Relative vulnerability to hurricane disturbance for endangered mammals in Mexico: a call for adaptation strategies under uncertainty

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Abstract:

Most climate change vulnerability assessments of species focus on characterizing the degree to which species are likely to be affected by changes in mean climatic conditions. Yet, there has been little progress in the explicit assessment of species vulnerability to extreme climatic events (ECEs) which have the potential to cause substantial environmental disturbance and potentially catastrophic declines of wildlife populations. Using a trait-based approach, we assessed the relative vulnerability of populations of wild animal species to hurricanes, focusing on 25 terrestrial mammals at high risk of extinction in Mexico. Our assessment uses biological traits associated with heightened sensitivity (low vagility and territoriality) and low adaptive capacity (restricted diet and habitat specialization) in relation to their predicted exposure to hurricanes, based on records of occurrence of hurricanes in their geographical range over the past 45 years. We found that territoriality was present in most of the species assessed (n = 20) followed by habitat specialization (n = 6), low vagility (n = 6) and diet specialization (n = 3). Two subspecies of spider monkeys (*Ateles geoffroyi vellerosus* and *A. g. yucatanensis*), two howler monkeys (*Alouatta pigra* and *Alouatta palliata mexicana*) and the silky anteater (*Cyclopes didactylus*) all emerged from this assessment as highly-vulnerable to population declines from exposure to hurricanes. In the absence of any robust predictive framework for assessing risk to species from ECEs we suggest that the integration of data on hurricane exposure and species' intrinsic biology, as presented here, represents a coherent and informative basis for risk evaluation and the design of possible mitigation strategies.

Keywords: Hurricane disturbance, Mammals, Population decline, Species traits, Vulnerability assessment

Introduction

A critical task for conservationists is the identification of sources of threat to wildlife populations, species, and ecosystems, and the development of comprehensive strategies to minimize irreversible losses while balancing the needs of people (Hooper *et al.,* 2012; Seddon *et al.,* 2014; Perring *et al.,* 2015). As a result of past and current rates of human appropriation of natural capital (Cardinale *et al.,* 2012; Newbold *et al.,* 2015), most conservation efforts focus on threats of direct anthropogenic origin such as urbanization, deforestation, and wildlife trade (Ceballos *et al.,* 2017). By contrast, less attention has been given to threats of indirect anthropogenic origin, such as those associated with climate change and in particular, the short-term impacts of extreme climatic events (ECEs). In the past decade, however, a growing body of studies suggest that ECEs such as cold waves, droughts, floods, heat waves, and hurricanes are becoming major forces contributing to biodiversity loss and change (Alcamo *et al.,* 2012; Wang *et al.,* 2015; Clark *et al.,* 2016).

The consequences of ECEs on wildlife populations are difficult to observe and document (Fey *et al.,* 2015) yet mitigating actions need to be designed and implemented. Geospatial information about recent ECEs is growing and can be used for the identification of areas and species most likely to be affected (Ameca y Juárez & Jiang, 2016; Lee *et al.,* 2017). For recently exposed and intrinsically susceptible species, pre-existing or novel environmental stressors can lead to serious population declines (Craig *et al.,* 1994; Munson *et al.,* 2008). Early identification of species' vulnerability from recent ECEs can enable managers to incorporate this information in existing action plans addressing short-term threats to populations' survival, and identify options for reducing the vulnerability over longer timeframes.

One analytical framework gaining support in biodiversity conservation and management is the climate change vulnerability assessment (CCVA). CCVAs were initially developed to safeguard human societies (e.g., Füssel & Klein, 2006). In the conservation planning and management of species, CCVAs broadly assess species' vulnerability as function of exposure, sensitivity, and adaptive capacity. Exposure describes the nature, magnitude and rate of climatic (e.g., precipitation) and associated environmental changes (e.g., drought frequency) experienced by populations of a species (Dawson *et al.,* 2011; Foden & Young, 2016). Sensitivity and adaptive capacity are expected to be shaped by species' intrinsic biological characteristics and the plasticity of such responses to new climate and environmental pressures (Dawson *et al.*, 2011; Nicotra *et al.,* 2015). In the analysis of these three elements, CCVAs can adopt correlative, mechanistic, and trait-based modelling approaches (Foden & Young, 2016). Given the stochastic nature of ECEs, predicting their intensity and distribution remains challenging (Seneviratne *et al.*, 2012). In this study, we adopted a trait-based approach focusing on species' sensitivity and adaptability, integrated with recent past exposure to hurricanes.

Standing out as the fourth ranked nation in terms of overall species richness and native mammalian fauna, Mexico hosts more than 10% of the world's biodiversity (Sarukhán *et al.,* 2014). At the same time, Mexico is recurrently impacted by ECEs, with hurricanes regularly occurring but expected to become more intense in coming decades (Bruyère *et al.,* 2017). While species historically exposed to hurricanes may be well adapted to cope with this environmental disturbance (Pascarella *et al.,* 2004; Cole *et al.,* 2014), increased exposure (rates or intensity) might surpass adaptability or the capacity to recover through e.g. high reproductive output. Even high reproductive rates do not prevent animals from experiencing large declines (Cuarón *et al.,* 2008; Ramírez-Barajas *et al.,* 2012). Investigating traits associated with heightened sensitivity and limited adaptive capacity to short-term hurricanes disturbance can help us to identify those species most likely to experience potentially large declines in the short-term as ECEs become more frequent and/or intense. In turn, context-specific management can be implemented to enhance the coping strategies of the most vulnerable species, particularly of those that are already at high risk of extinction due to human activities.

In this study, ECE vulnerability to population declines is assessed for 25 species and subspecies of terrestrial mammals within the Mexican territory (for simplicity, hereafter referred to as "species"). As observed changes in severe weather across Mexico may indicate even worse events to come (ANVCC 2017), it is imperative to learn about the potential vulnerability of resident biota to these phenomena, and move forward to prioritise limited resources to protect them. In this regard, the Mexican government strive to support the consolidation of tools and data with the aim of identifying species and areas most vulnerable to effects derived from climatic impacts (INECC 2014) and inform adaptation and mitigation strategies (CONABIO 2016; CONANP 2015). Hence, while we focus on endangered mammal species and on one type of ECE, this study illustrates how such identification processes may be conducted, and provides several alternatives to enhance the resilience of affected habitats that may benefit multiple species in the face of rapidly evolving environmental pressures.

Materials and Methods

Species data

25 terrestrial mammal species representing 9 taxonomic Orders (Carnivora, Cetartiodactyla, Cingulata, Didelphimorphia, Lagomorpha, Perissodactyla, Pilosa, Primates, and Rodentia) were selected. These species cover an array of different life-styles, ecologies, and habitat preferences while being categorized as "in danger of extinction" by the Mexican Official Norm for Environmental Protection of Wildlife (Semarnat 2010). The category includes species whose range or total population size within Mexico have fallen dramatically, threatening their biological viability as a result of diseases, overexploitation and drastic modification of their habitat. Terrestrial mammals were chosen because compared to marine or volant mammals they are expected to find it more difficult to avoid direct impacts from hurricane effects by

rapidly leaving the affected area (Ameca y Juárez *et al.,* 2013), and represent a high priority group for conservation in Mexico (Vázquez *et al.*, 2009; Urquiza-Haas *et al.,* 2011).

The IUCN Red List assessment process provides detailed information regarding the taxonomy, ecology, causes of endangerment, and geographic distribution of species (IUCN 2017a). The latter element is generated using bounding polygons associated with different certainty of a species' presence in an area as follows: "extant", "possible extant", "possibly extinct", "extinct", and "presence uncertain" (IUCN 2017b). In this regard, "extant" range polygons falling within Mexico in the original geospatial dataset (IUCN 2017a, Accessed November 2017) were clipped using spatial analysis tools in ArcGIS (ESRI 2011 Version 10.0) for further analysis. The "extant" code identifies areas where species are known or very likely to occur based on current and recent records and where suitable habitat at appropriate altitudes remains (hereafter refer to as current distribution). The choice of these polygons rather than the entire species range helps to reduce the risk of overestimating exposure while attempting to capture areas where populations are most likely to occur.

Based on expectations from ecological and extinction risk theory, we investigated species traits that have been associated with heightened sensitivity and low adaptive capacity to climate change impacts and identified those that could also be relevant to our vulnerability assessment. Accordingly, we reviewed the trait categorization compiled by the IUCN-SSC Guidelines for Assessing Species Vulnerability to Climate Change (Foden & Young, 2016) as well as recently published CCVAs using trait-based approaches (e.g, Graham *et al.,* 2011; Foden *et al.,* 2013, Garnett *et al.,* 2013). The review resulted in two traits indicative of "heightened sensitivity" (low vagility and territoriality), and two related to "low adaptability" (habitat and diet specialization) (Table 1). We set binary thresholds associated with presence or absence of a given trait by referring to widely accepted categorizations used in CCVAs for these traits (see Supporting Information Table S1). Trait data were then extracted from the peer-reviewed scientific literature, field guides, authoritative accounts of the natural history and ecology of mammals in the region (*Handbook of Mammals of Mexico*) and the species' technical reports from the Mexican Commission for the Knowledge and Use of Biodiversity assembled by expert assessors (Supporting Information Table S2).

Hurricane data and quantification of species exposure

Available geospatial data on hurricanes impacting the Mexican land area (period 1970 - 2014) were extracted as shapefiles from the joint database DEWA/GRID-Geneva of the United Nations Environment Programme (UNEP 2005). We defined hurricane exposure as any overlap between areas affected by one or more hurricanes and the species "extant" distribution. Thus in this first stage, the geographic distributions of areas affected by hurricanes were overlaid with the species' extant distributions one at the time, and the extent of coverage, expressed as a percentage, determined. In the second stage, indicators of "significant" and "high" hurricane exposure were defined as overlaps between one or more hurricanes and species' extant ranges of $\geq 25\% < 75\%$ and $\geq 75\%$ respectively, during the 45-year time period (See Table 1).

Vulnerability assessment

The vulnerability assessment to hurricane impacts (Figure 1) is based on a published conceptual framework for assessing population declines from extreme natural events (Ameca y Juárez *et al.*, 2012). Species that were significantly or highly exposed to hurricanes were initially grouped in a vulnerability rank coded as follows: "0" Low Vulnerability; "1" Medium Vulnerability; "2" High Vulnerability. Referring to Figure 1, a species possessing up to two traits indicative of heightened sensitivity (S) and up to two traits of low-adaptability (LA), indicated as "Yes > 0", will be considered as being associated with a low level of vulnerability provided that exposure (E) is either non-significant or entirely absent (Figure 1, case i). For a species which is significantly exposed, indicated as "E ≥ 25%", and lacks the traits indicative of sensitivity and low adaptability the level of vulnerability is also considered low (case i). However, if an exposed species has up to two traits indicative of sensitivity (case ii) "or" low-adaptability (case iii), then it will be considered as medium vulnerability. Finally, when an exposed species exhibits up to two traits indicative of sensitivity "and" up to two traits shaping low adaptability then it will be considered as highly vulnerable (case iv).

In the assessment, the percentage of a species range impacted by hurricanes was used to determine its ranking position within a vulnerability class (low, medium, high). In this regard, intrinsically susceptible species whose extant distribution overlaps most with hurricanes are expected to rank at the top of a vulnerability class. As a result, for sensitive species and those unable to adapt, it is possible to differentiate those who have minimal exposure (scenarios similar to case i) from those that exhibit higher levels of exposure (scenarios similar to case iv).

Lack of data and/or weak support about the role that a species trait may play under specific climate-related phenomena can affect estimates of its vulnerability (Foden & Young, 2017). To account for this, we evaluated the confidence of vulnerability estimates using two criteria for the species traits being assessed: missing data (criterion a) and uncertainty in the role of the species traits in relation to hurricane effects (criterion b) (See Supporting Methods). Finally, cluster analysis was carried out to examine associations between sensitivity and low adaptability traits as well as species most similar/dissimilar based on their respective scores for such traits. We ran the cluster analysis using the *hclust* function in the R software (Version 3.4.2, R Core Team 2017). The *hclust* function performs a hierarchical cluster analysis using a set of dissimilarities for the objects being clustered. We used the Ward's clustering criterion (method *ward.D2*) which is based on a sum of squares producing groups that minimize within-group dispersion at each binary fusion step (Murtag & Legendre, 2014).

Results

Species scores for sensitivity, adaptability, exposure and overall vulnerability are presented in Table 2. The level of vulnerability shaped by these indicators was not homogenous across taxa: Primates was the Order with the greatest number of highly vulnerable species, Carnivora and Rodentia comprised the greatest number of medium-vulnerability species, and representatives from Didelphimorphia and Cingulata exhibited low vulnerability (Figure 2).

The two subspecies of spider monkeys (*Ateles geoffroyi vellerosus* and *A. g. yucatanensis*), the two howler monkeys (*Alouatta pigra* and *Alouatta palliata mexicana*), and the elusive silky anteater (*Cyclopes didactylus*) all ranked as highly-vulnerable. The extant distribution affected by hurricanes for these species lies predominantly in the Yucatan's Peninsula but also in the southern states of Chiapas, Oaxaca, Tabasco, Veracruz, and southern Tamaulipas (Figure 3, panel a). The extant distribution of species classed as medium vulnerability (mainly from the Orders Carnivora and Rodentia) stretches along the Atlantic coast (states of Sinaloa, Nayarit, Jalisco, Colima, Michoacán, Guerrero, and Oaxaca) across the Isthmus of Tehuantepec into the Yucatan Peninsula, including the states of Veracruz and Tamaulipas in the Gulf of Mexico (Figure 3, panel b). Highly exposed to hurricanes, the brown four-eyed opossum (*Metachirus nudicaudatus*) and the water opossum (*Chironectes minimus*) did not exhibit any of the traits we associated with heightened sensitivity and low adaptability to hurricane impacts, as was the case for the northern naked-tailed armadillo (*Cabassous centrialis*). Thus, these species were classed as low vulnerable. The area of their geographic distribution that is affected by hurricanes overlaps partially with that of those mammals found to be highly vulnerable in southern Mexico (Figure 3, panel c).

A cluster analysis of species traits revealed that habitat and diet specialization were the most closely associated compared to other traits (Figure 4), and had the greatest influence in shaping the observed vulnerability ranks for the assessed species (Table 2). A cluster analysis focused on species revealed six main clusters, with species sharing similar traits shaping heightened sensitivity and low adaptability (Figure 5). In particular, of the five highly vulnerable species, three (*C. didactylus, A. g. vellerosus,* and *A. g. yucatanensis*; cluster d) clustered as a result of being territorial and diet/habitat specialists. The remaining two highly vulnerable species (*A. p. mexicana* and *A. pigra*; cluster b) clustered independently because in addition to being territorial and habitat specialist they exhibit low vagility.

Discussion

In response to the sustained pressures of global environmental change on biodiversity, CCVAs represent a useful tool for adaptation planning. They help identify biological or ecological systems (e.g., species or ecosystems) likely to be most affected by future climate events and provide a clear description of why they are likely to be vulnerable (Glick *et al.,* 2010). Depending on data availability and quality, CCVAs with a range of levels of complexity can be adopted to answer these questions and provide a basis for reactive or proactive interventions (Pacifici *et al.,* 2018; Willis *et al.,* 2015; Young *et al.,* 2016). Trait-based CCVAs make use of species biological characteristics to estimate sensitivity and adaptive capacity to a given amount of exposure to climate impacts (Foden & Young, 2016). The quantification of the exposure component in CCVAs is primarily based on projections of changes in continuous long-term climatic conditions (e.g., precipitation, solar radiation, temperature) overlapping relevant areas with species' geographic distributions (Pacifici *et al.,* 2015). By contrast, the stochasticity and spatiotemporal scale of ECEs, in particular of hurricanes, makes it difficult to predict future trends of exposure with any reliability (Seneviratne *et al.,* 2012). Nevertheless, observations of recent past exposure are valuable for identifying species and ecosystems that may be less resilient to current and/or near-future threats, and hence inform adaptive management (Lee *et al.*, 2017). This study illustrates how such identification process of vulnerable species may be conducted.

Vulnerability to hurricane-driven population declines for the 25 species assessed was not taxonomically homogenous. Species were clustered as a result of sharing the same combination of biological attributes associated with high sensitivity and low adaptive capacity. Territoriality was present in most of the species (n = 20) followed by habitat specialization (n = 6), low vagility (n = 6) and diet specialization (n = 3). Trait scores, however, arise from a summation rule procedure. Moreover, there is limited direct evidence about the weight of the species traits in relation to hurricane effects. With these caveats in mind, vulnerability classes determined for these species must be interpreted as relative rather than absolute measures of vulnerability.

The species identified as highly vulnerable, spider monkeys (*A. g. vellerosus* and *A. g. yucatanensis*) and howler monkeys (*A. p. mexicana* and *A. pigra*), are found in areas highly exposed to hurricanes, are territorial, and are habitat specialists favouring evergreen rainforest (Estrada & Coates Estrada, 1984; Van Belle *et al.*, 2013). Howlers exhibit a more flexible diet compared to spider monkeys, but hurricane-driven strong winds and precipitation can deplete food resources for these primates through massive defoliation and fruit loss. In Mexico, empirical and theoretical studies stress that neither howler monkeys nor spider monkeys can maintain viable populations in disturbed areas (Estrada & Coates Estrada, 1984; Ameca y Juárez *et al.*, 2010). Thus, these species should merit particular conservation attention to lessen risks of population declines as a result of hurricane-induced habitat degradation and food depletion.

The silky anteater is also a territorial and highly exposed species but in contrast to howler and spider monkeys, it makes use of a range of different forest habitats in southern Mexico such as semi-deciduous, evergreen, cloud and gallery forest (Miranda *et al.*, 2014). Depending on the forest structure this flexibility of habitat use may confer resident populations a variety of physical buffers against strong winds and heavy precipitation. However, the silky anteater ranked as highly vulnerable because it is a slow-moving animal and relies on an exclusive diet of ants all year around (Hayssen *et al.,* 2012), and ants are known to be negatively affected by hurricane-induced disturbance (Sánchez-Galván *et al.,* 2012). Generalist species are expected to be the least affected by habitat disturbance as they tend to have a wider distribution and are also able to exploit a variety of food resources, some of which may become abundant in disturbed areas (Ramírez-Barajas *et al.,* 2012). This is the case of the northern naked-tailed armadillo, the water opossum, and the brown four-eyed opossum, all ranked as low vulnerable in this study.

Although species-specific management practices to reduce the effects of ECEs would be ideal, in practice it could be very challenging, particularly under the prevalent financial constraints in the country. However, practices already in place to reduce vulnerability or enhance resilience against existing impacts for multiple species sharing a common habitat could be adopted to tackle disturbance caused by ECEs. Such management practices can be broadly classed as either reactive (aiming to deal with the disturbance during or right after it occurs) or preventative (aiming to build species and/or habitat resilience to disturbance before this is generated) (Knight *et al.,* 2006; Watson *et al.,* 2011).

Pertaining to reactive management against hurricane impacts, for example, translocation programs aimed to rescue populations affected by human pressures (Canales-Espinosa *et al.,* 2011) can also be implemented for species inhabiting areas where hurricanes are a threat (see also Carlile *et al.,* 2012, and references therein for examples in birds). Some species may be less able to disperse or difficult to locate and capture, and may also have limited flexibility to endure disturbance or to go through emergency transfers. For such species, preventative management focusing on decreasing the probabilities of physical exposure may be a more suitable intervention. For example, tree species with the highest wind resistance such as the gumbo limbo (*Bursera simaruba*), the white stopper (*Eugenia axilaris*) or lignum vitae (*Guaiacum sanctum*)

(See Duryea & Kampf, 2007 for a comprehensive list of tree species) can be used to buffer habitats common to one or more vulnerable animal species (e.g., *C. didactylus*, *P. pygmaeus*). Based on pre-existing monitoring of habitat use and patterns of movement, vegetation corridors with these multi-trunk tree species can also be adopted to connect habitats exposed to hurricanes (e.g., mangrove swamps) to suitable, less physically exposed habitats. In addition, a systematic assemblage of plant species chosen to shape these corridors could also include species that can provide provisional resources to individuals in transit (Luckett *et al.*, 2004; Nasi *et al.*, 2008).

The predictive power of trait-based CCVAs may be compromised by uncertainties such as species data availability and reliability, unknown interactions between traits, and trait scoring (Glick *et al.*, 2010). We evaluated the confidence of our vulnerability estimates using two criteria focusing on missing data (criterion a) and uncertainty about trait roles in relation to hurricane effects (criterion b) (See Supporting Methods). For criterion "a", 22 species scored "good confidence" because trait data were derived from the relevant species. For the remaining three species, (*Procyon pygmaeus*, *Cabassous centralis*, and *Microtus oaxacensis*) no more than one trait had to be inferred from congeneric species. Uncertainty introduced by missing data thus played a very small role in the overall vulnerability estimates. With regard to criterion "b", the traits we assessed have been associated with species susceptibility to climate change impacts (Graham *et al.*, 2011; Foden *et al.*, 2013, Garnett *et al.*, 2013; Foden & Young, 2016). Based on ecological theory, these traits may also be associated with susceptibility to hurricane impacts (Table 1). However, empirical evidence that species with these traits are more likely than others to experience hurricane-driven declines is not available, and this represents a significant source of uncertainty, and a research priority. In this context, species' populations subject to long-term demographic monitoring that are susceptible to hurricane landfalls or similar extreme events are ideal candidates for collecting data related to population size variations (see Mason-Romo et al., 2018). With this demographic fingerprint, future research can explore the associations between the species traits used in our study and the observed population responses. Studies reporting such responses to extreme climate and earth-system events keep accumulating (e.g., Reed et al., 2003; Anderson et al., 2017). Amidst the challenges posed by a changing global climate (Emmanuel 2017), the scientific instruments and modelling of hurricane activity also keep improving steadily (Kohno et al., 2017). We believe that as these population-level data become available, and can be coupled with increasingly available natural history data and improved long-term hurricane forecasting, the validity of our vulnerability estimates and the associated uncertainties can be reassessed.

The framework used in this assessment can also be enriched by accounting for threats from anthropogenic origin, which may interact with and probably amplify impacts from ECEs (Brook *et al.*, 2008; Root *et al.*, 2005). It is also unknown how areas with high incidence of ECEs relate to socioeconomic context and governance (e.g., poverty, population pressure, politic stability, corruption control) and to what extent may compromise on-the-ground actions to assist vulnerable species. In our assessment of 25 mammal species, the southern state Chiapas harboured a significant proportion of the five most vulnerable species while being the state ranking first in poverty, and also the fifth with the lowest per capita income and financial performance (CONEVAL 2014). An assessment inclusive of a thorough consideration of these factors will allow the identification of regional "vulnerability hotspots" where climatic impacts may be most challenging to abate due to low opportunities for successful interventions as a result of low governance and/or poor institutional capacities.

In order to minimize the risk of unanticipated biodiversity loss driven by novel pressures from climate change, we need to foresee the most vulnerable species and ecosystems and ensure they benefit from interventions to secure their long-term existence. Altogether, the integration of data pertaining to recent past exposure to hurricanes coupled with species' susceptibility while accounting for potential sources of uncertainty as presented here is a coherent and informative baseline towards better guidance of processes aimed at identifying species most in need of such interventions. It is hoped this information will help us to move forward to determine context-specific risks and opportunities derived from both natural and non-natural factors (e.g., policy, economy, governance) to better apportion conservation investment.

Author contributions:

G.M.M., G.C., and N.P. contributed substantially in the design of the trait scoring and vulnerability ranking of the framework proposed by E.I.A. G.M.M., G.C., and N.P. provided guidance in data analysis and interpretation. All authors contributed equally to the writing of the manuscript, and approved the final version to be published.

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Table 1. Species traits used to assess vulnerability to population declines under exposure to hurricane disturbance for 25 terrestrial mammals classified at high risk of extinction in Mexico. Thresholds of significant and high exposure are also shown. Trait data sources are summarised in Supporting Information - Table S1.

	Species traits	Rationale
Heightened Sensitivity	*Habitat specialization* Selectivity for particular habitats.	Hurricanes can drastically reduce habitat elements used by species as shelter from adverse weather conditions or protection from predators which may not be available in other habitats. Therefore, species heavily reliant on specific habitat or microhabitat conditions (e.g., thermal, screening/escape cover) may find it difficult to survive in alternative areas deprived from such elements.
	Diet specialization Selectivity for particular food resources.	For some species the bulk of their diet may consist mostly of specific items which could be diminished during harsh environmental conditions. These species may find it difficult to feed for a sustained time interval from alternative resources, and consequently become more susceptible to starvation and/or less resistant to diseases leading towards mortality events.
Low Adaptability	*Low vagility* Limited ability of long distance dispersal due to behavioural and/or physiological constraints.	Hurricane-induced mortality is expected to depend on the relative vagility of individuals in escaping from strong winds, heavy rain and/or flooded areas, particularly in the presence of anthropogenic disturbance. Low vagile species may also utilise a narrow range of habitat strata which may increase chances of exposure to hurricane disturbance.
	Territoriality Ability of defending particular areas for exclusive use of shelters, foraging or reproduction.	Territorial individuals might be less predisposed to abandon preferred areas (e.g., sleeping sites, latrines, feeding sites) and/or the existence of territorial neighbours may make it difficult to move to occupied areas. Territorial species might be highly vulnerable if they are poor dispersers and exhibit a high level of exposure, particularly in the presence of anthropogenic disturbance.
Exposure	*Significant exposure* ≥ 25% < 75% overlap of a species extant range by one or more hurricanes.	Hurricanes overlapping such an area may compromise a significant subset of the species' population through hurricane-driven habitat changes. Yet, assuming no constraints in habitat connectivity there may be a range of potential non-disturbed habitat patches still remaining.
	High exposure ≥ 75% overlap of a species extant range by one or more hurricanes.	Hurricanes overlapping such an area may seriously compromise the demographic stability of most of the species populations given the limited availability of non-disturbed areas for dispersal within its range, and hence increase the risk of range-wide declines should a subsequent hurricane or event of similar magnitude takes place.

	Exposure (E)	
	E ≥ 25%	E < 25%
Heightened Sensitivity (S)		
Do the species possess up to two sensitivity traits?		
Yes > 0	**1**	
No 0	**0**	**0**
Low adaptability (LA)		
Do the species possess up to two low-adaptability traits?		
Yes > 0	**1**	
No 0	**0**	**0**
Total sum of scores	**"1"** or **"2"**	**"0"**

Key to scores	Vulnerability classes
0 = ≥ 25% exposed but neither sensitive nor low adaptable	Low
1 = ≥ 25% exposed and either sensitive or low adaptable	Medium
2 = ≥ 25% exposed and both sensitive and low adaptable	High

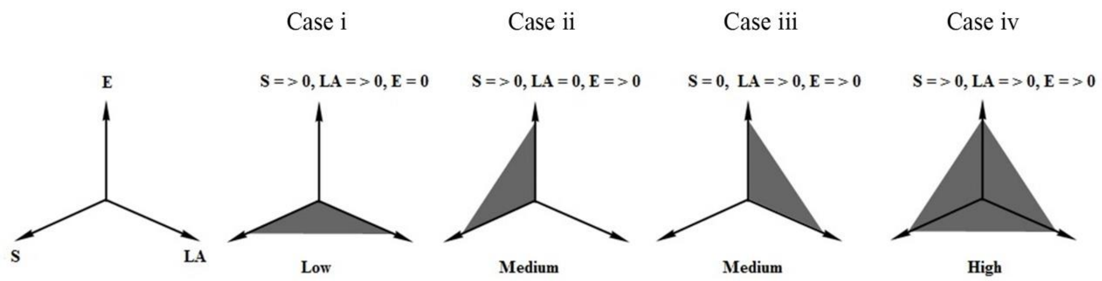

Figure 1. Criterion for assessing vulnerability to population declines under exposure to hurricane disturbance applied to 25 terrestrial mammals classified at high extinction risk in Mexico. A species highly predisposed by its intrinsic biology having its extant distribution largely overlapped with hurricanes is expected to be the most vulnerable, as in case "iv". Species non-significantly exposed (when the overlap of the hurricanes' paths with a species extant range is < 25%) but either sensitive and/or low adaptable are considered low vulnerable as in case "i".

Table 2. Results of the vulnerability assessment to population declines under exposure to hurricane disturbance for the 25 terrestrial mammals at high risk of extinction in Mexico. The confidence of vulnerability estimates based on data availability and uncertainty in the traits' role in relation to hurricane effects is also given (See evaluation criteria in Supporting Methods).

		Indicator of exposure	Traits associated with sensitivity		Traits associated with low adaptability			
Species	**Order**	Species extent range impacted by hurricanes (%)	Low vagility	Territoriality	Habitat specialist	Diet specialist	**Total scores & vulnerability rank**	**Level of confidence**
Ateles geoffroyi yucatanensis	Primates	66	0	1	1	1	2,66 High	Good
Alouatta pigra	Primates	53	1	1	1	0	2,53 High	Good
Cyclopes didactylus	Pilosa	51	1	1	0	1	2,51 High	Moderate
Ateles geoffroyi vellerosus	Primates	35	0	1	1	1	2,35 High	Good
Alouatta palliata mexicana	Primates	27	1	1	1	0	2,27 High	Good
Procyon pygmaeus	Carnivora	92	1	1	0	0	1,92 Medium	Good
Microtus oaxacensis	Rodentia	73	0	1	0	0	1,73 Medium	Moderate
Caluromys derbianus	Didelphimorphia	64	0	0	1	0	1,64 Medium	Moderate
Zygogeomys trichopus	Rodentia	62	0	1	0	0	1,62 Medium	Moderate
Tayassu pecari	Cetartiodactyla	66	0	1	0	0	1,66 Medium	Good
Antilocapra americana	Cetartiodactyla	57	0	1	0	0	1,57 Medium	Good
Castor canadensis	Rodentia	54	0	1	0	0	1,54 Medium	Good
Ursus americanus	Carnivora	46	0	1	0	0	1,49 Medium	Good
Panthera onca	Carnivora	41	0	1	0	0	1,41 Medium	Good
Leopardus pardalis	Carnivora	41	0	1	0	0	1,41 Medium	Good
Tapirus bairdii	Perissodactyla	39	0	1	0	0	1,39 Medium	Good
Ondatra zibethicus	Rodentia	37	0	1	0	0	1,37 Medium	Moderate
Lepus flavigularis	Lagomorpha	35	0	0	1	0	1,35 Medium	Moderate
Leopardus wiedii	Carnivora	34	0	1	0	0	1,34 Medium	Moderate
Erethizon dorsatum	Rodentia	34	1	1	0	0	1,34 Medium	Moderate
Tamandua mexicana mexicana	Pilosa	33	1	1	0	0	1,33 Medium	Good
Eira Barbara	Carnivora	30	0	1	0	0	1,30 Medium	Moderate
Chironectes minimus	Didelphimorphia	37	0	0	0	0	0,91 Low	Moderate
Cabassous centralis	Cingulata	69	0	0	0	0	0,69 Low	Moderate
Metachirus nudicaudatus	Didelphimorphia	67	0	0	0	0	0,67 Low	Moderate

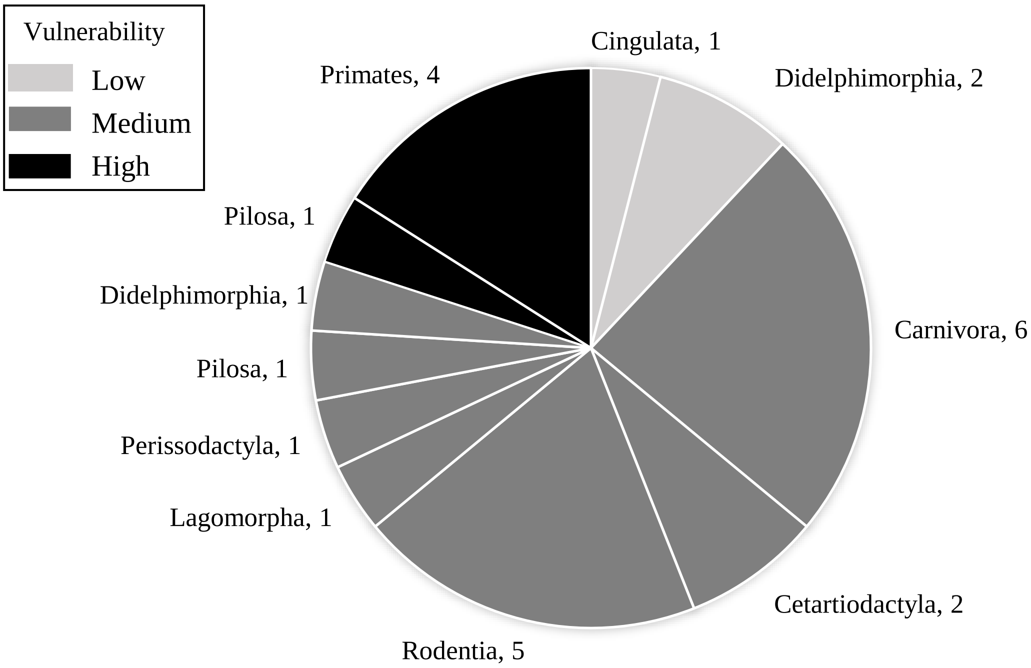

Figure 2. The 25 terrestrial mammals grouped by taxonomic Order, assessed for vulnerability to population declines under exposure to hurricane disturbance in Mexico. Vulnerability classes (low, medium, high) are indicated by different shading. Species traits and corresponding scores used to estimate the species' heightened sensitivity and low adaptability for a given amount of exposure are found in Table 2.

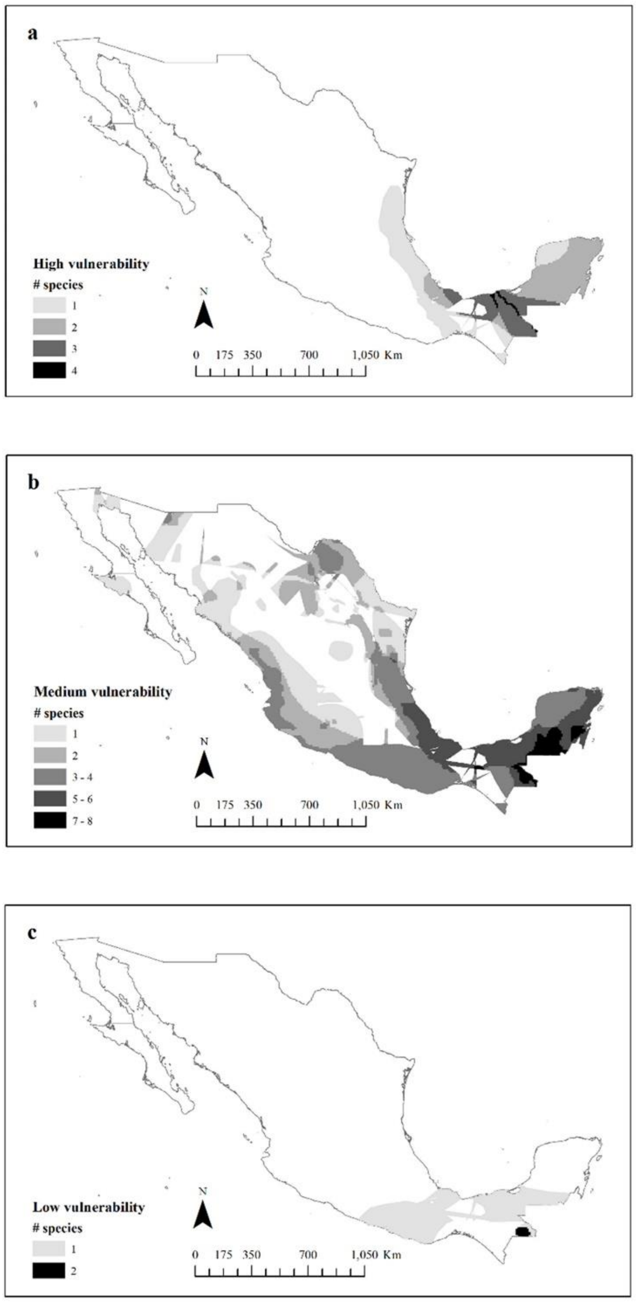

Figure 3. Density map of 25 terrestrial mammals in Mexico assessed for vulnerability to population declines under exposure to hurricane disturbance. Panels represent the number of species determined to be at high (a), medium (b), and low (c) vulnerability.

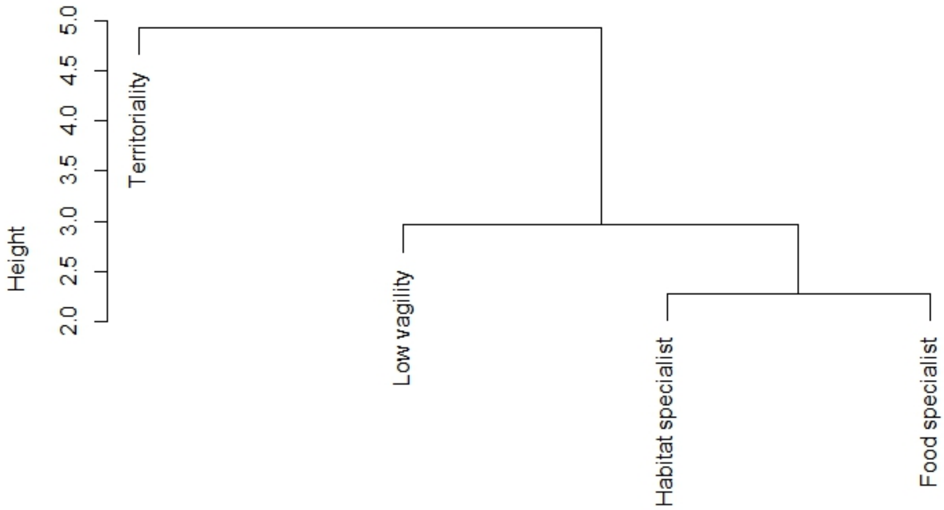

Figure 4. Cluster analysis of the four indicators used to estimate heightened sensitivity and low adaptability to hurricane-driven population declines for the 25 terrestrial mammals in Mexico. The clustergram is used to visualize the pattern of association between traits. The height of each node represents the distance of the two clusters that the node joins. The vertical axis represents the level of dissimilarity between clusters as equated via Euclidean distances. Clustergram built using the *hclust* function (method *ward.D2*) in the R software version 3.4.2.

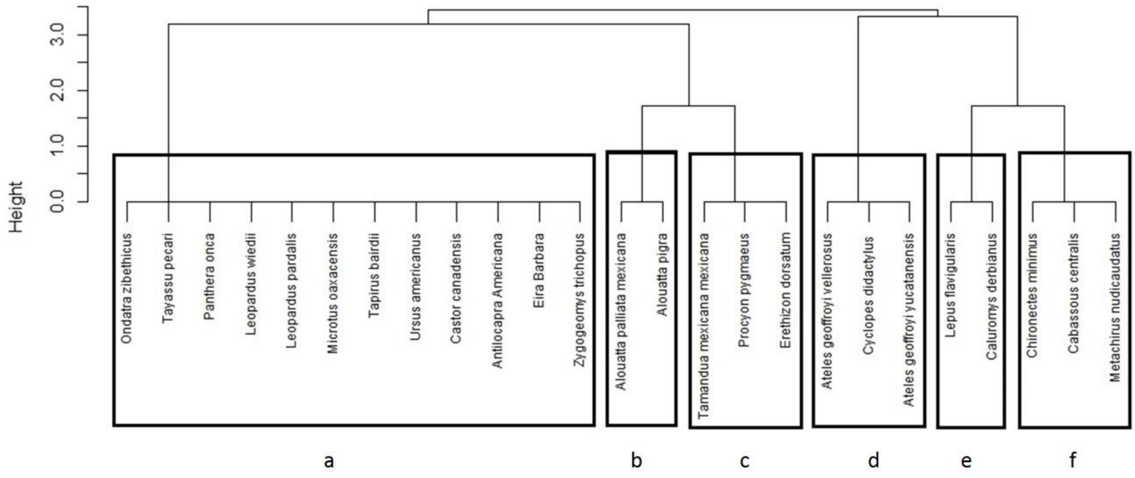

Figure 5. Cluster analysis for the 25 terrestrial mammal species assessed for vulnerability to population declines under exposure to hurricane disturbance. Black boxes highlight six major aggregations of species sharing similar traits shaping relative vulnerability. Of the five highly vulnerable species, three clustered as a result of being territorial and diet/habitat specialists (cluster d); the remaining territorial and habitat specialist species clustered independently due to their low vagility (cluster b). Most moderate-vulnerability species shared the single trait of being territorial (cluster a) and two grouped independently for being habitat specialists (cluster e). Low-vulnerability species clustered due to lacking traits associated with heightened sensitivity and low adaptability (cluster f). Clustergram built using the *hclust* function (method *ward.D2*) in the R software version 3.4.2.

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