







Article

Biogeographic Distribution of *Cedrela* spp. Genus in Peru Using MaxEnt Modeling: A Conservation and Restoration Approach

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Abstract: The increasing demand for tropical timber from natural forests has reduced the population sizes of native species such as *Cedrela* spp. because of their high economic value. To prevent the decline of population sizes of the species, all *Cedrela* species have been incorporated into Appendix II of the Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES). The study presents information about the modeled distribution of the genus *Cedrela* in Peru that aims to identify potential habitat distribution of the genus, its availability in areas protected by national service of protected areas, and highlighted some areas because of their conservation relevance and the potential need for restoration. We modeled the distribution of the genus *Cedrela* in Peru using 947 occurrence records that included 10 species (*C. odorata*, *C. montana*, *C. fissilis*, *C. longipetiolulata*, *C. angustifolia*, *C. nebulosa*, *C. kuelapensis*, *C. saltensis*, *C. weberbaueri*, and *C. molinensis*). We aim to identify areas environmentally suitable for the occurrence of *Cedrela* that are legally protected by the National Service of Protected Areas (PAs) and those that are ideal for research and restoration projects. We used various environmental variables (19 bioclimatic variables, 3 topographic factors, 9 edaphic factors, solar radiation, and relative humidity) and the maximum entropy model (MaxEnt) to predict the probability of occurrence. We observed that 6.7% (86,916.2 km²) of Peru presents a high distribution probability of occurrence of *Cedrela*, distributed in 17 departments, with 4.4% (10,171.03 km²) of the area protected by PAs mainly under the category of protection forests. Another 11.65% (21,345.16 km²) of distribution covers areas highly prone to degradation, distributed mainly in the departments Ucayali, Loreto, and Madre de Dios, and needs immediate attention for its protection and restoration. We believe that the study will contribute significantly to conserve *Cedrela* and other endangered species, as well as to promote the sustainable use and management of timber species as a whole.

Keywords: CITES; endangered species; SDM; degraded amazon; machine learning

1. Introduction

Forest covers have been reduced drastically in the Peruvian Amazon region over the last few decades as a result of agricultural expansion and livestock activities, deforestation, mining, and urban expansion [1,2]. In Peru, 2,433,314 ha of Amazonian forests have been lost during 2001–2019 [3]. Although the tropical Amazon forest covers about 60% of Peru [4], it has now been highly fragmented because of the forest harvesting activities. The need for more agricultural land also promoted heavy migratory agricultural practices, [5]

eliminating approximately 0.5 ha of forest cover for crop production [6,7]. As a result of such growing land-use changes induced by migratory agriculture and cattle ranching, many native species, including genus *Cedrela*, are now experiencing massive destruction of their habitats [8]. In addition, the selective falling of trees, mainly of species having high economic values, has also caused the near extinction of many vegetation species such as mahogany (*Swietenia macrophylla*) and cedar (*Cedrela odorata*) [9].

Cedrela is a genus of tropical trees that includes species such as *C. odorata* L. and *C. fissilis* Vell., which had been collected for wood for more than 500 years in Central and South America, with *C. odorata* being the second most demanded tropical wood [10–13]. Worldwide, this genus has 17 recognized species [13,14], out of which Peru alone has 10. Hence, Peru can be considered as a center of diversity for *Cedrela* species [15], which currently includes three endemic species with restricted distribution, i.e., *C. molinensis*, *C. longipetiolulata*, and *C. weberbaueri* [16]. However, because of the high economic value of the genus *Cedrela* species, their usage had started increasing since the end of the 1980s, mainly in Mexico, Brazil, Peru, and Bolivia [17,18]. Such overexploitation eventually resulted in the near-extinction of the *Cedrela* population and made the international conservation community call for its greater protection under the Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES). In Peru, the National Forest and Wildlife Service (SERFOR) has also recently incorporated the populations of genus *Cedrela* (*C. odorata*, *C. montana*, *C. fissilis*, *C. longipetiolulata*, *C. angustifolia*, *C. nebulosa*, *C. kuelapensis*, *C. Saltensis*, *C. weberbaueri*, and *C. molinensis*) in Appendix II of CITES on 28 August 2020.

This alarming situation indicates a strong need for further research studies that may effectively contribute to decision making related to the sustainability and conservation of biodiversity of the *Cedrela* and its habitat. Species distribution models (SDMs) are tools that combine species presence data with factors such as bioclimatic, edaphic, topographic, etc. and allow more effective and generous support for species conservation, biogeography, and climate change actions [19–23]. SDMs have made it possible to identify the distribution of timber forest species [24,25], other endemic species [26], wildlife [27,28], etc. on a regional scale facilitating proper identification, protection, and conservation of the endangered ones [29,30]. Among all the available SDMs, the maximum entropy algorithm (MaxEnt) [31] is one of the most widely used algorithms to find out the distribution of species under current and future conditions [32,33]. This way, MaxEnt allows habitat mapping and produces credible, defensible, and repeatable information, which contributes to a structured and transparent process of sustainable natural resources management by predicting the possible degradation of potential forest areas with species under risk in the future climate change scenarios [34].

After identifying the potential distribution areas of a species, the areas having the best aptitude to carry out reforestation or recovery initiatives of degraded areas are needed to be quantified and monitored properly. Such restoration is of great interest since 13.78% (177,592.82 km²) of the Peruvian territory has been identified as degraded areas as a consequence of deforestation, livestock activities, agriculture, mining, forest fires, etc. [35]. The strategies to be implemented must be oriented to the restoration and/or conservation of threatened species that are widely distributed over the geographic spaces integrated into the territorial order using environmental services, ecotourism, management of renewable resources, and productive practices promoted through Protected Natural Areas (PNAs) initiative [36].

The study has two main objectives—firstly, to model the biogeographic distribution of 10 available species of genus *Cedrela* (i.e., *C. odorata*, *C. montana*, *C. fissilis*, *C. longipetiolulata*, *C. angustifolia*, *C. nebulosa*, *C. kuelapensis*, *C. Saltensis*, *C. weberbaueri* and *C. molinensis*) over the Peruvian territory using the MaxEnt model in a current scenario, and secondly, to identify the locations of *Cedrela* within the designated conservation areas (to evaluate its effectiveness in conserving the species' habitat) and degraded areas (to implement forest restoration practices using these species). The study considered sample location

information of the *Cedrela* species (947 geographical records) and 33 different variables (19 bioclimatic variables, 3 topographic, 9 edaphic, solar radiation, and relative humidity).

2. Materials and Methods

2.1. Study Area

This study covers the entire territory of Peru (1,300,000 km² approx.) located between the parallels of 0°03'00'' and 18°30'0'' south and the meridians of 68°30'00'' and 81°30'00'' west, sharing borders with Ecuador and Colombia to the north, Brazil to the east, Bolivia to the southeast, Chile to the south, and the Pacific Ocean to the west. The altitudinal gradient of this region starts from 0 m above sea level (a.s.l.) in the north and goes up to 6800 m above sea level (Mataraju Mountain). Almost 60% of the study area is covered by the Amazon rainforest, which is characterized by heavy rainfall and high temperatures, except for its southernmost part, which has cold winters and seasonal rainfall. The Protected Natural Areas (PNAs) belong to the National System of Natural Areas Protected by the State (SINANPE) [36]. These broadly include regional conservation areas, private conservation areas, national sanctuary, historic sanctuary, wildlife refuge, national reserve, communal reserve, national park, and hunting and protection forest scattered all over the study region (Figure 1).

2.2. Dataset and Methodological Design

The methodological framework used in the present study has been described graphically in Figure 2. From the cartographic standardization through the rescaling in the raster calculator of Qgis 3.16, 33 variables at a spatial resolution of 250 m were derived as input for use in modeling with MaxEnt. The bioclimatic information under current conditions (average 1970–2000) with a spatial resolution of 30 s (~1 km) was obtained from Worldclim version 2.1 (<https://www.worldclim.org/data/worldclim21.html>; accessed on 5 January 2021) [37]. Topographic factors such as elevation, slope, slope, and ground orientation were obtained from the 90 m spatial resolution DEM generated by the Shuttle Radar Topography Mission (SRTM) [38], United States Geological Survey (USGS) (<http://srtm.usgs.gov>; accessed on 28 December 2020). The edaphic variables were collected from SoilGrids 0.5.3 (<http://soilgrids.org>; accessed on 15 January 2021) with a spatial resolution of 250 m.

Likewise, the geographic occurrence data of 10 target species of the genus *Cedrela* to be used in the MaxEnt model were obtained from GBIF's Global Biodiversity Information Service (<https://www.gbif.org/>; accessed on 1 February 2021) through "Species Explorer" plug-in of QGIS software. The registration information of CITES species was obtained from the Ministry of the Environment of Peru (<https://geoservidor.minam.gob.pe/recursos/intercambio-de-datos/>; accessed on 18 February 2021). Finally, to identify the locations of *Cedrela* habitats within the protected areas, and the areas prone to degradation but having high suitability for genus *Cedrela* habitat, the modeled potential distribution result was overlaid with the degraded areas identified by the Ministry of Environment (MINAM) and the spaces conserved by the National Service of Natural Areas Protected by the Peruvian State (SERNANP). These degraded areas were identified by the ministry mainly based on deforestation, soil erosion, forest fires, mining, illegal logging, etc.

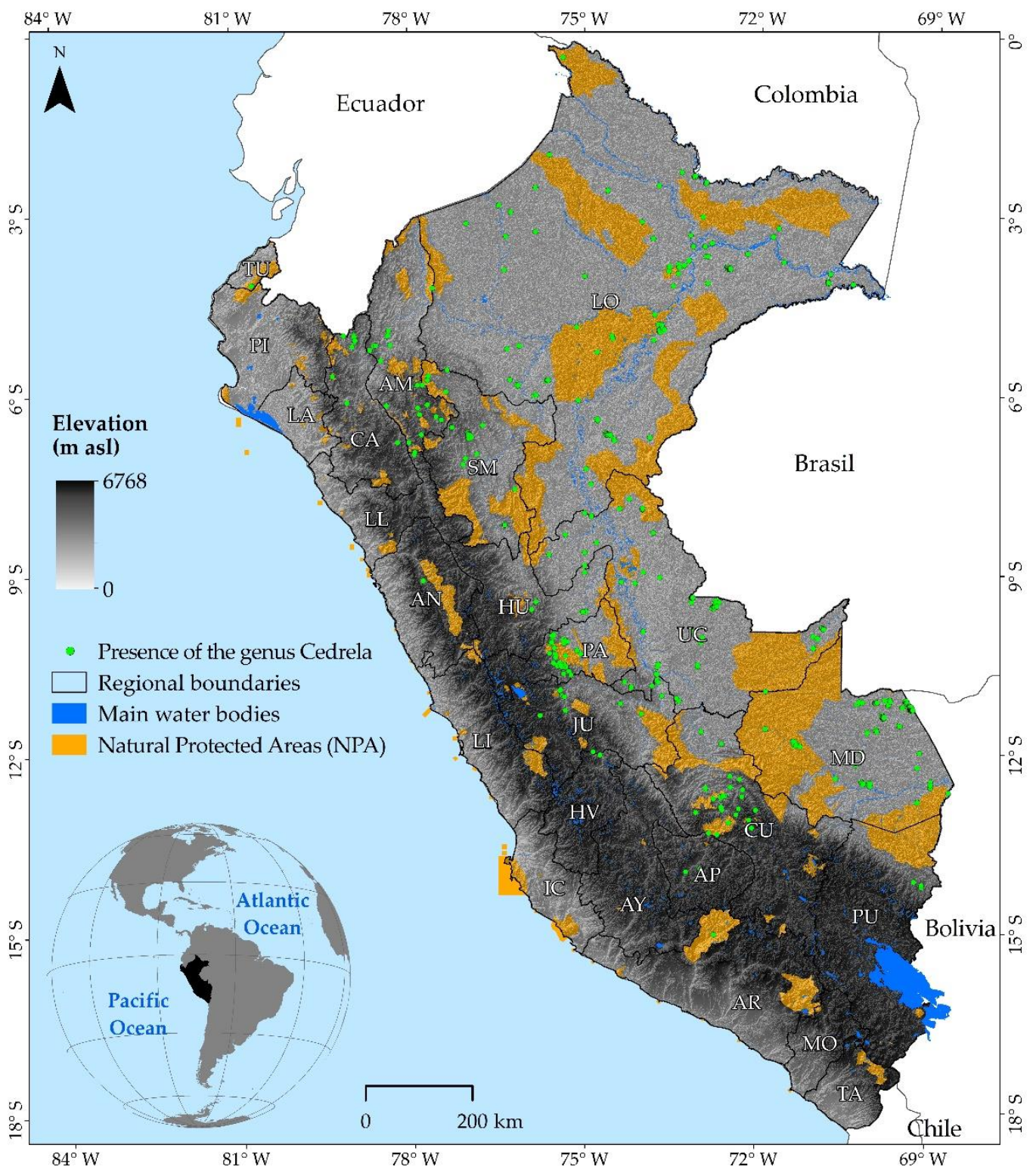


Figure 1. Study area and presence of *Cedrela* species.

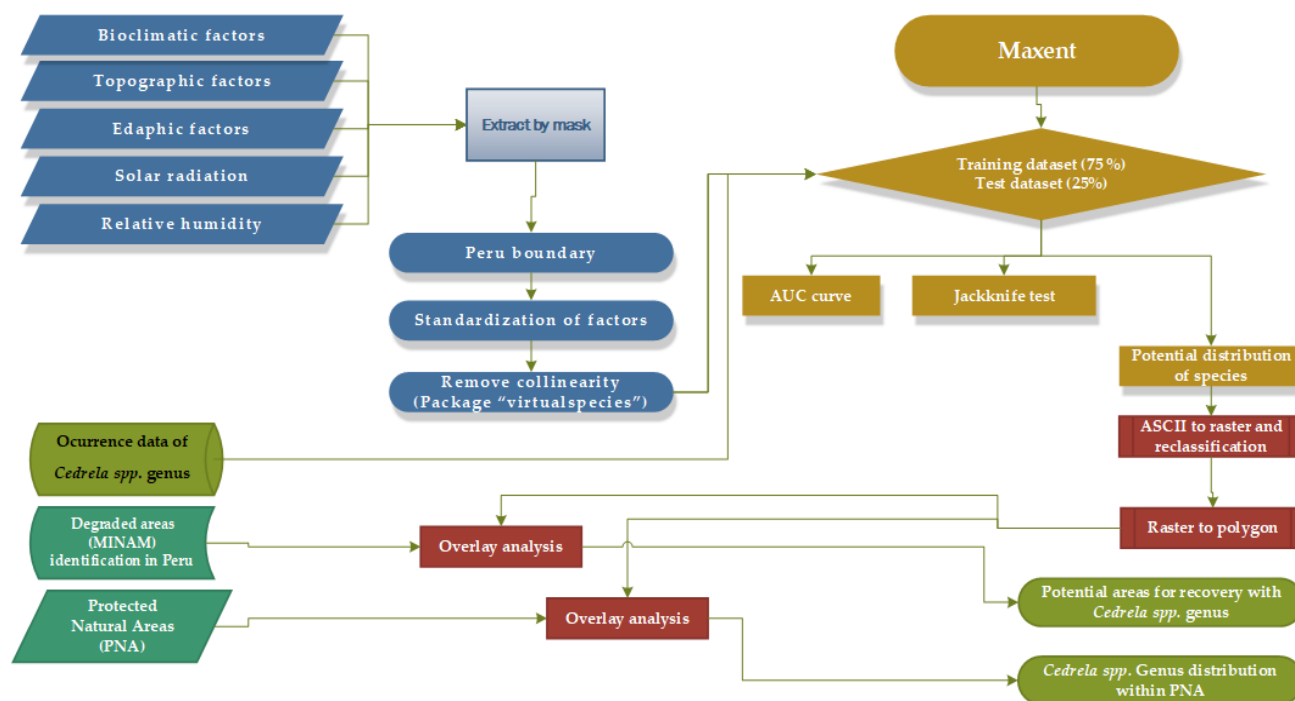


Figure 2. Methodological process for the biogeographic modeling of the genus *Cedrela* in Peru.

2.3. Geographical Records of Forest Species

The geographic coordinates of the 10 species of the genus *Cedrela* (Table 1) were obtained using the GBIF and Species Explorer plug-ins in QGIS 3.16 software. It was also complemented with the records of the presence of *Cedrela*, obtained from the Ministry of Environment of Peru. The CITES species information was collected from the systematization of forest inventories, review of national herbaria which is available in its geoservidor (<https://geoservidor.minam.gob.pe/recursos/intercambio-de-datos/>; accessed on 18 February 2021), and information related to the species of the genus *Cedrela* was separated. The data were then re-sampled at a spatial resolution of 250 m [39] by visually excluding those samples that were falling within lagoons, rivers, and roads, or urban areas. Finally, 947 resulting data were exported into CSV to be used for modeling in MaxEnt (https://biodiversityinformatics.amnh.org/open_source/maxent/; accessed on 10 November 2020).

Table 1. The number of records of 10 species of the genus *Cedrela* used in biogeographic modeling.

N°	Family	Genere	Species	Records Number
1			<i>fissilis</i>	42
2			<i>kuelapensis</i>	16
3			<i>molinensis</i>	1
4			<i>montana</i>	30
5	Meliaceae	<i>Cedrela</i>	<i>nebulosa</i>	32
6			<i>odorata</i>	787
7			<i>saltensis</i>	6
8			<i>angustifolia</i>	18
9			<i>longipetiululata</i>	8
10			<i>weberbaueri</i>	7
Total				947

2.4. Bioclimatic, Physiographic, and Soil Variables

The spatial distribution of species within a geographic area depends on the interaction with several environmental factors that contribute to their development and coexistence [40]. Considering this, 33 variables were selected (Table 2) to carry out the modeling. These variables include 19 bioclimatic and solar radiation obtained from WorldClim 2.1 (<https://www.worldclim.org/>; accessed on 5 January 2021) [37]; 3 topographic derived from digital elevation model (DEM) obtained from the United States Geological Survey (USGS) web portal (<http://srtm.usgs.gov>; accessed on 28 December 2020); the relative humidity obtained from the Climate Research Unit (CRU) [41] (www.cru.uea.ac.uk; accessed on 1 May 2021); and 9 soil properties collected from SoilGrids 0.5.3 (<http://soilgrids.org>; accessed on 15 January 2021) [42]. All variables were rescaled into a spatial resolution of 250 m to overcome the issues such as collinearity between variables, which causes overfitting problems, increases uncertainty, and decreases the statistical power of the model [43]. Therefore, using the function “remove collinearity” from the package “virtual species” [44] in R 3.6, the variables were grouped (clustering) according to the Pearson correlation coefficient, and only variables having Pearson’s $r \geq 0.7$ were considered. This threshold is an acceptable measure to minimize the multicollinearity of fitted models [43].

Table 2. Variables for MaxEnt modeling of *Cedrela* in Peru.

Variable	Units	Symbol	Δ Earnings in Jackknife ¹	Clúster
Bioclimatic				
Annual Mean Temperature	°C	bio01	0.7379	1
Mean Diurnal Range	°C	bio02	0.7627	7
Isothermality		bio03	0.9150	4
Temperature Seasonality	°C	bio04	0.7097	9
Max Temperature of Warmest Month	°C	bio05	0.6811	1
Min Temperature of Coldest Month	°C	bio06	0.7068	1
Annual Temperature Range	°C	bio07	0.7655	9
Mean Temperature of Wettest Quarter	°C	bio08	0.7608	1
Mean Temperature of Driest Quarter	°C	bio09	0.7107	1
Mean Temperature of Warmest Quarter	°C	bio10	0.7606	1
Mean Temperature of Coldest Quarter	°C	bio11	0.7067	1
Annual Precipitation	mm	bio12	0.6231	3
Precipitation of Wettest Month	mm	bio13	0.7674	2
Precipitation of Driest Month	mm	bio14	0.5525	3
Precipitation Seasonality	mm	bio15	0.6692	9
Precipitation of Wettest Quarter	mm	bio16	0.7524	2
Precipitation of Driest Quarter	mm	bio17	0.5481	3
Precipitation of Warmest Quarter	mm	bio18	0.7915	2
Precipitation of Coldest Quarter	mm	bio19	0.5147	3
Topographic				
Elevation above mean sea level	msnm	dem	0.6709	7
Slope of the terrain	°	slope	0.9104	7
Cardinal orientation of the slope	°	aspect	1.0117	5
Edaphic at 0.30 m				
pH in H₂O	pH × 10	ph	0.6543	7
Cation exchange capacity	cmol kg⁻¹	cec	0.7898	6
Organic carbon	g kg⁻¹	soc	0.8094	4
Bulk density of the fine earth fraction	cg/cm³	bdod	0.8881	8
Volumetric fraction of coarse fragments	cm ³ /dm ³ (vol %)	cfvo	0.7051	7
Total nitrogen	cg/kg	nitrogen	0.8375	6
Clay content	%	clay	0.8743	4
Sand content	%	sand	0.8155	7
Slime content	%	silt	0.7970	2
Solar radiation	MJ m ⁻² day ⁻¹	srad	0.6801	9
Relative humidity	%	rhm	0.7777	3

¹ In bold, the variables with less variation between the regularized training data and single variable for each cluster used for MaxEnt model are shown.

To select an important variable for each cluster, a preliminary MaxEnt model was run (the configuration is explained in Section 3.2.) using all the variables. The variable with the best performance in the Jackknife test [25] was selected (i.e., the smallest difference in regularized training gains obtained from a model generated with all criteria except that of interest and a model generated only with the criterion of interest [21] (Table 2).

2.5. Execution of the Model

The biogeographic distribution model for the 10 species of the genus *Cedrela* was performed using a maximum entropy algorithm [31] which estimates the probability of potential distribution of each species from the presence data (location) using the open-source software MaxEnt ver. 3.4.1 (https://biodiversityinformatics.amnh.org/open_source/maxent/; access on 10 November 2020). For the validation of this model, 75% of the randomly selected presence data were used for training purposes, and 25% were used for validation [31]. The algorithm was run using 100 repetitions in 5000 iterations with different random partitions (Bootstrap method), and other configurations (i.e., extrapolation, graph drawing, etc.) were kept as default [45].

The resulting model was validated based on the area under the curve (AUC) calculated from the operating characteristic of the receptor (ROC) [31,46,47]. According to the AUC values, five performance levels were differentiated: excellent (>0.9), good ($0.8-0.9$), accepted ($0.7-0.8$), poor ($0.6-0.7$) and invalid (<0.6) [46,48]. We used the logistic output format to obtain the model of the 10 evaluated species by generating a raster of continuous values in a range from 0 to 1. The raster obtained was further reclassified into four ranges: (1) “high potential” habitat (>0.6), (2) “moderate” habitat ($0.4-0.6$), (3) “low potential” habitat ($0.2-0.4$), and (4) “no potential” habitat (<0.2) [24,25,28,48].

2.6. Identification of Potential Areas for Restoration and Conservation

Subsequently, the areas of high distribution potential were overlapped with the Protected Natural Areas (PNA) information obtained from GeoServer (<https://geo.sernPNA.gob.pe/visorsernPNA/>; access on 18 February 2021) of the National Service of Natural Areas, which is protected by the State (SERNPNA) to promote conservation of the genus *Cedrela*, currently considered as endangered and overexploited in Peru.

Similarly, the raster layer (30 m resolution) of degraded areas as identified by the Ministry of the Environment of Peru (MINAM) in 2019 was also obtained from its geoservidor, (<https://geoservidor.minam.gob.pe/recursos/intercambio-de-datos/>; access on 18 February 2021) and overlapped with the potential distribution of *Cedrela*. Finally, the distribution surfaces of the 10 species within the PAs and degraded areas were quantified. This way, the analysis had made it possible to identify the protected areas that conserve the genus *Cedrela* and those degraded spaces that could be restored with one or more of the species under study.

3. Results

3.1. Model Performance and the Importance of Environmental Variables

Model performance evaluation aims to estimate the accuracy of machine learning-based prediction models and ensures confidence in the results obtained. The performance of this model obtained an area under the curve (AUC) value of 0.866 (Figure 3a), which is considered good ($0.8 < \text{AUC} < 0.9$). The response curves (Figure 3b–n) reflect the dependence of predicted suitability, both on the selected variable and on dependencies induced by correlations between the selected variable and other variables. Overall, 83% of the potential distribution of *Cedrela* was found to be driven mainly by four environmental variables, i.e., bio19 (precipitation of coldest quarter), soc (organic carbon), dem (elevation above mean sea level), and cec (cation exchange capacity) (Table 3). On the other hand, silt (slime content), bdod (bulk density of the fine earth fraction), and nitrogen were the three environmental variables that contributed the least. Figure 3o shows the results of jackknife test of variable importance. The environmental variable that reported the highest

gain when used in isolation was bio19, which therefore appeared to have the most useful information by itself. The environmental variable that decreased the gain the most on its omission was dem, which therefore appeared to have the most information that was not present in the other variables. Likewise, the Jackknife test (Figure 3o) identified that the variables bio 19 (coldest quarter precipitation), bio 12 (annual precipitation), soil pH, and elevation (DEM) contributed highly to the biogeographic distribution model of the *Cedrela* species.

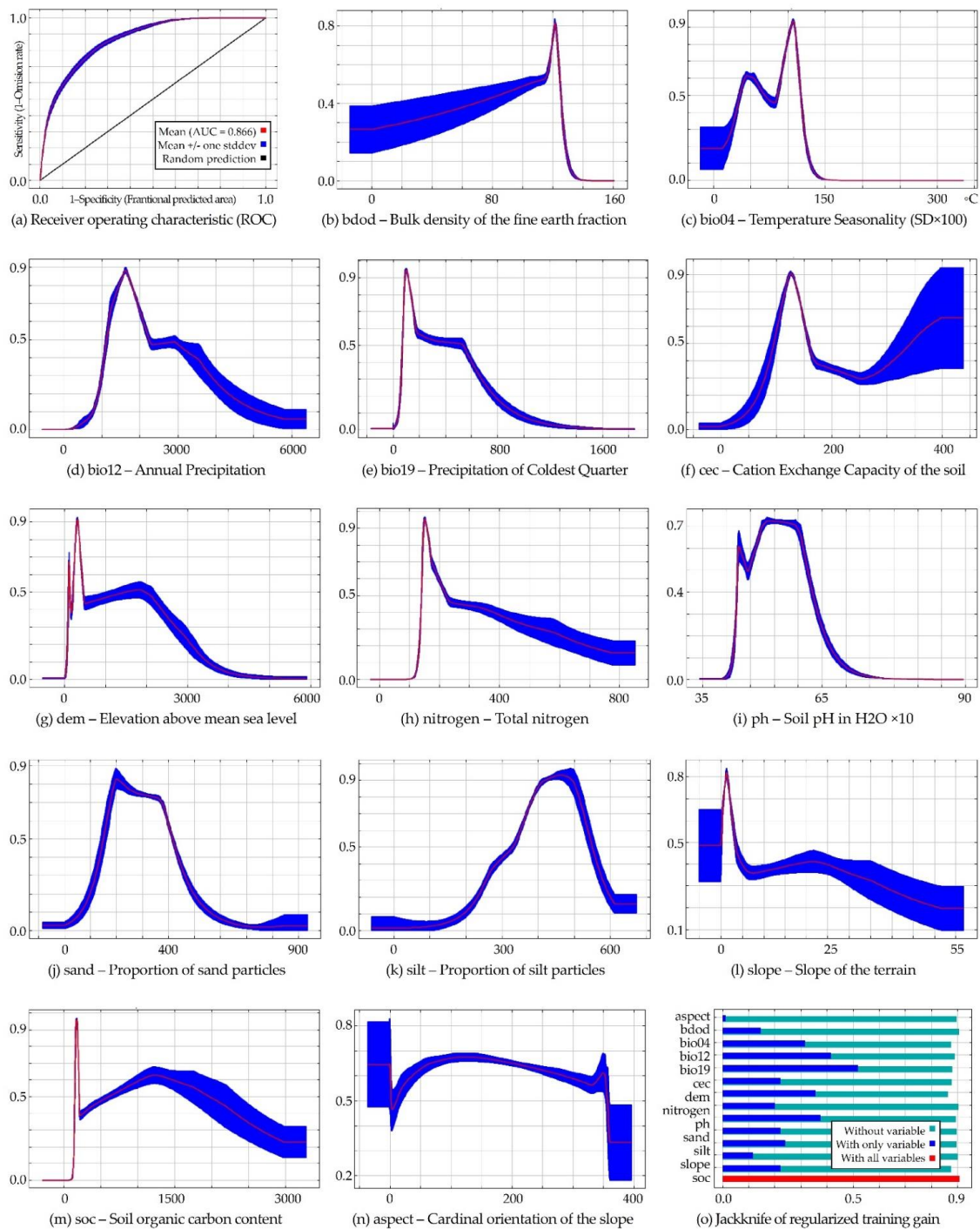


Figure 3. Model performance based on the area under the curve (AUC) (a), mean response curves of the 100 replicated MaxEnt runs (red) and standard deviation (blue), showing the relationships between environmental variables and the probability of the presence of the *Cedrela* (b–n), and Jackknife test of environmental variables importance to MaxEnt model of the *Cedrela* (o).

Table 3. Relative contributions (%) of environmental variables to the MaxEnt model of the genus *Cedrela* in Peru.

Variable	Percent Contribution	Permutation Importance
bio19	51.3	19.7
soc	18.3	6
dem	6.9	25.8
cec	6.5	2.3
bio12	4.6	19.2
bio04	3.7	9.1
ph	2.6	4.6
aspect	1.3	1.1
slope	1.3	1.2
sand	1.3	4.7
silt	0.9	4
bdod	0.7	1.1
nitrogen	0.7	1.1

3.2. Potential Distribution of the Genus *Cedrela*

The areas of a high probability of occurrence of genus *Cedrela* under present climatic and environmental conditions were identified mainly across the lowland Amazonia, covering 86,916.2 km² (6.7%) area of the study region. This potential habitat distribution covers about 17 regions of the Peruvian territory (Figure 4) with a high concentration in the departments of Ucayali (23,322.04 km²), Loreto (22,842.3 km²), and Madre de Dios (20,755.7 km²) (Table 4).

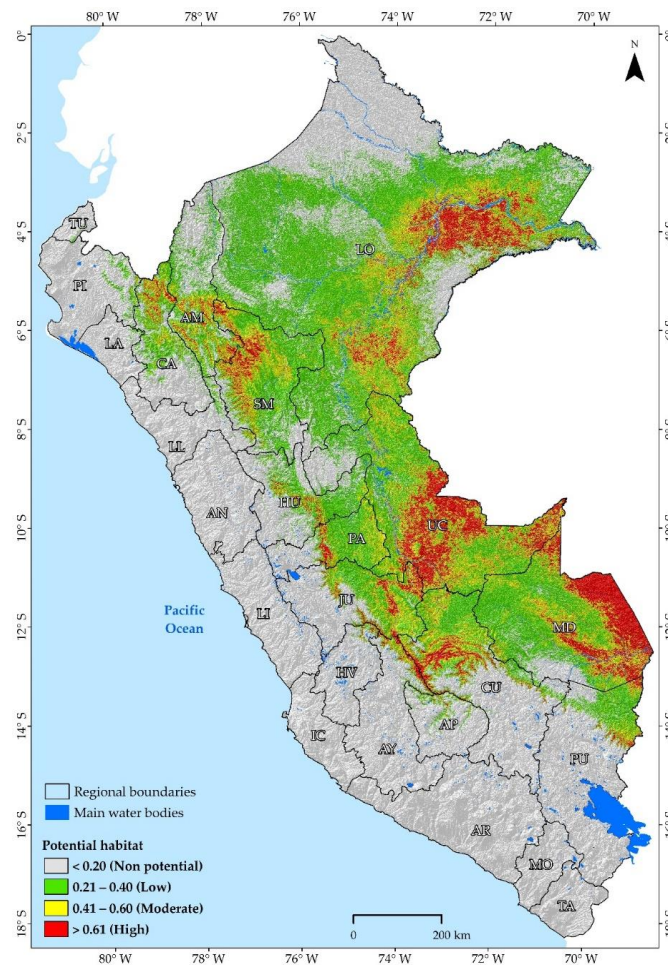


Figure 4. Distribution of the biographical model of the genus *Cedrela* in Peru.

Table 4. Area of distribution of the biographical model of the genus *Cedrela* in Peru.

Region/Country	Geographic Area km ²	Low		Moderate		High	
		km ²	%	km ²	%	km ²	%
Amazonas	39,306.46	12,692.78	32.3	6339.41	16.1	1925.42	4.9
Ancash	35,962.25	7.18	0	0.16	0	0.00	0
Apurimac	21,114.18	1719.01	8.1	476.60	2.3	148.55	0.7
Ayacucho	43,503.84	1150.37	2.6	1306.67	3	985.08	2.3
Cajamarca	33,044.68	8512.56	25.8	4444.75	13.5	1140.41	3.5
Cusco	72,076.2	15,217.89	21.1	11,450.66	15.9	5145.99	7.1
Huancavelica	22,065.07	444.75	2	260.12	1.2	194.12	0.9
Huánuco	37,200.53	12,279.44	33	2274.37	6.1	867.62	2.3
Junín	43,997.3	11,298.72	25.7	8212.08	18.7	3340.96	7.6
La Libertad	25,295.94	1025.67	4.1	270.80	1.1	39.08	0.2
Lambayeque	14,342.31	294.65	2.1	20.76	0.1	0.19	0
Loreto	375,115.94	161,464.72	43	53,151.91	14.2	22,842.30	6.1
Madre De Dios	85,045.87	34,710.95	40.8	20,326.56	23.9	20,755.70	24.4
Pasco	24,113.95	10,797.92	44.8	4771.88	19.8	979.54	4.1
Piura	36,065.1	1953.37	5.4	225.54	0.6	14.43	0
Puno	67,962.79	8270.85	12.2	3048.19	4.5	947.78	1.4
San Martin	50,961.26	23,558.38	46.2	13,728.27	26.9	4267.01	8.4
Tumbes	4690.28	122.44	2.6	0.00	0	0.00	0
Ucayali	105,341.77	38,186.29	36.2	32,564.53	30.9	23,322.04	22.1
Peru	1,288,564.27	343,708	26.7	16,2873	12.6	86,916.2	6.7

3.3. High-Priority Areas for Research, Conservation, and Restoration

The study identified that 4.4% (10,171.03 km²) of the areas of the high-occurrence probability of genus *Cedrela* was distributed in the designated Peruvian conservation areas (Figure 5a), out of which the PNA cover of 35.5% (8995.64 km²) was distributed among the reserved zones (85.18 km²), national sanctuary (130.76 km²), historic sanctuary (20.18 km²), wildlife refuge (0.13 km²), national reserve (2323.46 km²), communal reserve (1023.63 km²), national park (5000.93) and protection forest (411.37 km²). The distribution also included conservation areas administered by regional governments (1020.71 km²), and by individuals or institutions at a private level through private conservation areas, whose high-occurrence potential covered a total of 154.68 km² (Table 5) area of the study region.

Table 5. Total potential distribution area predicted that is protected by the modalities of Protected Natural Area in Peru.

PNA Modalities	Geographic Area (km ²)	Low		Moderate		High	
		km ²	%	km ²	%	km ²	%
Reserved Zone	6257.55	1799.22	28.8	358.28	5.7	85.18	1.4
Regional Conservation Areas	33,253.79	16,206.54	48.7	4309.78	13.0	1020.71	3.1
Private Conservation Areas	3963.05	764.34	19.3	536.13	13.5	154.68	3.9
National sanctuary	3173.66	1169.43	36.8	1226.79	38.7	130.76	4.1
Historic Sanctuary	412.79	50.46	12.2	31.67	7.7	20.18	4.9
Wildlife Refuge	207.75	44.25	21.3	20.11	9.7	0.13	0.1
National Reserve	46,528.52	15,987.96	34.4	9005.68	19.4	2323.46	5.0
Communal Reserve	21,665.88	7247.05	33.4	5636.40	26.0	1023.63	4.7
National Park	103,943.67	53,959.42	51.9	21,151.83	20.3	5000.93	4.8
Hunting	1247.35	7.51	0.6	0.00	0.0	0.00	0.0
Protection Forest	3899.87	1563.68	40.1	1175.82	30.2	411.37	10.5
PNA Peru	231,672.07	98,799.85	42.6	43,452.49	18.8	10,171.03	4.4

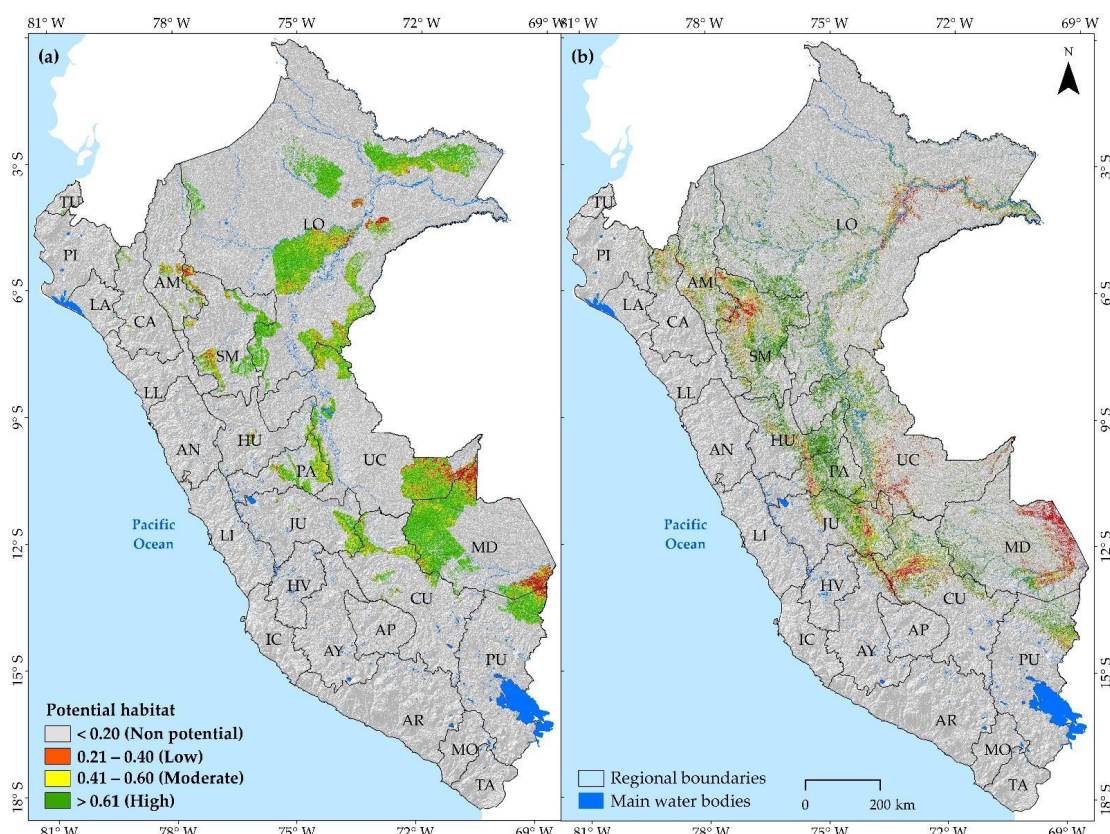


Figure 5. Priority areas (a) for research and conservation practices, and (b) for the restoration of degraded Peruvian areas with genus *Cedrela*.

After compiling the potential habitat distribution results with the information on degraded areas, a high-distribution potentiality of genus *Cedrela* was observed over 20,857.0 km² areas of the central and western parts of Peru (accounts for 11.4% of the study area) that are highly prone to degradation (Table 6). In other words, with proper conservation and management practices in these areas, 11.4% of degraded Peruvian Amazon can be potentially restored.

Table 6. Departments with potential area of recovery of degraded areas with *Cedrela* in Peru.

Region	Degraded Area (km ²)	Low		Moderate		High		Total	
		Km ²	%	Km ²	%	Km ²	%	Km ²	%
Amazonas	11,210	3758.4	33.5	2186.62	19.5	881.56	7.9	6826.58	60.9
Apurimac	146.36	10.93	7.5	4.58	3.1	2.05	1.4	17.56	12.0
Ayacucho	1983.93	444.99	22.4	601.95	30.3	450.5	22.7	1497.44	75.5
Cajamarca	3254.27	1013.86	31.2	927.43	28.5	359.49	11.0	2300.78	70.7
Cusco	14,955.42	5001.71	33.4	4241.09	28.4	2622.01	17.5	11,864.81	79.3
Huancavelica	255.84	62.53	24.4	34.26	13.4	34.1	13.3	130.89	51.2
Huanuco	12,492.15	6630.71	53.1	1057.65	8.5	487.87	3.9	8176.23	65.5
Junin	12,312.95	5537.25	45.0	3807.1	30.9	1449.93	11.8	10,794.28	87.7
La Libertad	1430	173.07	12.1	115.79	8.1	19.68	1.4	308.54	21.6
Lambayeque	1169.75	5.29	0.5	0.04	0.0	0	0.0	5.33	0.5
Loreto	45,320.82	19,959.46	44.0	8105.48	17.9	3635.89	8.0	31,700.83	69.9
Madre de Dios	16,224	4671.55	28.8	3127.58	19.3	5604.83	34.5	13,403.96	82.6
Pasco	7317.36	4689.39	64.1	1394.6	19.1	494.75	6.8	6578.74	89.9
Piura	2890.04	215.5	7.5	40.47	1.4	6.45	0.2	262.42	9.1
Puno	6561.03	7.64	0.1	17.85	0.3	15.47	0.2	40.96	0.6
San Martin	20,356.17	3530.22	17.3	3328.42	16.4	1621.72	8.0	8480.36	41.7
Tumbes	256.35	12.59	4.9	0	0.0	0	0.0	12.59	4.9
Ucayali	21,792.53	8418.18	38.6	5072.2	23.3	3170.73	14.5	16,661.11	76.5
Peru	183,288.15	64,143.3	35.0	34,063.1	18.6	20,857	11.4	11,9063.4	65.0

4. Discussion

4.1. Potential Distribution of Genus *Cedrela*

Our study is the first attempt that makes use of SDMs as a probabilistic decision-making tool [49], which allows the prediction and identification of geographic spaces of the genus *Cedrela* [50] through maximum entropy modeling technique [51]. The proposed model can be applied at regional [24,25] to national scale [52–54] that will significantly contribute to the decision-making system for the Peruvian Amazon authorities. Our model is evident with higher accuracies represented by the strong AUC values of 0.866. Among different topographic and bioclimatic variables, altitude emerges as the most significant variable, which proved to be a determining factor in distribution ranges [24,25]. Species such as *C. montana* and *C. lilloi*, are mostly located and distributed at the higher altitudes. However, the distribution of species depends on the biogeographic conditions and also has a strong influence on historical or evolutionary constraints along with biogeographical, physiological, and ecological factors [55]. In this study, we observed that the 10 species of the genus *Cedrela* covered 17 departments related to the National Forestry and Wildlife Service, as of 2021 [16], and evaluated the location of botanical collections and inventories of the species [13,53,54]. Overall, the modeled distribution of genus *Cedrela* will also help to understand the historic evaluation of genus *Cedrela* species under a spatiotemporal framework. Therefore, we believe that our modeling framework will help in the future in order to establish forest management strategies.

4.2. Conservation and Restoration of Genus *Cedrela*

Peru is one of the most megadiverse countries in the world and is enriched with the biogeographic distribution of various species that requires the implementation of adequate strategies for species conservation [56,57]. Among the 10 species of genus *Cedrela*, *C. odorata* is currently one of the important timber species, threatened by deforestation and unsustainable logging [58]. However, the PAs that harbor *C. odorata*, together with the other species of the *Cedrela* genus (10,171.03 km²), will allow the implementation of mechanisms to maintain its population and genetic diversity, given that the PAs constitute territorial protection reserves [59,60]. Similarly, the degraded areas are the result of anthropogenic pressure and forest fires in 2019 in Peru, occupying an area of 183,288.15 km² [35]. Among the degraded region, 11.4% of the area is currently having a high probability of recovery through the plantation of species of high economic value such as the *Cedrela* genus. The *Cedrela* genus needs to be protected from selective logging and overexploitation over time [9,12,18,61]. This is possible through the implementation of sustainable forest management strategies [62], strengthening forest monitoring and surveillance actions [48,63], and forming strategic alliances for conservation to protect these vulnerable species [56].

This study modeled the potential distribution of the genus *Cedrela* in Peru under current climatic conditions and identified which part of this potential distribution is protected by conservation areas or coincides with degraded areas. However, future studies could evaluate the distribution in future conditions of climate change, similar to Rojas et al. [25], who studied five timber forest species in Amazonas (northeastern Peru). However, it should be noted that species distribution models in climate change scenarios should be interpreted with caution since they may overestimate the decline or increase, by not considering the qualities of the species to adapt in situ to new conditions or persist outside the conditions in which they have been observed [64,65]. Despite the above, the relatively stable distribution sites (same current and future potential) of species would be of interest and essential to ensure the success of any conservation or restoration initiative.

5. Conclusions

The current biogeographic distribution of the 10 genus *Cedrela* (*C. odorata*, *C. montana*, *C. fissilis*, *C. longipetiululata*, *C. angustifolia*, *C. nebulosa*, *C. kuelapensis*, *C. saltensis*, *C. weberbaueri* and *C. molinensis*) using MaxEnt, covers around 6.7% of Peru, found in 17 departments under Ucayali, Loreto, and Madre de Dios that are more likely to be located

in the Amazon region. Likewise, the Natural Protected Areas categorized by the Peruvian State play a fundamental role in allowing the conservation of 4.4% of the potentially high-distribution regions of its territory. Such regions have high potentiality for the genus *Cedrela* plantations, and such plantations could possibly be protected through appropriate conservation strategies.

Our research has also allowed us to quantify that 11.4% of the degraded areas identified in Peru as of 2019, can possibly be recovered through the plantation of one or more species of *Cedrela* genus. Therefore, our study has a strong potentiality to serve as a tool for identifying geographic spaces of genus *Cedrela* under a spatiotemporal framework in order to conserve or recover its local populations in areas degraded by anthropic or natural factors.

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