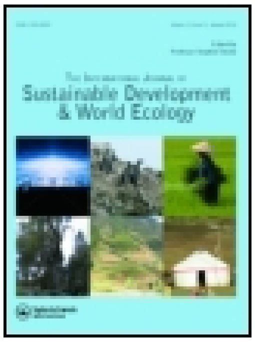

International Journal of Sustainable Development & World Ecology

ISSN: (Print) (Online) Journal homepage: https://www.tandfonline.com/loi/tsdw20

Expanding protected areas in a Neotropical hotspot

Jorge Antonio Gómez Díaz, Andrés Lira-Noriega & Fabricio Villalobos

INTERNATIONAL JOURNAL OF SUSTAINABLE DEVELOPMENT & WORLD ECOLOGY
https://doi.org/10.1080/13504509.2022.2163717

Taylor & Francis
Taylor & Francis Group

Expanding protected areas in a Neotropical hotspot

Jorge Antonio Gómez Díaz [a,b], Andrés Lira-Noriega [c] and Fabricio Villalobos [d]

[a]Centro de Investigaciones Tropicales, Universidad Veracruzana, Xalapa, Mexico; [b]Instituto de Investigaciones Biológicas, Universidad Veracruzana, Xalapa, Mexico; [c]Red de Biología Evolutiva, Instituto de Ecología A.C, Xalapa, Mexico; [d]Red de Estudios Moleculares Avanzados, Instituto de Ecología A.C., Xalapa, Mexico

ABSTRACT

The region of central Veracruz is considered a biodiversity hotspot due to its high species richness and environmental heterogeneity, but only 2% of this region is currently protected. This study aimed to assess the current protected area system's effectiveness and to identify priority conservation areas for expanding the existing protected area system. We used the distribution models of 1186 species from three kingdoms (Animalia, Plantae, and Fungi) together with ZONATION software, a conservation planning tool, to determine areas that could help expand the current network of protected areas. We applied three different parametrizations (including only species, using the boundary quality penalty, and using corridor connectivity). We found that protecting an additional 15% of the area would increase, between 16.2% and 19.3%, the protection of the distribution area of all species. We propose that the regions with a consensus of the three parametrizations should be declared as new protected areas to expand 374 km^2 to the 216 km^2 already protected. Doing so would double the protected surface in central Veracruz. The priority areas identified in this study have more species richness, carbon stock values, natural vegetation cover, and less human impact index than the existing protected areas. If our identified priority areas are declared protected, we could expect a future recovery of endangered species populations for Veracruz. The proposed new protected areas are planned and designed as corridors connecting currently isolated protected areas to promote biodiversity protection.

ARTICLE HISTORY
Received 1 April 2022
Accepted 24 December 2022

KEYWORDS
central Veracruz; conservation policy; habitat loss; systematic conservation planning; biodiversity; Mexico

Introduction

The region of central Veracruz includes relicts of two rare forest types within the Mesoamerica hotspot: i) the humid montane forest with an area of about 4,069 km^2, of which only 4% is covered by protected areas (Gillespie et al. 2012; Williams-Linera 2013; Gómez-Díaz 2016), and ii) the dry forest with an area of about 372 km^2 where only 2% is protected (Gillespie et al. 2012; López-Barrera et al. 2014; Gómez-Díaz 2016). Increasing forest conversion into cattle pastures and agricultural fields in the region represents the main pressure on the natural forests of this area (Harvey et al. 2008; Gómez-Díaz 2016). In addition to tropical forest loss and transformation, additional stress on biodiversity is exerted through landscape homogenization (Swift et al. 2004), mainly because of the land cover change (Benton et al. 2003; Gómez-Díaz 2016). The extensive conversion of these forest cover types will eventually impact the quantity of stored carbon and their remarkably high species richness. Indeed, forest loss in Mesoamerican ecosystems can potentially promote severe worldwide consequences on species richness and climate (de Albuquerque et al. 2015; Gómez-Díaz 2016).

Veracruz has one of the highest forest loss rates in Mexico, and to date, most of the natural forest has been transformed into agriculture and cattle areas (Ellis et al. 2011; Muñiz-Castro et al. 2015; Gómez-Díaz 2016). These forests have thus undergone substantial changes resulting in a highly fragmented landscape (Williams-Linera et al. 2007; Gómez-Díaz et al. 2018). It is estimated that if the current tendency continues by the next decade, only 1% of the natural forests of Veracruz will remain (Gómez-Díaz 2016). The study region of Central Veracruz is a highly biodiverse region due to its location in the transition zone between the Neotropical and the Nearctic region (Carvajal-Hernández et al. 2020). For this region, the estimated rate for annual forest cover change was −0.44% in the period from 1993 to 2000. However, this changed to a positive trend (+0.11%) of forest cover gain in 2000–2014 (Gómez-Díaz et al. 2018). Most of the species of Central Veracruz are affected by this recent conversion process (Halffter and Arellano 2002; Pineda and Halffter 2004; Aguirre et al. 2010).

While Central Veracruz is inhabited by many species with a wide distribution in Mexico, it also harbors at least 39 species whose distributions are mostly contained within Central Veracruz (Sosa et al. 1998;

CONTACT Jorge Antonio Gómez Díaz jorggomez@uv.mx Centro de Investigaciones Tropicales, Universidad Veracruzana, José María Morelos 44, Zona Centro, Centro, Veracruz, Xalapa-Enríquez 91000, México

Peterson et al. 2000b; Castillo-Campos et al. 2005). Species with a restricted and endemic distribution are known to be indicators of the conservation status of regions and other species (Manne et al. 1999; Jenkins et al. 2013). As such, and given the anthropogenic pressure on the state's natural resources and the difficulty of conserving them (Ellis et al. 2011; Gómez-Díaz et al. 2018), the priority to conduct conservation actions should be focused on endemic and threatened species found in the area.

Although Central Veracruz has been identified as needing urgent conservation actions (Toledo-Aceves et al. 2011), information about the biodiversity of this region needs to be more cohesive and unrestricted. Still, this limited information shows a worrying decrease in biodiversity. For example, populations of the Morelet's crocodile (*Crocodylus moreletii*) living in Central Veracruz are fragmented with low genetic diversity, which may lead to further loss of genetic variation (González-Trujillo et al. 2012). Also, it has been found that the change in land use harms several taxa of central Veracruz, such as trees, amphibians, ferns, and epiphytes (Pineda et al. 2005; Flores-Palacios and Valencia-Díaz 2007; Williams-Linera and Lorea 2009; Carvajal-Hernández et al. 2018).

The cornerstone of biodiversity protection is Protected areas (PAs). Though, their effectiveness and coverage rely on being carefully selected (Lemes et al. 2014). Therefore, it is imperative to identify remnants of habitat that can strategically expand the connectivity and current representativeness of PAs in a region using the scarce information available efficiently. An efficient PA network must ensure the viability and survival of key species as well as evolutionary and ecological processes. Sadly, short-term economic interests prevail over conservation objectives, historically relegating PAs to 'residual places' (Fuller et al. 2007; Nori et al. 2016), leaving as conservation areas those sites that are not suitable for human expansion and agriculture (Munthali 2007).

Systematic conservation planning provides a means to identify networks of protected areas that could help maintain biodiversity because they increase the representativeness of the processes that sustain it (Jantke 2011). The approach and solutions of the systematic conservation planning tools are much better for solving conflicts and, in that sense supporting decision-making and design of PAs compared with uninformed choice methods. The systematic planning of PAs can serve as an instrument that guides countries in the implementation of Programs in PA and in their efforts to conserve biodiversity effectively (Jantke 2011).

Systematic conservation planning can also benefit from including different variables to find more realistic solutions, such as carbon storage, an important ecosystem function of tropical forests, concerning climate change adaptation and mitigation (Marshall et al. 2012). Also, there is a strong association between carbon storage and biodiversity conservation (Strassburg et al. 2010). Various areas with a high species richness correlate with sites with high carbon stores; these areas can also benefit from the payment of environmental services related to carbon storage and capture (Strassburg et al. 2010).

Despite the current PAs network in Mexico, at the national level, there are extensive gaps representing high-priority sites for conservation (Koleff et al. 2009). Recently, Mexico has begun to update and generate information relevant to planning the PA system and biological corridors. New efforts need to be conducted to identify these important sites and the best way to protect them, and in this way, contribute to Mexico's commitment to conserving at least 17% of its terrestrial surface as a signatory of the Convention on Biological Diversity (UNEP 2010; Vergara-Tabares et al. 2018). Indeed, in the case of Central Veracruz, there are gaps in the protection of biodiversity in the current PAs (Peterson et al. 2000a; Sánchez-Cordero et al. 2005; Valenzuela Galván and Vázquez 2008; Urbina-Cardona and Flores-Villela 2010; Ochoa-Ochoa et al. 2011).

As expected, major gaps are in those potentially productive areas, including the lowlands of Central Veracruz, for which forecasts of biodiversity conservation are not optimistic (Ellis and Martínez Bello 2010; Prieto-Torres et al. 2016; Gómez-Díaz et al. 2018). Unfortunately, the PAs in the study area is immersed in a degraded or productive matrix, are isolated from each other, and are mostly ineffective, which has negative consequences for the conservation of the area (Peterson et al. 2000a; Urbina-Cardona and Flores-Villela 2010; Ellis et al. 2011; Gillespie et al. 2012; Prieto-Torres et al. 2016; Gómez-Díaz et al. 2018).

On a national scale, the National Commission for the Knowledge and Use of Biodiversity (CONABIO, by its acronym in Spanish) identified Priority sites for the conservation of terrestrial biodiversity by integrating various biological criteria and information about main threats, a large group of specialists (Koleff et al. 2009). According to the prioritization of CONABIO, central Veracruz has been found as a region of priority for biodiversity. However, the previous prioritization attempt was at a gross scale (resolution) and based on a national process. At the regional scale, two assessments defined priority conservation areas for Central Veracruz considering: 1) endemic birds and mammals (Peterson et al. 2000a) and 2) ecological criteria and socio-economic threats in the landscape context (Ellis et al. 2011). However, both studies had several flaws, like the absence of a standardized and accurate procedure for choosing species' distributions and input species (Fu et al. 2021). Moreover, those analyses were performed between 10 and 21 years ago, and since then, there has been a tremendous advance in deforestation and land-use change in the study area (Gómez-Díaz et al. 2018).

Despite the above problems and the urgency to reinforce the current PAs network, it has yet to be known which are the priority sites for conserving Central Veracruz and much less if the PA network of this vulnerable region is efficient in favoring the conservation of species. Thus, it is necessary to update and provide accurate information to help guide the effective conservation of the threatened species of central Veracruz using the PA network of the region. Therefore, this study had as objectives: (1) to assess the effectiveness of the current PA system in Central Veracruz and (2) to identify priority conservation areas for the biodiversity of this region. To do so, we used revised information on the geographic distribution of species for three taxa from different kingdoms (Animalia, Plantae, and Fungi) and identified areas that could efficiently expand the current network of PAs using systematic conservation planning tools.

Materials and methods

Study area

The study area is at 95° 54′ to 97° 18′ W and 18° 42′ to 19° 42′ N, covering about 9797 km^2 in the central region of the state of Veracruz, Mexico (Figure 1). The study area is situated at the intersection of the Sierra Madre Oriental and the Trans-Mexican volcanic belt (Gómez-Díaz et al. 2017), showing high topographic heterogeneity with an elevation gradient (0 to 4,600 m), with five climatic areas (Lauer 1973); from warm at the lower part, over temperate at the mountainous mid-elevations to cold in the higher regions (Soto-Esparza and Giddings 2011).

The orographic and climatic differences within the area allow the presence of six vegetation types following Miranda and Hernández-Xolocotzi (Miranda and Hernández-Xolocotzi 1963), from the dry environments with elevated temperatures (tropical semi-deciduous forest and tropical oak) over the humid-temperate (humid montane forest, pine-oak forest) to cold and dry at the higher parts of the gradient (pine and fir forest; Gómez-Díaz 2016). In addition, from a biogeographic perspective, this area is at the confluence between the Nearctic and Neotropical regions, which is why it has a biogeographic value as a scene of even greater diversity (Gómez-Díaz 2016).

This area was selected due to its inclusion in the main sub-hydrological region of Veracruz (CONABIO 1970; Gómez-Díaz et al. 2018), which is part of the Actopan-La Antigua River watersheds. Also, the area is considered a national priority for restoration to maintain ecosystem services like water supply and quality (Cotler Avalos and Garrido Pérez 2010). Additionally, our study area was chosen due to the outstanding biodiversity within Veracruz, with approximately 1894 animals, 1695 plants, and 26 fungi, representing almost 20% of the biodiversity of Veracruz and 9.6% of Mexico

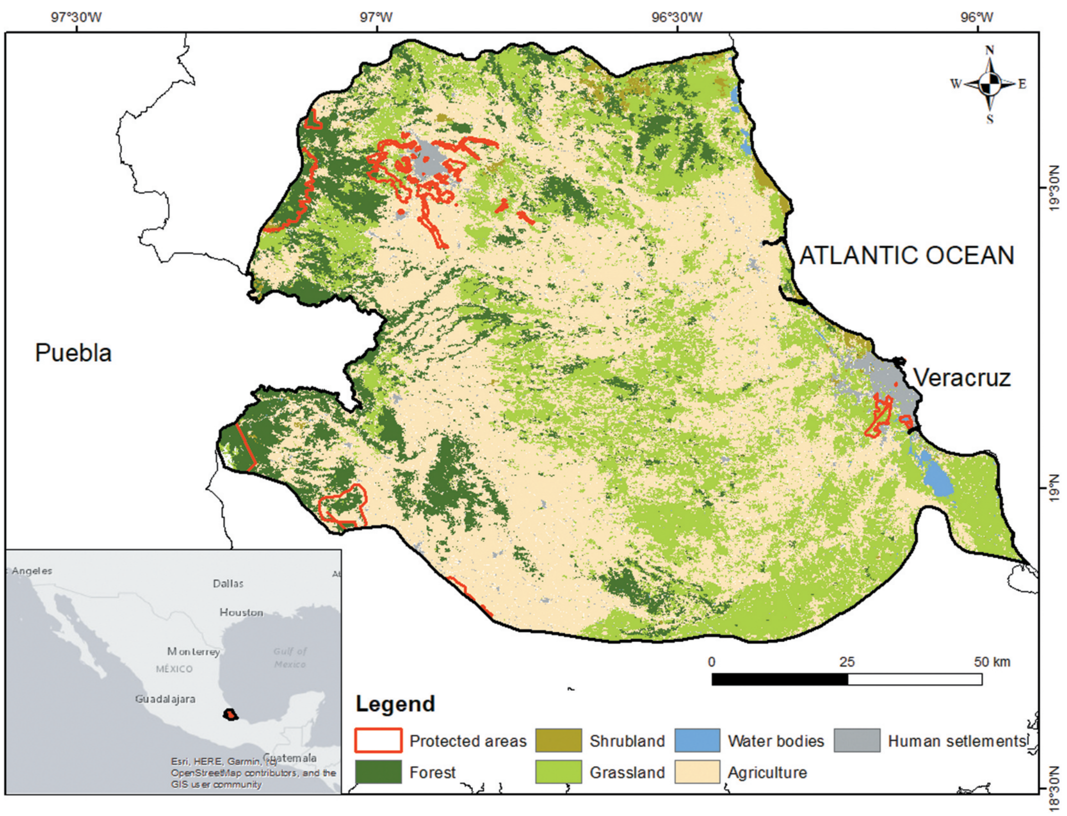

Figure 1. The study area in Central Veracruz, Mexico, shows different land cover classes (CONABIO 2017).

(CONABIO 2008; Cruz-Angón 2011; Villaseñor 2016). More than 80% of Veracruz's primary vegetation has been converted to pastures, plantations, and secondary vegetation. The remaining forest or vegetation is highly fragmented, especially in the central part of the state (Ellis et al. 2011). The study area is therefore recognized as a priority region for conservation within Mexico (Ellis et al. 2011).

Selected species and geographic distributions

In our study area, we compiled a list of those species from the three main kingdoms (Animalia, Plantae, and Fungi). This list was created using several sources of information (Sosa and Gómez-Pompa 1994; CONABIO 2012; González and Arroyo-Cabrales 2013) and was carefully curated, removing taxonomical and distributional issues, resulting in a list of 3631 species. Then, we used range maps provided by the Mexican Commission for the Knowledge and Use of Biodiversity (CONABIO 2018a). From this source, we obtained 1134 species' ranges (948 animals and 186 plants) generated by experts in each taxonomic group using species distribution modeling techniques. In addition, we created 52 distribution models for 39 plants, 12 animals, and one fungus species that are considered critically endangered according to the IUCN but were not included in CONABIO's database. To create these models, we gathered records from the XAL Herbarium (in the case of plants) and the GBIF (2019). We only consider one point of presence for each pixel of 1 km^2 to minimize spatial autocorrelation (Benítez-Badillo et al. 2018). We used Maxent v.3.4.1 (Phillips et al. 2006) to build a potential distribution model for each species. The algorithm formulates geographic predictions utilizing a method called maximum entropy, with the occurrence records of the species as inputs and their corresponding environmental conditions as predictors, to estimate potential distributions (Phillips et al. 2006; Benítez-Badillo et al. 2018); we used ten thousand of pseudo-absence records according to Benítez-Badillo et al. (2018).

The 19 bioclimatic variables of CHELSA v.1.2 were used at a resolution of ~1 km^2 (Karger et al. 2017) which is more suitable than the WorldClim dataset for tropical and mountainous zones (Benítez-Badillo et al. 2018). We used the climate data set for each species with the least-correlated variables (Spearman's rank correlation $r_s \leq 0.7$) since high collinearity might lead to over-parameterized models affecting their interpretation. We eliminate highly correlated variables to avoid multicollinearity and reduce the number of bioclimatic variables. Lastly, to assess the predictive accuracy and performance of each model, the AUC metric was used (Benítez-Badillo et al. 2018).

In total, 1186 out of the 3631 species in the study area were included in the analyses (Figure 2). The remaining species were not considered, given the absence or the small number of occurrence records. We assigned a conservation weight to each species (Nori et al. 2016) based on their conservation status according to the IUCN red list (DD = 0.2, LC = 0.5, NT = 1, LR/cd = 2, VU = 3, EN = 4, CR = 5), endemicity to the state of Veracruz (Gómez-Pompa et al. 2010; no = 0, yes = 1), considered priority by the CONABIO (no = 0, yes = 1), the Mexican list of protected species (SEMARNAT 2010; Subject to special protection = 1, threatened = 2, in danger of extinction = 3) and the appendices of the CITES (III = 1, II = 2, I = 3; Pouzols et al. 2014). We used the R software v.3.5.3 (R Core Team 2020) to perform all the analyzes.

Priority conservation areas

We used ZONATION 4.0.0rc1 (Moilanen et al. 2005; di Minin et al. 2014) to identify priority conservation areas. This software establishes a hierarchical prioritization of areas of the study region in terms of conservation importance (or zones to increase the network of protected areas) based on the distribution of species and additional spatially explicit information, such as the economic value of the land (Nori et al. 2016; Prieto-Torres et al. 2018). The prioritization ensures the maximization of species' occurrence levels while considering the complementarity of species composition among areas (Nori et al. 2016). We implemented the Core Area Zonation (CAZ) removal rule, which prioritizes those areas with endemic or rare species (Moilanen et al. 2014; Nori et al. 2016). Additionally, we selected the parameter of elimination of cells (edge removal) to aid in eliminating parts of the landscape (Moilanen et al. 2014).

In searching for priority areas for conservation, the parameterization and parameter adjustment will influence the final solution (Tan et al. 2008), so selecting the best model a priori is not easy (Elith and Graham 2009). Therefore, we used three parametrizations (including only species, SPP; the boundary quality penalty, BQP; and corridor connectivity, COR) to represent parameter heterogeneity and its influence on prioritization. The first parametrization (SPP) only gives importance to the species to select priority cells; this algorithm was chosen because it is the simplest (relatively) and provides a basis for comparison with other parameterizations. In addition, this parameterization aims to prioritize the representation of a set of species with greater conservation weight without considering the condition of the habitat (Lehtomäki and Moilanen 2013).

The second one (BQP) describes how the local occurrence level of a feature (species) in a site is influenced by the loss of surrounding habitat; this algorithm was chosen because it considers the species-

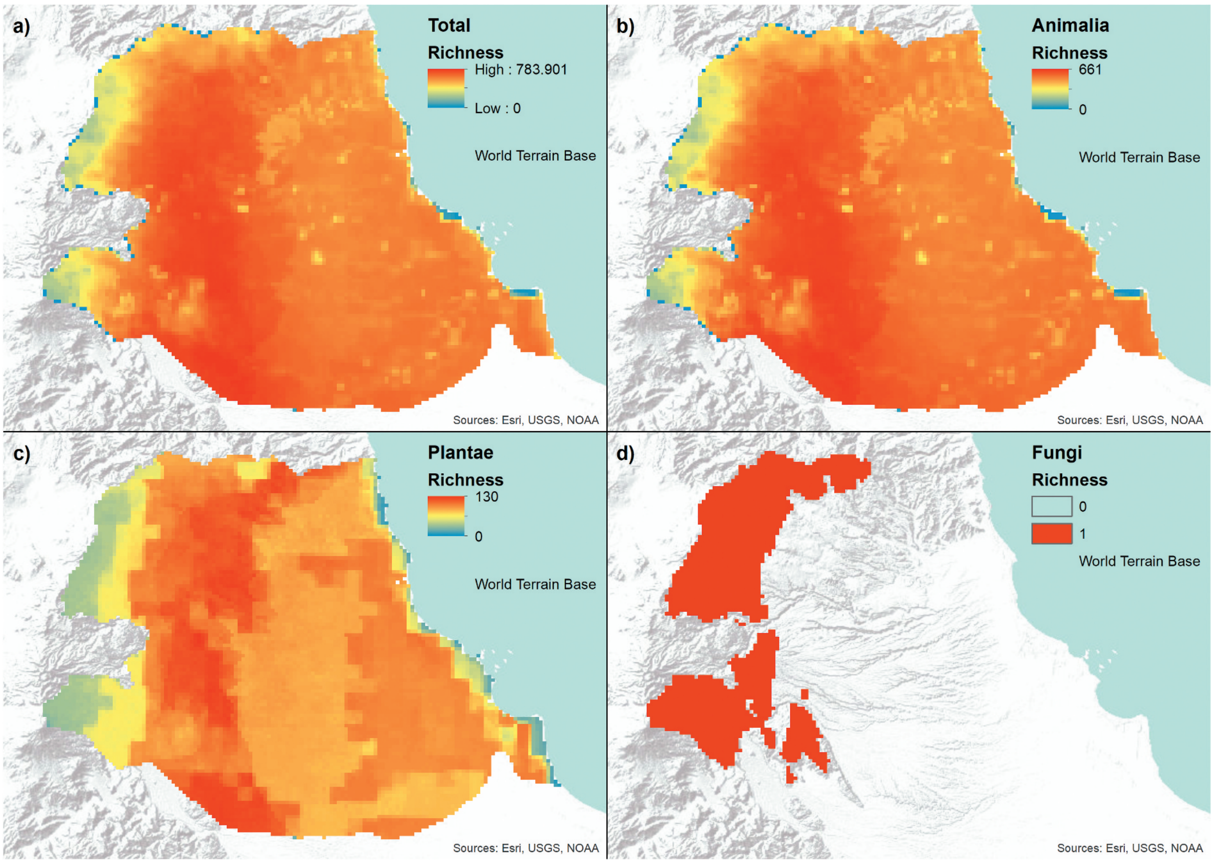

Figure 2. Species richness map for all species (a), Animalia (b), Plantae (c), and Fungi (d) kingdom. Blue represents low species richness, and red represents high species richness.

specific response to habitat loss around the focal cell (Moilanen and Wintle 2007), that is, how sensitive species are to fragmentation (Lehtomäki and Moilanen 2013). The third one (COR) is an approach to building corridors based on a penalty mechanism that is embedded in the prioritization (or ranking) process (Pickens et al. 2017); this algorithm was chosen because it serves to design solutions that increase connectivity when there are several types of partially similar environments (such as forest types) that help create biological corridors (Lehtomäki et al. 2009; Lehtomäki and Moilanen 2013).

The variability between parameterizations can provide an estimate of an important source of uncertainty. Using such information in reserve selection could result in more reliable identification of conservation priorities (Meller et al. 2014). Therefore, the results from these different parametrizations were compared, and areas of consensus among them were delimited.

Additional variables

In the case of BQP and COR, we included carbon stock as another conservation feature along with the species. For this, we used a detailed national map of forest aboveground carbon stocks in Mexico (Cartus et al. 2014). We also included a variable that reflects the history of the ecosystems of the study area. This variable was created using all the Landsat images of the study area. We created an algorithm on the Google Earth Engine platform (Gorelick et al. 2017) that allowed us to calculate the mean NDVI of each year (from 1973 to 2018) of the study area and sum it across years. If there is a negative change in NDVI in one year, the count starts again, so we can know how old the forests of each pixel are. This variable was included as an additional feature along with species and carbon stock in the case of BQP and as a condition file in the case of COR.

In the case of BQP and COR, we used the boundary quality penalty as a connectivity parameter in mode 1. We used a negative linear response curve (negative effect of fragmentation on species) for all the species. This parametrization was chosen because boundary quality penalty is a quantitative feature-specific way of inducing aggregation in Zonation solutions (Pickens et al. 2017). Using species as features can be seen as a way of approximating nonlinear effects of connectivity that may be present in species distribution models. In species distribution modeling techniques, the abundance of a species at a location is influenced by the local habitat quality, as well as the habitat of the site. Such a neighborhood influence states that the species somehow depends on connectivity, edge effects, or both (Pickens et al. 2017).

Table 1. Parametrizations of the Zonation software.

Parameter	Species (SPP)	Boundary quality penalty (BQP)	Corridor connectivity (COR)
Connectivity	No	Boundary quality penalty, mode 1, linear decreasing	Boundary quality penalty, mode 1, linear decreasing
Corridor	No	No	Yes, strength = 0.055, minimum width = 1, use of domain layer (land cover)
Condition file	No	No	Yes (NDVI accumulated)
Additional features to species distribution models	No	Yes (carbon stock and NDVI accumulated)	Yes (carbon stock)

In the case of COR, we used the parameter corridor loss penalty (CLP), which maintains structural connections guided by species or feature-specific spatial patterns (Pickens et al. 2017). The CLP prevents the loss of structural relationships in networks of patches. The CLP requires adjusting two key parameters: i) penalty strength which is a real number that regulates the trade-off between increased connectivity via corridors and any other considerations relevant to conservation, we used a penalty strength of 0.055, and ii) corridor width, which defines the minimum width of corridors (number of cells; Pickens et al. 2017). The method will try to keep patches connected by corridors of at least this width (Pickens et al. 2017). Connections narrower than this parameter are not considered corridors (Pickens et al. 2017). We established a corridor width of 1 pixel (1 km) for the corridors and the use of a domain layer where only the areas with forest can be used as corridors. For this, we reclassified a land cover map of Mexico (CONABIO 2017) into a continuous map where we gave the maximum value to the forest or natural vegetation cover (native grasslands = 0.5, scrubs = 0.8, water bodies, and forests = 1). The most significant difference among parametrizations is summarized in Table 1.

Algorithm parameterization

PAs that currently exist were included in the analysis to find areas that could be used to increase the network of PAs (Nori et al. 2016; Prieto-Torres et al. 2016). PAs were downloaded from the CONABIO database (CONABIO 2018a) and assumed that several species could not be effectively protected in built-up areas or crop fields within farm fields or highly urbanized areas (Nori et al. 2016). Also, most endemic or rare species are sensitive to elevated landscape fragmentation (Thompson et al. 2017); we masked the areas that contained urbanized areas or crops (Nori et al. 2016). For this, we reclassified a land cover map of Mexico (CONABIO 2017) on a map where all pixels that had 100% urbanization or crops were removed (Nori et al. 2016). Thus, we excluded urban areas and crops (Nori et al. 2016). Finally, given that the quality of ecosystems decreases due to anthropic effects and therefore its conservation value, we used the Human impact index on Mexican biodiversity (CONABIO 2018b) as a negative variable, 'penalizing' those pixels with strong human influence (Andrade-Díaz et al. 2019).

After prioritization analysis, we used performance curves that estimate the percentage of original species' incidences retained at each top fraction of the landscape chosen for conservation (Nori et al. 2016; Prieto-Torres et al. 2016). Performance curves describe the representativeness and performance of the solution at a given level of cell conservation (proportion of landscape under protection). They show the relationship between the conservation of the average species distribution range (y-axis) and the balance of protected landscape (x-axis). In this way, multiple parameterizations can be compared to determine the conservation cost of each one from the difference between the yield curves (Moilanen et al. 2014.). With this, we were able to quantify the area protected by the current network of PAs and identify the 17% of the highest priority that should be protected (according to the Convention on Biological Diversity; Pouzols et al. 2014; Nori et al. 2016) using the three parametrizations (SPP, BQP, and COR; Figure 3).

Comparison between existing protected areas and new priority conservation areas

To compare the differences and advantages between the existing PAs and the priority areas identified in this study, we clipped with the mask of the current PAs and the priority areas identified in this study the following variables in raster format: i) total species richness (sum of the species distribution models), ii) carbon stock, iii) mean NDVI, iv) natural vegetation cover, and v) human impact index. Then, we compared the median of each variable between the existing PAs and the priority areas identified in this study using the nonparametric Mann-Whitney U test using the function 'wilcox.test' of the R software because neither of these distributions was statistically normal, and the areas were different.

Results

Out of our 1186 studied species, there 83 species were categorized as threatened (VU, EN, CR), seven were classified as DD by the IUCN, 40 are endemic to the state of Veracruz, and 90 are considered a priority for

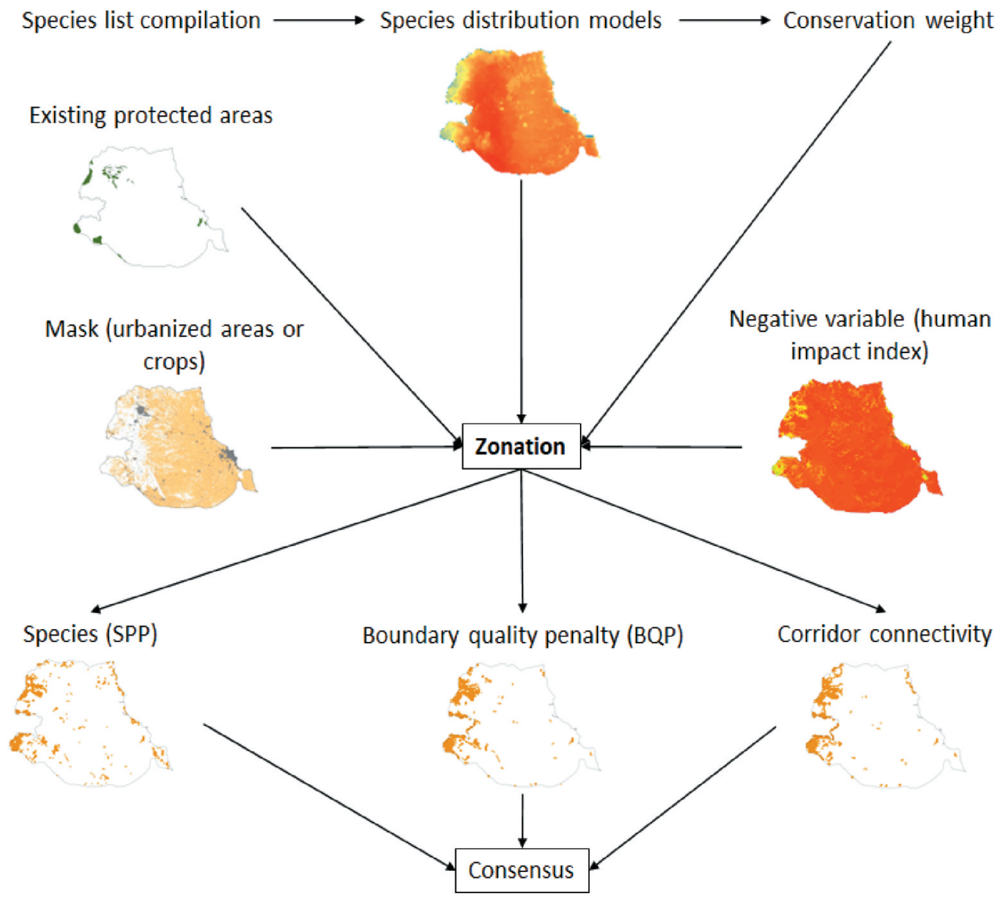

Figure 3. A conceptual framework diagram represents the stages of the spatial conservation prioritization process in central Veracruz, Mexico.

Table 2. Summary of the species included in the prioritization analysis arranged in a taxonomic category, with species number, species included in the IUCN in any risk category (threatened), endemic to the state of Veracruz (Endemic), priority for Mexico (Priority), included in the red list of Mexico (Mexican risk) and CITES.

Taxonomic category	Species	Threatened	Endemic	Priority	Mexican risk	CITES
Animalia	**960**	**801**	**24**	**74**	**259**	**129**
Amphibia	67	40	8	4	26	1
Aves	590	510	5	52	136	104
Branchiopoda	1	1				
Malacostraca	1	1				
Mammalia	155	143	8	6	27	16
Reptilia	146	106	3	12	70	8
Fungi	**1**				**1**	
Agaricomycetes	1				1	
Plantae	**225**	**85**	**15**	**15**	**46**	**42**
Cycadopsida	7	6	4	5	6	7
Liliopsida	39	12	10	4	13	15
Magnoliopsida	165	59	1	4	22	18
Pinopsida	8	8		1	2	
Polypodiopsida	6			1	3	2

the country. Also, 44 species are in danger of extinction, 119 are threatened, and 142 are subject to special protection, according to the Mexican risk categories. Moreover, 19 are listed in Appendix I, 136 in Appendix II, and 16 in Appendix III of the CITES (Table 2).

The PAs represented 2% of the study area, protecting an average of 2.5% of the total distribution of the 1,186 species studied. We find that if 15% more of the entire territory is protected (17% of central Veracruz; orange areas in Figure 4), the representativeness of the PA network will increase, protecting between 16.2% (COR) and 19.3% (SPP) of the distribution area of the studied species (Figure 5). The curves show that the average proportions (lines) of the species distributions increase linearly in the three parameterizations as a greater proportion of the landscape is protected (Figure 5).

The main differences among the three parametrizations are the selection of pixels at mid-elevations of the study area; for example, in SPP, there are more pixels

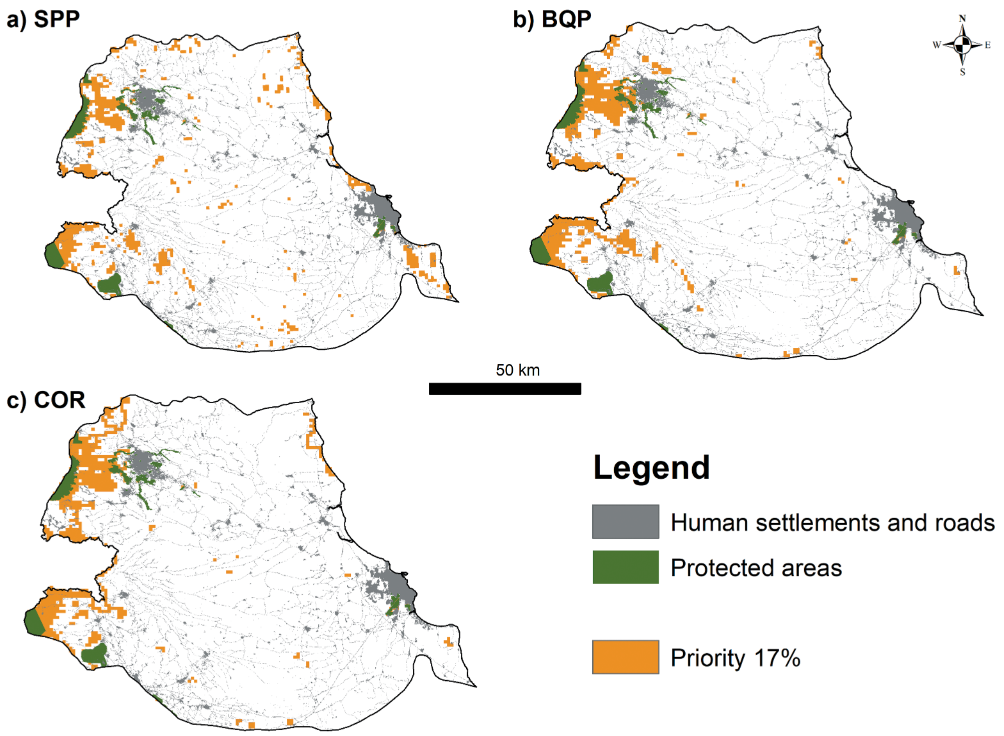

Figure 4. Map showing priority sites (orange) for conservation to increase to 17% of the network of existing natural areas (green) of central Veracruz, Mexico, with different parametrization (a: SPP; b: BQP, c: COR).

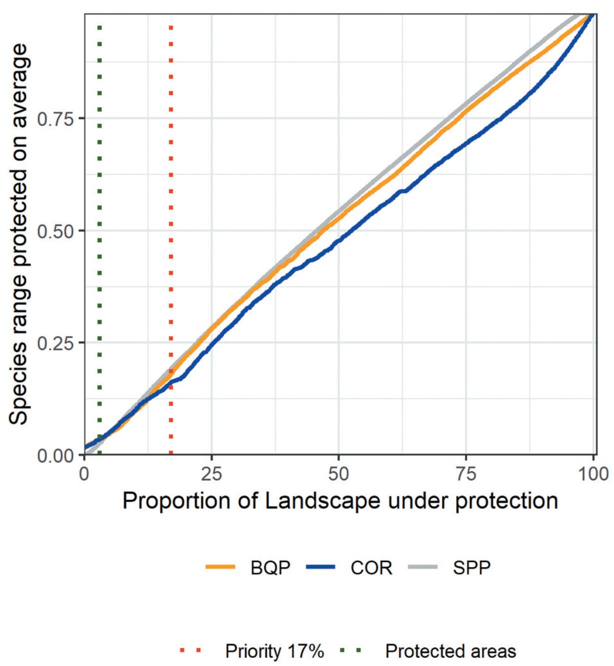

Figure 5. Performance curves of the prioritization models, on the x-axis, the percentage of protected pixels is shown. On the y-axis, the average distribution area of protected species is displayed using the parameterization that only considers the species (SPP), boundary quality penalty (BQP), and corridor (COR).

distributed in the study area's southern and central regions of the study area. Also, there is a cluster of pixels near Veracruz city (Figure 4a). In the case of BQP, priority pixels are compacted around the protected areas with some pixels in the central region of the study area; there is also a cluster between the cities of Huatusco and Coscomatepec (Figure 4b). Finally, in the case of COR, most of the pixels are connecting the protected areas with high clustering among them, this is the most compact parametrization with just a few pixels selected in the central region of the study area (Figure 4c).

The algorithms show similar spatial patterns with the consensus area (Figure 6) if 17% of the study area is protected. Our identified priority conservation site covered large areas close to existing PAs (Figures. 4 and 6). Mountain forests (west of the study area) are of higher conservation value, with little surrounding urbanization, than the lowland forest (central and east of the study area) in all parametrization scenarios. High-priority areas identified west of central Veracruz are attributed to their proximity to Protected regions, the high species richness, and the low values of the human impact index (good forest quality). In addition to places of high conservation value near the mountain cloud forest (e.g. Xalapa), wetlands throughout east central Veracruz (near the coast) are also prioritized. Lower priority areas for conservation are concentrated in the middle area of the study area (Figure 6).

Most of these priority sites were located connecting the 'Cofre de Perote' National Park, the Multifunctional Biological Corridor 'Archipiélago de Bosques y Selvas de Xalapa' and the state reserve 'San Juan del Monte' (25% considering SPP prioritization, 37% considering BQP, and 52% considering COR) and around the National Park 'Pico de Orizaba' (18% considering SPP, 26% considering COR and 29% feeling BQP). Areas of consensus among the three prioritization algorithms

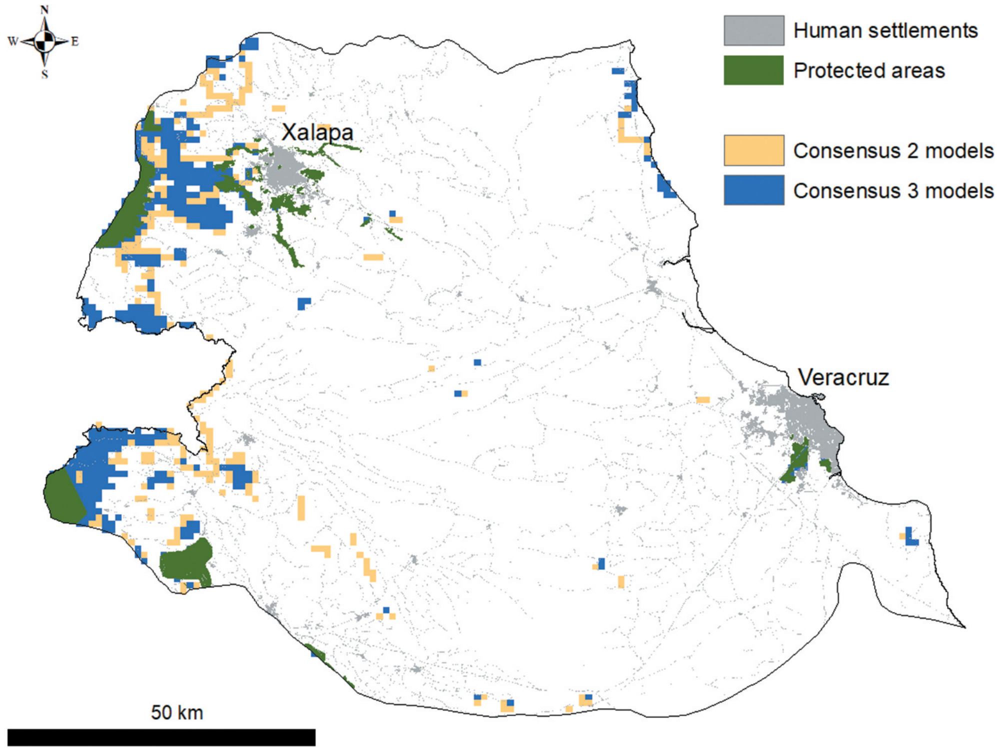

Figure 6. Comparison among all parametrizations.

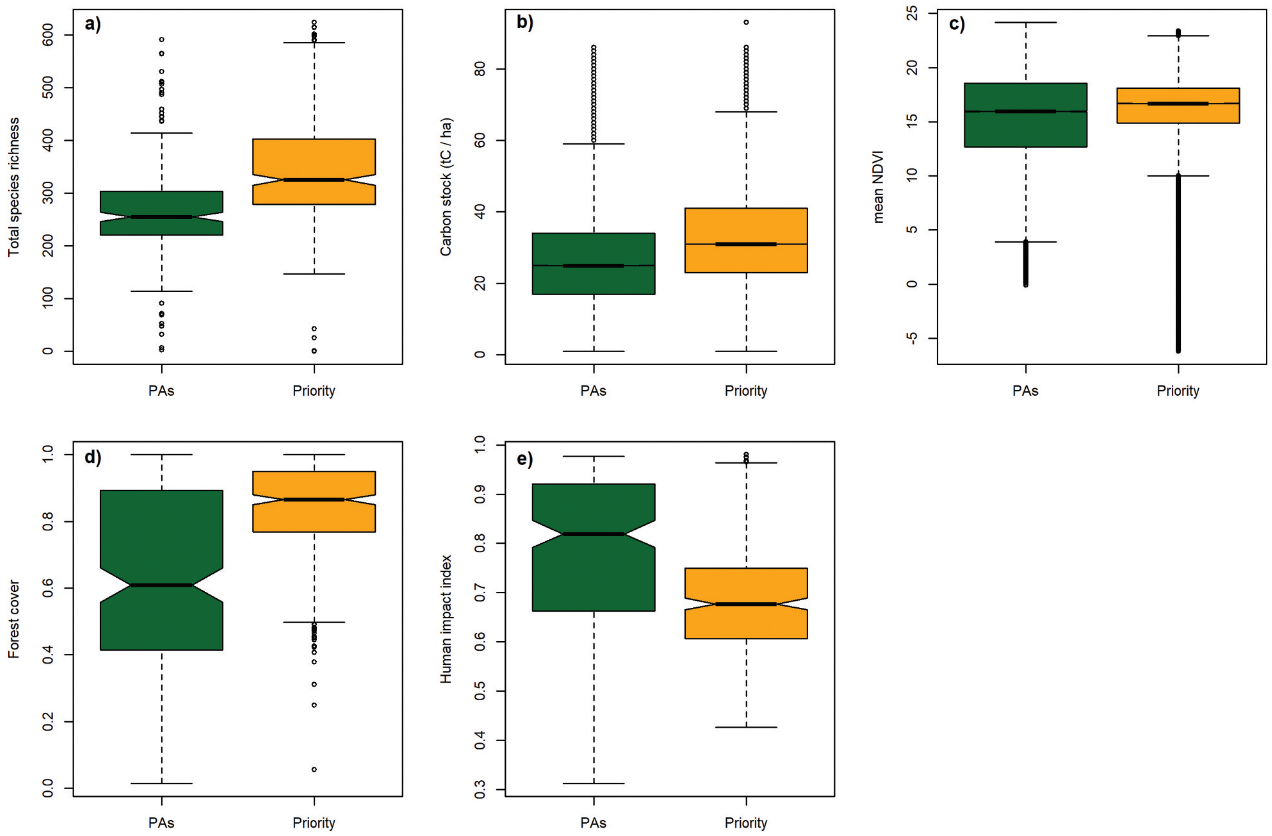

Figure 7. Differences in a) total species richness, b) carbon stock values, c) mean NDVI, d) natural vegetation cover, and e) human impact index between existing protected areas (PAs) and proposed priority areas (Priority) for expansion of PAs in central Veracruz, Mexico.

were located connecting the National Park 'Cofre de Perote,' the Multifunctional Biological Corridor 'Archipiélago de Bosques y Selvas de Xalapa' and the state reserve 'San Juan del Monte' (38%) (Figure 6).

We propose that the areas with a consensus of the three algorithms should be declared as new protected areas to achieve an expansion of 374 km^2 to the 216 km^2 already protected, thus creating a PA network that would cover 590 km^2 in total (6% of the region and 0.8% of the state). Doing so would double the protected surface in central Veracruz. The priority areas identified in this study have more species richness ($W = 20127$, p-value <0.001), carbon stock values ($W = 34600$, p-value <0.001), mean NDVI ($W = 31246$, p-value <0.001), natural vegetation cover ($W = 22976$, p-value <0.001), and less human impact index ($W = 26571$, p-value <0.001) than the existing PAs (Figure 7).

Discussion

In this study, we examined the effectiveness of the current PA network in Central Veracruz, and priority sites for the conservation of species of the region were identified. Currently, the PA network of Central Veracruz does not fulfill its important function of protecting biodiversity, and, unfortunately, only a few species have their distributions guaranteed by this protection scheme. There are 19 protected areas in our study area (four federal and 15 state areas) that comprise only about 2% of the total surface (about 216 km^2; Figure 1), with almost no additions to the system of protected natural areas in recent times (Gómez-Díaz 2016).

As an exception, in 2015, a new reserve was declared, increasing by 56 km^2 in the PA system of central Veracruz in the mountainous areas where cloud forests are found (Gómez-Díaz et al. 2018). This new reserve felt a precedent of organization among civil organizations, academia, and government for conserving Central Veracruz. Nevertheless, protection actions are an urgent task, as indicated by the gross forest loss in the study area (Gómez-Díaz et al. 2018). Fortunately, some local projects are considering the creation of better implementation of existing PAs. Hence, cooperation between NGOs, decision-makers, and researchers is necessary to face increasingly urgent ecological problems (Nori et al. 2016).

The immediate effects of deforestation (WWF 2015) and the problems in the ecosystems it generates can be reduced if quick decisions are taken to favor conservation (Spash and Aslaksen 2015; Nori et al. 2016). Considering that our study region has one of the highest rates of habitat loss in the tropics (Ellis et al. 2011; López-Barrera et al. 2014; Gómez-Díaz et al. 2018), the exposure of Central Veracruz species to these fast, large and continuous alterations (Pineda et al. 2005; Gómez-Pompa et al. 2010; Krömer et al. 2014; Armenta-Montero et al. 2015; Vergara-Rodríguez et al. 2017; Carvajal-Hernández et al. 2018; Gómez-Díaz et al. 2018; Benítez-Badillo et al. 2018), the need for well-informed decisions is crucial.

Nevertheless, there is still hope for improving this situation. Using species distribution models across the study area and applying a systematic conservation planning scheme, which is based on complementarity to prioritize sites for conservation, we identified priority sites that could be considered to increase 374 km^2 to the current PAs and more than double the protected distributional area of our studied species. This highlights the fantastic opportunity to find new places for species conservation and support decision-making (Veach et al. 2017). Other comparable spatial prioritization studies using species distributions of indicator groups and ecosystem services will be necessary to support conservation decisions in Mesoamerican ecosystems, one of the world's most threatened regions (Ramírez-Albores et al. 2021).

Most of the potential areas for protection that we identified in our prioritization are close to current PAs, which would simplify the expansion and creation of new PAs and further improve the connectivity of the existing PA network. For example, the areas around the established PAs are viable to be protected since they are in common lands (ejidos). In addition, most of these priority sites harbor mature forests of excellent quality surrounded by secondary forests that can be used as buffers. Importantly, our identified priority sites are planned and designed as corridors that can connect the isolated protected areas to promote the protection and development of biodiversity.

To balance regional development with environmental protection, the owners and inhabitants of the identified priority sites for conservation can obtain monetary resources through diverse options. The first is through the Payment for Environmental Services in Protected Natural Areas, a payment scheme to promote recognition of the value of environmental services provided by the forest, agroforestry, and natural resource ecosystems (CONANP 2010). Also, each year the government of the state of Veracruz issues a call to support those initiatives for financially conserving protected areas (SEDEMA 2022). Likewise, the owners and inhabitants of the identified priority sites for protection could use the secondary forests through sustainable practices such as the establishment and management of agroforestry systems with native species, beekeeping with an emphasis on native species, the establishment of barriers and live fences with fruit and forest species of native origin, the sustainable use of local forest resources and ecotourism activities.

Our prioritization results based on the three parametrizations (SPP, BQP, and COR) reached the same conclusions, ensuring that the identified priority sites have a high priority for conserving species of central Veracruz. Our results are consistent with previous findings by a conservation assessment of Veracruz that identified priority sites for the state (Ellis et al. 2011). We used three different parametrizations to explore a range of solutions, the first one (SPP) was used as a 'control' parameter giving only importance to the cells that protect most of the species' ranges without a connectivity criterion. The second one (BQP) was used due to its property of inducing spatial aggregation in the solutions (Moilanen and Wintle 2007). The third one (COR) was used to add path-like connectivity among the priority fragments creating corridors (Pouzols and Moilanen 2014). However, to verify the advantages and accuracy of the results of our conservation effectiveness assessment and previous studies, it is necessary to validate the model with field work and consider the opinions of the inhabitants and the authorities (Whitehead et al. 2014). This process would be the next step in seeking to decree the priority sites as new protected areas and may lead to an update of the analysis.

Thinking about the low protection currently offered by the PA network, it is noteworthy to stress that 1.4% of our studied species are presently categorized as critically endangered by the IUCN (2020), and 10% are categorized as threatened by Mexican laws (SEMARNAT 2010) and 1.6% are listed in appendix I of CITES (CITES 2020). Because of this, it is necessary to monitor the conservation status of the priority species of the region (Nori et al. 2016). It is also required to obtain information on the species found in the DD classification of the IUCN (Howard and Bickford 2014; Nori and Loyola 2015). Also, since there needs to be updated information regarding the biodiversity of the area, prioritization of sites for conservation in central Veracruz must be conducted repeatedly using the added information generated (Nori et al. 2016).

Even though our results show those priority sites where the PA network should be expanded in Central Veracruz, we should also mention that our analysis was limited by fragmented and limited information regarding the spatial distribution of species in the area. Our study was based on two taxa kingdoms (Animalia and Plantae), well-known globally and nationally (CONABIO 2018a). Conserving these taxa is a global priority (Kier et al. 2005; Kreft and Jetz 2007; Thuiller et al. 2015; Roll et al. 2017) and considering that we focus on species that have a higher priority for conservation, we still cannot know how well other taxa would be represented, especially those without enough information to create species distribution models. Consequently, more studies must be conducted to add data from different species and taxonomic groups. Furthermore, given the high deforestation rates in Central Veracruz (Gómez-Díaz et al. 2018), information on the current state of vegetation and land use on the scale used is constantly changing (CONABIO 2017). It is necessary to use additional information on the economic value of the land and the ecosystem services to refine the algorithm's results; unfortunately, for our study area, this information is unavailable.

Conclusion

Better planning for expanding protected areas is necessary for biologically diverse regions like Central Veracruz. In this study, we found that our site urgently needs to implement conservation actions since only 2% of its coverage is protected by some PA. After all, the types of vegetation most threatened in Veracruz must be protected, and work must be done to reduce and control the causes that promote deforestation at the regional level. Our results can help favor the conservation and management of forest remnants in the Center of Veracruz since the priority sites we have identified could become PAs increasing the protection to 6% of the region's surface. Ideally, if our identified priority areas are declared protected, we could expect a future recovery of endangered species populations for Veracruz.

Acknowledgments

JAGD thanks CONACyT for the scholarship provided to conduct his post-doctorate research (grant number 406377) under the supervision of FV.

Disclosure statement

No potential conflict of interest was reported by the authors.

Funding

The work was supported by the Consejo Nacional de Ciencia y Tecnología [Post-doctorate research (grant number 406377)].

ORCID

Jorge Antonio Gómez Díaz http://orcid.org/0000-0001-8182-7584
Andrés Lira-Noriega http://orcid.org/0000-0002-3219-0019
Fabricio Villalobos http://orcid.org/0000-0002-5230-2217

References

Aguirre A, Guevara R, García M, López JC. 2010. Fate of epiphytes on phorophytes with different architectural characteristics along the perturbation gradient of Sabal mexicana forests in Veracruz, Mexico. J Veg Sci. 21 (1):6–15. doi:10.1111/j.1654-1103.2009.01131.x.

Andrade-Díaz MS, Sarquis JA, Loiselle BA, Giraudo AR, Díaz-Gómez JM. 2019. Expansion of the agricultural frontier in the largest South American dry forest: identifying priority conservation areas for snakes before everything is lost. PLoS ONE. 14(9):e0221901. doi:10.1371/JOURNAL.PONE.0221901.

Armenta-Montero S, Carvajal-Hernández CI, Ellis EA, Krömer T. 2015. Distribution and conservation status of *Phlegmariurus* (Lycopodiaceae) in the State of Veracruz, Mexico. Trop Conserv Sci. 8(1):114–137. doi:10.1177/194008291500800111.

Benítez-Badillo G, Lascurain-Rangel M, Álvarez-Palacios JL, Gómez-Díaz JA, Avendaño-Reyes S, Dávalos-Sotelo R, López-Acosta JC. 2018. Influence of land-use changes (1993 and 2013) in the distribution of wild edible fruits from Veracruz (Mexico). Trop Conserv Sci. 11:194008291875866. doi:10.1177/1940082918758662.

Benton TGT, Vickery JAJ, Wilson JJD. 2003. Farmland biodiversity: is habitat heterogeneity the key? Trends Ecol Evol. 18(4):182–188. doi:10.1016/S0169-5347.03.00011-9.

Cartus O, Kellndorfer J, Walker W, Franco C, Bishop J, Santos L, Fuentes J. 2014. A national, detailed map of forest aboveground carbon stocks in Mexico. Remote Sens. 6(6):5559–5588. doi:10.3390/rs6065559.

Carvajal-Hernández CI, Gómez-Díaz J, Bautista-Bello AP, Krömer T. 2020. From the sea to the mountains. In: Goldstein M DellaSala D, editors. Encyclopedia of the World's Biomes. 1st ed. Amsterdam: Elsevier; p. 79–87.

Carvajal-Hernández CI, Gómez-Díaz JA, Kessler M, Krömer T. 2018. Influence of elevation and habitat disturbance on the functional diversity of ferns and lycophytes. Plant Ecol Divers. 11(3):335–347. doi:10.1080/17550874.2018.1484526.

Castillo-Campos G, Medina Abreo ME, Dávila Aranda PD, Zavala Hurtado JA. 2005. Contribución al conocimiento del endemismo de la flora vascular en Veracruz, México [Contribution to the knowledge of the endemism of the vascular flora in Veracruz, Mexico]. Acta Bot Mex. 57 (73):19–57. Spanish. doi:10.21829/abm73.2005.1004.

[CITES] Convention on International Trade in Endangered Species of Wild Fauna and Flora. 2020. Convention on international trade in endangered species of Wild Fauna and Flora. Geneva: CITES Secretariat.

[CONABIO] Comisión Nacional para el Conocimiento y Uso de la Biodiversidad. 2008. Capital natural de México, vol. I: Conocimiento actual de la biodiversidad [Natural capital of Mexico, Vol. I: current knowledge of biodiversity]. Mexico D.F.: Comisión Nacional para el conocimiento y uso de la biodiversidad. Spanish.

[CONABIO] Comisión Nacional para el Conocimiento y uso de la Biodiversidad. 2012 Diversidad de especies [Species diversity]. La biodiversidad en Veracruz: Estudio de Estado Vol. II Mexico D F: pp. 71–86. Spanish. Comisión Nacional para el Conocimiento y uso de la Biodiversidad

[CONABIO] Comisión Nacional para el Conocimiento y Uso de la Biodiversidad. 2017. Cobertura del suelo de México a 30 metros [Mexico ground cover at 30 meters]. 2010. Mexico City: CONABIO. Spanish.

[CONABIO] Comisión Nacional para el Conocimiento y Uso de la Biodiversidad. 2018a. Portal de Información Geográfica – CONABIO [Geographic Information Portal - CONABIO]. Mexico DF: CONABIO; [accessed 2019 Aug 16]. http://www.conabio.gob.mx/informacion/gis/. Spanish

[CONABIO] Comisión Nacional para el Conocimiento y Uso de la Biodiversidad. 2018b. Índice de impacto humano a la biodiversidad mexicana [Index of human impact on Mexican biodiversity] [quality map]. Mexico DF: CONABIO. Spanish.

[CONABIO] Comisión Nacional para el Conocimiento y Uso de la Biodiversidad, cartographer. 1970. Subcuencas hidrológicas [Hydrological sub-basins] [hydrological map]. Mexico DF: CONABIO; [accessed 2018 Feb 18]. http://www.conabio.gob.mx/informacion/metadata/gis/subcu1mgw.xml?_httpcache=yes&_xsl=/db/metadata/xsl/fgdc_html.xsl&_indent=no. Spanish.

[CONANP] Comisión Nacional de Áreas Naturales Protegidas. 2010. Pago por servicios ambientales en áreas naturales protegidas [Payment for environmental services in protected natural areas]. Mexico DF: CONANP; [accessed 2022 Aug 3]. https://www.gob.mx/conanp/documentos/pago-por-servicios-ambientales-en-areas-naturales-protegidas. Spanish

Cotler Avalos H, Garrido Pérez A. 2010. Las cuencas hidrográficas de México: diagnóstico y priorización [The hydrographic basins of Mexico: diagnosis and prioritization]. Mexico DF: Pluralia Ediciones e Impresiones. Spanish.

Cruz-Angón A. 2011. La biodiversidad en Veracruz: Estudio de estado [Biodiversity in Veracruz: State Study]. Mexico City: Comisión Nacional para el Conocimiento y Uso de la Biodiversidad. CONABIO. Gobierno del Estado de Veracruz Universidad Veracruzana Instituto de Ecología, A.C. Spanish.

de Albuquerque FS, Benito B, Beier P, Assunção-Albuquerque MJ, Cayuela L. 2015. Supporting underrepresented forests in Mesoamerica. Natureza & Conservação. 13(2):152–158. doi:10.1016/j.ncon.2015.02.001.

di Minin E, Veach V, Lehtomäki J, Pouzols, FM, Moilanen, A. 2014. A quick introduction to Zonation. Helsinki: University of Helsinki.

Elith J, Graham CH. 2009. Do they? how do they? why do they differ? On finding reasons for differing performances of species distribution models. Ecography. 32(1):66–77. doi:10.1111/j.1600-0587.2008.05505.x.

Ellis EA, Martínez Bello M. 2010. Vegetación y uso de suelo [Vegetation and land use]. In: Florescano E Ortíz J, editors. Atlas del patrimonio natural, histórico y cultural de Veracruz. Xalapa: Comisión del Estado de Veracruz para la Conmemoración de la Independencia Nacional y la Revolución Mexicana; p. 203–226. Spanish.

Ellis EA, Martínez-bello M, Monroy-ibarra R . 2011. Focos rojos para la conservación de la biodiversidad [Red flags for biodiversity conservation]. In: Comisión Nacional para el Conocimiento y Uso de la Biodiversidad (CONABIO), editors. La Biodiversidad en Veracruz: Estudio de Estado. Vol. I Mexico D F: Comisión Nacional para el Conocimiento y uso de la Biodiversidad, Gobierno del Estado de Veracruz, Universidad Veracruzana, Instituto de Ecología, A C; pp. 351–367. Spanish.

Flores-Palacios A, Valencia-Díaz S. 2007. Local illegal trade reveals unknown diversity and involves a high species richness of wild vascular epiphytes. Biol Conserv. 136 (3):372–387. doi:10.1016/j.biocon.2006.12.017.

Fu W, Ding Q, Sun Z, Xu T. 2021. Spatial conservation prioritization considering socioeconomic costs and degradation conditions in the Southwest China biodiversity hotspot. Environ Conserv. 48(3):1–8. doi:10.1017/S0376892921000138.

Fuller T, Sánchez-Cordero V, Illoldi-Rangel P, Linaje M, Sarkar S. 2007. The cost of postponing biodiversity conservation in Mexico. Biol Conserv. 134(4):593–600. doi:10.1016/j.biocon.2006.08.028.

[GBIF] Global Biodiversity Information Facility. 2019. Free and Open Access to Biodiversity Data | GBIF.org; [accessed 2019 Jun 21]. http://www.gbif.org/.

Gillespie TW, Lipkin B, Sullivan L, Benowitz DR, Pau S, Keppel G. 2012. The rarest and least protected forests in

biodiversity hotspots. Biodivers Conserv. 21 (14):3597–3611. doi:10.1007/s10531-012-0384-1.
Gómez-Díaz JA. 2016. Diversity patterns of herbaceous angiosperms along gradients of elevation and forest use intensity in Central Veracruz, Mexico [dissertation]. Göttingen: Georg-August-Universität Göttingen.
Gómez-Díaz JA, Brast K, Degener J, Krömer T, Ellis E, Heitkamp F, Gerold G. 2018. Long-term changes in forest cover in Central Veracruz, Mexico (1993–2014). Trop Conserv Sci. 11:194008291877108. doi:10.1177/1940082918771089.
Gómez-Díaz JA, Krömer T, Kreft H, Gerold G, Carvajal-Hernández CI, Heitkamp F. 2017. Diversity and composition of herbaceous angiosperms along gradients of elevation and forest-use intensity. PLoS ONE. 12(8):e0182893. doi:10.1371/journal.pone.0182893.
Gómez-Pompa A, Krömer T, Castro-Cortés R. 2010. Atlas de la flora de Veracruz: un patrimonio natural en peligro [Atlas of the flora of Veracruz: a natural heritage in danger]. Mexico D.F.: Universidad Veracruzana. Gobierno del Estado de Veracruz. Spanish.
González GJC, Arroyo-Cabrales J. 2013. Lista Actualizada de los mamíferos de México 2012 [Updated list of mammals of Mexico 2012]. Rev Mex Mastozool. 2(1):27–80. Spanish. doi:10.22201/ie.20074484e.2012.2.1.20.
González-Trujillo R, Rodríguez D, González-Romero A, Forstner MRJ, Densmore III LD, Reynoso VH. 2012. Testing for hybridization and assessing genetic diversity in Morelet's crocodile (*Crocodylus moreletii*) populations from central Veracruz. Conserv Genet. 13(6):1677–1683. doi:10.1007/s10592-012-0406-2.
Gorelick N, Hancher M, Dixon M, Ilyushchenko S, Thau D, Moore R. 2017. Google earth engine: planetary-scale geospatial analysis for everyone. Remote Sens Environ. 202:18–27. doi:10.1016/j.rse.2017.06.031.
Halffter G, Arellano L. 2002. Response of Dung Beetle diversity to human-induced changes in a tropical landscape1. BIOTROPICA. 34(1):144. doi:10.1646/0006-3606.2002.034[0144:rodbdt]2.0.co;2.
Harvey CA, Komar O, Chazdon R, Ferguson BG, Finegan B, Griffith DM, Martínez-Ramos M, Morales H, Nigh R, Soto-Pinto L, et al. 2008. Integrating agricultural landscapes with biodiversity conservation in the Mesoamerican hotspot. Conserv Biol. 22(1):8–15. doi:10.1111/j.1523-1739.2007.00863.x.
Howard SD, Bickford DP. 2014. Amphibians over the edge: silent extinction risk of data deficient species. Divers Distrib. 20(7):837–846. doi:10.1111/ddi.12218.
[IUCN] International Union for Conservation of Nature. 2020. The IUCN red list of threatened species. Version 2020-2; [accessed 2020 Aug 22]. http://www.iucnredlist.org/.
Jantke K. 2011. Systematic conservation planning in Europe–the case of wetland biodiversity [dissertation]. Hamburg: University of Hamburg.
Jenkins CN, Pimm SL, Joppa LN. 2013. Global patterns of terrestrial vertebrate diversity and conservation. Proc Natl Acad Sci U S A. 110(28):E2602–2610. doi:10.1073/pnas.1302251110.
Karger DN, Conrad O, Böhner J, Kawohl T, Kreft H, Soria-Auza RW, Zimmermann NE, Linder HP, Kessler M. 2017. Climatologies at high resolution for the earth's land surface areas. Sci Data. 4(1):170122. doi:10.1038/sdata.2017.122.
Kier G, Mutke J, Dinerstein E, Ricketts TH, Küper W, Kreft H, Barthlott W. 2005. Global patterns of plant diversity and floristic knowledge. J Biogeogr. 32(7):1107–1116. doi:10.1111/j.1365-2699.2005.01272.x.
Koleff P, Tambutti M, March IJ, Esquivel R, Cantú C, Lira-Noriega A. 2009. Identificación de prioridades y análisis de vacíos y omisiones en la conservación de la biodiversidad de México [Identification of priorities and analysis of gaps and omissions in the conservation of biodiversity in Mexico]. Capital Natural de México: Estado de conservación y tendencias de cambio Vol. II. Mexico DF: CONABIO; pp. 651–718.
Kreft H, Jetz W. 2007. Global patterns and determinants of vascular plant diversity. Proc Natl Acad Sci U S A. 104 (14):5925–5930. doi:10.1073/pnas.0608361104.
Krömer T, García-Franco JG, Toledo-Aceves T. 2014. Epífitas vasculares como bioindicadoras de la calidad forestal: impacto antrópico sobre su diversidad y composición [Vascular epiphytes as bioindicators of forest quality: anthropic impact on their diversity and composition]. In: González-Zuarth C, Vallarino A, Pérez-Jimenez J Low-Pfeng A, editors. Bioindicadores: guardianes de nuestro futuro ambiental. Mexico DF and Campeche: Instituto Nacional de Ecología y Cambio Climático (INECC) – El Colegio de la Frontera Sur (ECOSUR); p. 606–623. Spanish.
Lauer W. 1973. Zusammenhänge zwischen Klima und Vegetation am Ostabfall der mexikanischen Meseta [Relationships between climate and vegetation on the eastern slope of the Mexican Meseta]. Erdkunde. 27 (3):192–213. German. doi:https://doi.org/10.3112/erdkunde.1973.03.03.
Lehtomäki J, Moilanen A. 2013. Methods and workflow for spatial conservation prioritization using Zonation. Environ Mod Soft. 47:128–137. doi:10.1016/j.envsoft.2013.05.001.
Lehtomäki J, Tomppo E, Kuokkanen P, Hanski I, Moilanen A. 2009. Applying spatial conservation prioritization software and high-resolution GIS data to a national-scale study in forest conservation. For Ecol Manag. 258(11):2439–2449. doi:10.1016/j.foreco.2009.08.026.
Lemes P, Melo AS, Loyola RD. 2014. Climate change threatens protected areas of the Atlantic Forest. Biodivers Conserv. 23(2):357–368. doi:10.1007/s10531-013-0605-2.
López-Barrera F, Manson RH, Landgrave R. 2014. Identifying deforestation attractors and patterns of fragmentation for seasonally dry tropical forest in central Veracruz, Mexico. Land Use Policy. 41:274–283. doi:10.1016/j.landusepol.2014.06.004.
Manne LL, Brooks TM, Pimm SL. 1999. Relative risk of extinction of passerine birds on continents and islands. Nature. 399(6733):258–261. doi:https://doi.org/10.1038/20436.
Marshall AR, Willcock S, Platts PJ, Lovett JC, Balmford A, Burgess ND, Latham JE, Munishi PKT, Salter R, Shirima DD, et al. 2012. Measuring and modelling above-ground carbon and tree allometry along a tropical elevation gradient. Biol Conserv. 154:20–33. doi:10.1016/j.biocon.2012.03.017.
Meller L, Cabeza M, Pironon S, Barbet-Massin M, Maiorano L, Georges D, Thuiller W and Ferrier S. (2014). Ensemble distribution models in conservation prioritization: from consensus predictions to consensus reserve networks. Diversity Distrib. 20(3): 309–321. doi:10.1111/ddi.12162.
Miranda F, Hernández-Xolocotzi E. 1963. Los tipos de vegetación de México y su clasificación [The types of vegetation of Mexico and their classification]. Bol Soc Bot México. 28(28):29–162. Spanish. doi:10.17129/botsci.1084.
Moilanen A, Franco AMA, Early RI, Fox R, Wintle B, Thomas CD. 2005. Prioritizing multiple-use landscapes for conservation: methods for large multi-species planning problems. Proc Royal Soc B. 272(1575):1885–1891. doi:10.1098/rspb.2005.3164.

Moilanen A, Pouzols FM, Meller L, Veach V, Arponen A, Leppänen J, Kujala H. 2014. ZONATION version 4 user manual. Spatial conservation planning methods and software. Helsinki: University of Helsinki.

Moilanen A, Wintle BA. 2007. The boundary-quality penalty: a quantitative method for approximating species responses to fragmentation in reserve selection. Conserv Biol. 21(2):355–364. doi:10.1111/j.1523-1739.2006.00625.x.

Muñiz-Castro MA, Williams-Linera G, Benítez-Malvido J. 2015. Restoring montane cloud forest: establishment of three Fagaceae species in the old fields of central Veracruz, Mexico. Restor Ecol. 23(1):26–33. doi:10.1111/rec.12155.

Munthali SM. 2007. Transfrontier conservation areas: integrating biodiversity and poverty alleviation in Southern Africa. Nat Resour Forum. 31(1):51–60. doi:10.1111/j.1477-8947.2007.00130.x.

Nori J, Loyola R. 2015. On the worrying fate of data deficient amphibians. PLoS ONE. 10(5):e0125055. doi:10.1371/journal.pone.0125055.

Nori J, Torres R, Lescano JN, Cordier JM, Periago ME, Baldo D. 2016. Protected areas and spatial conservation priorities for endemic vertebrates of the Gran Chaco, one of the most threatened ecoregions of the world. Divers Distrib. 22(12):1212–1219. doi:10.1111/ddi.12497.

Ochoa-Ochoa LM, Vázquez L-B, Urbina-Cardona JN, Flores-Villela OA. 2011. Priorización de áreas para conservación de la herpetofauna utilizando diferentes métodos de selección [Prioritization of areas for herpetofauna conservation using different selection methods]. In: Koleff P Urquiza-Haas T, editors. Planeación para la conservación de la biodiversidad terrestre en México: retos en un país megadiverso. Mexico DF: Comisión Nacional para el Conocimiento y Uso de la Biodiversidad–Comisión Nacional de Áreas Naturales Protegidas; p. 89–108. Spanish.

Peterson AT, Egbert SL, Sanchez-Cordero V, Price KP. 2000a. Geographic analysis of conservation priorities using distributional modelling and complementarity: endemic birds and mammals in Veracruz, Mexico. Biol Conserv. 93 (1):85–94. doi:10.1016/S0006-3207.99.00074-9.

Peterson AT, Egbert SL, Sánchez-Cordero V, Price KP. 2000b. Geographic analysis of conservation priority: endemic birds and mammals in Veracruz, Mexico. Biol Conserv. 93 (1):85–94. doi:10.1016/S0006-3207.99.00074-9.

Phillips SJ, Anderson RP, Schapire RE. 2006. Maximum entropy modeling of species geographic distributions. Ecol Model. 190(3–4):231–259. doi:10.1016/j.ecolmodel.2005.03.026.

Pickens BA, Mordecai RS, Drew CA, Alexander-Vaughn LB, Keister AS, Morris HLC, Collazo JA. 2017. Indicator-driven conservation planning across terrestrial, freshwater aquatic, and marine ecosystems of the South Atlantic, USA. J Fish Wildl Manag. 8(1):219–233. doi:10.3996/062016-JFWM-044.

Pineda E, Halffter G. 2004. Species diversity and habitat fragmentation: frogs in a tropical montane landscape in Mexico. Biol Conserv. 117(5):499–508. doi:10.1016/j.biocon.2003.08.009.

Pineda E, Moreno CE, Escobar FS, Halffter G. 2005. Frog, bat, and dung beetle diversity in the cloud forest and coffee agroecosystems of Veracruz, Mexico. Conserv Biol. 19 (2):400–410. doi:10.1111/j.1523-1739.2005.00531.x.

Pouzols FM, Moilanen A. 2014. A method for building corridors in spatial conservation prioritization. Landsc Ecol. 29 (5):789–801. doi:10.1007/s10980-014-0031-1.

Pouzols FM, Toivonen T, di Minin E, Kukkala AS, Kullberg P, Kuusterä J, Lehtomäki J, Tenkanen H, Verburg PH, Moilanen A. 2014. Global protected area expansion is compromised by projected land-use and parochialism. Nature. 516(7531):383–386. doi:10.1038/nature14032.

Prieto-Torres DA, Navarro-Sigüenza AG, Santiago-Alarcón D, Rojas-Soto OR. 2016. Response of the endangered tropical dry forests to climate change and the role of Mexican protected areas for their conservation. Glob Change Biol. 22(1):364–379. doi:10.1111/gcb.13090.

Prieto-Torres DA, Nori J, Rojas-Soto OR. 2018. Identifying priority conservation areas for birds associated with endangered Neotropical dry forests. Biol Conserv. 228:205–214. doi:10.1016/j.biocon.2018.10.025.

Ramírez-Albores JE, Prieto-Torres DA, Gordillo-Martínez A, Sánchez-ramos LE, Navarro-sigüenza AG. 2021. Insights for protection of high species richness areas for the conservation of Mesoamerican endemic birds. Divers Distrib. 27(1):18–33. doi:10.1111/ddi.13153.

R Core Team. 2020. R: a language and environment for statistical computing. Vienna: R Foundation for Statistical Computing; [accessed 2020 Dec 16]. https://www.r-project.org/.

Roll U, Feldman A, Novosolov M, Allison A, Bauer AM, Bernard R, Böhm M, Castro-Herrera F, Chirio L, Collen B, et al. 2017. The global distribution of tetrapods reveals a need for targeted reptile conservation. Nat Ecol Evol. 1 (11):1677–1682. doi:10.1038/s41559-017-0332-2.

Sánchez-Cordero V, Cirelli V, Munguía M, Sarkar S. 2005. Place priorization for biodiversity representation using species' ecological niche modelling. Biodivers Inform. 2:11–23. doi:10.17161/bi.v2i0.9.

[SEDEMA] Secretaría de Medio Ambiente del Estado de Veracruz. 2022. Proyectos para el fomento ambiental 2022 [Projects for environmental promotion 2022]. Mexico Xalapa: SEDEMA; [accessed 2022 Aug 3]. http://www.veracruz.gob.mx/medioambiente/2022/07/18/proyectos-para-el-fomento-ambiental-2022/. Spanish

[SEMARNAT] Secretaría de Medio Ambiente y Recursos Naturales. 2010. Norma Oficial Mexicana. Protección ambiental-Especies nativas de México de flora y fauna silvestres. Categorías de riesgo y especificaciones para su inclusión, exclusión o cambio [Mexican official standard. Environmental protection-Mexico's native species of wild flora and fauna. Risk categories and specifications for their inclusion, exclusion, or change]. Mexico DF: Diario Oficial. Spanish.

Sosa V, Gómez-Pompa A. 1994. Lista Florística [Floristic List]. In: de Veracruz F, editor. Instituto de Ecología A.C. Xalapa: University of California; p. 1–82. Spanish.

Sosa V, Vovides AP, Castillo-Campos G. 1998. Monitoring endemic plant extinction in Veracruz, Mexico. Biodivers Conserv. 7(11):1521–1527. doi:10.1023/A:1008809332490.

Soto-Esparza M, Giddings BL. 2011. Clima [Weather]. In: Cruz Angón A, editor. La biodiversidad en Veracruz: Estudio de Estado. Mexico DF: Comisión Nacional para el Conocimiento y Uso de la Biodiversidad, Gobierno del Estado de Veracruz, Universidad Veracruzana, Instituto de Ecología, A. C.; p. 35–52. Spanish.

Spash CL, Aslaksen I. 2015. Re-establishing an ecological discourse in the policy debate over how to value ecosystems and biodiversity. J Environ Manage. 159:245–253. doi:10.1016/j.jenvman.2015.04.049.

Strassburg B BN *et al* . (2010). Global congruence of carbon storage and biodiversity in terrestrial ecosystems. Conservation Letters, 3(2), 98–105. 10.1111/j.1755-263X.2009.00092.x

Swift MJ, Izac AMN, van Noordwijk M. 2004. Biodiversity and ecosystem services in agricultural landscapes—are we asking the right questions? Agric Ecosyst Environ. 104 (1):113–134. doi:10.1016/j.agee.2004.01.013.

Tan CC, Tung CP, Tsai FTC. 2008. Applying zonation methods and tabu search to improve the ground-water modeling 1. J Am Water Resour Assoc. 44(1):107–120. doi:10.1111/J.1752-1688.2007.00141.X.

Thompson PL, Rayfield B, Gonzalez A. 2017. Loss of habitat and connectivity erodes species diversity, ecosystem functioning, and stability in metacommunity networks. Ecography. 40(1):98–108. doi:https://doi.org/10.1111/ecog.02558.

Thuiller W, Maiorano L, Mazel F, Guilhaumon F, Ficetola GF, Lavergne S, Renaud J, Roquet C, Mouillot D. 2015. Conserving the functional and phylogenetic trees of life of European tetrapods. Philos Trans R Soc Lond B Biol Sci. 370(1662):20140005. doi:10.1098/rstb.2014.0005.

Toledo-Aceves T, Meave JA, González-Espinosa M, Ramírez-Marcial N. 2011. Tropical montane cloud forests: current threats and opportunities for their conservation and sustainable management in Mexico. J Environ Manage. 92 (3):974–981. doi:10.1016/j.jenvman.2010.11.007.

[UNEP] United Nations Environment Programme. 2010. Report of the tenth meeting of the conference of the parties to the convention on biological diversity; Oct 18-29; Nagoya, Japan.

Urbina-Cardona JN, Flores-Villela O. 2010. Ecological-niche modeling and prioritization of conservation-area networks for Mexican herpetofauna. Conserv Biol. 24(4):1031–1041. doi:10.1111/j.1523-1739.2009.01432.x.

Valenzuela Galván D, Vázquez LB. 2008. Prioritizing areas for conservation of Mexican carnivores considering natural protected areas and human population density. Anim Conserv. 11(3):215–223. doi:10.1111/j.1469-1795.2008.00171.x.

Veach V, di Minin E, Pouzols FM, Moilanen A. 2017. Species richness as criterion for global conservation area placement leads to large losses in coverage of biodiversity. Divers Distrib. 23(7):715–726. doi:10.1111/ddi.12571.

Vergara-Rodríguez D, Mathieu G, Samain M-S, Armenta-Montero S, Krömer T. 2017. Diversity, distribution, and conservation status of Peperomia (Piperaceae) in the State of Veracruz, Mexico. Trop Conserv Sci. 10:194008291770238. doi:10.1177/1940082917702383.

Vergara-Tabares DL, Lammertink M, Verga EG, Schaaf AA, Nori J. 2018. Gone with the forest: assessing global woodpecker conservation from land use patterns. Divers Distrib. 24(5):640–651. doi:10.1111/DDI.12710.

Villaseñor JL. 2016. Checklist of the native vascular plants of Mexico. Rev Mex Biodivers. 87(3):559–902. doi:10.1016/j.rmb.2016.06.017.

Whitehead AL, Kujala H, Ives CD, Gordon A, Lentini PE, Wintle BA, Raymond CM. 2014. Integrating biological and social values when prioritizing places for biodiversity conservation. Conserv Biol. 28(4):992–1003. doi:10.1111/cobi.12257.

Williams-Linera G 2013. The cloud forest communities in the mountains of central Veracruz, México: heterogeneity along an elevation gradient? Paper presented at: New Frontiers in Tropical Biology: The Next 50 years. A joint meeting of ATBC and OTS; Jun 23-27; San Jose, Costa Rica.

Williams-Linera G, Guillén-Servent A, Gómez-García O, Lorea-Hernández F. 2007. Conservación en el centro de Veracruz, México. El bosque de niebla: ¿reserva archipiélago o corredor biológico? [Conservation in central Veracruz, Mexico. The cloud forest: archipelago reserve or biological corridor?]. In: Halffter G, Guevara S, and Melic A, editors. Hacia una cultura de conservación de la diversidad biológica Madrid: Sociedad Entomológica Aragonesa, Comisión Nacional para el Conocimiento yUso de la Biodiversidad, Comisión Nacional de Áreas Naturales Protegidas, Consejo Nacional de Ciencia yTecnología, Instituto de Ecología, A.C., Organización de las Naciones Unidas; p. 303–310. Spanish.

Williams-Linera G, Lorea F. 2009. Tree species diversity driven by environmental and anthropogenic factors in tropical dry forest fragments of central Veracruz, Mexico. Biodivers Conserv. 18(12):3269–3293. doi:10.1007/s10531-009-9641-3.

[WWF] World Wide Fund for Nature. 2015. Saving forests at risk. WWF living forests report. Gland: The WWF International Secretariat.