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Current and Future Distribution of Shihuahuaco (*Dipteryx* spp.) under Climate Change Scenarios in the Central-Eastern Amazon of Peru

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Abstract: The consequences of climate change influence the distribution of species, which plays a key role in ecosystems. In this work, the modeling of the current and potential future distribution was carried out under different climate change scenarios of a tree species of high economic and commercial value, *Dipteryx* spp. This is a hardwood species that plays an important role in carbon sequestration, providing food and nesting for wildlife species, reaching more than 40 m in height with an average diameter of 70 to 150 cm. This species is currently threatened by overexploitation. Thirty-six bioclimatic, topographic and edaphic variables with ~1 km^2 spatial resolution obtained from the WorldClim, SoilGrids and SRTM databases where used. Highly correlated variables were identified with the MaxEnt software for forecasting how the species distribution will be affected until the year 2100, according to the climate scenarios SPP1-2.6, SSP2-4.5, SSP3-7.0, SSP5-8.5, representing the periods 2021–2040, 2041–2060, 2061–2080 and 2081–2100, respectively. The AUC accuracy value of 0.88 to 0.89 was found for the distribution models and the highest contributing variables used were Bio 5, precipitation, Bio 2, and Bio 14. In the climate scenario SPP1-2.6 (Bio 5, precipitation and Bio 2) in 2061–2080, suitable and very suitable habitats represented 30.69% of the study area (2616 ha and 586.97 ha, respectively) and those increased by 1.75% under current climate conditions, and the suitable and unsuitable habitats represented 69.31% of the total area. The results of this research provide valuable information on the current and future distribution of the species and identify zones that can be used as the basis for the creation of conservation areas, formulation of restoration projects, reforestation and sustainable management to avoid the extinction of the species in the face of the effects of climate change.

Keywords: maximum entropy; ecological niche; biodiversity conservation; models of species distribution; climate change; sustainability of shihuahuaco

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1. Introduction

The world is currently facing global climate change, which constitutes the main threat to biodiversity, affecting many ecosystems around the world, and generating impacts on the growth and diversity of the potential distribution of species habitats [1–3]. The effects of climate change will cause the extinction of approximately one quarter of species worldwide at the population and ecosystem community levels [4,5]. On the other hand, climate change can also affect forests and change the frequency, density and diversity of forest cover [6].

The growth of trees depends on the changes of various climatic factors, the sensitivity of each tree species and the ability to adapt to new climatic conditions [7].

The Peruvian Amazon possesses forest species with high commercial value, such as the *Dipteryx* spp., also known as shihuahuaco [8] which grows up to 40 m in height and has an average diameter of 70 to 150 cm [9]. There are 12 species of *Dipteryx* in the world, which are mainly distributed in the Amazonian rainforests and Central America [10]. Shihuahuaco is a species widely used in the timber industry, due to its hardness, commercial value and ecological importance as a food source and habitat for many species [11,12]. However, it is currently one of the most threatened species due to illegal logging and commercial over-logging, which limits its rate of recovery [8]. In addition, these activities affected the potential distribution of this tree species' habitats throughout the Peruvian Amazon.

Understanding the future habitat distribution of plant species is one of the key tools for management and conservation [13]; it helps to identify potential zones to protect threatened ecosystems [14] and to develop strategies to alleviate the consequences of potential climate change [15]. Thus, in recent years, several studies have employed Species Distribution Models (SDM) to identify hotspots in the biodiversity distribution [16]. Other studies have evaluated the climate change impact on the endangered species distribution [17] and have developed plans for the effective management of forest resources [18]. There are different SDM to determine the forest species potential distribution, and four main t groups can be distinguished: (a) statistical regression models (Generalized Linear Model (GML), Generalized Additive Models (GAM)); (b) classification methods (Random Forest (RF), Boosted Regression Trees (BRT)); (c) "envelope" methods (Bioclimatic Envelope Algorithm (BIOCLIN) and Ecological Niche Factor Analysis (ENFA)) and (d) methods based on specific algorithms (Genetic Algorithm for Rule-set Production (GARP) and Maximum Entropy (MaxEnt)) [19–21]. The most widely used model is MaxEnt; it has a high simulation accuracy due to its simple algorithm and the availability of software to analyze climate data that help estimate the current and future species distribution [22,23], providing fitness values and a set of additional results such as the Receiver Operating Characteristic (ROC) curve (Area Under the ROC Curve (AUC) is used to fit the mean data) [24].

The SDMs were applied in different areas of the world such as Turkey, China, Burkin, Iberian Peninsula and Mexico to determine the current and future distribution of forest species, such as *Quercus libani*, *Pinus tabuliformis*, *Ostryopsis davidiana*, *Pterocrpus erinaceus*, *Stipa purpurea* and *Linaria nigricans* [19,25–29]. Studies in Peru were mainly related to the biogeographic distribution modeling of the cacao. It was reported that the regions of San Martin, Madre de Dios, Ucayali, Loreto and Junin were highly suitable for cacao cultivation, and with respect to the Analytical Hierarchy Process (AHP), MaxEnt and APH-MaxEnt methodologies, 1.5%, 5.35 and 23% of the Peruvian territory is highly suitable for this crop [30], and for the genus *Cedrela* (*C. odorata*, *C. montana*, *C. fissilis*, *C. longipetiolulata*, *C. angustifolia*, *C. nebulosa*, *C. Kuelapensis*, *C saltensis*, *C. weberbaueri* and *C. molinensis*) a modeling study was carried out with the objective of prioritizing areas for research and conservation/restoration of this genus, finding that 6.7% of the Peruvian territory presented a high probability of distribution of the evaluated species and 11.65% of the area has a high propensity to degradation for this genus [31]. In addition, the Forest and Wildlife Resources Oversight Agency (OSINFOR for its acronym in Spanish) conducted spatial modeling of 18 forest species in the Loreto region and ecological niches modeling for the evolution of the presence of timber forest species in the Peruvian Amazon [32,33].

In recent years, the Shihuahuaco has been included in the list of endangered species in the Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES). Therefore, it is necessary to determine the habitat distribution of this species in the Ucayali region under different climatic conditions, using Geographic Information Systems (GIS) and MaxEnt tools.

2. Materials and Methods

2.1. Study Area

The department of Ucayali is located in the central-eastern zone of Peru and has an area of 102,199.28 km^2 (Figure 1). It is the second largest department and is part of the Amazon region. It covers an altitudinal range from 125 to 1408 m above sea level and is characterized by a tropical rainforest climate with an annual average temperature of 25.8 °C and an annual rainfall of approximately 2000 to 3500 mm [34] Land cover and use in the study area is represented by forests and mostly natural areas (88.2%), agricultural areas (5.8%), wetlands (4.1%), water surfaces (1.5%) and urban areas (0.9%) of the total surface of the study area [35]. At the forest resource level, the most representative species on low hill forests are ochavaja (*Ruizodendron* sp.), caimitillo (*Pouteria* sp.), shimbillo (*Inga* sp.), chimicua (*Pseu-dolmedia* sp.), sapote (*Matisia* sp.) and renaco (*Ficus* sp.). In the middle terrace forests, the most common species are shimbillo (*Inga* sp.), cumala (*Virola* sp.), caimitillo (*Pouteria* sp.) and huicungo (*Astrocaryum* sp.) [34,35]. The high terrace forests are dominated by sapote (*Matisia* sp.), yanchama (*Poulsenia* sp.), shihuahuaco ((*Dipteryx odorota*, *D. ferrea* and *D. alata*).) [12], and lupuna blanca (*Chorisia* sp.), among other species [35]. The mountain forest is dominated by caimitillo (*Pouteria* sp.), quina (*Cinchona* sp.) and requia (*Guarea* sp.) [35].

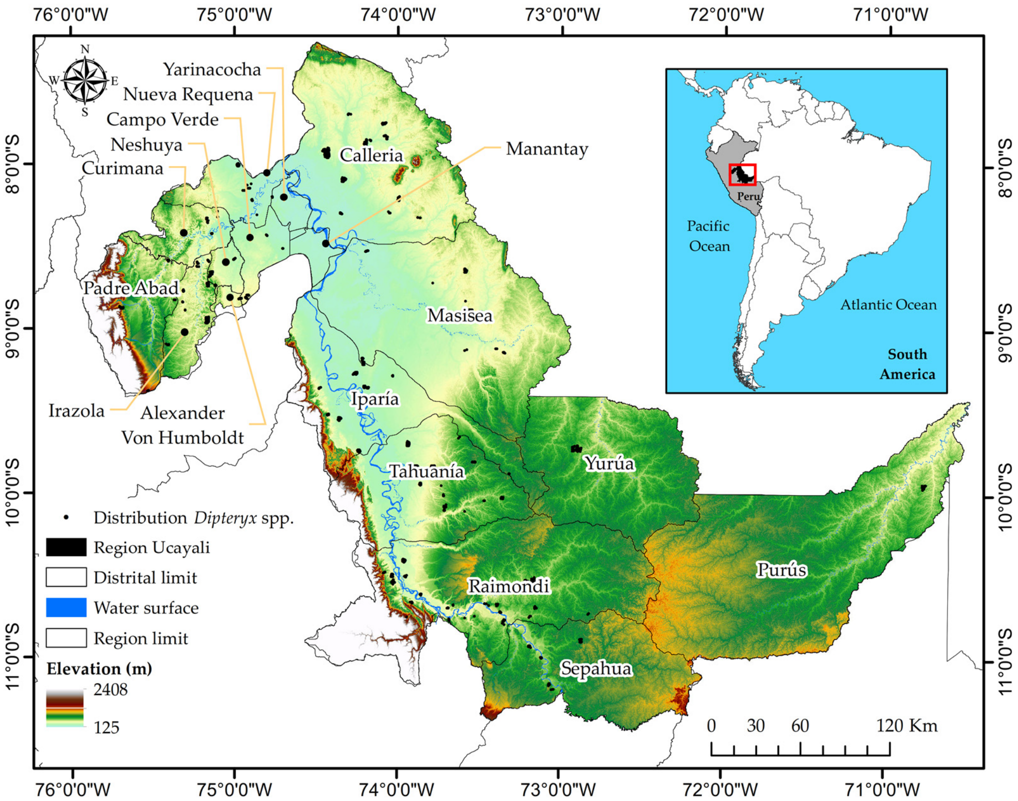

Figure 1. Sampling points of *Dipteryx* spp. along the elevation gradient of Ucayali region (Peru).

Figure 2 depicts the methodology framework used to evaluate the current and future distribution of the genus *Dipteryx* spp. (*D. odorota*, *D. ferrea* and *D. alata*) The first step was to obtain the 36 bioclimatic, topographic and edaphic variables, where the data were at 250 m spatial resolution and exported in .csv formats. Subsequently, the current distribution was determined, using bioclimatic data from 1970–2000 (Figure 2). Then, the future modeling to 2100 was conducted [36].

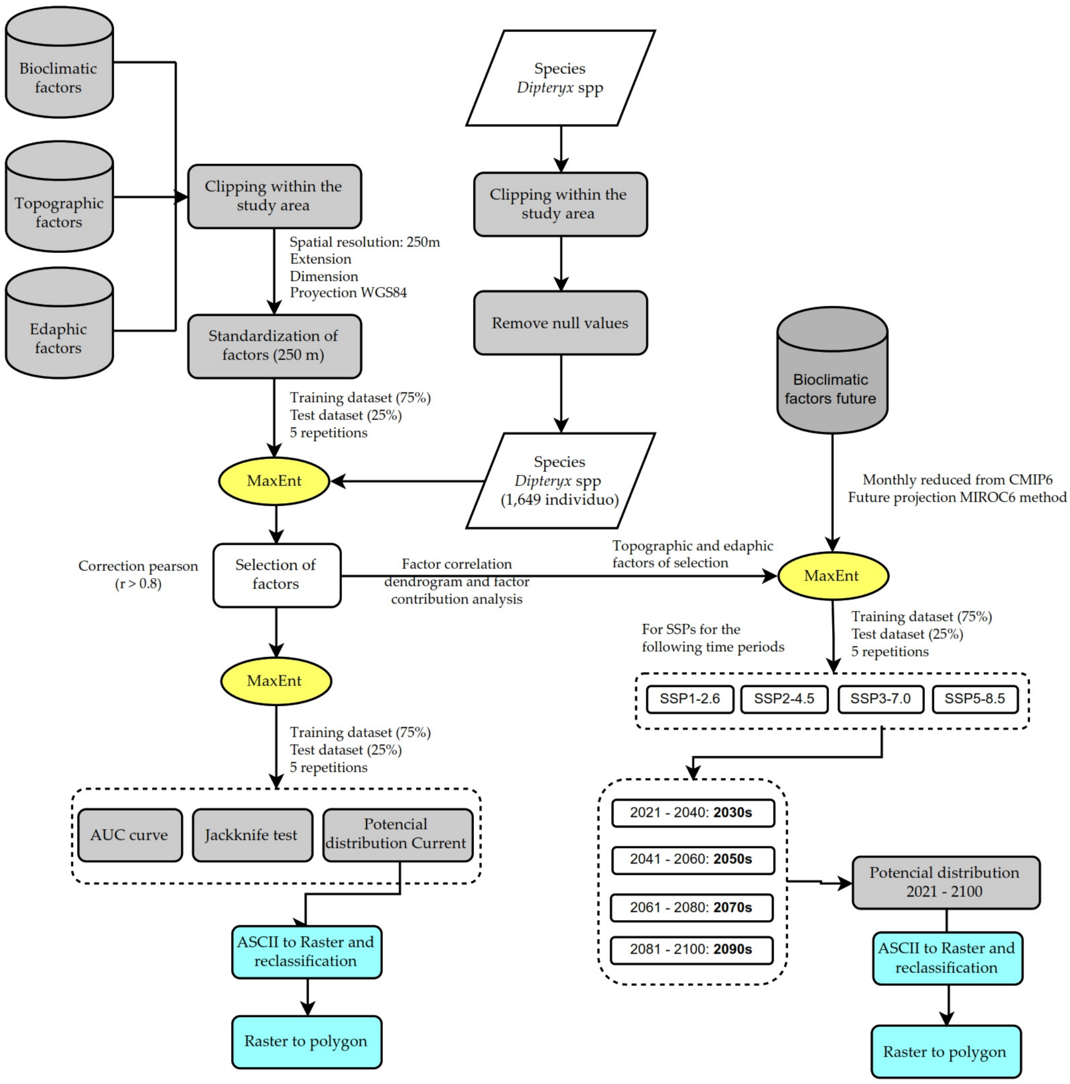

Figure 2. Methodological process to assess the current and future distribution of *Dipteryx* spp. Gray color are the variables and tools employed in this study. Yellow color is the modeling tool, the white ones are the species data and climatic scenarios, and finally the ones in light blue are the results of the analysis.

2.2. Geographic Register of Forest Species

The geographic registry of *Dipteryx* spp. species was obtained from the platform of OSINFOR (https://sisfor.osinfor.gob.pe/visor/, accessed on 10 January 2023) [37]. The data were downloaded in .csv format, and geographic coordinates (latitude and longitude) and species name were included. Subsequently, it was standardized, according to the format required by QGIS and MaxEnt [38]. At the Peru national level, 6900 individuals were obtained and they were filtered to the study area, obtaining a total of 1649 individuals for the Ucayali department.

2.3. Bioclimatic, Topographic and Edaphic Variables

The current bioclimatic variables were obtained from WorldClim (https://www.worldclim.org/, accessed on 27 December 2022) [39] from years 1970–2000 and were represented by average temperature and precipitation. We downloaded a compressed file containing 19 GeoTiff (.tif) files. The variables were rescaled at 250 m spatial resolution and trimmed for the area of study. Based on the four Shared Socioeconomic Pathways (SSP1-2.6, SSP2-4.5, SSP3-7.0 and SSP5-8.5), we downloaded the future bioclimatic variables (monthly average values of minimum, maximum temperature and precipitation) from the Model for Interdisciplinary Research on Climate (MIROC) v6, at 1.40625° and 1.40625° cell sizes [40]. Periods of 20 years (2021–2040, 2041–2060, 2061–2080, 2081–2100) (https://www.worldclim.org/data/cmip6/cmip6climate.html, accessed on 27 December 2022) [39] were considered to obtain monthly averages. Subsequent data were processed in the same way as current variables.

Topographic variables as digital elevation models were downloaded from WorldClim at 90 m resolution, generated by the Shuttle Radar Survey Mission (SRSM) and the United States Geological Survey (USGS). From the Digital Elevation Model (DEM), the terrain slope, terrain roughness index (TRI), topographic position index (TPI) and flow direction variables were generated using RStudio v4.1.1 software [31].

Soil variables related to PH, soil organic carbon content in the fine fraction, bulk density of the fine fraction, total nitrogen (N), sand, silt and clay content, and carbon stocks were downloaded from the SoilGrids v2.0 platform (https://gee-community-catalog.org/projects/isric/, accessed on 27 December 2022) via Google Earth Engine (GEE) [41]. The 36 variables were reclassified at 250 m spatial resolution and inverted for the study area (Table 1). All information was processed into geographic coordinates using QGIS software.

Table 1. Bioclimatic, topographic and edaphic variables for modeling *Dipteryx* spp.

Variable	Units	Symbol	Δ Earnings in Jackknife 1
Bioclimatic Factor			
Average annual temperature	°C	bio01	2.4
* Average diurnal range	°C	bio02	10.7 *
Isothermality		bio03	1.8
Seasonality of temperature	°C	bio04	0.2
* Maximum temperature of the warmest month	°C	bio05	27.7 *
Minimum temperature of the coldest month	°C	bio06	1.9
Annual temperature range	°C	bio07	0.2
Average temperature of the wettest quarter	°C	bio08	1.8
* Average temperature of the driest quarter	°C	bio09	13.7 *
Average temperature of the warmest quarter	°C	bio10	2
Average temperature of the coldest quarter	°C	bio11	2
Annual precipitation	mm	bio12	0
Precipitation of the rainiest month	mm	bio13	0.3
* Precipitation in the driest month	mm	bio14	5.1 *
Seasonality of precipitation	mm	bio15	4.5
* Precipitation in the wettest quarter	mm	bio16	0.4 *
Precipitation in the driest quarter	mm	bio17	0.2
Precipitation in the warmest quarter	mm	bio18	0
* Precipitation in the coldest quarter	mm	bio19	0.4 *
Minimum temperature	°C	Tem_min	7.8
Maximum temperature	°C	Tem_max	6.7
Average temperature	°C	Tem_mean	0.8
* Precipitation	mm	Prec	0.8 *
Topographic factor			
* Elevation above mean sea level	masl	dem	0.2 *
Slope of the terrain	%	Slope	0
Terrain Roughness Index—TRI		TRI	0.1
Topographical Position Index—TPI		TPI	0
Direction of flow		Flowdir	0.2
Edaphic factor			
* pH en H 2 O	pH × 10	pH	1 *
Soil organic carbon content in fine soil fraction	gram kg^{-1}	soc	0.1
Bulk density of fine soil fraction	kg/dm^3	bdod	0.4
* Total nitrogen (N)	g/kg	nitrogen	0.9 *
Clay content	%	clay	1.6
Sand content	%	sand	2.9
Silt content	%	slime	0.7
Carbon stock	kg/m^2	ocs	0.5

* They represent the variables that contribute the most to the current modeling.

2.4. Current and Future Distribution Modeling in MaxEnt

MaxEnt software (https://biodiversityinformatics.amnh.org, accessed on 15 December 2022) was used for the modeling, which requires environmental data with species presence. MaxEnt has been widely used in many studies ranging from endangered species prediction to disease spreading [42,43]. To model the current and future distribution of *Dipteryx* spp., 36 variables and attendance data were used. In the model validation, 75% of the randomly selected existing data were used for training purposes and 25% for validation [21]. We ran the algorithm with five replicates of 5000 interactions, with different random partitions (bootstrap method) leaving other settings as default.

To select the variables that contribute the most to the model, RStudio software was used with the *virtualspecies* library [44], and damerograms were prepared. Clusters were identified to define the best contribution, correlation coefficients > −0.8 and < 0.8 were selected and compared with to MaxEnt's Jackknife test [45]. For comparison, variables with the lowest contribution were discarded, leaving 10 variables for the current and future distribution simulations.

We validated the results on the basis of the AUC calculated from the ROC. According to the AUC values, five levels of performance were identified: excellent (>0.9), good (0.8–0.9), acceptable (0.7–0.8), poor (0.6–0.7) and ineffective (0.6). We also considered (2) "medium" habitat (0.4–0.6), (3) "low potential" habitat (0.2–0.4) and (4) "no potential" habitat (0.2–0.4) (<0.2) [30,46,47].

2.5. Change of the Centroid of Habitats under Different Climatic Conditions

It was necessary to assess changes in suitable habitats over time. For this purpose, the current centroid was compared with the habitat's centroid under future climatic conditions. We calculated the distance and direction of the center of mass movement using the methodology proposed by Yu et al. [48] and Gong et al. [49]. Using Equation (1), where "t" is the time variable; "I" is the number of patches; $S_i(t)$ is the patch area; $S(t)$ is the total area of the patch; ($Xi(t)$, $Yi(t)$) are the latitude and longitude coordinates of the geometric center of the patch; ($x(t)$, $y(t)$) is a center of gravity of a very suitable habitat.

$$\begin{cases} x(t) = \sum_{i=1}^{I} \frac{s_i(t) \cdot X_i(t)}{S(t)} \\ y(t) = \sum_{i=1}^{I} \frac{s_i(t) \cdot Y_i(t)}{S(t)} \end{cases} \tag{1}$$

On the other hand, it was also necessary to determine the distance and the direction of the center of gravity movement from the current period to the next period, which is given by Equations (2) and (3), where D is the two centers of gravity from period t to period $t + 1$; θ is two masses direction of motion between habitats, where 0° is east, 90° is north, 180° is west and 270° is south; 0° < θ < 90° is northeast, 90° < θ < 180° is northwest, and 180° < θ < 360° is southeast:

$$D = \sqrt{(x(t+1) - x(t))^2 + (y(t+1) - y(t))^2} \tag{2}$$

$$\theta = arctg\left(\frac{y(t+1) - y(t)}{x(t+1) - x(t)}\right) \tag{3}$$

3. Results

3.1. Model Performance and Importance of Variables

Seventeen species distribution models were obtained, one of them under current conditions and 16 under climate change conditions. The AUC values ranged from 0.88 to 0.89, which are considered good (0.8 < AUC < 0.9). The 2030s and 2090s periods showed the lowest AUC values (0.88). Additionally, the highest values were reported in the 2050s and 2070s in almost all SSPs as shown in Table 2.

Table 2. Species distribution model (AUC) performance under current and future conditions for *Dipteryx* spp.

Representation		**AUC**		
Current		**0.89**		
MIROC6	SSP1-2.6	SSP2-4.5	SSP3-7.0	SSP5-8.5
2030s	0.89	0.88	0.89	0.88
2050s	0.89	0.89	0.89	0.89
2070s	0.88	0.89	0.89	0.89
2090s	0.88	0.88	0.89	0.88

The contribution of the variables modeled in MaxEnt reported that only three environmental variables had the greatest contribution to the current and future distribution of *Dipteryx* spp. The environmental variables Bio 5, Precipitation and Bio 2 contributed 81% by 2030s. By the 2090s, the precipitation, Bio 2 and Bio 14 variables contributed 78.6% in the future distribution of this species. Likewise, under current conditions, the Bio 5, Bio 9 and Bio 14 variables contributed 75.9% as shown in Table 3.

Table 3. Percentage contribution of environmental variables to current and future scenarios.

Variables		**Variable 1 (%)**	**Variable 2 (%)**	**Variable 3 (%)**	**Total of Contribution**
Current		Bio 5 (31.3)	Bio 9 (22.9)	Bio 2 (21.7)	75.9
2030s	SSP1-2.6	Bio 5 (36.3)	Precipitation (27.1)	Bio 2 (13)	76.4
	SSP2-4.5	Bio 5 (39)	Precipitation (20.4)	Bio 2 (14.6)	74
	SSP3-7.0	Bio 5 (62.2)	Precipitation (10.9)	Bio 2 (7.9)	81
	SSP5-8.5	Bio 5 (39.3)	Precipitation (14.4)	Bio 2 (12.3)	66
2050s	SSP1-2.6	Bio 5 (35.3)	Precipitation (26.4)	Bio 2 (11.6)	73.4
	SSP2-4.5	Precipitation (31.7)	Bio 5 (26.1)	Bio 2 (13)	70.8
	SSP3-7.0	Bio 5 (49.5)	Precipitation (17.8)	Bio 2 (8.2)	75.5
	SSP5-8.5	Precipitation (35.8)	Bio 5 (21.7)	Bio 2 (12.4)	70
2070s	SSP1-2.6	Bio 5 (38.1)	Precipitation (22.4)	Bio 2 (10.9)	71.4
	SSP2-4.5	Precipitation (33.1)	Bio 5 (32.4)	Bio 2 (10.9)	75.8
	SSP3-7.0	Precipitation (29.3)	Bio 5 (23.1)	Bio 2 (20.8)	73.2
	SSP5-8.5	Precipitation (50.8)	Bio 2 (11)	Bio 14 (10.2)	72
2090s	SSP1-2.6	Bio 5 (38.5)	Precipitation (24.7)	Bio 2 (9.3)	72.5
	SSP2-4.5	Bio 5 (32.1)	Precipitation (25.7)	Bio 2 (10)	67.8
	SSP3-7.0	Precipitation (29.1)	Bio 2 (21.6)	Bio 2 (20)	70.7
	SSP5-8.5	Precipitation (54.5)	Bio 2 (12.7)	Bio 14 (11.4)	78.6

3.2. Current and Future Potential Distribution of *Dipteryx* spp.

The current distribution of *Dipteryx* spp. is shown in Figure 3. The highly suitable habitat is located to the north and west of the study area. The moderately suitable habitat followed the same patterns, but increased in surface area towards the center of the study area. Low and unsuitable habitats are located to the east and west of the study area.

The areas of "high", "moderate" and "low" potential habitat under current conditions for *Dipteryx* spp. correspond to 5869 km^2 (5.62%), 24,334 km^2 (23.32%) and 27,491 km^2 (26.34%) of Amazonian land, respectively (Table 4). Considering future scenarios, the "high" habitat by 2100 reported a decreasing, while "moderate" and "low" potential habitat increased. On the other hand, under current conditions, the "moderate" potential habitat increased 25.65% and 26.06% by the year 2070 (SSP3-7.0) and 2090 (SSP5-8.5), respectively. On the contrary, the "Low" potential habitat decreased as the years progress.

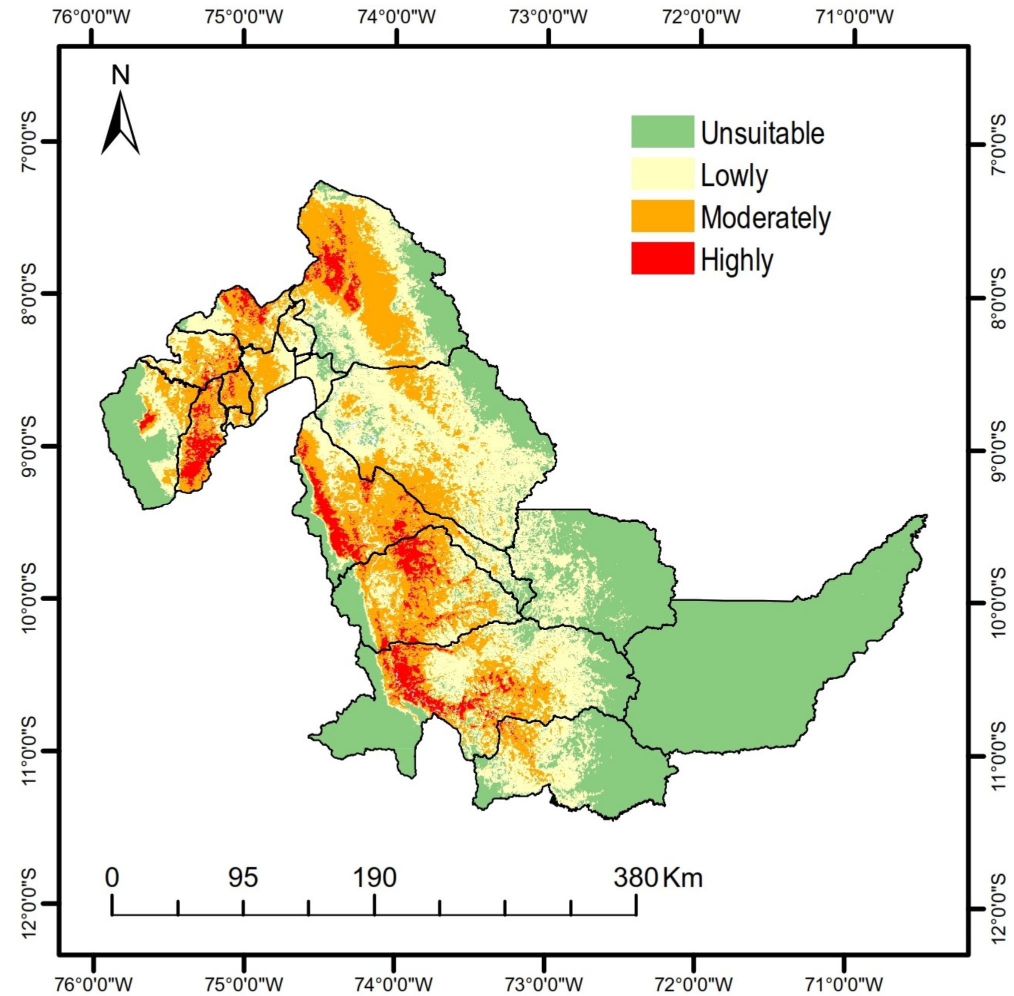

Figure 3. Habitat suitability for *Dipteryx* spp. in the Ucayali region under current climatic conditions.

Table 4. Habitat areas for *Dipteryx* spp. in the scenarios according to time period.

Climate Scenarios	Time Period	Not Suitable		Low		Moderate		High	
		km^2	%	km^2	%	km^2	%	km^2	%
Current	1970–2000	46,666	44.72	27,491	26.34	24,334	23.32	5869	5.62
2021–2040 (2030s)	SSP1-2.6	47,399	45.42	27,719	26.56	23,487	22.51	5754	5.51
	SSP2-4.5	46,863	44.91	26,458	25.35	24,344	23.33	6694	6.41
	SSP3-7.0	46,129	44.2	27,546	26.4	24,531	23.51	6154	5.9
	SSP5-8.5	48,168	46.16	26,131	25.04	23,820	22.82	6241	5.98
2041–2060 (2050s)	SSP1-2.6	46,056	44.13	26,926	25.8	25,520	24.45	5858	5.61
	SSP2-4.5	48,707	46.67	26,598	25.49	23,265	22.29	5789	5.55
	SSP3-7.0	46,192	44.26	27,141	26.01	24,491	23.47	6535	6.26
	SSP5-8.5	46,963	45	26,509	25.4	25,016	23.97	5872	5.63
2061–2080 (2070s)	SSP1-2.6	46,152	44.22	26,175	25.08	26,164	25.07	5870	5.62
	SSP2-4.5	47,735	45.74	26,475	25.37	25,055	24.01	5096	4.88
	SSP3-7.0	48,118	46.11	23,630	22.64	26,767	25.65	5845	5.6
	SSP5-8.5	46,640	44.69	27,067	25.94	25,379	24.32	5275	5.05
2081–2100 (2090s)	SSP1-2.6	45,457	43.56	26,886	25.76	25,618	24.55	6398	6.13
	SSP2-4.5	47,748	45.75	23,492	22.51	26,338	25.24	6781	6.5
	SSP3-7.0	45,825	43.91	27,511	26.36	26,159	25.07	4865	4.66
	SSP5-8.5	44,339	42.49	27,203	26.07	27,194	26.06	5624	5.39

The current distribution of *Dipteryx* spp. with high habitat suitability stretched across 5.62% (5869 km^2) of the Ucayalino territory, and the moderate suitability habitat represented 23.32% (24,334 km^2). When the SSP1-2. 6 model was applied by 2030, the area of moderate and high potential habitat decreased by 0.92%; however, in the period 2081–2100, the area with high and moderate potential habitats increased by 2.26%, representing an area of 32,016 km^2. For the SSP2-4.5 model, the high habitat potential increased by 0.79% and the moderate potential habitat remained in the same range, and it is shown for the period 2041–2060 that the unsuitable area increased by 2.041% and the moderate and high potential habitats decreased by 1.1% with respect to the current scenario, showing that, for this model in the different periods, the moderate potential areas tended to increase by 2.8% under these conditions. There was an increase in the suitable area for *Dipteryx* spp. in the period 2081–2100, counting 33,119 km^2 of Amazonian land.

The potential distribution under future scenarios is shown in Figure 4, where the "high" habitat is distributed toward the north and west of the Ucayali region. The "moderate" and "low" habitats are distributed from south to northwest for all scenarios.

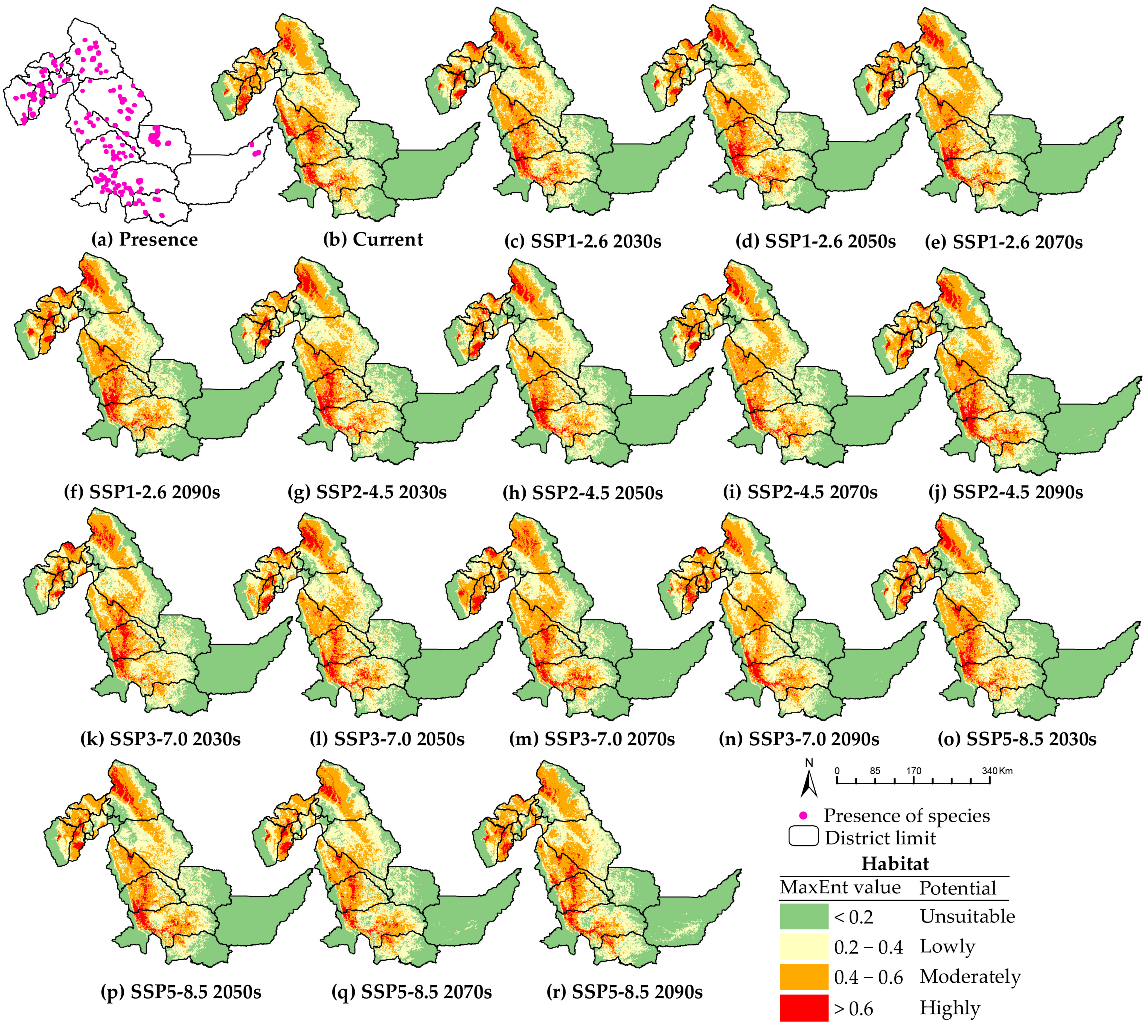

Figure 4. Forecast of future suitable areas for *Dipteryx* spp. under climate scenarios.

Figure 5 shows the area of "high" habitat calculated for the four climate scenarios in order to analyze the climate change impact in different scenarios on the potential distribution of *Dipteryx* spp. Under the SSP1-2.6 climate scenario, the suitable and very suitable habitats represented 30.69% of the study region for the years 2061–2080 (2616.381 km^2 and 586.965 km^2, respectively), increasing 1.75% more than in the current climate conditions.

The low and unsuitable habitats showed 69.31% of the total area, which decreased 1.75% under current conditions.

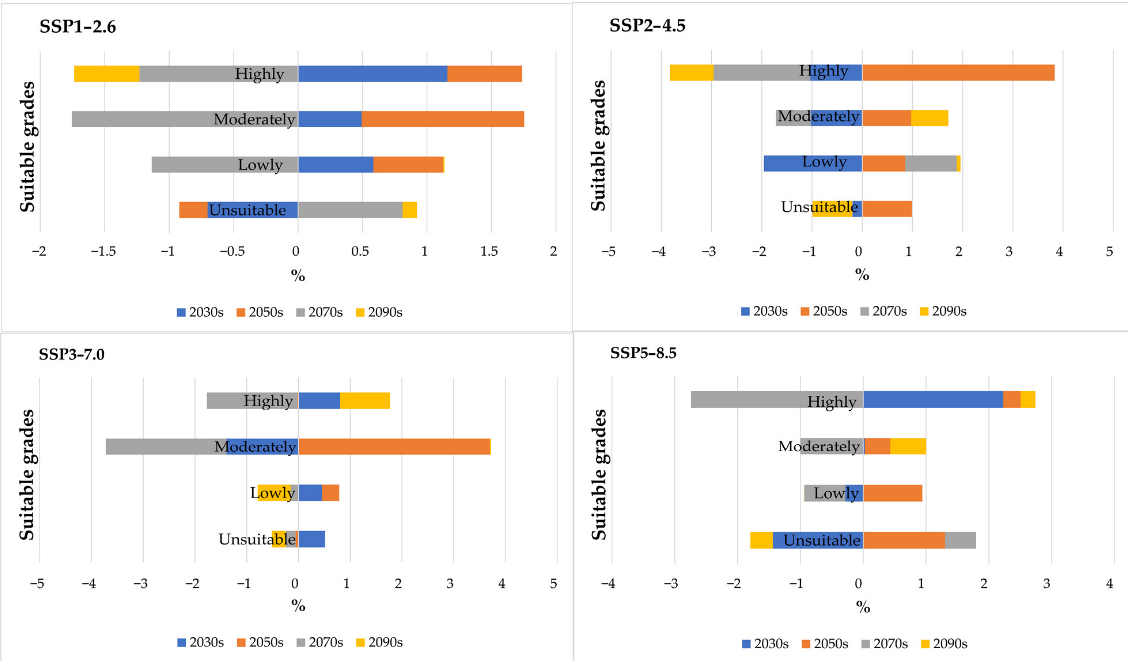

Figure 5. Proportional changes in the potential distribution of *Dipteryx* spp. under climate scenarios.

Figure 6 shows the distribution map of highly suitable areas for *Dipteryx* spp. They are located in the Callería, Masisea, Irazola, Tahuania and Raymondi districts, occupying a total area of 11.9 km^2. Likewise, the districts are located along the Ucayali River.

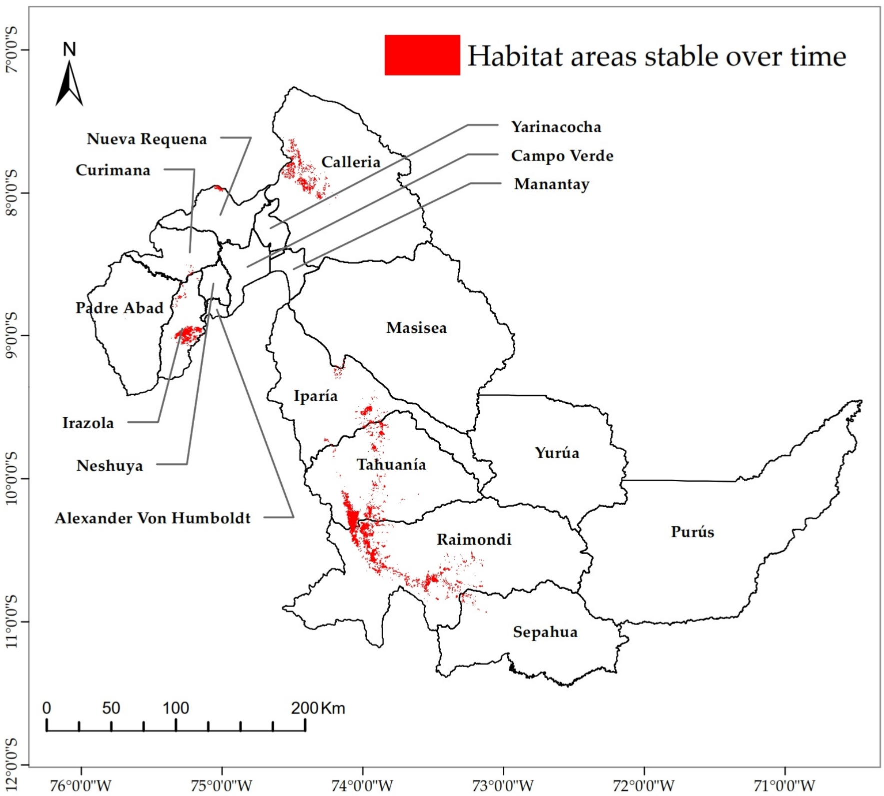

Figure 6. Area of stable habitats.

3.3. Change in the Centroid of Highly Suitable Habitats under Different Climatic Conditions

In Figure 7, the highly suitable centroids under current and future climate scenarios are shown. The direction and distance of highly suitable habitats for *Dipteryx* spp. were located in the Iparia district (Figure 7a–c), showing the habitats predicted under the four climate scenarios and under current conditions.

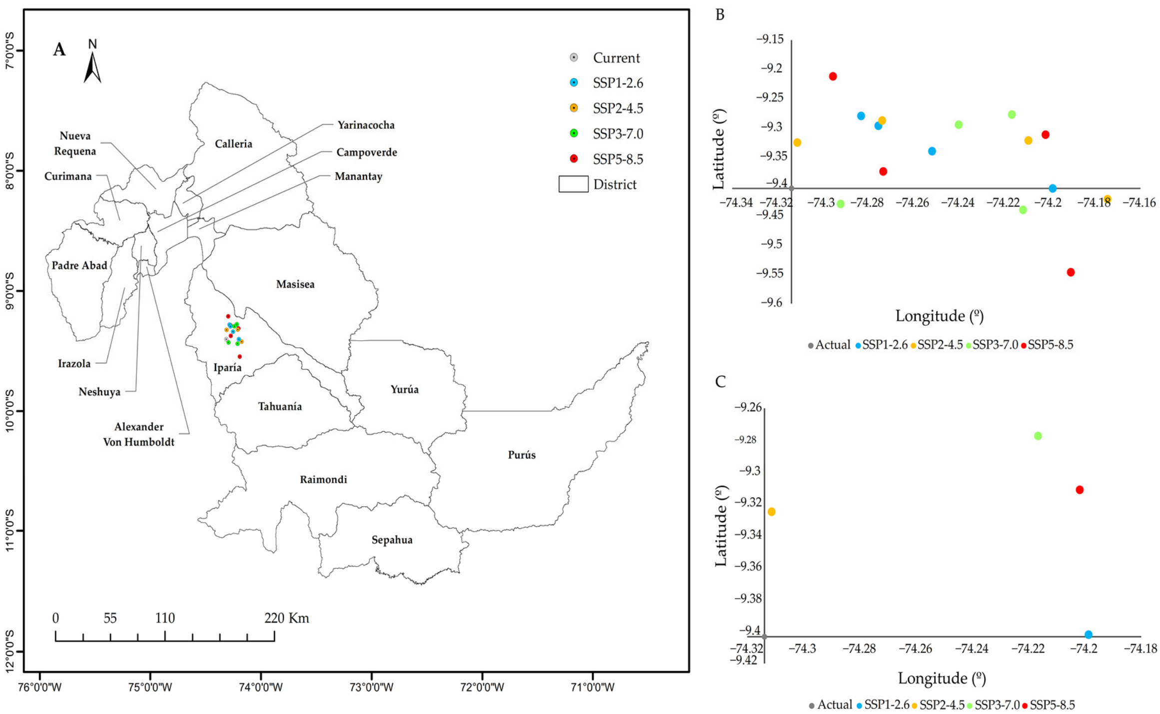

Figure 7. Centroids of highly suitable habitats for *Dipteryx* spp. in Ucayali under current climate conditions under the four climate change scenarios (**A**,**B**). Centroid of the climate scenario representing the period 2080–2100 (**C**). The gray point represents the centroid under current climate conditions and the other points indicate the centroids under future climate scenarios.

4. Discussion

This study evaluated the current and future distribution of *Dipteryx* spp. in the department of Ucayali. This is a commercial species threatened by commercial overharvesting and an apparent low regeneration rate [8]. The use of tools such as MaxEnt made it possible to use large volumes of numeric and remote sensing data [31] for current and future modeling to the year 2100.

The spatial changes in the current distribution of *Dipteryx* spp. probably will experience future changes. To model distribution areas in the periods 2021–2040, 2041–2060, 2061–2080 and 2081–2100, we employed scenarios SSP1-2.6, SSP2-4.5, SSP3-7.0 and SSP5-8.5, where we obtained prediction pressures higher than 0.88 AUC, indicating good accuracy [47]. These values are similar to those reported in other studies in Mexico, South Korea and Peru [14,47,50], which showed high reliability. The results are also in agreement with those reported by Li et al. [21] for the prediction model of suitable habitats for the *Sapindus delavayi* and *Pinus densiflora*. Similarly, Ma et al. [29] mentioned that high values reflect a greater ability to discriminate between conditions suitable for the distribution of species suitability. Stranges et al. [51] considered the AUC models above 0.75 as potentially useful, 0.80–0.90 as good and 0.90 to 1.0 as excellent.

On the other hand, according to the jackknife test, the bioclimatic variables that will affect the future distribution of *Dipteryx* spp. habitat more are (i) the mean diurnal range (bio02), (ii) the maximum temperature of the warmest month (bio05), (iii) the precipitation of the driest month (bio14), and (iv) the precipitation and elevation. Therefore, these variables had more importance and impact than other variables used in the geographic distribution modeling and they are closely related to the physiological growth and the species distribution [42]. These results are consistent, because the *Dipteryx* spp. is related to environmental conditions of high temperatures and precipitation, with high levels of light in its initial growth being a determining factor in the growth in diameter and height and particularly associated with streams [8–11,52], and is a species with a high natural resistance to attack by biological agents [53]

This study predicted the area suitability under future climate scenarios (SSP1-2.6) from the year 2021 to 2100. The suitability of high and moderate habitat tended to decrease in the period 2021–2040 and after that it tended to increase. In the period 2081–2100, for the model (SSP2-4.5), the high habitat potential increased and the moderate potential habitat was maintained for the period 2021–2040 and then decreased, and in the period 2081–2100 it increased, having a maximum decrease of 4.88%. In the period 2061–2080, in the scenario SSP3-7.0, the suitable habitat increased in the period 2041–2060, but in the period 2081–2100 it decreased, while, in the model SSP5-8.5 the moderate habitat gradually increased and the habitat with high potential decreased (Figure 8). Navarro et al. [3] mentioned that, if the surface areas tend to be maintained or increased, they are not affected by the new future climatic conditions, which would be associated with their vegetative cycles. On the other hand, Li et al. [21] mentioned that species have a high probability of being distributed in suitable habitats and belong to the core regions of resource distribution with rich genetic diversity, while other studies showed that climate change may reduce the potential area of species distribution [54,55]. This study showed that the area with moderate and high habitat suitability for shihuahuaco in different periods is not the same. However, other studies indicated that human activities and climatic changes promote the adaptation of species to new conditions in different ranges [56].

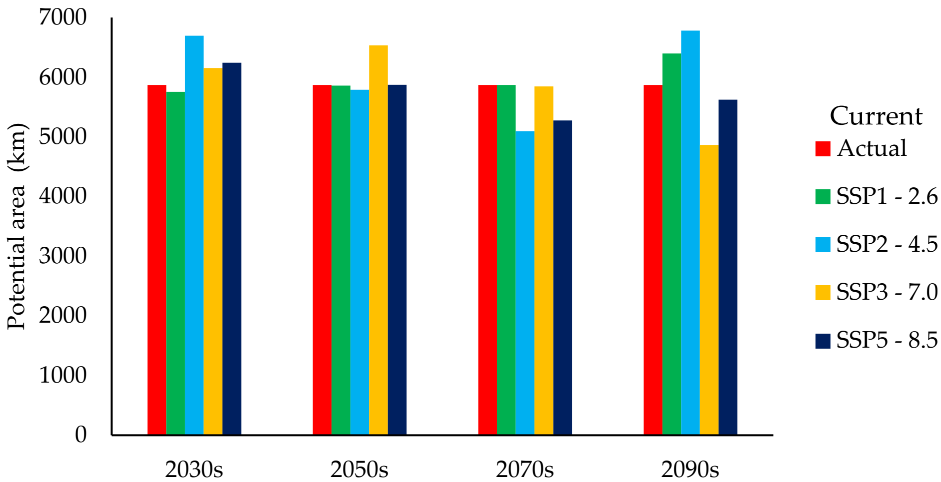

Figure 8. Potential distribution of habitat under current conditions and climate change scenarios *Dipteryx* spp. in Ucayali.

Maps of the probability of potential occurrence of *Dipteryx* spp. helped to identify areas of occurrence of the species to improve forest management and monitoring [50,57]. In this study, the maps of current and future potential distribution were developed using the MaxEnt model, which reported acceptable results. We were able to identify five districts (Callería, Masisea, Irazola, Tahuania and Raymondi) with areas suitable for the development of *Dipteryx* spp. with a total of 11.9 km^2, and these districts are located along the Ucayali river. Interestingly, *Dipteryx* spp. are better adapted to localities with high water availability [1,9].

The centroids of highly suitable habitats for the *Dipteryx* species under current and future climate change scenarios are located in the Iparía district. This information shows a direct relationship between the movement distance of the centroids with the change of the adequate distribution area [53]. Other extremely important aspects are that each species has its own habitat and their variation over time is inferred in various studies [53,54]. In the future, *Dipteryx* spp. shows an increasing trend and that may be related to the increase in global temperature [55].

Maximum Entropy modeling in recent years has become an important tool for ecological studies of flora and fauna species, allowing the use of species occurrence data [58–60]. These results will contribute to better understanding of the behavior of *Dipteryx* spp. under complex climatic and environmental conditions, providing a theorical basis and guidance for management and conservation, as well as for the establishment of sustainable forest plantations in areas with suitable potential for its development in the Ucayali region. In future studies, current and future modeling of the potential habitat of other forest species can be considered, regarding the combination with other techniques such as Random Forest, multi-criteria evaluation and correlation with cover types and land use.

5. Conclusions

The distribution of the *Dipteryx* spp. species in the Ucayali department (Peru) was successfully modeled under the current and future climate change scenarios. More than 4% of the high species distribution reported a decrease for the year 2100. Climate change altered species distribution ranges, which was crucial for understanding the spatio-temporal dynamics of this tree species. Current highly suitable areas should be conserved through the creation of protected areas and restoration programs. This study provides maps of potential distribution areas of *Dipteryx* spp. in Ucayali, and a robust methodology that can be replicated in other areas of Peru.

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