, with its low distribution level also associated with relatively low elevations (1000–2000 masl) (Figure 5a). The *Discoide* and *Gynoxys* clades strongly associate with the puna and high jungle ecoregions, mainly at the low, moderate, and high distribution levels. In addition, both clades show weaker associations with limited areas of the steppe highlands and paramo at high levels and with the Amazon rainforest and equatorial dry forest at low levels. In contrast, the *Praegynoxys* clade is strongly associated with the highland forest at high distribution levels and the puna at low levels. Its associations with the Amazon rainforest and equatorial dry forest are more limited, being restricted to low levels of distribution (Figure 5b).

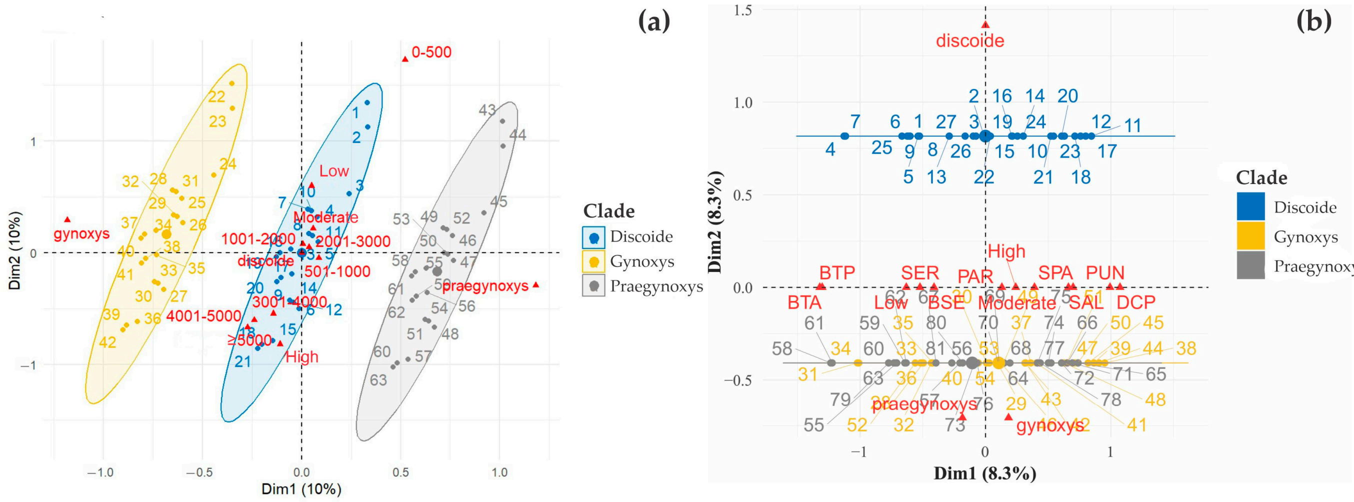

Figure 5. Association between the potential distribution of the genus *Gynoxys* with elevation and ecoregions of Peru using MCA. Where: (**a**) MCA altitude and potential distribution, and (**b**) MCA ecoregions and potential distribution.

3.5. Protected and Degraded Areas

Figure 6a–c shows the potential distribution of the *Gynoxys* clades within Peru's protected areas. A total of 32.05% of the potentially habitable area for the *Discoide* clade is located in various categories of protected areas, equivalent to 42,497.50 km^2. Of this area, 20.50% (8710.72 km^2) is safeguarded in NPA, 19.20% (8159.96 km^2) in BA, 0.83% (351.51 km^2) in ZR, 46.79% (19,884.29 km^2) in BR, 7.25% (3081.60 km^2) in RCA, and 5.43% (2309.42 km^2) in PCA. In total, 23,130.43 km^2 of high and moderate areas for the discoid clade are located within these protected areas. As for the *Gynoxys* clade, 35.46% of its potential distribution area in Peru is found in conservation areas, corresponding to 59,768.47 km^2. Of this, 20.37% (12,175.98 km^2) is located in ANP, 18.19% (10,865.72 km^2) in ZA, 1.21% (670.15 km^2) in ZR, 49.76% (29,737.99 km^2) in RB, 5.92% (3540.11 km^2) in ACR, and 4.65% (2778.52 km^2) in ACP. In total, 33,762.85 km^2 of areas with high and moderate potential for this clade are protected within conservation areas. Finally, for the *Praegynoxys* clade, 61.02% of its potential area in Peru is within conservation areas, representing 23,260.97 km^2. Of this area, 24.38% (5670.20 km^2) is in ANP, 15.59% (3625.24 km^2) in ZA, 0.39% (89.92 km^2) in ZR, 47.57% (11,065.12 km^2) in RB, 6.05% (1408.31 km^2) in ACR, and 6.02% (1402.18 km^2) in ACP. In total, 12,258.56 km^2 of areas with high and moderate potential for *Praegynoxys* are included in these protected areas.

Table 4 and Figure 6d–f present the results on the degradation of the predicted areas of occurrence for the clades of the *Gynoxys* (*Discoide*, *Gynoxys*, and *Praegynoxys*) in Peru. According to these data, 12.76% (16,903.43 km^2) of the potential distribution of the *Discoide* clade is degraded, while 13.56% (22,863.63 km^2) of the *Gynoxys* clade and 37.68% (14,362.90 km^2) of the *Praegynoxys* clade also show signs of degradation. The main form of degradation in the *Gynoxys* clades in the country is forest fragmentation, which affects large areas of their distributions: 14,809.24 km^2 in *Discoide*, 19,739.29 km^2 in *Gynoxys*, and 13,129.46 km^2 in *Praegynoxys*. Loss of soil productivity is the second most significant cause of degradation in the *Discoide* clade, affecting 988.49 km^2. In contrast, for the *Gynoxys* and *Praegynoxys* clades, forest loss constitutes the second most crucial form of degradation, with affected areas of 1,236.55 km^2 and 654.98 km^2, respectively. In terms of loss of soil productivity and changes in vegetation cover, these processes have minimal influence on habitat degradation for the three clades, with degraded areas of 10.41 km^2 for *Discoide*, 13.98 km^2 for *Gynoxys* and 1.74 km^2 for *Praegynoxys*. Finally, the moderate and high probability of clade presence in degraded areas covers 58.83% of the degraded surface for *Discoide* (9945.08 km^2), 57.46% for *Gynoxys* (13,138.41 km^2), and 53.87% for *Praegynoxys* (7736.73 km^2).

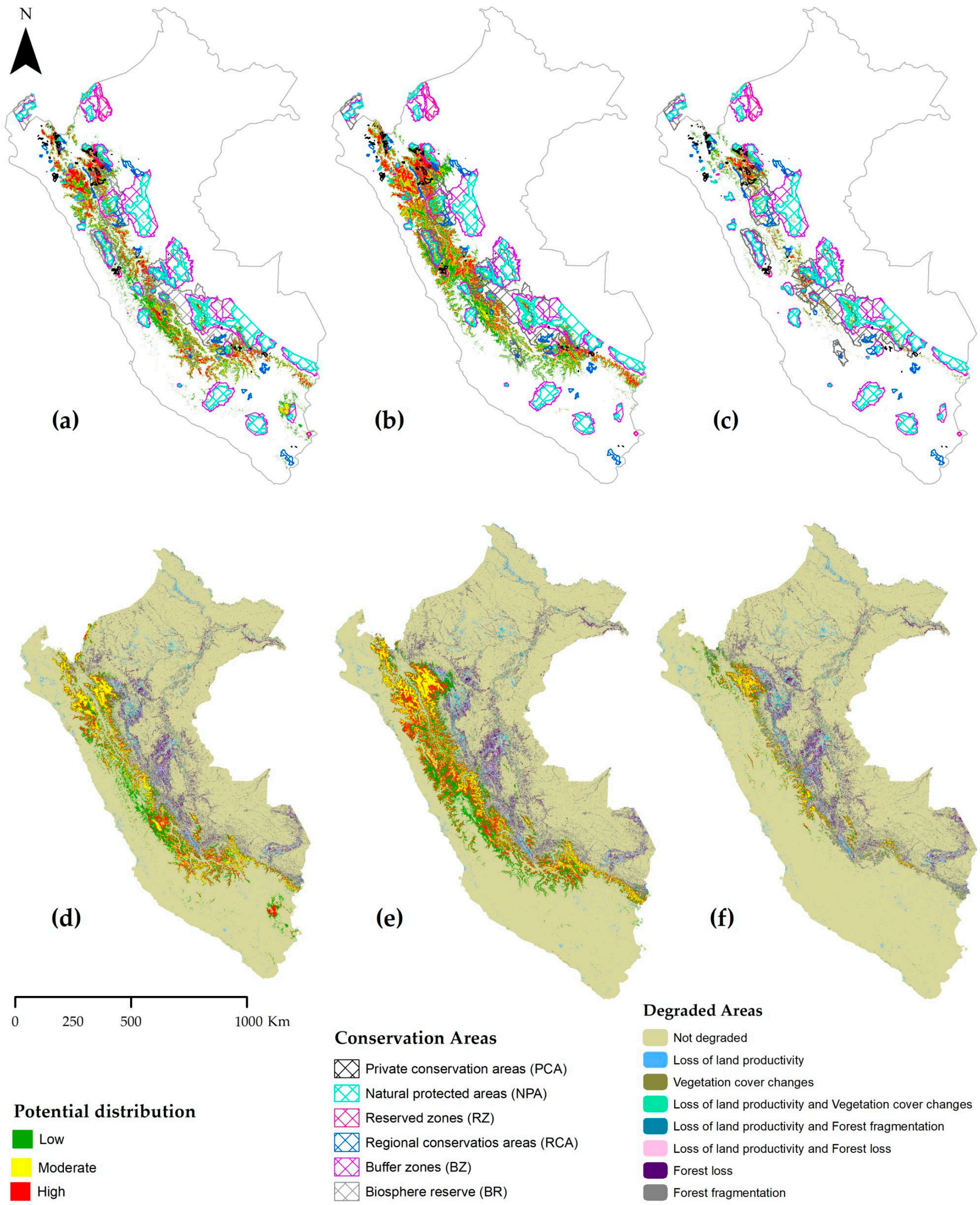

Figure 6. Association between the areas of occurrence of the genus *Gynoxys* with conservation areas (CA) and the degraded regions (AD) in Peru. Where: (**a**–**c**) represent the association of the areas of occurrence of the *Discoide* clade, *Gynoxys*, and *Praegynoxys* with the CA, and (**d**–**f**) represent the potential distribution of the areas of occurrence of the *Discoide* clade, *Gynoxys*, and *Praegynoxys* with the AD.

Table 4. Areas in Peru that are protected and degraded by the clades of the genus *Gynoxys*.

Degraded Areas	**Potential Areas (km²)**								
	Discoide			*Gynoxys*			*Praegynoxys*		
Class	**Low**	**Moderate**	**High**	**Low**	**Moderate**	**High**	**Low**	**Moderate**	**High**
Loss of land productivity	478.14	225.19	285.16	606.49	314.74	274.63	120.05	52.56	48.52
Vegetation cover changes	43.47	17.26	21.02	41.88	29.84	26.57	18.12	3.16	1.12
Loss of land productivity and Vegetation cover changes	4.55	1.72	4.14	5.09	4.97	3.91	1.3	0.4	0.04
Loss of land productivity and Forest fragmentation	124.50	62.60	86.66	192.06	111.97	100.73	119.64	57.81	69.77
Loss of land productivity and Forest loss	43.58	19.54	24.64	98.01	48.85	28.05	43.9	20.16	21.91
Forest loss	336.61	147.65	167.76	687.82	319.04	229.69	327.98	161.57	165.43
Forest fragmentation	5927.50	3713.76	5167.98	8093.87	5111.48	6533.94	5995.18	3249.75	3884.53
Total	6958.35	4187.72	5757.36	9725.22	5940.89	7197.52	6626.17	3545.41	4191.32
Conservation Areas	**Potential areas (km²)**								
	Discoide			*Gynoxys*			*Praegynoxys*		
	Low	**Moderate**	**High**	**Low**	**Moderate**	**High**	**Low**	**Moderate**	**High**
Natural Protected Areas	4688.95	2086.68	1935.09	5441.71	3361.63	3372.64	3018.10	1213.38	1438.72
Buffer Zones	4000.62	2283.45	1875.89	5057.53	3012.16	2796.03	1881.70	810.56	932.98
Reserved Zones	281.22	17.25	53.04	366.04	82.59	221.52	55.43	6.97	27.52
Biosphere Reserve	8586.51	6425.85	4871.93	13,000.69	8501.61	8235.69	4809.03	3585.88	2670.21
Regional Conservation Areas	1197.17	937.90	946.53	1541.19	987.99	1010.93	744.93	280.73	382.65
Private Conservation Areas	612.60	1254.13	442.69	598.46	1469.03	711.03	493.22	591.77	317.19
Total	19,367.07	13,005.26	10,125.17	26,005.62	17,415.01	16,347.84	11,002.41	6489.29	5769.27

4. Discussion

The evaluation of the contribution of climatic variables showed that the genus *Gynoxys*' clades respond differently to Peru's climatic and geographic conditions. For the *Discoide* clade, the most influential variables were the minimum temperature during the warmest season (*tmintempwarmest*), nitrogen content, and the number of months with temperatures above 10 °C (*monthcountbytemp10*). These variables highlight the importance of temperature and nutrient availability in determining habitat suitability [56,57]. In contrast, the *Gynoxys* clade showed greater sensitivity to factors related to humidity and climatic seasonality, such as soil moisture index (*topowet*) and precipitation seasonality (*petseasonality*). For the *Praegynoxys* clade, the most determinant variables were those related to temperature and altitude, highlighting the relevance of altitudinal ranges in the presence of these species [57].

The application of the MaxEnt model chosen to model the distribution of the clades showed exceptional performance in predictive terms for all clades of the genus *Gynoxys*, with AUC values above 0.9, reflecting high reliability in the predictions generated. This high performance suggests that the selected bioclimatic variables are representative and could show the characteristics of the conditions that influence the presence of this genus in the study area [17]. In addition, differences in performance among clades may reflect greater ecological complexity [18] and the different environmental requirements of each clade. In particular, the *Praegynoxys* clade, which had the highest AUC, appears to have a more restricted and specialized distribution, suggesting a more specific adaptation to particular ecological conditions.

The analysis shows a precise concentration of areas suitable for clades of the genus *Gynoxys* along the Andes, particularly in the departments of Cajamarca, Cusco, Junín, Amazonas, and Ancash. This pattern is consistent with the known ranges of many Andean species adapted to temperate and cold mountain climates [58]. The notable absence of *Gynoxys* in coastal and Amazonian regions is probably due to the lack of ideal bioclimatic conditions for these species, which require lower temperatures and a well-defined climatic seasonality. As for the *Praegynoxys* clade, its distribution is more restricted, concentrating mainly in the northern and central macro-region of the country. This pattern is consistent with its smaller ecological amplitude, which has also been observed in other species endemic to high mountain areas [59,60]. Nevertheless, the *Gynoxys* clade has significantly larger potential ranges, suggesting a greater ecological tolerance than the other two clades, supporting the hypothesis that this clade has a more extensive distribution range within the Andes.

The altitudinal distribution of *Gynoxys* clades is key to understanding their adaptation to the diverse environments of Peru. It was found that *Discoide* and *Gynoxys* are primarily associated with elevations between 3000 and 5000 masl, while *Praegynoxys* is mainly distributed between 2000 and 3000 masl., with almost no presence above 4000 masl. These altitudinal patterns are related to the typical ecological zonation of the Andes, where species are distributed according to temperature, humidity, and climatic variability [57,60]. The close correlation between altitude and climate explains these differences, as higher altitudes are characterized by lower temperatures and greater thermal fluctuations, conditions that favor the presence of *Discoide* and *Gynoxys*, which may have adaptive traits such as greater cold tolerance and growth strategies suited to high-mountain ecosystems. In contrast, *Praegynoxys*, found at lower elevations, is likely better adapted to warmer climates with higher moisture availability. These results suggest that the ecological differentiation among *Gynoxys* clades may be driven by selective pressures associated with altitude and its effects on the microclimate. The report on the potential habitat of *Gynoxys* in ecoregions such as the Puna and the cloud forest highlights these areas as critical ecological refuges for Andean biodiversity [61].

The analysis of conservation and degradation areas shows that although a significant proportion of areas with high suitability for the clades are located within protected areas (32.05% for *Discoide*, 35.46% for *Gynoxys*, and 61.02% for *Praegynoxys*), significant habitat degradation is also observed, mainly because of forest fragmentation and loss of soil productivity. These results are consistent with other studies on deforestation and degradation in the Andes, which seriously impact endemic species and mountain ecosystems [62]. In particular, habitat fragmentation is a critical threat to biodiversity in the Andean region, and the restoration of these habitats should be a priority in conservation and sustainability strategies [63]. Although the existence of protected areas, such as biosphere reserves and natural protected areas, within the potential distribution areas of *Gynoxys* represents an advantage [64], human pressures, especially those caused by agriculture, mining, and urban expansion, remain a significant threat to the long-term conservation of these mountain ecosystems [65,66].

The results suggest that strengthening conservation strategies in the distribution zones of *Gynoxys* is essential, especially in areas such as Amazonas, Ancash, Cajamarca, Cusco, and Junín, which contain essential concentrations of suitable habitat for these species. Habitat fragmentation and forest degradation highlight the need to improve sustainable management policies and ecological restoration in the most affected areas. In addition, conservation areas need to be expanded and effectively connected to ensure biodiversity conservation from anthropogenic pressures [64].

Despite the encouraging results of the model, certain limitations must be considered. The model's accuracy is closely linked to the variables selected and the spatial resolution of used data [18]. In addition, the generated MaxEnt models do not consider biotic interactions, such as competition or mutualism, which may play a key role in the distribution of plant species [17,67]. To improve model accuracy, it is advisable to have presence data from *Gynoxys* genus records that would contribute to improving predictions [68,69]. This research focused on the distribution of the genus *Gynoxys* under current conditions, which limits the evaluation of future scenarios that could affect distribution areas and population dynamics [34,40].

In future research, it will be essential to expand the number of records of the genus and to cover its entire range along the Andes Mountain range in South America, enabling the development of a more accurate and robust potential distribution model. Additionally, it will be essential to incorporate the effects of climate change and land use dynamics into the models to improve the predictive capacity regarding the impacts of climate change on the habitats of the genus. Despite these restrictions, the results obtained in this study constitute the first detailed analysis of the potential distribution of the genus. They also provide a solid conceptual basis for further research and offer valuable perspectives for conserving forest ecosystems in the Andean region.

5. Conclusions

This study analyzed habitat suitability for clades of the genus *Gynoxys* in Peru using a MaxEnt model with excellent predictive performance (AUC > 0.9 for all sections). The results showed that the most influential variables vary according to the clade: in *Discoide*, minimum temperature and nitrogen content predominate, while in *Gynoxys*, humidity, and seasonality of precipitation stand out, and in *Praegynoxys*, elevations and temperature. The potential distribution of *Gynoxys* covers 132,594.5 km^2 for *Discoide*, 168,574.3 km^2 for *Gynoxys*, and 37,392.0 km^2 for *Praegynoxys*, mainly in the Andes, in departments such as Cajamarca, Cusco, and Amazonas. However, significant habitat degradation was detected, mainly due to forest fragmentation (14,809.24 km^2 in *Discoide* and 19,739.29 km^2 in *Gynoxys*). Even though, on average, 42.5% of the suitable areas for the genus are located in protected areas, anthropogenic pressure remains a threat. The results obtained underline the importance of strengthening conservation and ecological restoration strategies to protect and preserve the biodiversity of the Andean region.

Supplementary Materials: The following supporting information can be downloaded at https://www.mdpi.com/article/10.3390/su17062406/s1, Table S1: Records of the genus *Gynoxys* for Peru.

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