DISTRIBUTION MODELS AND SPATIAL ANALYSES PROVIDE ROBUST ASSESSMENTS OF CONSERVATION STATUS OF ORCHID SPECIES IN COLOMBIA: THE CASE OF *LEPHANTES MUCRONATA*

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Abstract. Orchidaceae is one of the most threatened families of vascular plants in the world, and in recent years, species distribution models (SDM) have been used as a tool to inform the conservation status of several species. However, the usefulness of SDM depends on appropriate knowledge of the use and limitations of these tools, otherwise there is a risk of getting erroneous models leading to wrong decisions in conservation plannning. We present the distribution model of *Lepanthes mucronata* in South America based on current and accepted knowledge in this discipline. The representativeness of protected areas for Colombia is evaluated, as well as ecosystems where it is present and its risk of extinction based on criteria of the IUCN. After reviewing these parameters, we found that *Lepanthes mucronata* meets the criteria for Least Concern (LC) IUCN status. We expect this investigation to serve as an appropriate example of this type of analysis and as a reference for future work in the conservation of this plant family.

Keywords: biogeography, conservation, MaxEnt, Orchidaceae

Resumen. Orchidaceae es una de las familias de plantas vasculares más amenazadas, y en años recientes se han utilizado modelos de distribución (MDS) como una herramienta para informar el estado de conservación de varias especies. No obstante, la utilidad de los MDS depende de un conocimiento apropiado sobre el uso y limitaciones de estas herramientas, de lo contrario existe el riesgo de obtener modelos erróneos que pueden llevar a malas decisiones en el establecimiento de planes de conservación. Presentamos la modelación de la distribución de *Lepanthes mucronata* en Suramérica con base en el conocimiento actual y aceptado en esta disciplina, donde se evalúa para la especie la representatividad de las áreas protegidas en Colombia, los ecosistemas donde está presente y su riesgo de extinción bajo los criterios de la IUCN, como un ejemplo más adecuado para realizar este tipo de análisis y un aporte que sirva de referencia para futuros trabajos en la conservación de las orquídeas.

Palabras claves: biogeografía, conservación, MaxEnt, Orchidaceae

Species distribution models (SDMs) predict the distribution of a species linking the occurrence records with environmental variables (Peterson and Soberón, 2012). They have been used widely to understand how biotic and abiotic factors limit distributions of species (Graham et al., 2010). In conservation studies, SDM have been used to identify the representativeness of species distributions in currently protected areas (Ortega-Andrade et al., 2015) and suggest new priority areas for conservation (Yan et al., 2018). Furthermore, SDMs have been used to predict biological invasions (Parsa et al., 2015) and to assess the exposure and sensitivity of a species distribution area to climate change (del Rosario and Hernández, 2015). Thus, SDMs are currently one of the primary tools for assessing the spatial conservation of biodiversity (Richardson and Whittaker, 2010; Ladle and Whittaker, 2011; Cox et al., 2016). However, many taxonomic groups still do not have proper distribution assessments in a context that allows the design of suitable conservation plans, and the inclusion or suggestion of potential geographic areas needed for the survival of certain species are going unnoticed. Such is the case of the Orchidaceae family, one of the largest families within vascular plants, with about 880 genera and over 28,000 species, and representing approximately 8% of all vascular flora in the world (Christenhusz and Bying, 2016; Givnish et al., 2016).

Colombia currently has 185 species of orchids in one of the threatened categories, constituting 10% of the Colombian orchid flora (Betancur et al., 2015). In these threatened categories, cultivated genera, such as *Masdevallia* Ruiz & Pav., *Dracula* Luer, and *Anguloa* Ruiz & Pav., are some of the main threatened groups because of

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their well-known distribution, being easily recognized, and importance as horticultural plants (Calderón-Sáenz, 2007). These threatened species lists leave out genera with higher numbers of species, such as the genus *Lepanthes* Sw. with more than 300 species (Bernal et al., 2019), which have minimal collection pressures from commercial growers and hobbyists because of their small flowers and overall size. However, *Lepanthes*'s distribution ranges are restricted to well-preserved forests meeting specific biological requirements, such as high humidity and particular symbiotic relationships (Crain, 2012). Therefore, estimating accurate distribution models is needed to determine or assess new threat categories.

One of the best examples of how SDMs have been used to evaluate the conservation status of species in Colombia is the *Red Book of Birds of Colombia* (Renjifo et al., 2014). This can be considered the first work that evaluated the conservation status of a large number of species using SDMs and IUCN criteria in this country. We believe that it should be a precedent for work done on orchid species, including *Lepanthes* species. Currently, *L. mucronata* Lindl is an endemic and common orchid species of the tropical Andes Hotspot region. This species has a conservation status of Least Concern (LC) according to the IUCN, indicating that the species is quite common in its distribution and has no direct threats at present. However, there are no specific data on populations of *L. mucronata*, its commercial use, or, especially, impacts and threats of habitat loss to their populations. Therefore, in this study we assess the conservation status of *L. mucronata* using SDMs as a backbone for conducting posterior spatial conservation analysis, following the methods used in the *Red Book of Birds of Colombia*. We had four major objectives: (1) estimate *L. mucronata* distribution using multiple model algorithms, (2) provide an assessment of how well this distribution is represented in protected areas in Colombia, (3) record the ecosystems where it occurs and the amount of habitat lost; and (4) assess the risk of extinction of *L. mucronata* following IUCN criteria. With this study of *L. mucronata*, we expect to provide a baseline for future orchid conservation studies of species with similarly limited information using distribution models and posterior spatial analyses.

Materials and Methods

Case Study: Lepanthes mucronata Lindl. (Fig. 1)

Lepanthes mucronata is one of the most common species within the genus distributed in South America. This species has wide floral and vegetative variation; from small to large plants, leaves varying from ovate to acuminate or even linear, flowers 4–6 mm in length, varying in shape of the margins of upper lobe of the petals, from truncated to erose. The species has a very consistent and distinctive lip, with a pair of thin, fragile blades overlying a proportionally large, scaphoid appendix (Luer and Thoerle, 2012). It can grow as an epiphyte or lithophyte in humid, high Andean forests and páramos. In Colombia, it is found in 13 departments (from Santander to Putumayo).

Figure 1. *Lepanthes mucronata*. **A**, habit; **B**, flower. Photographs by J. S. Moreno.

Occurrence Data

A total of 159 occurrence records were obtained from herbaria AMES, CAUP, COL, CUVC, FMB, JAUM, and TOLI; along with the W3 TROPICOS database (Missouri Botanical Garden, www.tropicos.org); GBIF (Global Biodiversity Information Facility, www.gbif.org), and KEW (Royal Botanical Gardens, Kew, www.kew.org), and a review of literature (Luer, 1996; Farfán et al., 2003; Viveros and Higgins, 2007; Idárraga-Piedrahita et al., 2011; Luer, 2010; Luer and Thoerle, 2011, 2012; Bernal et al., 2019).

In order to reduce the sampling bias, which can negatively affect the distribution models (Reddy and Davalos, 2003; Peterson et al., 2014; Radosavljevic and Anderson, 2014), spatial filters were applied and 93 records were obtained. The 66 records that were deleted were all within the same 10-km radius. One point was also discarded in Cochabamba, Bolivia, because it did not have exact geographic coordinates and was the only collection record in this area, making its determination questionable.

Environmental Data

Environmental information was obtained from the Worldclim database (www.worldclim.org, Hijmans et al., 2005), which presents 19 bioclimatic variables that summarize annual trends, seasonality, and extreme values of temperature and precipitation. In addition, evapotranspiration and aridity variables obtained from the CGIAR-CSI (Consortium for Spatial Information, http://www.cgiar-csi.org) were used. To avoid overfitting of the model due to co-linearity of climatic variables, six variables were selected that were not strongly correlated (Pearson <0.8) to an approximate resolution of 1 km^2: annual mean temperature (Bio1), mean diurnal range (Bio2), temperature seasonality (Bio4), annual precipitation (Bio12), precipitation seasonality (Bio15), and precipitation of warmest quarter (Bio18).

The modeling area was selected considering the accessible area of species M (diagram by BAM; Barve et al., 2011) over relevant periods of time, in order to include historical aspects related to the distribution of the species, which does not consider species distribution models (SDM). On the basis of records obtained from terrestrial ecoregions of the World Wide Fund for Nature (WWF) and biogeographic regions of endemism (Morrone, 2014; Hazzi et al., 2018), it was hypothesized that the accessible area of *Lepanthes mucronata* is the northern Andes of South America (> 900 m of elevation), between latitude 9°27'N and 13°74'S, and between longitude 80°41'W and 69°26'W. The selection of this area is consistent with the fact that this species is endemic to the Andes and that its elevation range is 900–3800 m.

Distribution Modeling

To make SDM models, the maximum entropy algorithm was used (MaxEnt program version 3.3.3K) (Phillips et al., 2006; Elith et al., 2011), which is considered to be among the best methods when using only occurrence data (Elith et al., 2006). In addition, models were made exploring other algorithms, because implementation of a single algorithm can lead to suboptimal models (Qiao et al., 2015). The following algorithms were used in Openmodeller program version 1.3 (Muñoz et al., 2011): Support Vector Machine (SVM), Euclidean Distance (MinDist), and GARP with the correction of "Best Subsets." All models were made with default settings presented by each algorithm.

The models obtained with the various algorithms were evaluated by the partial ROC (Receiver Operating Characteristic Curve), which estimates the area under the curve (AUC) only in the sectors of the ROC where error of omission is minimal (Peterson et al., 2008). This methodology is a correction of the traditional ROC and allows a more accurate comparison of the performance of different algorithms. For example, MaxEnt tends to have high AUCs in regions of the curve that are not important for the evaluation of the model and therefore can erroneously indicate how much greater one model's performance is than another. The partial ROC was carried out in the "Tool for Partial-ROC" program (Barve, 2008), taking two subsets of data, 70% of presence records to calibrate the models and 30% to validate them. We performed 100 pseudo-replicates with bootstrap and an $E = 10\%$ omission error allowed. To compare the performances of these models, the normality of the data was evaluated with the Shapiro-Wilks test. Because the data did not present a normal distribution ($p<0.05$), a nonparametric Kruskal-Wallis test was performed; these analyses were carried out using Past 3.14 software (Hammer et al., 2001). Finally, the continuous models with highest partial AUC values were assembled into a consensus map, averaging the continuous values of suitability.

Habitat suitability values obtained in the distribution consensus model were converted into binary values of presence and absence (or adequate and not adequate), using the 5th percentile as the threshold value. Basically, the distribution area obtained with this value covers 95% of the presence records of the species, excluding 5% of the records ($E = 5\%$; Peterson et al., 2011), which we assumed are in atypical areas or those of low habitat suitability for the species. The maps were edited in ArcMaP version 10.3 (ESRI, 2015).

Representativeness of the National System of Protected Areas and Ecosystems

After obtaining the final model of the distribution of *Lepanthes mucronata*, the representativeness of the species in the National System of Protected Areas of Colombia (SINAP, 2014; http://sinap.parquesnacionales.gov.co) and the percentage of the species' distribution represented was evaluated in each of the following categories: National Natural Parks, National Protective Forest Reserves, Regional Integrated Management Districts, Regional Natural Parks, Regional Protective Forest Reserves, Natural Reserves of Civil Society, Soil Conservation Districts, and Recreation Areas. This calculation was made with a resolution of 0.0083 degrees, which is equivalent to ~ 1 km^2. To evaluate the availability of ecosystems, the methodology of Ortega-Andrade et al. (2015) was applied.

The areas of the ecosystems within the distribution model were calculated and organized in descending order by their size, and then the Importance Factor was calculated (FI = [area of the ecosystem predicted by the model × 100] / total area of the suitability model).

To evaluate habitat loss of the species, we used the methodology proposed by Ortega-Andrade et al. (2015) and Figueroa et al. (2016). A map with anthropic coverage from 2012 obtained from SIAC (www.siac.gov.co), with a resolution of 30 m, was superimposed on the distribution model of *Lepanthes mucronata*. Subsequently, the types of coverage suitable for the presence of viable populations of the species that were found in the distribution model were selected. The coverage types "forest" and "forest and semi-natural areas" (the latter category being conserved areas that have had some degree of disturbance) were chosen as suitable habitats and the other types of coverage were excluded, such as human settlements, urban centers, livestock, and agricultural areas. Finally, the modeling map of *Lepanthes mucronata* without anthropic influence was labeled "historical distribution," and the map with anthropic influence was labeled "current distribution or "remnant habitat of the species." These analyses were done with software ArcGIS version 10.3.

Risk of Extinction

To evaluate the extinction risk for *Lepanthes mucronata*, the categories and criteria of the IUCN red lists (2016) were used, which are based on population sizes, geographical distribution, and reduction of one or both variables. The IUCN system allows the uncertainty associated with these measurements to be considered, while providing an objective method of categorizing risk of extinction of even diverse biological groups (Collen et al., 2016). Here we present a description of criteria A and B, since they usually generate confusion in their correct application. We suggest the revision of the *Red Book of Birds of Colombia* (Renjifo et al., 2014) as an example of how to use these criteria correctly.

Criterion A: Reduction in population size. As population information is scarce for most species, the loss of vegetative cover in a given period can be used to obtain estimates of population reduction rates in the same period (Buchanan et al., 2008; Tracewski et al., 2016). For example, a 20% coverage loss rate can be interpreted as a 20% reduction in populations. Better estimates can be obtained if more associated information is known. The minimum threshold for a species to qualify as threatened is a reduction in population size of 30%.

Criterion B: Geographic distribution. Two measurements of geographic distribution are used within this criterion: the extension of presence (EOO, B1) and the occupation area (AOO, B2). EOO is the area contained in the shortest imaginary limits drawn to cover all the sites where a species is found; this area is calculated using a minimum convex polygon using its known, inferred, or projected distribution (IUCN, 2016). Note that the EOO is not the range of the potential species or habitat obtained through an SDM; it is a measure of spatial correlation, based on the observation that zones in proximity are more likely to be exposed to the same risk factors, which can disperse throughout the species' distribution and increase its risk of extinction. The minimum threshold EOO for a species to qualify as threatened is < 20,000 km^2.

In addition to exceeding the thresholds for criteria A or B, at least two of three subcriteria must be met:

(1) Severe fragmentation or threshold of localities of the species.

(2) Continuous decrease observed, estimated, inferred, or projected.

(3) Extreme fluctuations in populations, mature individuals, EOO, or AOO.

Results

Distribution Models of Lepanthes mucronata

The models developed with the four algorithms (MaxEnt, Garp, MinDist, and SVM) indicate that the areas suitable for *Lepanthes mucronata* are Andean and high Andean ecosystems, altitude being primarily the main factor (approximately 1700–4000 m of elevation) (Fig. 2). A reduction in suitable environments for the species toward the southern end of its distribution is indicated, with few adequate areas in northern Peru and no areas further south (however, as mentioned above the species is recorded in Bolivia). On the other hand, the models indicate that part of the Venezuelan Andes is also a suitable environment for this species, although it has not been reported there. The algorithms with the highest AUC radius values were MaxEnt and SVM, with no significant difference between them ($p < 0.05$), but they were significantly different from other algorithms (Fig. 3). Therefore, these two models were chosen to generate the consensus map of the distribution of *Lepanthes mucronata* (Fig. 4).

Representativeness of the System of Protected Areas and Ecosystems

In Colombia, 10.14% of the distribution of *Lepanthes mucronata*, which covers approximately 198,282 km^2, is within various categories of the protected area system (PAS). As expected, the National Natural Parks (Table 1; Fig. 5A) is the category that most represents the distribution of this species, covering 24,820 km^2 (6.33%) of its distribution and 62.40% within all PAS. Other important categories are the Integrated Management Districts and the National Protective Forest Reserves, which together cover 2.40% (9441 km^2) and 23.74% of the PAS. The largest ecosystems in the area (Table 2) were the montane forests of the Magdalena Valley (79,494 km^2, FI = 40.09), the montane forests of the Eastern Cordillera (34,459 km^2, FI = 17.40), the montane forests of the Northwest (28,793 km^2, FI = 14.54), and the montane forests of Valle del Cauca (28,182 km^2, FI = 14.23).

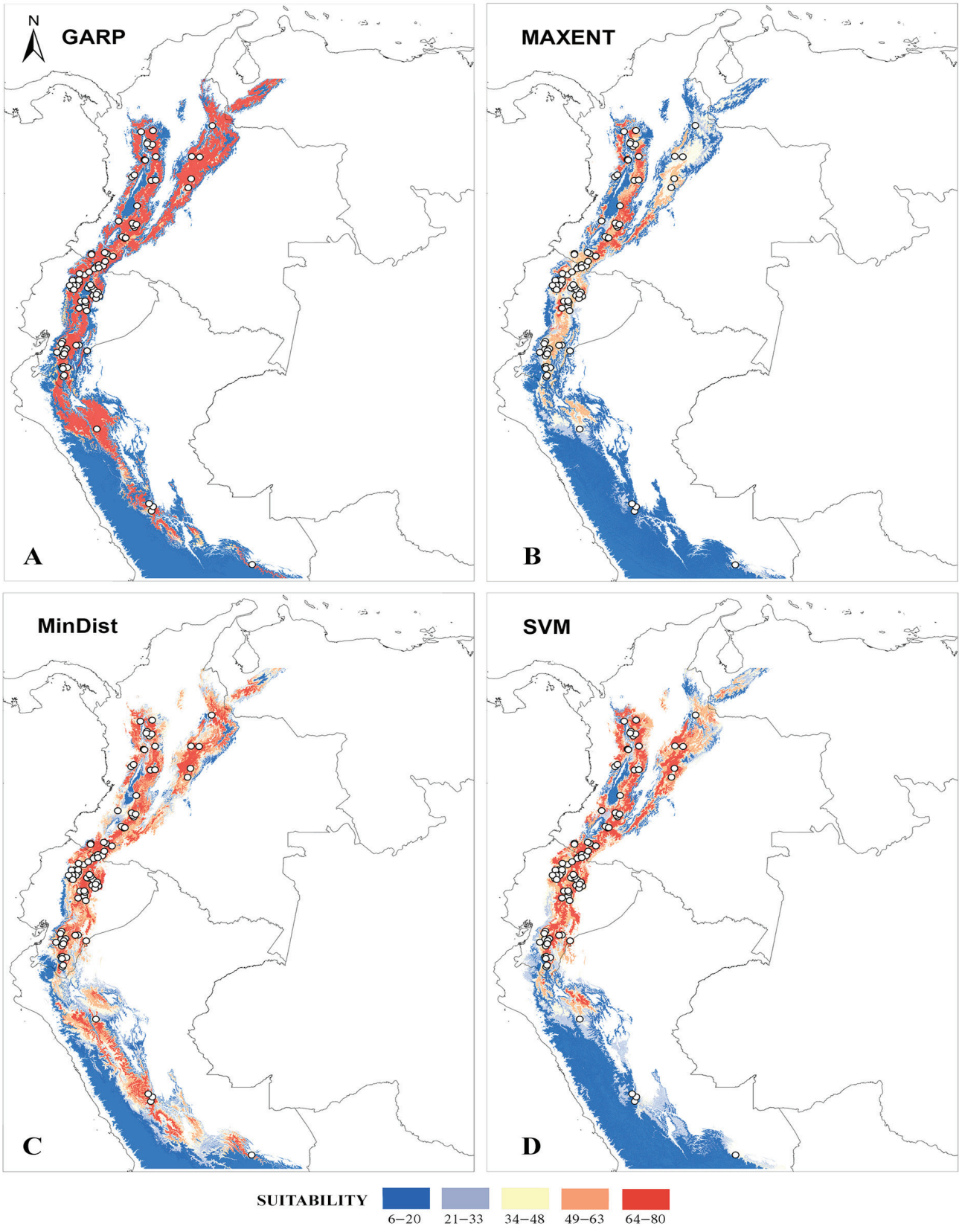

FIGURE 2. Distribution models of *Lepanthes mucronata* obtained with four algorithms in the northern Andes.

Table 1. Representativeness of the National System of Protected Areas of Colombia (SINAP) in the distribution of *Lepanthes mucronata*.

Category	Model area (km2)	Percentage within SINAP (%)	Percentage within distribution (%)
National natural parks	24,820	62.40	6.327
Regional integrated management districts	4826	12.13	1.230
National protective forest reserves	4615	11.60	1.176
Regional natural parks	3846	9.67	0.980
Regional protective forest reserves	1142	2.87	0.291
Soil conservation districts	429	1.08	0.109
Natural Reserves of Civil Society	91	0.23	0.023
Recreation areas	5	0.01	0.001
TOTAL	39,774	100.000	10.139

Table 2. Ecosystem availability (km^2) according to the distribution model (km^2) of *Lepanthes mucronata* in Colombia.

Ecosystem	Available area in Colombia (km2)	Area in the model (km2)	Importance factor (FI%)	Cumulative importance (%)
Montane forests of the Magdalena Valley	90,277.000	79,404.000	40.095	40.095
Montane forests of the Cordillera Oriental	45,312.000	34,459.000	17.400	57.496
Montane forests of the northwestern Andes	36,363.000	28,793.000	14.539	72.034
Montane forests of Valle del Cauca	35,720.000	28,182.000	14.231	86.265
Northern páramo of the Andes	16,615.000	16,077.000	8.118	94.383
Andean montane forests of the Eastern Cordillera	9751.000	9733.000	4.915	99.298
Wet forests of Chocó-Darién	542.000	381.000	0.192	99.49
Dry forests of Valle del Cauca	5098.000	341.000	0.172	99.662
Dry forests of the Magdalena Valley	3298.000	335.000	0.169	99.831
Wet forests of Napo	528.000	208.000	0.105	99.936
Dry forests of Apure and Villavicencio	100.000	100.000	0.050	99.986
Dry forests of the Patía Valley	698.000	22.000	0.011	99.997
Montane forests of the Venezuelan Andes	8.000	2.000	0.001	99.998
Wet forests of Magdalena-Urabá	8.000	1.000	0.001	99.999
TOTAL	24,4318.000	19,8038.000	100.000	100.000

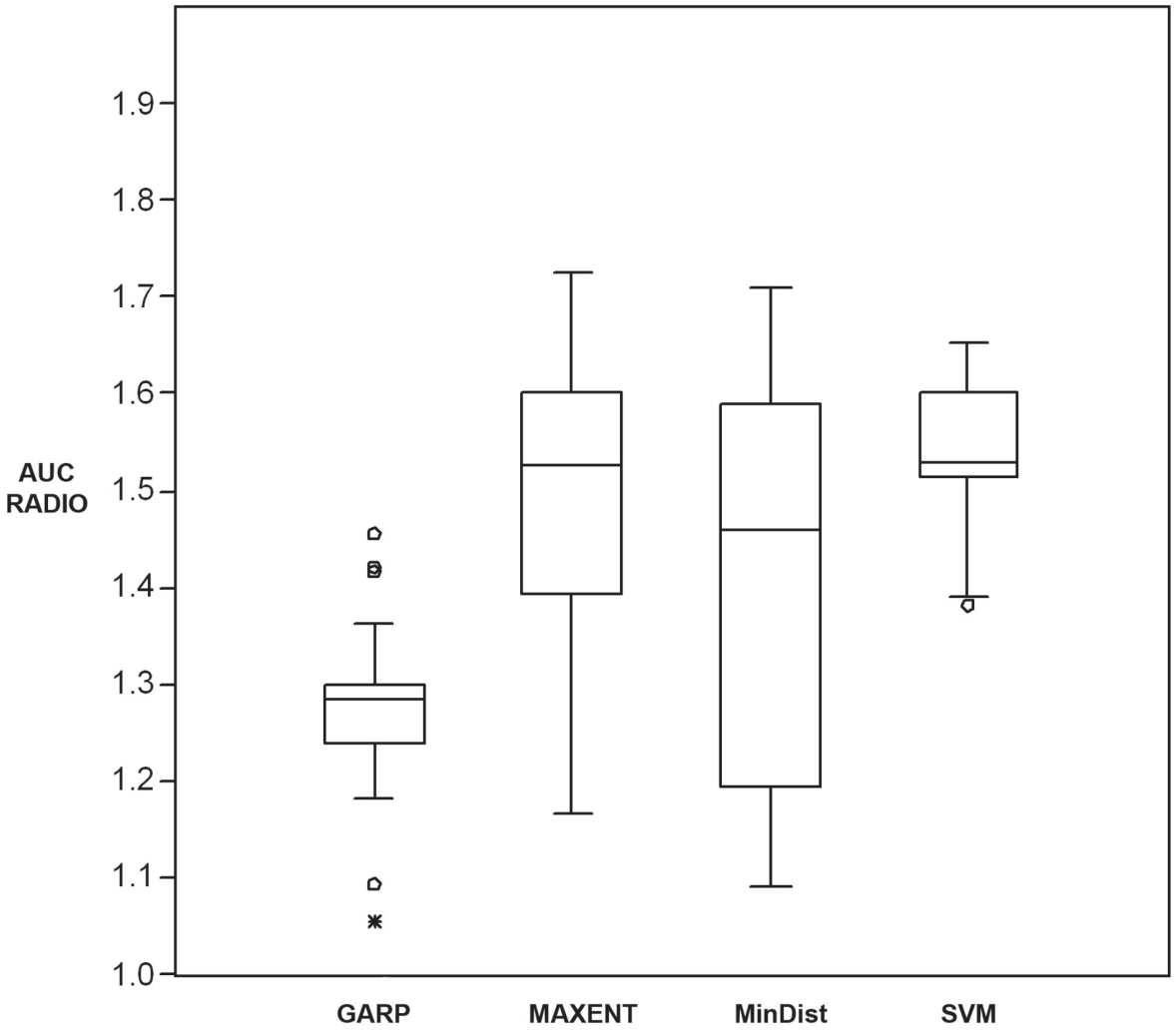

FIGURE 3. Performance of each of the models obtained using four algorithms, through partial ROC.

Risk of Extinction

Criterion A. Anthropic influence analyses (Fig. 5B) indicate that *Lepanthes mucronata* has lost 47% (93,961km^2) of its historical habitat, caused mainly by deforestation and the loss of vegetation cover. This is the result of the high anthropic impacts in the Colombian Andes, where the country's largest population resides (Etter and van Wyngaarden, 2000). However, in recent years there has been a recovery of plant cover in the Andes and a decrease in deforestation rates (Sánchez-Cuervo et al., 2012; IDEAM, 2016). Because of this decrease, and because the species has not had a population decline of more than 30% in the past 10 years or three generations, *Lepanthes mucronata* does not qualify as threatened under Criterion A.

Criterion B. B1. EOO >> 20,000 km^2 for *Lepanthes mucronata*. The geographic area of *L. mucronata* in Colombia far exceeds the threshold for Criteria B1, so the species does not qualify as threatened under this criterion. B2. Estimated area of occupancy = 104,321 km^2> 2000 km^2. Although the AOO must be smaller, it would be well above the threshold; thus the species does not qualify as threatened under Criterion B2.

Subcriterion 1. There is no estimated size of the population, but it is an abundant species with a large remaining habitat area, so the species does not qualify as threatened under Subcriterion 1.

Subcriterion 2. The species does not qualify as threatened under Subcriterion 2, since it does not have a very small or restricted population.

Subcriterion 3. There are not enough data to evaluate the species under this criterion of quantitative analysis.

Conclusion

Lepanthes mucronata does not meet any of the criteria of the categories In Danger, In Critical Danger, Vulnerable, or Near Threatened of the Red List prepared by the IUCN organization (2016). It therefore meets the criteria for a status of Least Concern (LC).

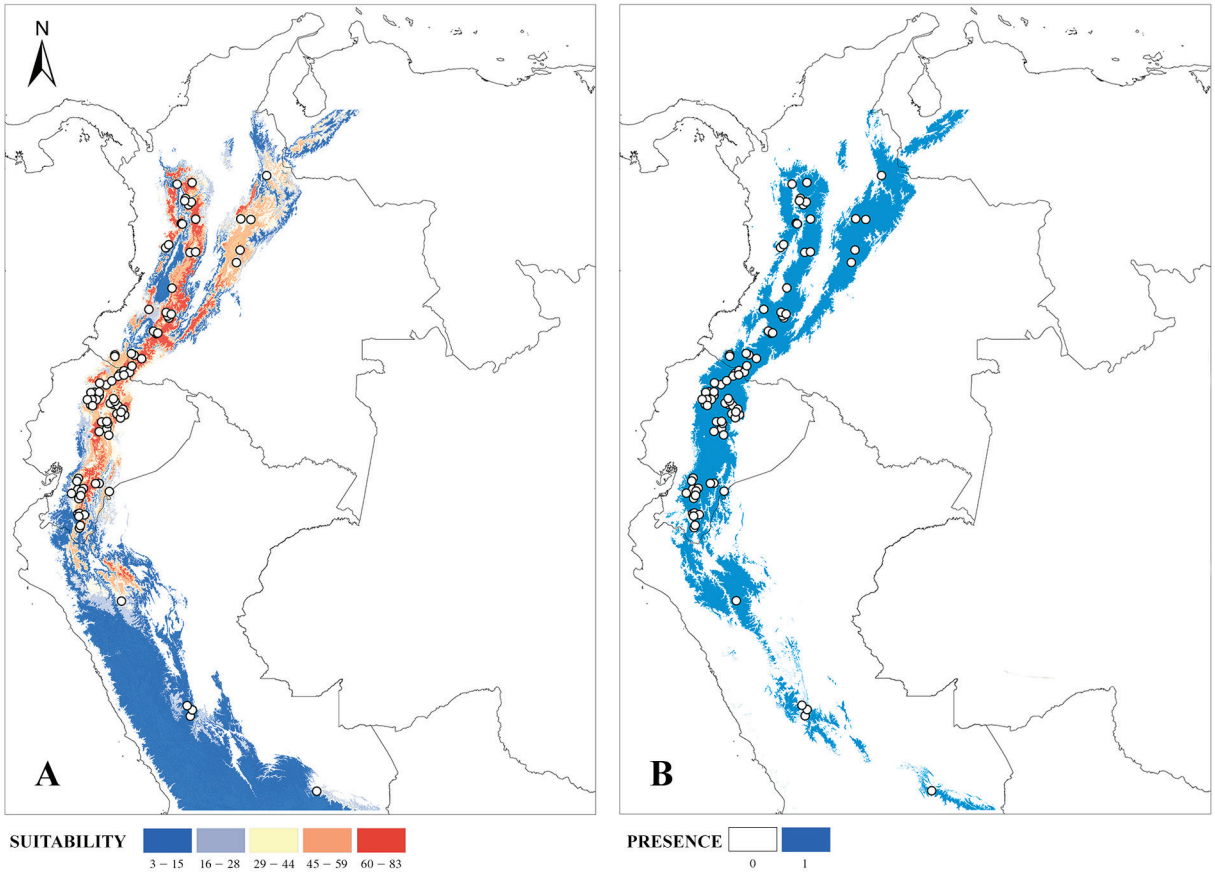

FIGURE 4. Consensus model of the distribution of *Lepanthes mucronata* obtained combining models generated by MaxEnt and SVM. **A**, continuous model; **B**, binary model.

DISCUSSION

The present study integrated SDMs, geographic information systems (GIS), and biogeographic concepts (Richardson and Whittaker, 2010) to estimate the distribution and assess the conservation status of *Lepanthes mucronata*. In our model, we found that the species is present mainly in the Andean and high Andean cloud forests of Colombia and Ecuador. It has a low climatic suitability in Peru, and its distribution area decreases toward the south of Peru. These results are consistent with studies that show that the diversity of *Lepanthes* is much lower in Peru and in the southern Andes (Luer and Thorle, 2012; Crain and Tremblay, 2014). The genus *Lepanthes* is little known in Peru and Bolivia and has been in taxonomic oblivion for decades (Luer, 2010; Damian and Larsen, 2017). At the present time, Peru and Bolivia have 55–63 and 67 known species of *Lepanthes*, respectively, of which the majority are endemic (Luer, 2010; Damian and Larsen, 2017). In these countries the species are distributed mainly in the narrow strip of humid forest that stretches from Peru to central Bolivia, along the eastern edge of the Andes between the páramo and the warm lowlands (Luer, 2010). As extensive exploration studies continue, and with more sampling data, the prediction of the suitability in these countries may become higher, but *Lepanthes mucronata* would continue to be limited to the montane and humid ecosystems. This pattern of habitat suitability decreases toward the south and can be explained by precipitation regimes in the Andes, where there is a gradual decrease of precipitation from north to south, transitioning to large areas of dry montane ecosystems (Cheng et al., 2013). These dry areas are not suitable for most *Lephantes* species. However, as mentioned above, there are a few records from Bolivia that were not included in the model because we could not confirm their identification and exact location.

The distribution area with the largest representation of *Lepanthes mucronata* was located in montane forests of Andean and high Andean ecosystems (Table 1). These high-elevation habitats (1800–4200 m) present humid, low-temperature conditions that allow populations of *Lepanthes mucronata* and other species of this genus to be found easily here (Luer and Thoerle, 2011). The humidity of most Andean tropical ecosystems, caused by the almost permanent fog, results in high coverage of moss and other bryophytes that apparently form commensal relationships with this genus (Crain, 2012). This hypothesis is supported by the positive correlation between *Lephantes* richness and area cover of bryophytes (Crain, 2012).

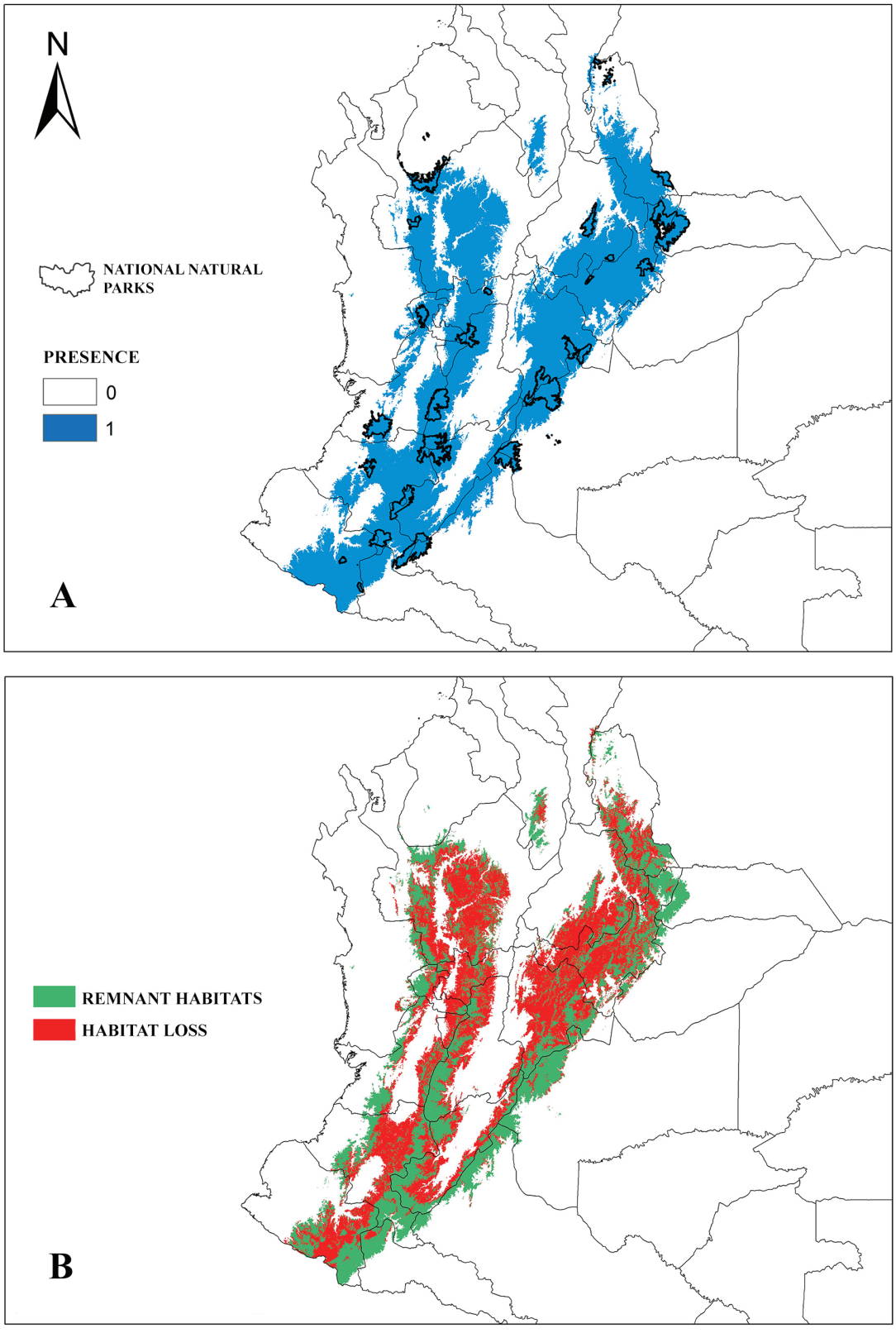

FIGURE 5. Consensus model of the distribution of *Lepanthes mucronata* in Colombia. **A**, representativeness of Natural National Parks (PNN); **B**, lost and remaining habitat.

The spatial analyses allowed us to determine that 10% of the distribution of *Lepanthes mucronata* is represented in some category of protected areas and that it has lost 47% of its habitat in Colombia. However, this species is not yet under any category of threat according to the criteria of the IUCN (2016) because of its extensive remaining range. In Colombia there are three main factors that may be affecting populations of orchids: excessive collection for ornamental purposes of species with showy and/or large flowers (Calderón-Sáenz, 2007); fragmentation and loss of habitat due to excessive deforestation and indiscriminate use of the soil (Orejuela, 2012); and finally, climate change, which can have a strong impact on species restricted to high altitudes, such as *Lepanthes mucronata* (Thuiller, 2007). *Lepanthes* is a genus of very small orchids in floral and vegetable size, and they go almost unnoticed by commercial growers, so the pressure by collection is minimal and its risk of extinction is reduced as compared with other orchid genera. Therefore, it may be safe from the anthropic intervention with the greatest impact locally and globally.

Thus, our study found that the main threat for *Lepanthes mucronata* is loss of habitat, of which 47% has disappeared, indicating that the greatest pressure exerted on this species is not overcollecting but the loss of forest cover in the three mountain ranges of Colombia. In addition, habitat loss could be one of the main threats of extinction for most of Andean *Lephanthes* species, because this genus is one of the most diverse genera in Orchidaceae, presenting high levels of endemism and association with well-conserved habitats in Colombia. Other species of this genus with more restricted ranges in the Andes could be in danger, and conservation assessments should be carryed out using methodologies of the type proposed in this study. Therefore, we expect that this work will be used as a guideline for future conservation assessments of other species of orchids.

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