

World historical mapping and potential distribution of *Cinchona* spp. in Peru as a contribution for its restoration and conservation

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ABSTRACT

Peru is a megadiverse country in neotropical flora and is home to an important genus of plants called *Cinchona* and commonly all its individual species are called Cinchona Tree (*Cinchona* spp.), which represents the national tree for this nation. This country has 18 species, a group of these species are listed as vulnerable, endangered, and their population trend is currently unknown. This genus is at risk of extinction due to overexploitation for its medicinal, constructive and food uses. The IUCN also mentions that increased species assessments and records will help make the IUCN Red List a “barometer of life”. Based on the fact that understanding the effects of environmental change on ecosystems requires the identification of historical and current baselines, which can act as reference conditions, this research generated georeferenced global historical maps of *Cinchona* spp. and then determined the appropriate sites based on environmental variables using the MaxEnt software and established the probabilities of occurrence of this genus in Peru to establish priority areas for its conservation and restoration. Four maps were obtained, one for each centennial, from 1737 to the present, with 10 860 occurrences of *Cinchona*. In the MaxEnt modeling, 10.30 % (13 3172.56 km²) and 19.20 % (24 7371.32 km²) of Peru’s surface area had high (> 0.6) and moderate (0.4–0.6) probabilities, respectively, of hosting *Cinchona*. Only 7.6 % (17 305.32 km²) and 22.0 % (50 153.73 km²) of the areas with high and moderate distribution potential, respectively, were covered by natural protected areas. Likewise, 11.90 % (21 738.75 km²) and 33.20 % (60 789.17 km²) of the high and moderate probability lands, respectively, correspond to degraded areas (DAs) and, therefore, are considered a priority for restoration with *Cinchona* spp. The results may stimulate the rethinking of decision making for the National Action Plan for Reforestation with Species of the Genus *Cinchona* and other plans or tools for *Cinchona* conservation in Peru.

1. Introduction

Peru as part of the Amazon basin, is one of the most megadiverse countries in the world (Rodríguez and Young 2000), and its neotropical flora is one of the most diverse in species and endemisms (León et al. 2006a). The *Cinchona* tree (*Cinchona* spp.) is present in Peru, which has such importance for the country, that it is in the National Coat of arms and represents the wealth of plant resources (flora) of this nation (Álvarez 2013; Pollito 1989). However, some species of the *Cinchona* genus are in the vulnerable and endangered categories and for others their status is unknown in Peru. Due to overexploitation, because of its medicinal, construction and food uses, *Cinchona*s are in danger of extinction; for example, *Cinchona rugosa* and *Cinchona lucumifolia* were

assessed on the IUCN Red List of Threatened Species in 2004 as vulnerable but their population trend is unknown at present (<https://www.iucnredlist.org/>; accessed on February 05, 2021). As well, *Cinchona mutisii* was assessed on the IUCN Red List of Threatened Species in 2004 as endangered but its population trend is unknown at present and *Cinchona pyrifolia* is considered vulnerable in the IUCN Red List of Threatened Species in 2014, and its population is declining. The high morphological variability present in *Cinchona* could be attributed to environmental factors, as well as to processes of hybridization or duplication of their genomes, but there is no update on the status of *Cinchona* species in Peru since diversity is associated with genetic and environmental components related to phenotypic variation in these individuals (Andersson, 1998). Therefore, it is necessary to determine

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georeferenced occurrences of *Cinchona* in Peru to estimate the potential habitat in different climatic scenarios to improve reforestation or conservation plans for this genus. (IUCN 2022; Albán-Castillo et al. 2020). IUCN mentions that increased assessments will help make the IUCN Red List a “barometer of life”. This requires increasing the number of species assessed to at least 160 000, which will improve global taxonomic coverage and thus enable better policy and conservation decisions (IUCN 2022).

Historically, studies of the genus *Cinchona* have been on the botanical (Bonpland and Humboldt 1815; Bourke 1821; Macbride 1938; Ruiz and Pavon 1957; Verveen 1984) and anthropic uses of the species (Hodge 1948), along with taxonomy and distribution studies of *Cinchona* at the country and local level (Andersson, 1998; Andersson and Taylor, 1994; Huamán et al., 2019a; Pollito, 1989), few have made use of georeferenced occurrences. Therefore, it is necessary to study historical maps with occurrences and update the current distribution of *Cinchona*. These efforts would allow us to analyze the current potential distribution within the system of Natural Protected Areas (PNAs) (SERNANP 2020) for this genus. Likewise, such maps may guide *Cinchona* repopulation plans (Albán-Castillo et al. 2020) by identifying climatically adequate areas that have high priority for restoration, such as degraded lands. Today, 13.80 % (177 592.82 km²) of the Peruvian territory is degraded (Albán-Castillo et al. 2020), and the government’s technological proposals focus on reforestation with tree species (native, exotic, or a combination of them), agroforestry systems, and management of secondary regeneration (Meza et al. 2006). On the other hand, combining quantitative historical data with ‘naturalistic’ descriptive information organized in a chronological chain, allows for example highlighting long-term trends and can be used to inform current conservation schemes (Gatti et al. 2015). If one knows where a species inhabits, one can infer what climatic conditions this species can tolerate (Ireland and Kriticos 2019). With sufficient resources, an Species Distribution Model (SDM) can be based on data collected according to rigorously defined sampling designs (S. J. Phillips et al. 2009). For instance, in new forward modeling research, where occurrence is recorded at an environmentally and spatially representative selection of sites (Cawsey, Austin, and Baker 2002), which can be used to estimate the potential distribution of the species in other independent locations or novel climates (Ireland and Kriticos 2019). Therefore, understanding the effects of environmental change on ecosystems requires the identification of baselines that can act as reference conditions (Gatti et al. 2015).

On May 4, 2020, the Ministry of Agriculture of Peru (MINAGRI 2020) approved the Action Plan for Forest Repopulation with species of the genus *Cinchona* (*Cinchona* Tree) 2020–2022 to be applied in 10 of the 24 regions and a constitutional province (Albán-Castillo et al. 2020). This plan contains three strategic bases: (1) take into account the threats to the habitats of the species *Cinchona calisaya* Wedd. (MINAGRI 2006), (2) make plans for ecosystem services to reforest the *Cinchona* species, and (3) prioritizing these plans through the collection of seeds, especially of three species of *Cinchona* (*C. officinalis*, *C. calisaya*, *C. pubescens*). These species have been selected for nursery production and subsequent use in reforestation by the Peruvian Ministry of Agriculture because they were depredated for their medicinal uses, construction, land use and change, migratory agriculture, and forest fires. It is only known that they are species with a high genetic plasticity that is still not well known, that they thrive in high humidity sites and that forest management is complex (Huamán et al., 2019b). In this context, Peru, upon reaching 200 years of independence in 2021, attempts to accelerate the race to repopulate the country with *Cinchona*s for being a national symbol of its flora, seeking to comply with the plan and resolutions issued by the government. However, there are already conceptual problems in this plan (Action Plan for Forest Repopulation with species of the genus *Cinchona*) (Albán-Castillo et al. 2020), putting it in danger of failing due to a lack of information on climate-appropriate places for *Cinchona* afforestation and reforestation.

This sum of alerts that threaten the presence of *Cinchona* in Peru, need to be evaluated from historical aspects that allow gathering information to support decisions from a current aspect, and with a view to the future under a context of climate change, allowing effective conservation plans. For this reason, the predictive modeling of the geographic distribution of species using SDMs is an important process that has applications in conservation and reserve planning, ecology, evolution, among others (Peterson and Shaw 2003; Scott et al. 2002). The correlative species distribution models (SDMs), for example, have been used in a wide range of theoretical and practical applications to understand the relationship between species and the environment (Valavi et al. 2022), and these are presented as a management tool for conservation prioritization and planning (Whitehead, Kujala, & Wintle, 2017). The Maximum Entropy Algorithm (MaxEnt) (S. B. Phillips et al. 2006a), it is one of the most widely used SDMs to propose improvements in a structured and transparent process of sustainable natural resource management (S. J. Phillips et al. 2009; Elith and Graham 2009; Robinson et al. 2011), with MaxEnt it is possible to determine potential areas of geographical distribution of species for conservation (Cotrín Sánchez et al., 2020; Rojas Briceño et al., 2020; Cotrín Sánchez et al., 2021), species repopulation (Bravo Verde, Castro Pulido, & Cornejo Tueros, 2022), vulnerable species (Fremout et al. 2020), endemic species (Villasante Benavides et al., 2021) among others (Hailu et al. 2017; Yue, Zhang, and Shang 2019).

Due to the applications of MaxEnt on the potential distribution of species, already mentioned above in Peru, this SDM was selected for this research. For these reasons, our study aimed i) mapping old maps to generate georeferenced historical world maps for the species of the genus *Cinchona*, compiling information from internet bibliographic databases, museums, and Peruvian and international herbaria; ii) to identify potentially climatically suitable places for the current distribution of *Cinchona* using MaxEnt in Peru; and iii) to establish priority areas for conservation and restoration with *Cinchona* spp. according to the PNAs and degraded areas within Peru. The results of this research can spur a rethinking, under a new approach, of the decision-making of the National Plan of Action for Reforestation with Species of the Genus *Cinchona* and other plans or tools for *cinchona* conservation.

2. Materials and methods

2.1. Study area

Peru is a South American country located on the Pacific Coast (0°02′, 18°20′ south and 68°30′, 81°25′ west) and covers an area of 1 285 215 km² (Fig. 1). Currently, Peru is divided into 15 ecoregions (Britto 2017) and has 38 climates (SENAMHI 2020). The most extensive climates are arid and temperate on the coast, rainy and cold in the mountains, and very rainy and warm in the jungle. The high elevation gradient (from sea level to 6 768 masl. in Mount Huascarán) and the physiographic complexity of the Andes Mountain Range influence the air circulation and the climate overall (Emck et al. 2006; Young 2011).

2.2. Methodological process for the historical world mapping and current distribution in Peru of *Cinchona* spp.

In Fig. 2, the methodological process of this research is described. It is divided into three parts. The first part corresponds to the elaboration of the database for the presence of the genus *Cinchona* for Peru and globally. The second part corresponds to the modeling of the *Cinchona* genus under current climate conditions using the MaxEnt Software for Peru, as well as the statistical analyses used to obtain this map. Finally, the third part analyzes the potential distribution map of the *Cinchona* genus in areas for restoration and natural protected areas for Peru.

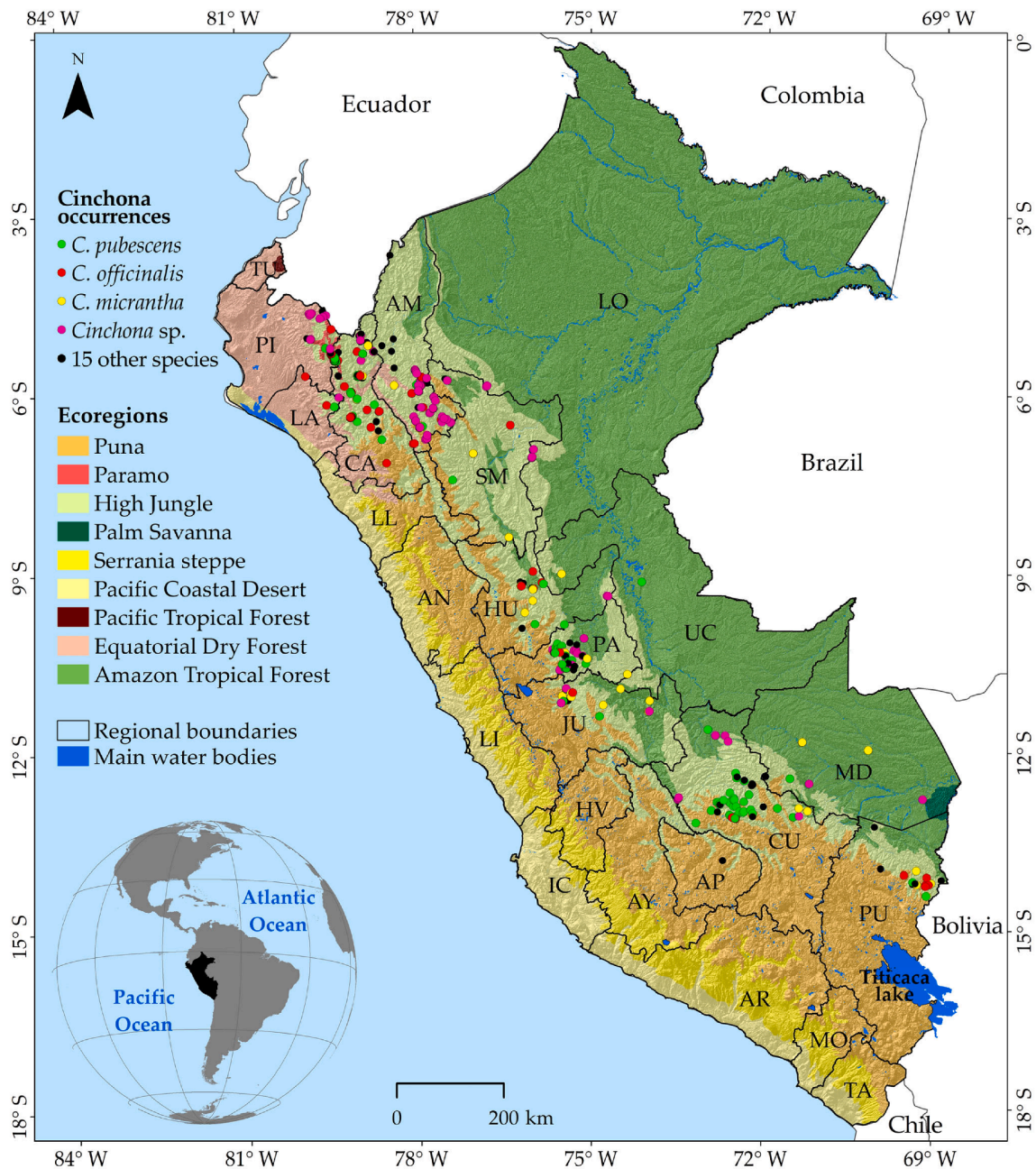


Fig. 1. Ecoregions and Regions of Peru using the abbreviations suggested by Brako and Zarucchi (León, Pitman, & Roque, 2006): AM (Amazonas), AN (Ancash), AP (Apuhímac), AR (Arequipa), AY (Ayacucho), CA (Cajamarca), CU (Cusco), HU (Huánuco), HV (Huancavelica), IC (Ica), JU (Junín), LA (Lambayeque), LL (La Libertad), LI (Lima), LO (Loreto), MD (Madre de Dios), MO (Moquegua), PA (Pasco), PI (Piura), PU (Puno), SM (San Martín), TA (Tacna), TU (Tumbes), and UC (Ucayali). Georeference colors of species of the genus *Cinchona* used in the modeling: green dots are *C. pubescens*; red dots are *C. officinalis*; yellow dots are *C. micrantha*, lilac dots are *Cinchona* sp.; black dots correspond to other species of the genus *Cinchona*. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

2.3. Development of georeferenced historical maps

For each species of the genus *Cinchona*, the history of its collection was reconstructed. Digital information was collected from specimens deposited in Peruvian and foreign herbaria, from taxonomic literature, from databases that gather information from collections, and from scientific articles with georeferenced records. The main web portal consulted was the Global Biodiversity Information Facility (GBIF, <https://www.gbif.org/https://doi.org/10.15468/dl.58c8rd>; accessed on 29 December 2020), which is validated and complemented with other web sources (Appendix). The data collected were verified for compliance with international nomenclatural standards and to record the

original historical descriptions of the species of the genus *Cinchona*. Subsequently, their spatial data were extracted for the modeling of this genus.

A table of 27 fields (e.g., reference source, continent, country, region, locality, species, date of collection, collector, altitude, plant status, view from the database in Data Availability Statement, available at [10.6084/m9.figshare.14246327.v6](https://figshare.14246327.v6)) was constructed to collect the information and was filled out as completely as possible. We sought to represent the greatest amount of data on the distribution of species of the genus *Cinchona*. From this database, maps of historical georeferences were generated for each centenary since the first identified collection in the mountain of Caxanuma, Loja Province, Ecuador, this collection (lat.

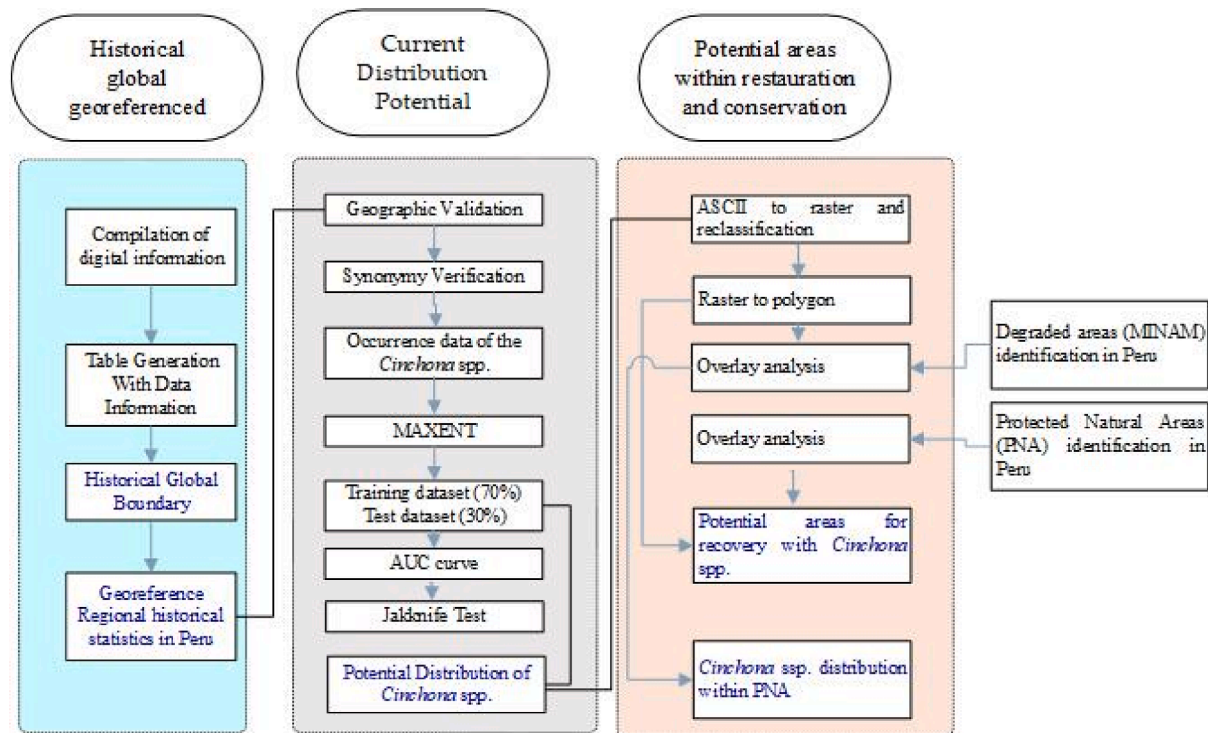


Fig. 2. Methodological process for the Historical world mapping and current distribution in Peru of *Cinchona* spp.

–4.08, long. –79.19), was described by Condamine (de La Condamine, 1738) in 1737 at the locality level while participating in the French Geodetic Commission to measure the length of a degree of terrestrial meridian near Ecuador as were historical graphs of collections worldwide, of regions in Peru, of species, and of the years of records worldwide. Additionally, 77 records with georeferences were described from 1737 to 1799 (Fig. 4a), where Ruiz & Pavon (Ruiz and Pavon 1957) recorded collections at the level of 37 new species inhabiting a specific study area, taking two points as centroids: a) lat. –9.18, long. –74.14; and b) lat. –1.46, long. –78.18), in the year 1778 (Fig. 3). Data were even recorded if they were only identified at the genus level based on data of the relative abundance of georeferenced and total occurrences recorded (e.g., including occurrences without geospatial data) (Ireland and Kriticos 2019). The information table was filled out in an Excel (version 19.0) spreadsheet with the support of the bibliographic manager Mendeley version 2021. The historical graphs of collections worldwide, regions in Peru, species, and record years were made in SPSS version 20.

The political divisions of the countries were verified at different scales such as departmental and provincial (Adm1 and Adm2) in geo-Boundaries (Runfola et al. 2020) as well as in national entities for the national cartography of Peru, such as the National Geographic Institute (IGN) (<http://www.ign.gob.pe/>; accessed on 12 December 2021) to understand the historical changes in political boundaries (León et al., 2006). A few records were excluded from the list for being presented in locations of known geographic conflicts that currently correspond to other countries or subnational areas. We also exclude historical records that refer to species of the genus *Cinchona*, but these are of the genus *Ladenbergia* according to Andersson's (1984) reclassification (Andersson 1998a). In cases where the latitude and longitude coordinates were not accurate for *Cinchona* occurrence, the distribution field within the excel table was left empty (García et al. 2015; Stropp et al. 2016). In addition, georeferenced records for *Cinchonas* that were not georeferenced in natural habitat conditions were excluded. For example, there are *Cinchona* species that were collected from markets as dried plant parts, i.e., there are ethnobotanical researchers who also record plant parts

such as stem bark or leaves with a medicinal approach and assign spatial data to the markets but not to the place of origin of these plants. The final database was imported into the ArcGIS version 10.7 software, where the geo-references collected for each species were located in the fields of national and sub-national divisions (regions and provinces) (García et al. 2015); then, the standardization of localities and the process of geographic validation of the georeferenced data set were performed according to a reference guide for biological collections (Escobar et al. 2016) i.e. we reviewed whether the assigned coordinates were within the limits of the political-administrative division described, together with the locality (country, region or province, and finally at the level of latitude and longitude for the occurrence of *Cinchonas*).

2.4. Development of current maps of potential distribution

In this study, in addition to historical records, potentially climatically suitable places with a high likelihood of occurrence and the current distribution of the genus *Cinchona* were analyzed. Therefore, the MaxEnt Model was used for its maximum entropy basis, that is, from a set of environmental data and occurrence data of a species, the model estimates a probability distribution of the suitability of the conditions for the species (S. B. Phillips et al. 2006a).

Records of historical occurrences worldwide for the genus *Cinchona* were made following the recommendations of the Reference Guide for Biological Collections (Escobar et al. 2016). The maps with all records have the following coordinate system of WGS 1984 (Beck et al., 2018). Duplicate presence records were removed and to avoid spatial/environmental pseudo-replication, an automatic cross validation of climate data and presence records was performed using the MaxEnt program.

Out of a total of 10 086 historical references found, 735 georeferences were used for the modeling process. These georeferences were obtained after precision filtering for validation of the period of data records with respect to the period of climatic data (view the database in Data Availability Statement). This stipulates that the time frame or period of data collection on species occurrence should be more or less similar to the time scale of the environmental variables. (S. B. Phillips

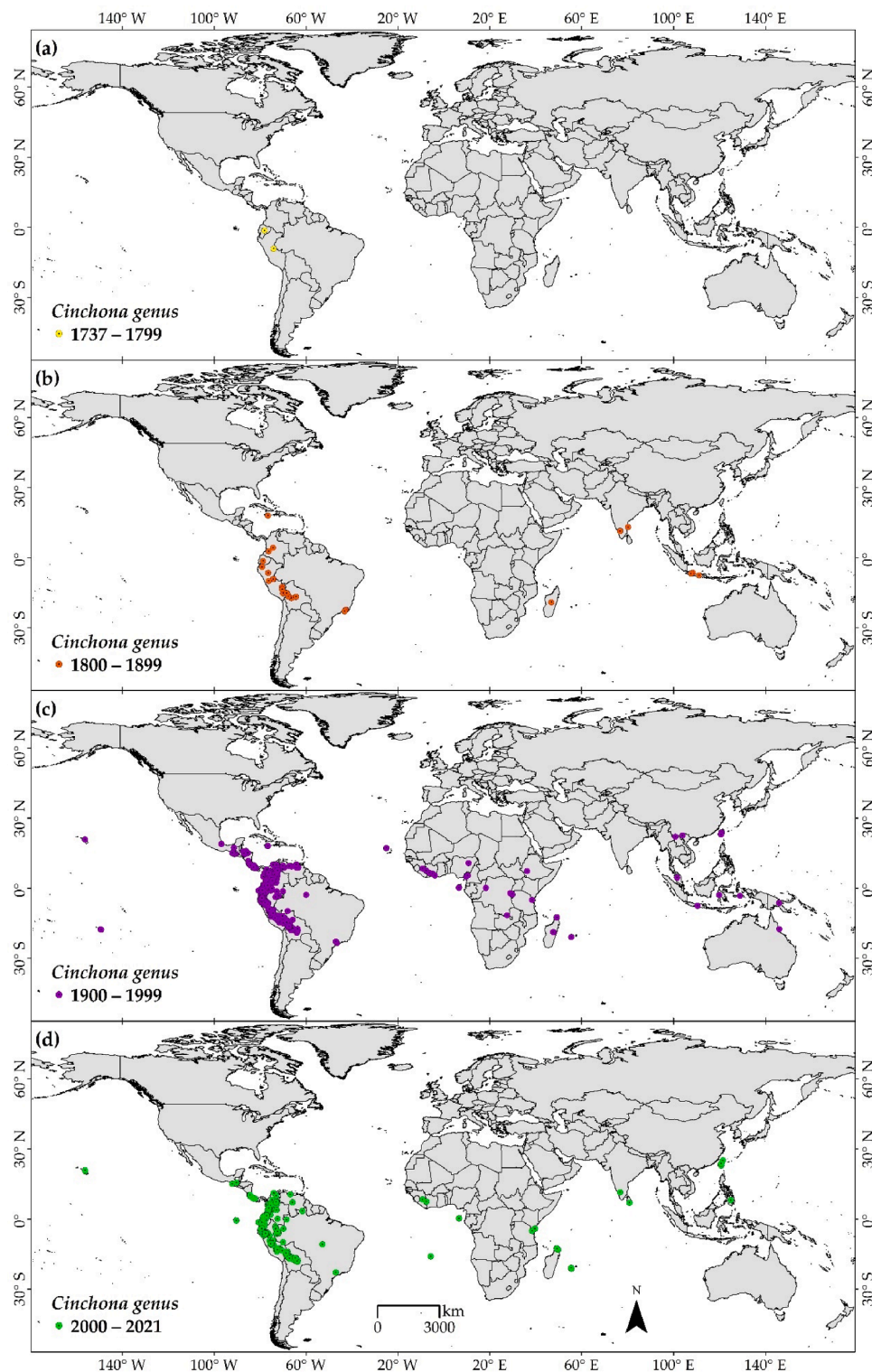


Fig. 3. World historical georeference records for *Cinchona* spp. from 1737 to 2021.

et al. 2006b). Peru has 18 species of this genus which were also used for the validation of the model results according to the data of these 735 cinchona georeferences which is consistent with the publication of Aymard in 2019 (Aymard 2019). The MaxEnt software version 3.4.1 was chosen to model this genus *Cinchona* because it presented an AUC of 0.97 over the Bioclim AUC of 0.72, this analysis was performed using the R package called SDM version 1.1–8 (Naimi and Araújo 2016). From all the georeferences (See the Figshare), 70 % were randomly put into the

validation set, and 30 % were used for model training (S. J. Phillips and Dudík 2008) with 10 replicates put through 500 iterations, with different random partitions, a convergence threshold of 0.00001, and a maximum background of 10 000 points (Elith et al. 2006).

The potential distribution areas were obtained using 10 bioclimatic variables **bio2**: Mean Diurnal Range (Mean of monthly (max temp - min temp)), **bio3**: Isothermality (BIO2/BIO7) ($\times 100$), **bio4**: Temperature Seasonality (standard deviation $\times 100$), **bio9**: Mean Temperature of

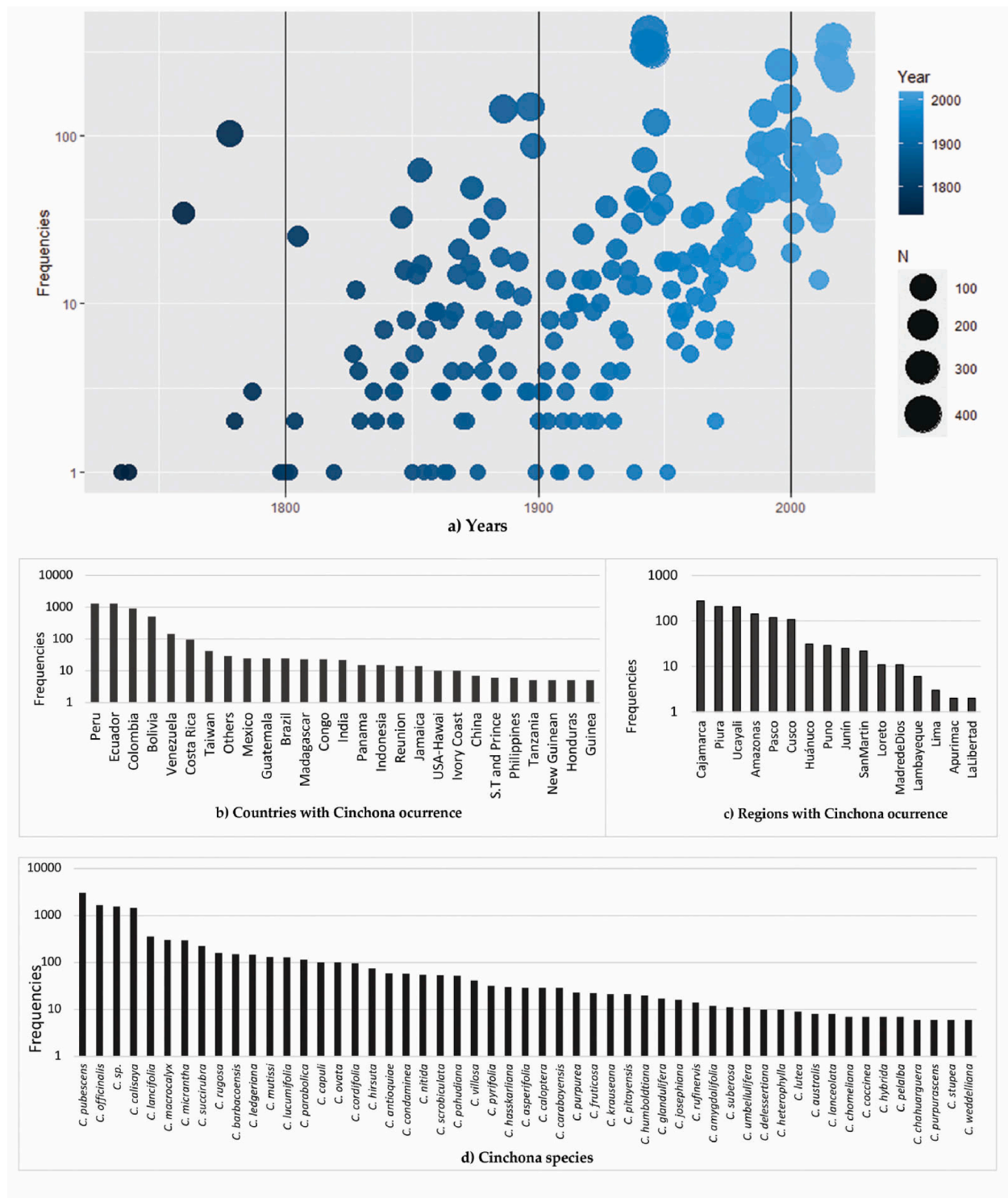


Fig. 4. a) World historical frequency of geographical references for the genus *Cinchona*. Historical records of geographical references classified by b) representative country, c) regional jurisdiction in Peru, and d) historical nomenclature of species of the genus *Cinchona*.

Driest Quarter, **bio13**: Precipitation of Wettest Month, **bio14**: Precipitation of Driest Month, **bio15**: Precipitation Seasonality (Coefficient of Variation), **bio18**: Precipitation of Warmest Quarter, **bio19**: Precipitation of Coldest Quarter, **elevation** of 20 bioclimatic variables from the WorldClim database (version 2.1) (www.worldclim.org/bioclim.htm; accessed on 22 February 2021) after performing a collinearity analysis in the R program version 4.1.3. For the collinearity analysis, VIF (Variance Inflation Factor) was used, and 10 variables were discarded. A

VIF > 10 is a signal that the model has a collinearity problem (Naimi and Araújo 2016), the spatial resolution of the bioclimatic data used is 1 km.

The output map of probabilities (from 0 to 1) of *Cinchona* occurrence was classified into four levels of habitat potential (no potential: < 0.2; low: 0.21–0.40; moderate: 0.41–0.60; and high: > 0.60) (Rojas Briceño et al., 2020), where each range can be considered by decision makers to according to the climatic needs for the afforestation/reforestation of the genus *Cinchona*.

2.5. Identification of priority areas for the conservation of *Cinchona* and restoration of degraded areas

In the potential distribution map obtained for the *Cinchona*, a cartographic superposition with the Peruvian PNAs was performed. The PNA shapefile was obtained from the SERNANP geoserver (The National Service of Natural Areas Protected by the State) (<https://geo.sernanp.gob.pe/visorsernanp/>; accessed on 5 January 2021). The crossed matrices

identified the size of the priority areas for the conservation of diversity of *Cinchona* using the same four levels as the classification of the model. The modeling map was also superimposed onto the National Map of Degraded Areas, obtained from the MINAM geoserver (Ministry of Environment) (<https://geoservidor.minam.gob.pe/recursos/intercambio-dedatos/>; accessed on 03 January 2022). In this way, we identified the size of the areas that could be considered priorities for restoration through afforestation/reforestation and that complied with

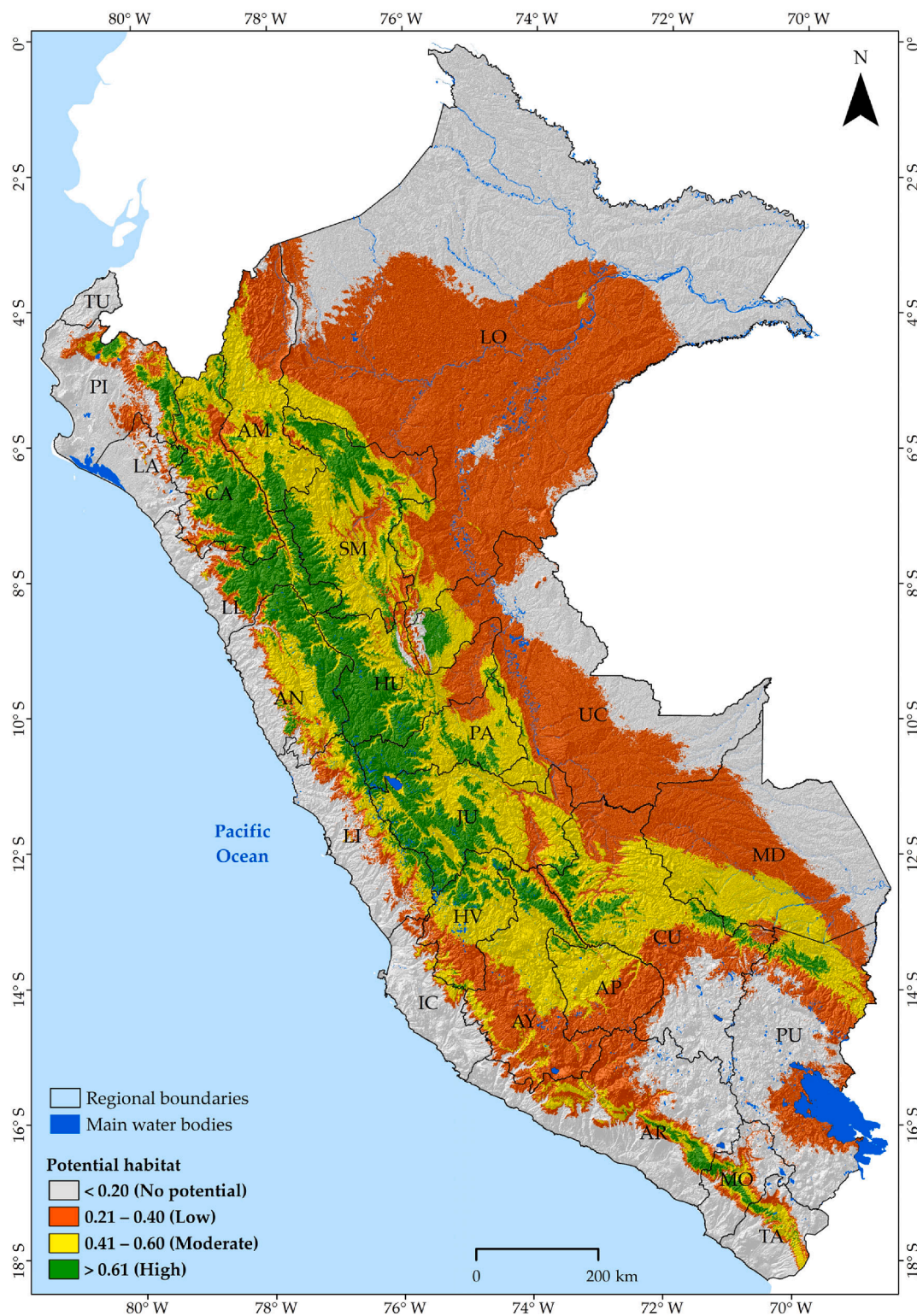


Fig. 5. Probability of occurrence of *Cinchona* spp. in Peru according to the biogeographic model.

the Action Plan for Reforestation with Species of the Genus *Cinchona*.

3. Results

3.1. Historical global maps of the geographical distribution of *Cinchona* spp.

The first historical geographic reference recorded for the genus *Cinchona* was in the Caxanuma Mountain in 1735 but this record was published in 1737 (Loja Province, Ecuador), which still has the same name (Fig. 3) (Eras et al. 2019). The historical georeferences increased notably from 1800 to 1999; with 1 113 and 1 942 specimens, respectively (Figs. 3 and 4a). Between 1800 and 1899, georeferences covered not only Andean countries (Peru, Ecuador, Colombia, Bolivia) but also included introduced specimens in Jamaica, Madagascar, India, and Indonesia (Crawford 2016). The country with the most *Cinchona*s records in these years was India between 1900 and 1999, it presented the largest number of geographic references without increasing the number of georeferenced countries. Colombia reached the highest number of geographical references from 2000 to 2021 reached 2 439 records, mostly located in the Andean region.

The years 1944 and 2017 are especially relevant. In 1944, Karst and de Ruiz and Pavon referenced 407 232 specimens (Andersson and Taylor 1994). In 2017; the collection of 370 specimens of *Cinchona officinalis* in Malacatos, Loja, Ecuador (Eras et al. 2019) where “*Cinchona* was first identified at the genus level in 1735” stands out. In the timeline, the Andean countries led the collections of this genus. Out of a total of 41 countries with *Cinchona* spp. occurrences, Peru and Ecuador had the most (Fig. 4b). In Peru, *Cinchona* is georeferenced in 16 of the 24 regions (Fig. 4c), with the Cajamarca region leading. Historically, a total of 53 names were put under the genus *Cinchona* (Fig. 4d).

3.2. Potential climatic sites for the current distribution of *Cinchona* spp. In Peru

3.2.1. Behavior of the model (AUC) and bioclimatic variables

The performance of the model obtained an AUC = 0.977 for the training data and an AUC = 0.975 for the test data (Fig. 5), putting it in the range of very good in both cases (AUC > 0.90) (Hirzel et al. 2006).

The variables Bio 04 (Temperature Seasonality: standard deviation $\times$ 100), elevation (masl), Bio 03 (Isothermality (Bio 1/Bio 7) $\times$ 100), and Bio 14 (Precipitation of Driest Month) most effectively predicted the potential distribution of *Cinchona* spp. in Peru. Bio 04, elevation, and Bio 03 made a total relative contribution of 86.2 %, Bio 04 being the most prominent, with a 53.4 % contribution (Table 1). The potential distribution of *Cinchona* decreased in areas with great differences between summer and winter temperatures (temperature seasonality up to 312.04 standard deviation index $\times$ 100) (Xu et al. 2013). The response curves for the variables and jackknife test of variable importance are in Figure S1.

Table 1

Estimation of the relative contributions and descriptive values of the bioclimatic variables used in the MaxEnt modeling of *Cinchona* spp. in Peru.

Variable	Variable	Percent contribution	Min	Max	Mean	SD
Bio 04	Temperature Seasonality (standard deviation $\times$ 100)	53.40	9.49	312.04	85.15	59.97
Elevation	SRTM elevation data	21.90	-64	6551	1490	1631
Bio 03	Isothermality (Bio2/Bio7) ($\times$ 100)	10.90	42.03	92.69	79.64	7.38
Bio 14	Precipitation of Driest Month (mm)	6.10	0.00	295.00	64.81	65.22
Bio 2	Mean Diurnal Range (Mean of monthly (max temp - min temp))	3.70	4.77	19.5	11.71	2.24
Bio 19	Precipitation of Coldest Quarter	2.50	0	1697	250.41	255.95
Bio 15	Precipitation Seasonality (Coefficient of Variation)	0.70	0.00	226.14	57.30	38.98
Bio 13	Precipitation of Wettest Month (mm)	0.40	00.00	973.00	208.78	110.10
Bio 09	Mean Temperature of Driest Quarter	0.20	-42.22	33.67	1.38	19.61
Bio18	Precipitation of Warmest Quarter (mm)	0.10	0.00	2169	464.06	249.11

3.2.2. Potential climatic areas for the potential distribution of the genus *Cinchona*

There were high probabilities of potential distribution of *Cinchona* spp. in 10.30 % (133 172.56 km²) of the Peruvian territory; 19.20 % (247 371.32 km²) of the country was moderate-level areas, while 34.40 % (442 940.48 km²) was areas with a low potential distribution (Fig. 5). Habitats with the high potential distribution were found to a greater extent in the regions of Huánuco, San Martín, and Junín, with 47.60 % (17 718.96 km²), 33.0 % (16 813.68 km²) and 36.3 % (15 953.46 km²) of their respective territories (Table S1).

Also, Fig. 5 shows the probability of occurrence of the genus *Cinchona* at the regional level in Peru. Of the national territory, 36.10 % (465 079.66 km²) had no probability of occurrence of the cinchona tree.

3.3. Priority sites for the Action Plan for forest repopulation with species of the genus *Cinchona* for its conservation and restoration

Of the PNA territory, 22.00 % (50 153.73 km²) and 7,6 % (17 305.32 km²) corresponded to habitat areas of moderate and high potential, respectively (Fig. 6a, Table 2). This meant that 29.60 % of the PNA territory had priority areas that could be considered potential ecological niches for the preservation, care, safeguarding, and protection of the diversity of *Cinchona*s in fifteen regions of the country. The regions of San Martín (5 179.57 km²) and Pasco (2 269.80 km²) were the largest, with high potential distribution areas. Also, high level extensions of potential *Cinchona* habitat in the regions of Junín (1 995.61 km²), Cusco (1 358.00 km²), and Ancash (1 088.92 km²) (Table S2) were important. There were also DAs with moderate and high probability of occurrence of *Cinchona* corresponding in 82 527.92 km² of the territory. For example, 33.20 % (60 789.17 km²) of the territory was found at the moderate level, and 11.90 % (21 738.75 km²) of the degraded territory was classified as high-level (Fig. 6b, Table 2). The regions with the largest areas of high habitat potential for *Cinchona* within degraded areas were San Martín (7 157.78 km²), Cusco (2 674.16 km²), and Huánuco (2 479.70 km²) (Table S3).

4. Discussion

4.1. Historical occurrences

Effective management of flora at regional and global scales requires studies with a multidimensional approach, including knowledge of non-climatic historical causes, land use change, and socio-economic and political developments (Dale 1997); for instance, migrations from the Old World to the New World since the 8th century as in the case of *Quassia amara* L. (Odonne, Tareau, and van Andel 2021), or the role of potato cultivation for the Old World population and the growth of urbanization during the 18th and 19th centuries (Justin Cook 2014). The case of *Cinchona* spp. regained importance because of a long history of botanical sampling worldwide. We managed to compile information from databases, and historical and contemporary literature, to construct

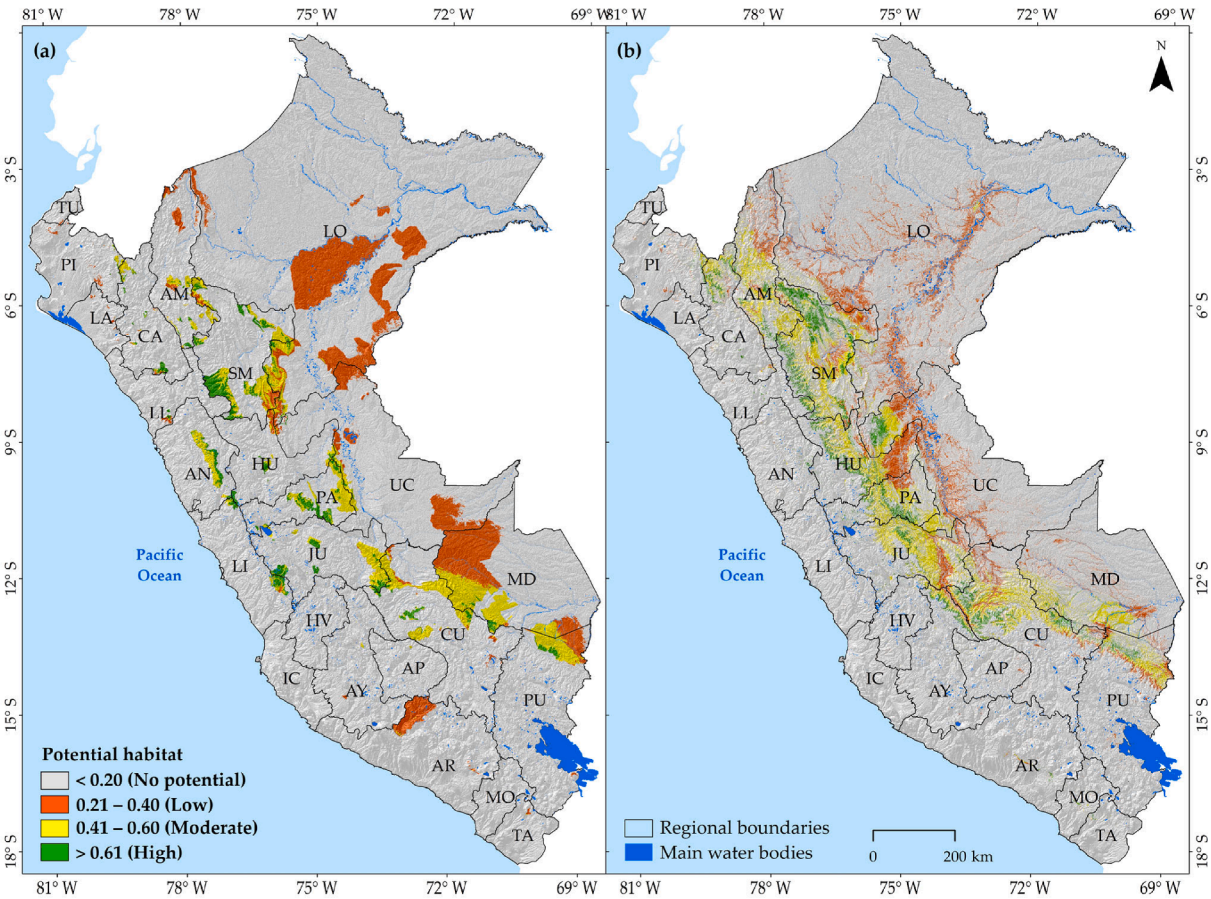


Fig. 6. Probability of occurrence of *Cinchona* spp. in Peru, a) within PNAs for conservation and b) within DAs for restoration.

Table 2
Potential Biogeographical Distribution Levels for *Cinchona* spp. in Peru, according to a biogeographic model, within PNAs for conservation and DAs for restoration.

	Extension Potential (km ²)	No potential		Low		Moderated		High	
		km ²	%	km ²	%	km ²	%	km ²	%
Peru	1 288 564.02	465 079.66	36.1	442 940.48	34.4	247 371.32	19.2	133 172.56	10.3
PNA	227 835.77	75 764.08	33.3	84 612.64	37.1	50 153.73	22.0	17 305.32	7.6
DA	183 288.15	37 114.76	20.2	63 645.47	34.7	60 789.17	33.2	21 738.75	11.9

for the first time in a consolidated manner, historical maps from 1737 to 2020 of the geographic distribution of the cinchona tree worldwide. Occurrences are recorded for historical medicinal, healing properties (Aymard 2019), herbalization and economic aspects. Likewise, using for the first time, information from all possible sources, a complete database is offered to experts, which also serves for future research in paleoecology (de Jesús Hernández-Hernández, Cruz, and Castañeda-Posadas 2020), cultural biogeography (Odonne, Tareau, and van Andel 2021), as well as other purposes (Stropp et al. 2016) for this genus. Thanks to this data, important information came to light from the early 16th century, when Jesuits arriving in America were interested in the bark of the cinchona tree for medicinal purposes (Ferreira Júnior et al. 2012). The records coincide with the area called the health axis, on the map of the Andean world that extends from Ecuador to Bolivia (Ramírez 1996) and were first recorded in the eighth century (Fig. 3a).

The growth of records in the 19th century, presented in this study, was due to data showing the demand for the bark of the cinchona tree, whose exports to Europe reached half a million kilograms of bark per year (Roersch and Pieters 2015), and for the three cinchona booms in

Colombia (Sandoval and Echandía 1986). In 1804 and 1805 there was a focus on the use for herbalism in southern Ecuador and northern Peru. In this same century, cinchona plantations were installed in Indonesia from seeds collected in Bolivia by Weddell (Ferwerda and Wit 1969). By the 19th century, the 1 272 georeferences in 35 countries were marked by events such as the Second World War and the increase in malaria cases, which led to imports of Cinchona bark to the USA from Bolivia, Peru, Ecuador, and Colombia (Hodge 1948). In fact, these are the countries with the most historical georeferences in our study (Fig. 3b). We found 1911 georeferences in Africa because in the 19th century, plantations for the export of tree bark were installed to combat malaria in Europe (Hodge 1948; Roersch and Pieters 2015), in addition to medicinal use to combat the 219 million cases of malaria infection across the world, of which 92 % are reported on the African continent (OMS 2018). Regarding the historical records of the species of Cinchona during the 18th and 19th centuries, new species were described by J.C. Mutis (1793), H. Ruiz-López and J.A. Pavon and Jiménez (1799; 1802), and A. von Humboldt and A. Bonpland (1805, 1808) (Andersson, 1998). Later, Lambert (1821), P. de Candolle (1829), and J. Lindley (1938) reported

several species of *Cinchona* (Aymard 2019).

In this sense, thanks to studies of the medicinal importance of the cinchona tree, Andersson (1998), based on pollen morphology, bark morphology, general anatomy of the plant, and cladistics, classified the 330 names collected for cinchona trees into 23 taxonomic species (Andersson, 1998), all mentioned with georeferences in this research (view the database in Data Availability Statement). In 2019, Aymard presented a list of 24 species of the genus *Cinchona* currently accepted based on information from Taylor (Taylor et al. 2004), Delprete & Cortés-Ballén (Taylor et al. 2004), and Ulloa-Ulloa et al. (Ulloa et al. 2017).

4.2. Geographic model of its current potential distribution

The maximum entropy modeling technique, commonly applied to flora and fauna (Alfaya et al. 2019). And although it is very common the use of one large amount of historical data and remote sensing techniques, MaxEnt was used to determine more precisely the priority areas for species conservation and restoration actions (Cotrina et al. 2020). This research is the first time that highly potential zones for the geographic distribution of the genus *Cinchona* in Peru have been determined. The predictive performance of the model (AUC = 0.975) is in the range reported for current conditions for other forest species of Peru, such as those of forests with conservation and restoration priority in the Andean-Amazonian landscape (Rojas et al. 2020).

The first plant geographers were concerned with explaining the distributions of different types of plants in physiological terms (Prentice et al. 1992). However, it was only recently that predictive models have been explicitly derived from physiological considerations (Woodward and Williams 1987) and climatic considerations (S. J. Phillips and Dudík 2008). Also, abiotic variables have a key role in the estimation of the potential niche of the species; in this research, the percentage contribution of abiotic variables to cinchona habitat was measured. The seasonality of mean annual temperatures plays an important role in the suitability of plant habitat and is one of the most important climatic factors for plant distribution together with precipitation (Wang et al. 2021; Gardner, Maclean, and Gaston 2019), this is also shown in our results, where the variable BIO4 (Temperature Seasonality), was the variable that had the highest percentage of influence on habitat modeling for cinchona and those derived from precipitation and temperature such as Bio 03 (isothermality (Bio 1/Bio 7) × 100), and Bio 14 (Precipitation of Driest Month). Isothermality and temperature determine the tolerance of plants in their distribution range (Amissah et al. 2014; Huang et al. 2021; Duque et al. 2021). It should also be noted that almost all plant physiological processes are directly or indirectly affected by water supply (Moeslund et al. 2013; Austin and Van Niel 2011).

Researchers found that the altitudinal movement of ecological niches is due to the impacts of climate change, and that temperature is inversely related to altitude in the Andean region (de Meyer, Ortega-Andrade, and Moulatlet 2022; Rapp et al. 2012; Cuyckens A. E et al. 2016), thus explaining that altitude influences cinchona habitat by 21.90 % in the modeling and these climatic variables (abiotic) (Gardner, Maclean, and Gaston 2019), have a high probability of providing optimal physiological responses of *Cinchona* to climate survival.

The use of predictive modeling of geographic distributions of species in this study, showed that of Peru's 24 regions and one constitutional province, 22 regions had high-probability habitats for the cinchona tree, while the executive directorate resolution (which approves the Action Plan for the Forest Repopulation with Species of the genus *Cinchona*) only includes 10 regions with certain provinces. These regions are Amazonas, Cajamarca, Cusco, Huánuco, Junín, Lambayeque, Lima, Pasco, Piura and Puno. (MINAGRI 2020). Therefore, the areas to be prioritized in the ecosystem service plans should be reviewed according to the identification of the optimal bioclimatic variables, and if necessary, nature conservation areas should be established that cover the

distribution of species modeled here and human intervention should be reduced in these areas (Rojas et al. 2020). This study also shows that, even though the resolution excludes the provinces of Rodríguez de Mendoza and Chachapoyas in the Amazon region, > 90 % of that territory has moderate and very high potential for the distribution of cinchona trees. In the same sense, the identification of potential places of occurrence of *Cinchona* species goes for the collection of seeds and prioritized use of three species of this genus in the aforementioned Resolution (Albán-Castillo et al. 2020).

4.3. Priority areas for conservation and restoration of *Cinchona*

Assessing conservation priorities in protected areas is essential for the effective allocation of limited conservation resources and the optimization of the structure of the territory (Wang et al. 2021). Thus, in Peru, the regions that showed the highest priority in terms of abiotic variables for cinchona conservation within Protected Natural Areas were the regions of San Martín (5 179.57 km²) and Pasco (2 269.80 km²). This would promote the conservation of biological diversity (More, Villegas, and Alzamora 2014). Likewise, there are thirteen more regions in Peru with areas with high potential for the distribution of *Cinchona* (Fig. 6a, Supplementary data S2), and these regions should be taken into account in decision-making, as they are natural geographic spaces that are invaluable and must be set aside for the conservation of its biodiversity (Esenarro et al. 2021).

Approximately 14.3 % of the Peruvian territory is in the range of degraded areas, and given current trends, the Neutrality of Land Degradation (NLD), target 15.3 of the SDG (Sustainable Development Goal) by 2030 could be difficult to achieve (Debonne et al. 2021). Thus, 183 288.8 km² of degraded Peruvian areas show total or partial loss of some of their essential components (water, soil, species), therefore decreasing their ability to provide ecosystem services in the territory (MINAM 2017). As for actionable items, this research shows that 82 527.92 km² of degraded areas can be restored with *Cinchona* in terms of its potential distribution for the moderate and high level in Peru (Fig. 6b). These areas are in 22 regions, of which San Martín (7 157.78 km²) and Cusco (2 674.16 km²) are home to the largest areas with high potential for *Cinchona* distribution (Supplementary data S3).

We proposed that the maps resulting from the potential distribution of *Cinchona*s within PNAs and DAs obtained in the present investigation can be used to reinforce the Action Plan for Forest repopulation with Species of the genus *Cinchona* (*Cinchona* Tree) 2020–2022 in Peru (Albán-Castillo et al. 2020).

Finally, the estimated geographical distribution provides relevant information for repopulating priority areas with cinchona from district, provincial and regional levels in Peru. The proposed National Plan may be applied according to regions where there are moderate and high likelihoods of occurrence of *Cinchona* spp., and which at the same time could be set aside as conservation and restoration areas.

5. Data Availability Statement

The datasets analyzed for this study can be found in the: Historical world mapping and current distribution in Peru of *Cinchona* spp.: Contribution to restoration and conservation strategies https://figshare.com/articles/dataset/Historical_world_mapping_and_current_distribution_of_Cinchona_sp_in_Peru/14246327/6.

Author contributions

Conceptualization, J.V. and L.G.; methodology, J.V., L.G.; software, J.V. and N.B.R.B.; validation, J.V. and L.G.; formal analysis, J.V., L.G. and N.B.R.B.; investigation, J.V. and L.G.; resources, J.V., S.C. and M.O.; data curation, J.V.; writing—original draft preparation, L.G. and N.B.R.B.; writing—review and editing, J.V., L.G. and N.B.R.B.; visualization, L.G. and N.B.R.B.; supervision, J.V., S.C. and M.O.; project administration,

J.V. and M.O.; funding acquisition, J.V., S.C. and M.O. All authors have read and agreed to the published version of the manuscript.”.

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Declaration of Competing Interest

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

Data availability

The data is available in this repository https://figshare.com/articles/dataset/Historical_world_mapping_and_current_distribution_of_Cinchona_sp_in_Peru/14246327/6

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Appendix A

Digital information was collected from specimens deposited in Peruvian and foreign herbaria, from taxonomic literature, from databases that gather information from collections, and from scientific articles with georeferenced records. The main web portal consulted was the Global Biodiversity Information Facility (GBIF, <https://www.gbif.org/>), which is validated and complemented with pages such as the Missouri Botanical Garden (<https://www.missouribotanicalgarden.org/>); the National Museum of Natural History of the Smithsonian Institution (<http://ravenel.si.edu/botany/types/>); the New York Botanical Garden (<https://sciweb.nybg.org/science2/VirtualHerbarium.asp>); the Natural History Museum of London (<http://www.nhm.ac.uk/research-curation/projects/search/results.jsp?details=true&department=1>); the Field Museum of Chicago (<https://fm1.fieid-museum.org/vrrc/>); the Institute of Botany and Botanical Garden, University of Vienna, Austria (<https://www.botanik.univie.ac.at/annonaceae/indices/neotropics/typehome.htm>); CABI (<https://www.cabi.org/dmpp>); and the Royal Botanic Gardens, Kew (<https://www.kew.org/>).

Appendix B. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.jnc.2022.126290>.

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