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Combining modeling tools to identify conservation priority areas: a case study of the last large-bodied avian frugivore in the Atlantic Forest

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Abstract
Applicability of modeling tools to tackle conservation problems is key for conservation planning. However, modeling papers regarding real-world conservation issues are scarce. Here, we combined two modeling tools to identify priority areas in the Brazilian Atlantic Forest, focusing on the last large-bodied frugivorous bird in the region, the red-billed curassow (*Crax blumenbachii*). We used population viability analysis (PVA) to determine (1) the minimum viable population size under different hunting scenarios; and (2) the minimum critical forest patch size required to maintain viable populations. We used ecological niche modeling (ENM) to identify remnants that retain suitable environmental conditions to ensure the long-term persistence of this species. We overlapped the outputs from PVA and ENM models to identify priority areas for curassows. Under our best-case scenario, 56 individuals would suffice to maintain a viable population and 71 forest patches located within the species' known range are above the critical size of 3,141 ha. In the worst-case scenario, at least 138 individuals would be required to maintain a viable population in forest patches larger than 9,500 ha, corresponding to only 20 Atlantic Forest fragments within the species range. Among these, 17 presented median habitat suitability values higher than 0.70, eight of which were selected as priority areas for law enforcement and nine as priority areas for reintroduction. We encourage conservation biologists and land managers to combine modeling tools which can be guided by our conservation planning framework. This approach is promising to inform long-term conservation planning of a flagship species and its entire ecosystem.

Key words: conservation planning; Cracidae; habitat fragmentation; hunting; population viability; ecological niche modeling

1. Introduction

Systematic conservation planning has the elementary role of protecting regional biotas from processes that threaten their integrity and are often focused on reserve design and siting criteria for conservation purposes. Population viability analysis (PVA) and ecological niche modeling (ENM) are two key modeling tools that may be combined to define species conservation strategies (Akçakaya et al., 2004; Franklin et al., 2013). These models may help to design a protected area network of forest reserves or validate the sufficiency of existing ones, to minimize the risk of species extinction based on rational criteria (Taylor et al., 2017). Despite the widespread claims of the applicability of modeling tools to confront practical conservation problems, studies on methodological modeling frameworks far outnumber those that are actually applied to real-world conservation challenges, particularly in the tropics (Cayuela et al., 2009; Guisan et al., 2013).

PVA combines stochastic and deterministic effects to simulate the extinction risk of a species (Brook et al., 2000; Miller and Lacy, 2005), whereas ENM takes into account an algorithm that relates presence/absence data to environmental variables to build a representation of the required conditions for species survival (Guisan and Zimmermann, 2000; Peterson and Soberón, 2012). ENMs are typically used to identify previously unknown populations, to project species geographic distributions based on climate change scenarios or the spread of exotic species, and select potential areas for species reintroductions (Engler et al., 2004; Ortega-Huerta and Peterson, 2008). PVAs provide several competing scenarios that can be compared to select the best available option for species management (e.g. reintroduction, reinforcement) and/or habitat management (e.g. suppress hunting pressure, restore habitats, create new or implement existing protected areas) (Bernardo et al., 2014; Brook et al., 2000).

Several studies have integrated habitat suitability with PVA models to characterize a spatial metapopulation model. Within this approach, both modeling strategies are simultaneously fitted to data using commercial softwares, such as RAMAS® GIS (Akçakaya et al., 2004; Franklin et al., 2013). We used ENM and PVA tools separately, overlaying the outputs thereafter to identify suitable habitat patches that can hold viable populations of any endangered species. Our approach is particularly useful in conservation plans of completely isolated populations, which do not form a metapopulation.

We combined outputs from ENM and PVA models using open-source softwares, thereby incurring no costs to practitioners, to identify priority areas for one of the most threatened species in the Neotropics, the red-billed curassow *Crax blumenbachii* (Cracidae, Galliformes). This cracid is endangered according to the IUCN's red list (Birdlife International, 2018) and critically endangered in the Brazilian red list (Brasil, 2014), mainly due to habitat loss and fragmentation, aggravated by poaching (IBAMA, 2004; Alvarez and Develey, 2010). The species is endemic to a small portion of the lowland Brazilian Atlantic Forest, from Rio de Janeiro and Minas Gerais to southern Bahia (IBAMA, 2004). It has become extinct throughout much of its former range and, nowadays, the few extant native populations in southern Bahia and northern Espírito Santo are highly isolated (IBAMA, 2004; Bernardo et al., 2011b). Captive-bred individuals have been successfully reintroduced in some Atlantic Forest patches of Minas Gerais and Rio de Janeiro (IBAMA, 2004; Bernardo et al., 2011b).

The red-billed curassow is the last extant large-bodied frugivorous bird of the northern Atlantic Forest, where most other large frugivores including woolly spider monkeys (*Brachyteles hypoxanthus*), lowland tapirs (*Tapirus terrestris*), white-lipped peccaries (*Tayassu pecari*) are virtually extinct, mainly due to historical hunting pressure and extensive deforestation since the early-1970s (Canale et al., 2012). Large frugivores are sensitive to hunting and habitat loss followed by fragmentation due to their large body mass, large spatial requirements, low reproductive rates and often narrow geographic distributions (Franklin, 1993; Margules and Pressey, 2000). In the Brazilian Atlantic Forest, where ~89% of all woody species are animal-dispersed (Almeida-neto et al., 2008), an effective way to prioritize conservation areas is to identify forest patches that both (1) hold viable populations of large frugivores and (2) provide suitable environmental conditions for the species persistence.

We selected conservation areas for curassow populations by answering the following questions: (1) what is the minimum viable population size of curassows once different hunting scenarios are taken into account?; (2) what is the minimum critical forest patch size required to maintain a minimum viable population under different hunting scenarios?; and (3) of all remaining forest patches larger than a minimum critical size throughout the species geographic range, how many still retain suitable environmental conditions for the species?

2. Methods

2.1 Study area

We here consider priority areas for red-billed curassows within the species distribution map adapted from IUCN (Birdlife International, 2018). We judiciously adjusted the IUCN range polygon boundaries for this species by encompassing forest remnants located (1) 50 km north of the Michelin Ecological Reserve in Bahia (Lima et al., 2008), (2) across the southern state of Rio de Janeiro (Pacheco, 2013), and (3) including areas west of the IUCN polygon boundaries. See Appendix (section A2.1) for more information on the original and current distribution range of red-billed curassows.

2.2 Data availability

ENMs require occurrence records while PVAs require reproductive data, survival rates and information on home range use (Fig. 1). The species Action Plan was the crucial starting point for gathering some of these data into a single document (IBAMA, 2004). Published in 2004, it is the very first action plan developed for a tropical endangered species and was taken as a template for the other 54 action plans for threatened species (or group of species) that are already published in Brazil (ICMBio, 2017a). We extracted curassow reproductive data and historical and contemporary records of the species from the original and reviewed Action Plan of this species (CEMAVE, 2013; IBAMA, 2004). Species survival probabilities and home range data were extracted from literature (Bernardo et al., 2011a; Bernardo et al., 2011b) (see Appendix, section A2.2).

Figure 1 here

2.3 Population viability analysis

We used the Vortex 10 software (Miller and Lacy, 2005) to explore how different scenarios of hunting pressure may affect the population viability of curassows. We defined a population to be viable within 100 years if the extinction probability was <2%, i.e. ensuring a >98% probability of population persistence within a specific area. This is a conservative definition of population viability, following the precautionary principle recommended when highly threatened species are considered (Gregory and Long, 2009).

Although it is well-known that hunting pressure is one of the main threats confronting cracids (Brooks and Fuller, 2006; Kattan et al., 2016), crucial data such as sex-biased hunting or the intensity of sustainable hunting offtake are unavailable. Therefore, we simulated four scenarios: (a) no hunting; (b) hunting of one adult heterosexual pair; (c) hunting of two adult females; and (d) hunting of two adult males. We modelled these scenarios as annual threats from the first to the last year of simulation. We set hunting intensity to a minimum to conservatively assess whether even low levels of hunting pressure would suffice to drive populations to local extinction.

We began the simulation by setting the initial population size to one adult heterosexual pair for a carrying capacity (K) of four individuals, which is analogous to a typical family group consisting of one adult heterosexual pair and two chicks. We then used forward simulations to evaluate whether that population was viable. If the population was not viable over a 100-year period, we increased the initial population size by one individual and K by four individuals. We repeated this procedure until we determined the K value and the minimum starting number of individuals required to reach an acceptable extinction risk (i.e. <2% over a 100-year period).

We considered a worst- and a best-case scenario to calculate the minimum forest patch size (S_{min}) required to sustain a viable curassow population, assuming that K is a product of forest area and the density of relatively undisturbed populations (Mandujano and Escobedo-Morelos, 2008). In the worst-case scenario, we assumed that there is no overlap between home ranges of neighboring curassow family-groups (i.e. at a lower population density). In the best-case scenario, we assumed overlap between home ranges of any two family-groups (i.e. higher population density). See details in Appendix (section A2.3).

2.4 Ecological niche modeling

We developed ecological niche models for red-billed curassow to identify forest remnants that still retain suitable environmental conditions for the species persistence. We used climatic variables as a proxy of environmental conditions as climate is related to elevation, vegetation type, and the normalized difference vegetation index (Ichii et al., 2002). It is also related to habitat productivity, which affects cracid densities (Kattan et al., 2016). Moreover, climate is the main driver of species distributions at the global scale (Elith and Leathwick, 2009). We did not use data on present-day land cover in our models because even the oldest available satellite images (~1974) describing forest cover within the species range are relatively recent, whereas confirmed incidence records of the species include historical occurrences at sites converted into agriculture and other anthropogenic land uses centuries ago.

Given the climatic data available in the WORDCLIM database (Hijmans et al., 2005), we used factor analysis to select five variables because they explained most of the data variability in the study region: (1) mean diurnal temperature range; (2) isothermality, i.e. (mean diurnal temperature range / annual temperature range)*100; (3) maximum temperature of the warmest month; (4) precipitation of the driest month; and (5) total precipitation of the wettest quarter. These climatic variables did not exhibit multicollinearity, and their variance inflation factor (VIF) did not exceed ten (O'Brien, 2007). Factor analysis was conducted using the *psych* package (Revelle, 2017) in R 3.4.3 (R Development Core Team, 2017) and VIFs were calculated using the *rms* package (Frank and Harrel, 2017).

We used 67 presence records for red-billed curassows (CEMAVE, 2013) throughout its historical and relictual range. We used six different modeling techniques to develop the ecological niche model for curassows (see Appendix, section A2.4). We adopted the consensus forecasting approach by measuring the mean across all models and using the "no omission" threshold to create a final average model (Araújo and New, 2006; Marmion et al., 2009). Models were generated using 75% of the dataset for training and the additional 25% to evaluate their predictive performance. We used 10,000 background points (i.e. random samples of available environmental conditions) and we used the area under the receiver operating characteristic curve (AUC) (Liu et al., 2011) and the true skill statistic (TSS), which is an alternative measure of model accuracy (Allouche et al., 2006), to evaluate the discriminative ability of the models.

2.5 Combining ENM and PVA outputs to identify priority areas

We identified priority forest patches for the conservation of red-billed curassow by overlapping outputs from PVA and ensemble forecasting into a single spatial representation. Firstly, we used QGIS 2.18.2 (http://www.qgis.org/) to display all forest patches that still provide the minimum habitat fragment size required to sustain a viable population under our 'best-case' and 'worst-case' PVA scenarios. Among these, we only selected forest patches that exhibited median habitat suitability values of ≥0.70, assuming that they still present highly suitable environmental conditions to ensure species persistence.

We prioritized areas that could be set-aside to either protect extant native populations or for the reintroduction of populations. Therefore, we mapped these priority areas for (1) intensification of law enforcement, by pinpointing the forest patches with suitable environmental conditions that hold extant viable populations, (2) both population reintroduction and law enforcement, by indicating the forest patches with suitable environmental conditions that could safeguard viable populations, where native populations are known to be extinct and (3) increasing forest connectivity where the current size of a priority forest patch alone is smaller than 9,500 ha, thereby failing to support a viable population under our worst-case scenario.

We considered that forest patches containing extant native populations have higher conservation priority value than forest patches identified for reintroduction attempts. For further details on priority level ranking, see Appendix (section A2.5).

3. Results

3.1 Population Viability Analysis (PVA)

Our models revealed that a minimum resident population of 56 individuals can be viable in the long-term should hunting pressure not be a threat at any given forest patch and this population exhibit an empirically validated degree of home range overlap. In this 'best-case' scenario, the critical forest patch size threshold would be 3,141 ha, below which the population is no longer considered to be viable (Table 2). Currently, 71 forest fragments spread across the known range of this cracid retain a forest area of 3,141 ha or larger (Table 2).

We found that subsistence or recreational hunting of two adult males or one adult heterosexual pair per population were almost equally detrimental to the long-term population viability (Table 2). Of even greater concern would be the harvesting of two adult females, in which case the population size would be required to be 138 individuals or at least 2.5 times larger than that of the best-case scenario defined as viable. Under the 'worst-case' scenario (i.e. hunting of two adult females and no home range overlap), forest patches of at least 9,500 ha would be required to support viable populations (Table 2). This corresponds to only 20 forest fragments within the entire known range of red-billed curassows or only 0.02% of the combined aggregate area of all extant forest patches within the same region (Table 2).

3.2 Ecological niche modeling

The model outputs for red-billed curassows were highly accurate, as indicated by the high discriminative ability of models with mean AUC values = 0.96 (±0.02) and mean TSS values = 0.90 (±0.05) for the testing data (Fig. A1). The Maxent (AUC= 0.99, TSS= 0.95) and SVM (AUC= 0.99, TSS= 0.98) were the best performing models (Fig. A1, Fig. 2).

Figure 2 here

The final consensus model showed that habitat suitability values of forest fragments located within the species' known distribution ranged from 0.32 to 0.85. Forest patches located in southern Bahia and northern-central Espírito Santo still provide highly suitable environmental conditions for the species survival, compared to forest remnants in the states of Rio de Janeiro and Minas Gerais (Fig. 2-G).

The regions containing highly-suitable forest patches for the species were characterized by low values of mean diurnal temperature range, low values of maximum temperature of the warmest month, low precipitation within the wettest quarter, high precipitation of the driest month and isothermality values close to 1. In other words, these sites had more uniform temperatures and precipitation, being wetter during the driest month of the year and drier during the wettest months.

3.3 Identification of priority areas

Following our site selection criteria, we identified 71 forest patches larger than the minimum size required to sustain a viable population under our best-case PVA scenario. Among these, 26 forest patches presented median suitability values ≥0.70, nine of which were excluded because they were surrounded by less than 30% of forest cover within a 12-km radius (see Appendix section A2.5 for further details on site selection criteria). Thus, 17 forest patches were prioritized, eight of which were selected as priority areas for intensified law enforcement and nine as priority areas for reintroductions (Fig. 3, Table 3).

Figure 3 here

The top priority forest patches holding extant populations are all located in Bahia, as well as the largest forest patches for reintroduction (Fig. 3, Table 3). The best candidate landscape for reintroducing curassow populations is in the state of Rio de Janeiro (ID 14 - Fig. 3, Table 3), which provided the largest amount of forest cover within a 12-km buffer radius (57 020 ha), considering both the target and surrounding forest patches (Fig. 3, Table 3 and Appendix section A2.5 for further details).

4. Discussion

We combined two well-known modeling conservation tools to identify priority areas for a tropical endangered species clinging to the hyper-fragmented Atlantic Forest. We assigned a set of conservation actions for each priority area, namely law enforcement intensification, reintroductions and enhanced habitat connectivity. Such approach is particularly useful in determining exactly where and why financial resources will be allocated for rescuing an endangered species.

For those species with wide distribution, this approach reduces the large number of potential priority areas, helping stakeholders and conservationists to downscale strategies from regional to more local scales. Our conservation planning framework (Fig. 1) can be reproduced for a broad suite of threatened species, specifically when populations are completely isolated and provides clear guidance for practitioners charged with identifying priority areas for species conservation. We, therefore, encourage conservationists and land managers to use similar combined modeling tools to guide conservation planning frameworks to confront regional-scale conservation priority challenges.

Ecological models are considered data-hungry and too complex to be applicable in decision-making processes by most non-scientist practitioners and stakeholders involved in conservation actions (Addison et al., 2013). Indeed, ENMs and PVAs demand a wide spectrum of data sources and their combined use considers both (1) the biophysical conditions to predict environmental conditions for the species, i.e. ENM, and (2) the socioecological requirements of the species, i.e. PVA, to identify conservation priority areas for species restricted to highly-disturbed environments (Fig. 1). In the case of red-billed curassow, two data sources have proved to be efficient in gathering species data required by ENMs and PVAs: the species Action Plan and the Virtual Library of Cracids (see “Species data availability” section in Methods). We recommend the elaboration of action plans and virtual libraries for other species/groups of species, as they facilitate the process of gathering information to feed biodemographic models and help identify knowledge gaps, guiding future studies using similar modeling tools.

Several studies have shown that cracids cannot persist in heavily hunted areas (Barrio, 2011; Brooks and Fuller, 2006; Chiarello, 2000; Kattan et al., 2016; Thiollay, 2005). We have shown that removing curassow females from any relict population is the worst possible threat for the species, combined with habitat loss. Other cracids exhibiting similar home range sizes and population parameters, such as yellow-knobbed curassow *Crax daubentoni*, black curassow *Crax alector* and Salvin's curassow *Mitu salvini*, may also be sensitive to female-biased hunting-induced mortality (Bernal and Mejía, 1995; Bertsch and Barreto, 2008; Santamaría and Franco, 2000). Therefore, the modeling criteria we used here can be adopted by other conservation planning studies focused on related cracids and other game birds.

4.1 Priority areas for extant native populations

We simulated very low levels of hunting pressure to demonstrate the detrimental role of this parameter to the population viability of curassows. Subsistence and recreational hunting is widespread within the remaining species distribution area, including the strictly protected areas where curassows persist (Canale et al., 2012; Chiarello, 2000; Flesher and Laufer, 2013; Pereira and Schiavetti, 2010). Curassows are currently very unlikely to move between forest patches due to the presence of human hunters and domestic dogs which often kill wildlife (Bernardo et al., 2011a; Canale et al., 2012; Cassano et al., 2014), thereby aggravating inbreeding depression and genetic drift in small populations stranded in isolated protected areas (O'Grady et al., 2006).

Among the eight priority areas that currently hold remaining populations of red-billed curassows, seven are strictly protected and one is part of a multiple-use protected area (APA, an acronym for Environmental Protected Area), a private landholding within the Michelin Ecological Reserve (ID 02, Fig.3 and Table 3). Although APAs often overlap private landholdings and fail to enforce environmental legislation (de Marques et al., 2016), this 3,711-ha reserve is one of the few exceptions, safeguarding a curassow population, which is regularly monitored by researchers, reserve staff and park rangers (Flesher and Laufer, 2013; Lima et al., 2008). However, as our PVA analysis shows, this population would likely have been extirpated had it been exposed to hunters because of its modest reserve size (Table 3). Forest patches with similar size to Michelin (e.g. ID 01) continue to be vulnerable to human disturbance, so we ranked them as top priorities (Fig. 3, Table 3).

4.2 Priority areas for reintroduction

Most of the forest patches for reintroduction are multiple-use protected areas in Bahia (Table 3), where strong law enforcement is needed to curb hunting before and during any reintroduction attempt. This game bird is already locally extinct in several sites that have experienced high levels of hunting pressure, such as Monte Pascoal National Park, in Bahia (Alvarez and Develey, 2010). According to our criteria, this is the second largest area prioritized for reintroduction followed by intensified law enforcement to suppress hunting (ID 10, Fig. 3, Table 3), but conflicts therein between indigenous peoples and biodiversity conservation continue to date (Redford, 1989).

The best landscape for reintroductions of captive-bred red-billed curassows is in the State of Rio de Janeiro (site ID 14 - Fig. 3, Table 3). This region provides excellent landscape connectivity (Ribeiro et al., 2009) and already holds a reintroduced captive-bred population (Bernardo et al., 2014; Bernardo and Locke, 2014). Areas surrounding the potential range of reintroduced curassows need to be identified and surveyed by researchers before any reintroduction attempt, particularly those with smallholdings near forests and/or dominated by shade-cocoa agroforestry, where hunters and domestic dogs imposes tangible threats to game birds (Bernardo et al., 2011a; Cassano et al., 2014).

Protected areas within private landholdings, especially private forest reserves (e.g. RPPN, Private Natural Heritage Reserve), could play an essential role in the conservation of curassows, particularly in the northern portion of the species distribution (ICMBio, 2017b).

These areas increase levels of connectivity in landscape structure and severely restrict public access, resulting in lower hunting pressure. Two priority areas for reintroduction (ID 13 and ID 15, Fig. 3 and Table 3) are privately owned, without any federal or state protection. The identification of both priority areas is related to the action number 2.4 contained in the species Action Plan, which states that landowners should be stimulated to conserve forest patches within their properties through RPPNs (IBAMA, 2004).

5. Conclusion

The use of both ENM and PVA for red-billed curassow conservation planning is just one example of how priority areas can be selected for a target species. Researchers frequently prioritize areas based only on measures of diversity, such as species richness or beta diversity, but, although they may account for the occurrence of threatened species, they often ignore long-term population viability. Our approach combines two modeling tools that reconciles often available information on species occurrence and population viability. Our conservation planning framework, albeit focused on a single species, is a promising way forward to inform long-term conservation planning of charismatic flagship species that can mobilize political will and, in turn, the entire ecosystem on which they depend. Priority areas for flagship species should become a central pillar in biodiversity safety nets to protect other species with similar spatial requirements and all additional components of residual biotas in highly-fragmented tropical ecosystems.

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Table 1. Parameters used in the VORTEX software to estimate minimum viable populations of red-billed curassows, *Crax blumenbachii* (LE= lethal equivalents, SD= standard deviation)

Parameters	Values	References
Number of iterations	1,000	-
Number of populations	1	
Inbreeding depression	6 LE	(Crnokrak and Roff, 1999; O'Grady et al., 2006)
% of the effect of inbreeding due to lethal recessive alleles	50	(Crnokrak and Roff, 1999; O'Grady et al., 2006)
Breeding system	Monogamy	(IBAMA, 2004)
Age of first reproduction (♀ / ♂)	3 / 3	(IBAMA, 2004)
Maximum age of reproduction	10	(IBAMA, 2004)
Annual % of breeding adult females (SD)	70% (5)	(IBAMA, 2004)
Mate monopolization	95%	(Bernardo *et al*., 2014)
Clutch size distribution	80% (2 chicks) e 20% (1 chick)	(IBAMA, 2004)
Maximum clutch size	2	(IBAMA, 2004)
Overall offspring sex ratio	50:50	(IBAMA, 2004)
% Annual mortality rate (SD)	Age 0-1 years= 35(5), age 1-2 years = 25(5), age 2-3 years = 10 (5) and age >3 years = 8 (2)	(IBAMA, 2004)

540

Table 2. Minimum viable populations of red-billed curassow, *Crax blumenbachii* (MVP, as the number of individuals), minimum size (ha) and number of forest patches available under different scenarios of hunting pressure with and without home range overlap between neighbouring family groups. K= carrying capacity (expressed as number of individuals); * Best-case scenario; ** Worst-case scenario.

Scenarios	MVP	K	Minimum forest patch size (ha)		Number of forest patches available	
			Without overlap	With overlap	Without overlap	With overlap
No hunting	56	67	4,188	3,141*	51	71*
Hunting of two adult males per year	95	107	6,688	5,016	32	44
Hunting of an adult heterosexual pair per year	100	110	6,875	5,156	30	43
Hunting of two adult females per year	138	152	9,500**	7,125	20**	30

Table 3. Priority areas for the conservation of red-billed curassow *Crax blumenbachii* in the Brazilian Atlantic Forest.

ID[a]	Size[b]	Brazilian State[c]	Surrounding forest patches[d]	Forest cover[e]	Current population[f]	Protection status	Recommended management action[g]	Latitude[h]	Longitude[h]
1	3,430	BA	28 689	35%	Yes	Integral protection	law & connect	-40.081	-19.010
2	3,711	BA	18 808	17%	Yes	Sustainable use	law & connect	-39.957	-19.148
3	6,258	BA	31 904	32%	Yes	Integral protection	law & connect	-39.309	-17.067
4	11 967	BA	50 884	41%	Yes	Integral protection	law	-39.257	-13.780
5	17 707	ES	41 519	32%	Yes	Integral protection	law	-39.091	-14.455
6	21 893	BA	50 728	32%	Yes	Integral protection	law	-39.060	-14.234
7	23 313	ES	49 010	31%	Yes	Integral protection	law	-39.116	-15.146
8	24 084	BA	51 755	29%	Yes	Integral protection	law	-39.238	-16.511
9	12 116	BA	45 370	37%	No	Sustainable use	reintrod	-39.045	-14.354
10	11 326	BA	38 757	27%	No	Integral protection	reintrod	-39.324	-16.873
11	11 503	BA	42 025	34%	No	Sustainable	reintrod	-39.039	-16.193

						use			
12	8,798	BA	44 184	39%	No	Sustainable use	reintrod & connect	-39.416	-17.014
13	7,844	BA	39 070	31%	No	No protection	reintrod & connect	-39.051	-14.363
14	7,810	RJ	57 020	42%	No	Sustainable use	reintrod & connect	-39.039	-16.193
15	5,709	RJ	42 722	38%	No	No protection	reintrod & connect	-42.197	-22.440
16	5,493	BA	30 563	31%	No	Sustainable use	reintrod & connect	-39.110	-16.330
17	3,444	BA	27 663	32%	No	Sustainable use	reintrod & connect	-42.037	-22.298

[a]ID= identification number of the forest patch, which corresponds to those in Fig. 3.
[b]Size= forest patch size (ha).
[c]Brazilian states: A= Bahia state; ES= Espírito Santo state; RJ= Rio de Janeiro state.
[d]Surrounding forest patches= amount of forest cover within a 12-km buffer radius, including the forest patch size (ha).
[e]Forest cover = percentage of forest cover within the 12-km radial buffer.
[f]Current population = presence of extant native populations of red-billed curassows.
[g]Recommended management action: law & connect = intensification of law enforcement and enhanced forest connectivity; law= intensification of law enforcement; reintrod = reintroduction of red-billed curassow population after law enforcement.; reintrod & connect = reintroduction of red-billed curassow population after law enforcement, and enhanced forest connectivity.
[h]Latitude and Longitude: geographic coordinates in decimal degrees.

FIGURE CAPTIONS

Figure 1. Representation of conservation planning framework using both PVAs and ENMs, showing key data requirements to feed combined modeling tools, such as in this study, used to identify priority areas for long-term species persistence.

Figure 2. Ecological niche models of red-Billed Curassow *Crax blumenbachii* using six different modeling techniques: generalized additive models (A), generalized linear models (B), support vector machine (C), climatic envelope (D), random forest (E), and Maxent maximum entropy (F). The final consensus model is represented in panel G. Top left inset map shows the geographic distribution of the red-Billed Curassow within the phytogeographic boundaries of the Atlantic Forest biome (grey shading).

Figure 3. Priority areas for the conservation of the red-billed Curassow *Crax blumenbachii* in our 'best-' and 'worst-case' PVA scenarios. Numbers correspond to the forest patch ID column shown in Table 3. Forest patches with extant native populations: 1= one of the forest patches within Conduru State Park; 2= Michelin Ecological Reserve; 3= Capitão Private Reserve/ Conduru State Park; 4= Una Biological Reserve; 5= Vale Natural Reserve; 6= Pau Brasil National Park; 7= Sooretama Biological Reserve; 8= Descobrimento National Park.

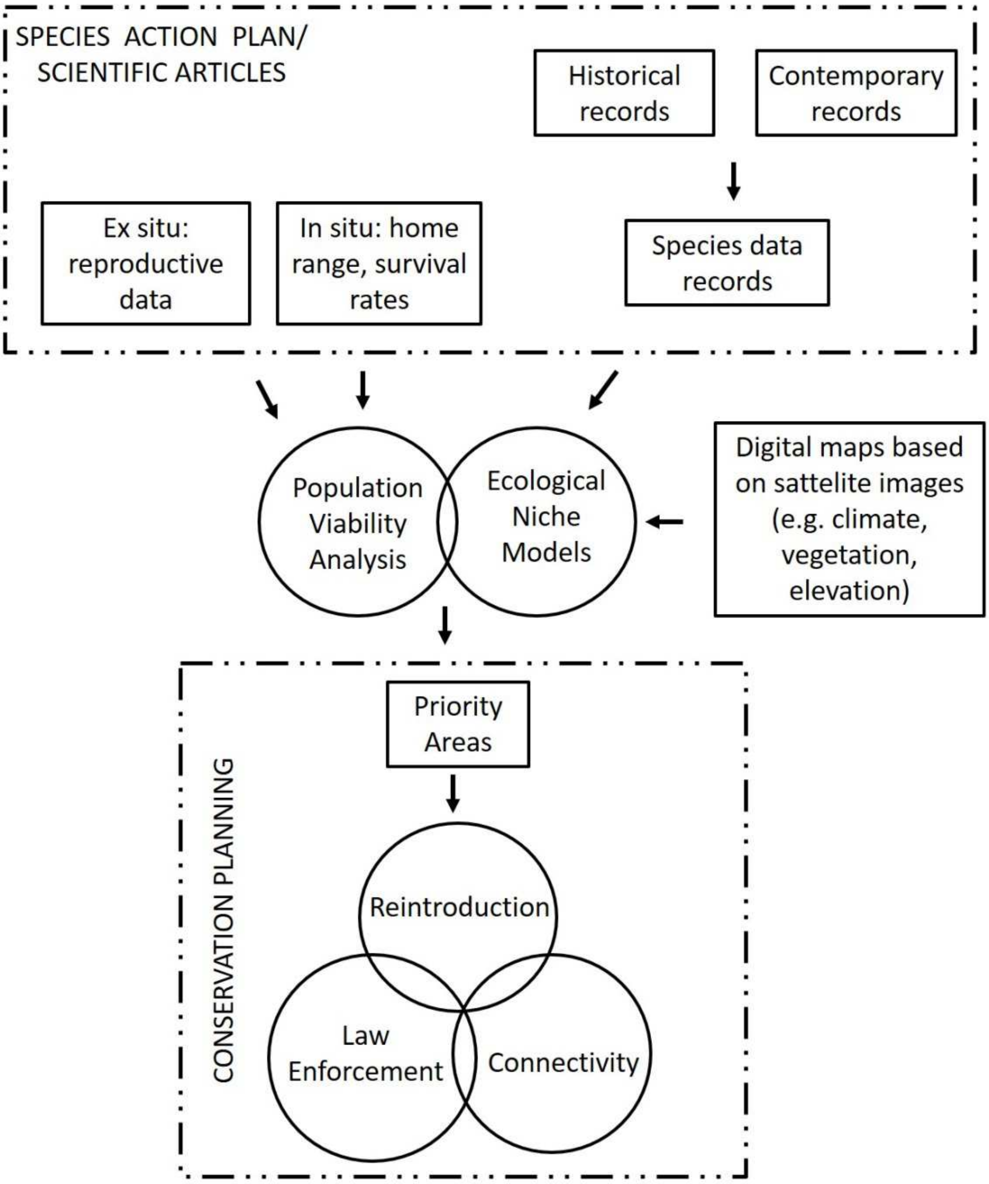
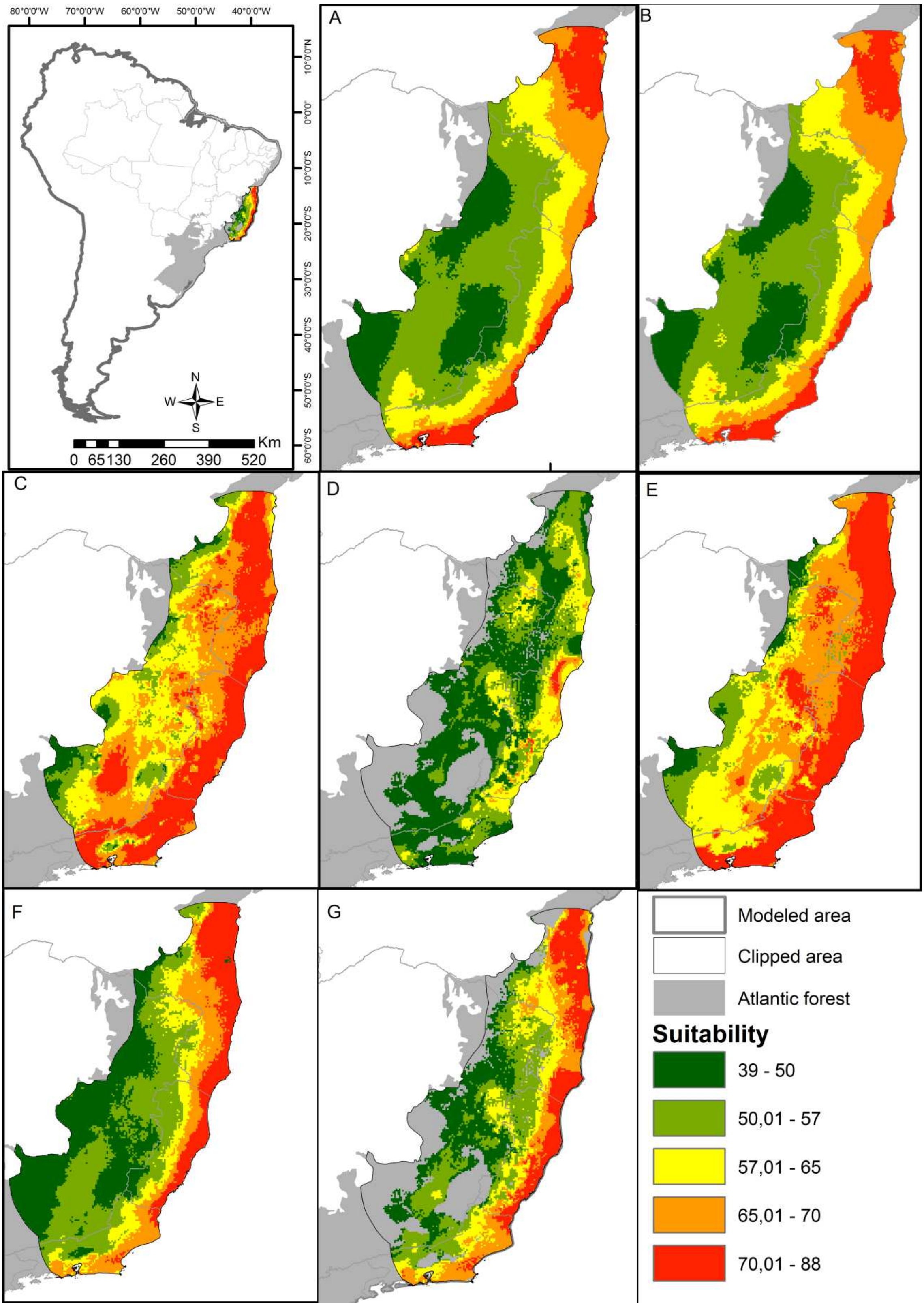
595

SPECIES ACTION PLAN/
SCIENTIFIC ARTICLES
Historical records
Contemporary records
Ex situ: reproductive data
In situ: home range, survival rates
Species data records
Population Viability Analysis
Ecological Niche Models
Digital maps based on sattelite images (e.g. climate, vegetation, elevation)
CONSERVATION PLANNING
Priority Areas
Reintroduction
Law Enforcement
Connectivity

Figure 1.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70,01 - 88

Figure 2.

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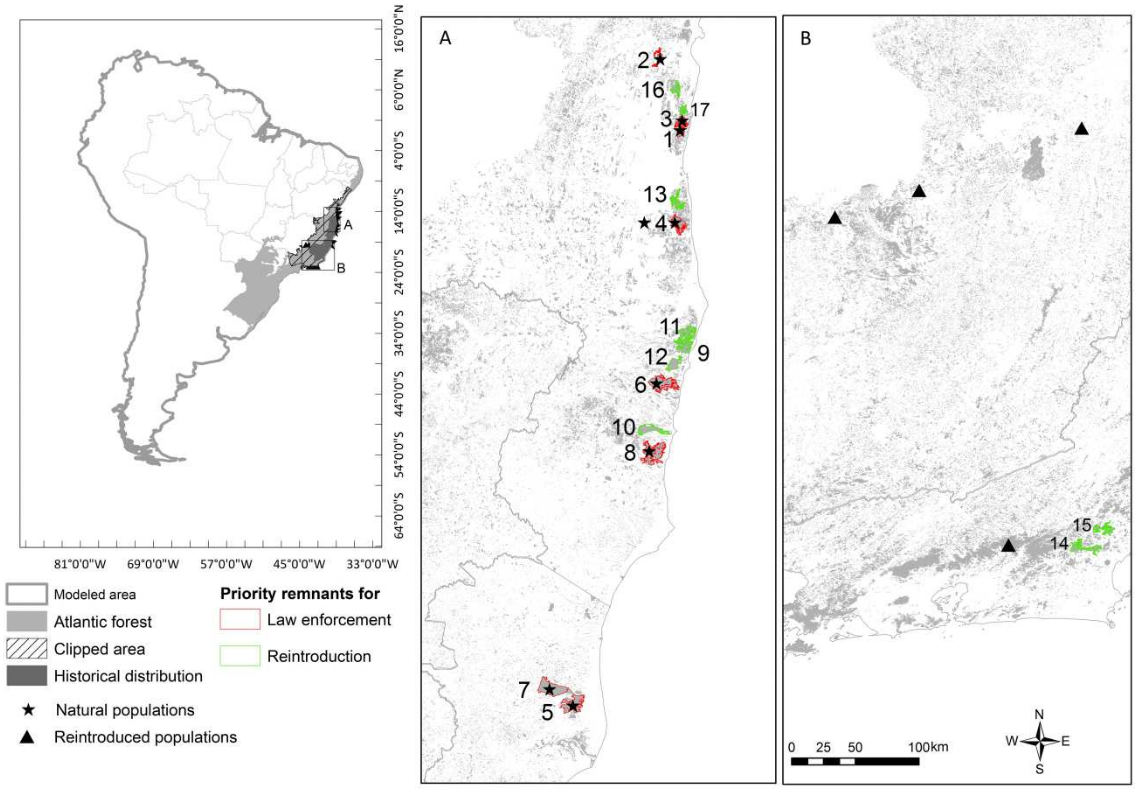
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Figure 3.

Appendix

Combining modeling tools to identify conservation priority areas: a case study of the last large frugivorous bird in the Atlantic Forest

Fernando César Gonçalves Bonfim, Paulo Henrique Chaves Cordeiro, Carlos A. Peres, Gustavo Rodrigues Canale and Christine Steiner São Bernardo

A2. Methods

A2.1 Study area

The original distribution range of red-billed curassows formerly encompassed only a small portion of the Atlantic Forest, which is one of the "hottest" and yet most threatened and most densely populated biodiversity hotspots (Cincotta et al., 2000; Myers et al., 2000). This is one of the most diverse ecosystems on the planet, which stretches along the Brazilian Atlantic coastline, and reaches northeast Argentina and eastern Paraguay. The Atlantic Forest is vulnerable to logging and agricultural expansion, particularly by extensive single-crops of soybean and sugarcane (Ribeiro et al. 2009). Reduced to 12.5% of its original area, the Brazilian Atlantic Forest is highly fragmented, with most remnants smaller than 50 ha and ~1.5 km from the closest forest patch (Ribeiro et al. 2009).

A2.2 Data availability

The workshop which generated the species action plan was organized by the Brazilian Environmental Agency (IBAMA/ICMBio) and was attended by 17 Brazilian and three foreign specialists, researchers and stakeholders, who compiled information on the species biology and conservation actions to be implemented within a pre-defined timescale according to a priority rank (IBAMA, 2004). An action plan must be reviewed periodically to monitor and evaluate the actions implemented and to update the species conservation requirements. In the case of red-billed curassow, a meeting to review its action plan took place in 2012. One of the outcomes of this meeting was an updated database on historical and contemporary records of the species occurrence (CEMAVE, 2013), which was used in our models.

Species survival probabilities and home range data were derived from 53 captive-bred red-billed curassows tagged with backpack transmitters and subsequently released and monitored at an Atlantic Forest remnant in the state of Rio de Janeiro between 2006 and 2008 (Bernardo et al., 2011a; b). This reintroduction programme followed the protocol established by the Species Action Plan (IBAMA, 2004). These scientific articles, as well as others reporting ex-situ observations and/or a few records from small wild populations of red-billed curassows can be found in the "Virtual Library of Cracids", which consists of a collection of all peer-reviewed papers encompassing this galliform family, which is regularly updated by researchers who publish on cracids.

On the basis of data available for red-billed curassows, we were able to combine modeling tools to identify conservation priority areas for the species which is relevant to four actions included in its Action Plan: 2.4 (creation of private areas within the species distribution range), 2.5 (evaluate the expansion of protected areas within the species distribution range), 3.3.1 (refine the potential distribution model presented in the action plan) and 5.2 (selection of potential areas for reintroduction) (IBAMA, 2004).

A2.3 Population viability analysis

Vortex 10 software (Miller and Lacy, 2005) models deterministic forces and stochastic events to simulate the extinction processes of wildlife populations (Miller and Lacy, 2005). Vortex is a widely used software that has been applied to conservation planning of threatened species and provides accurate population predictions (Brook et al., 2000).

We were particularly interested in demonstrating the synergetic effect of deterministic forces (i.e. hunting) with demographic stochasticity on the persistence of red-billed curassow populations. Therefore, we did not include other stochastic processes that are known to have even greater impacts on populations, such as environmental variation, catastrophic events, and genetic drift.

K is commonly assumed to be a product of forest area and the density of relatively undisturbed populations (Mandujano and Escobedo-Morelos, 2008). As a typical curassow family group occupies a home range size of ~250 ha (Bernardo et al., 2011b), we established that the population density of one family group (D_{ofg}) = 4 individuals / 250 ha = 0.016 individuals/ha. Therefore, we were able to estimate the minimum forest patch size (S_{min}) required to sustain a viable curassow population, according to the equation $K= S_{min}* D_{ofg}$. This is the worst-case scenario, in which we assumed that there is no overlap between home ranges of neighboring curassow family groups. This scenario is consistent with data from reintroduced adult males which exhibit high levels of territoriality and have shown no overlap between adjacent home ranges (Bernardo et al. 2011b). However, the home range of curassows may overlap in some cases (Bertsch and Barreto, 2008), although there is a lack of consensus on the proportion of home range overlap. For instance, reintroduced sub-adult and adult females red-billed curassows exhibited up to 17% overlap between neighboring home ranges (Bernardo et al. 2011b). In addition, an adult male *Crax daubentoni* displayed >95% overlap with home ranges of several females during the breeding season (Bertsch and Barreto, 2008). Due to a lack of consensus, we ran sensitivity tests to check whether home range overlap is a sensitive parameter that significantly alters the extinction risk of curassows (Miller and Lacy, 2005). Therefore, we constructed a best-case scenario to calculate S_{min}, whereby we arbitrarily assumed a 50% overlap between home ranges of any two family-groups, i.e. 8 individuals occupy an area of 375 ha, of which 125 ha overlap. We concluded that population density of two family groups with overlapping home range areas (D_{ove}) = 8 individuals/375 ha = 0.021 individuals/ha, and we used this value in the equation $K= S_{min}* D_{ove}$.

Life history parameters of red-billed curassow used in the PVA were extracted from the species action plan and from the outcome of monitoring a reintroduced population in the state of Rio de Janeiro over a 25-month period (IBAMA, 2004; Bernardo *et al.*, 2011b, 2014) (Table 1).

A2.4 Ecological niche modeling

We obtained a total of 85 reliable presence records for red-billed curassows (CEMAVE, 2013) throughout its historical and relictual range, from which we selected 67 after discarding duplicate records within 2.5 arcmin pixels (~5-km^2). This pixel size enabled us to use historical records for which spatial precision of known localities is inexact and lower than those of contemporary records (Guisan et al., 2007). As we used both historical (dating back to 1938) and current records (collected between 2001-2014), we assumed that the climatic conditions examined here did not change over these ~7 decades (Wiens et al., 2010).

We used six different modeling techniques to develop the potential geographic distribution model for curassows, including regression methods (generalized linear models and generalized additive models) (Guisan et al., 2002), machine learning methods (random forest and support vector machine) (Breiman, 2001; Drake et al., 2006), maximum entropy (Phillips et al., 2006) and climatic envelope (Busby, 1991). These six single-models provided an ensemble of predictions, which contained the six separate predicted distributions generated for curassows. We adopted the consensus forecasting approach by measuring the mean across all models and using the "no omission" threshold to create a final average model (Araújo and New, 2006; Marmion et al., 2009). This approach has clear advantages over single-model forecasting mainly because it reduces prediction uncertainty and, therefore, may be used for planning conservation and management strategies (Araújo and New, 2006; Marmion et al., 2009).

A2.5 Combining ENM and PVA outputs to identify priority areas

Among all sites holding viable populations given the best-case scenario, we allocated the highest priority level to those that would support a viable population under the worst-case scenario, i.e. those that need (1) urgent intensification of law enforcement to halt hunting and (2) to increase forest connectivity. Among the sites prioritized for reintroduction, we allocated a higher priority to forest patches that would support a viable population of red-billed curassow even under our worst-case scenario (i.e. patches >9,500 ha). Forest patches between 3,141 and 9,500 ha were only prioritized for reintroduction when embedded within a landscape containing >30% of forest cover within a 12-km radius — the maximum dispersal distance from release sites exhibited by reintroduced individuals (Bernardo et al., 2011b).

Conservation managers should bear in mind that the selection of priority areas for reintroductions, as reported in this study, is only the first step in a reintroduction program. Further studies on local hunting pressure and other potential threats, e.g. nest-predation (Canale and Bernardo, 2016), must be systematically evaluated prior to any translocation or reintroduction attempt (IUCN/SSC, 2013).

Figure A1

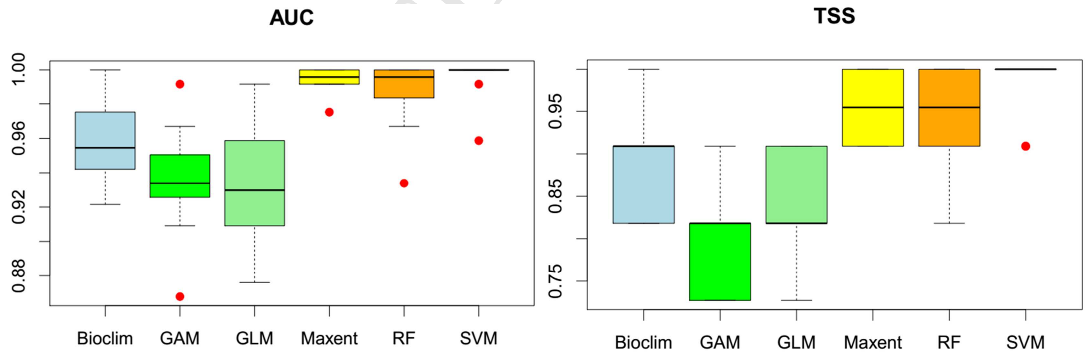

Figure A1. Box-whisker plots summarizing the results of the discriminative ability of our models (AUC and TSS) when testing the data, including median values (line across box), range excluding outliers (error bars), interquartile range containing 50% of values (box), and outliers (red dots). Modeling techniques (along x-axes) include Bioclim = climatic envelope, GAM = generalized additive models, GLM = generalized linear models, Maxent = maximum entropy, RF= random forest, and SVM = support vector machine.