MINI REVIEW

Assessing exposure to extreme climatic events for terrestrial mammals

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Keywords
Climate change; cyclones; droughts; IUCN red list; species conservation; vulnerability.

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Received
14 July 2012
Accepted
22 October 2012

Editor
Dr. Wayne Linklater

doi: 10.1111/j.1755-263X.2012.00306.x

Abstract

There is robust evidence that climate change will modify the frequency and intensity of extreme climatic events. The consequences for terrestrial biota may be dramatic, but are yet to be elucidated. The well-established IUCN Red List does not, for example, include any explicit quantification of the current level of exposure to extreme climatic events in any species-based risk assessment. Using globally distributed data for cyclones and droughts as well as information on the distribution of 5,760 terrestrial mammals (species and subspecies) we: (1) define mammals with significant exposure as those with an overlap of at least 25% of their extant geographic range with areas that have been impacted by either cyclones or droughts; and (2) pinpoint those with ≥75% overlap as being at the highest exposure. Although a species' risk of negative impacts from extreme climatic events depends not only on its exposure but also its intrinsic sensitivity and adaptive capacity, identifying taxa currently exposed can help to (1) reduce the uncertainty in identifying species least likely to be resilient to future impacts, and (2) complement extinction risk assessments and provide a more informed evaluation of current conservation status, to better guide management.

Introduction

Evidence is accumulating that the current increase in global temperatures will lead to changes in the frequency and intensity of extreme climatic events in the coming decades (IPCC 2012). Such changes may have detrimental consequences for the Earth's biota (Parmesan *et al.* 2000; Jiguet *et al.* 2011). In terrestrial mammals, severe population declines following such phenomena have been reported for a variety of species (Caughley *et al.* 1985; Solberg *et al.* 2001; Dunham *et al*. 2003; Pavelka *et al.* 2003; Gordon *et al*. 2006; Scorolli *et al*. 2006; Miller & Barry 2009; Worden *et al*. 2010). It is expected that exposed species whose biology makes them more susceptible and/or unable to adapt promptly to changes in the frequency and intensity of extreme climatic events will be those most vulnerable to this source of disturbance (Ameca y Juárez *et al.* 2012). Cyclones and droughts are examples of such natural forcing for which historical data and state-of-the-art climate change modeling suggest that some areas of the world have experienced a trend to more intense or frequent events, a trend which might continue in the future depending on the region and season (Seneviratne *et al.* 2012 and references therein).

Despite a limited understanding of the mechanisms shaping extreme climatic events, there is consensus that the severity of their impacts strongly depends on the level of exposure to them (IPCC 2012). "Exposure" has been defined as "the nature and degree to which a system is exposed to significant climatic variations" (IPCC 2001). With this rationale, a species' exposure to extreme climatic events can be described as the degree of contact (overlap) between the geographic area within which a species occurs and the spatial extent of extreme climatic events over a given time period. It follows that the greater such area of overlap, all else being equal, the greater the probability that a species will be affected.

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Exposure by itself does not necessarily equal risk. The overall risk of a species experiencing negative impacts from climate change, including extreme events, is expected to depend not only on exposure but also the species' intrinsic characteristics and adaptability to disturbance (Foden *et al*. 2008; Ameca y Juárez *et al.* 2012). Future changes in the location and intensity of extreme climatic events are complex to predict accurately (Bader *et al.* 2008; Ghil *et al.* 2011; Seneviratne *et al.* 2012), but records of current frequency distributions for specific types of extreme climatic events are sufficient for the identification of areas where the background level of exposure is elevated. In this context, identifying taxa recently exposed can help to identify those species likely to possess less resilience to impacts in the near future and use this information to complement extinction risk assessments and guide management actions.

Currently, risk assessments for mammals in the IUCN Red List (IUCN 2008) are based on a categorization that incorporates continuing, expected or anticipated threats, but does not reflect extreme climatic events in any systematic way (Mace *et al.* 2008). Hence, in this article, we use geographic ranges of species and subspecies of volant and non-volant terrestrial mammals (hereafter, terrestrial mammals), risk status data from the IUCN Red List Assessment (Version 3.1), and observed frequency distribution data of cyclones and droughts to: (1) determine terrestrial mammals at significant exposure to either cyclones or droughts, and identify the geographic patterns in exposure; and (2) pinpoint terrestrial mammals at high exposure with a particular focus on those classified as "Threatened" or "Non-Threatened" by the IUCN. We defined "significant" exposure as an overlap of at least 25% between a species' extant geographic range and areas impacted by cyclones or droughts. Similarly we defined "high" exposure when such a species' range overlap with areas impacted by either cyclones or droughts was equal or greater than 75%. We focused on terrestrial mammals because all known species (and a large number of subspecies) have been assessed against the IUCN Red List criteria and their geographic distribution delimited.

Methods

Data sets

We obtained from the 2008 IUCN Red List Assessment (Accessed November 2011) (IUCN 2008) the distribution maps in shapefile format for species and subspecies of terrestrial mammals ($n = 5{,}798$). Species' distributional ranges have been commonly used as indicators to detect symptoms of decline and extinction risk from multiple threats (Cardillo *et al.* 2008; Hockey & Curtis 2009; Davidson *et al.* 2009; Collen *et al*. 2011). However, species are unlikely to be evenly distributed throughout their range. In the Red List assessment, a given species distribution map takes the form of range polygons linking known areas where each polygon is associated with a particular level of confidence. We only used range polygons for which presence was coded as "Extant," as these reflect areas where occurrence is most likely (IUCN 2008) By focusing on species' extant distributional areas (rather than the entire species' range) we aimed to avoid overestimating the degree of exposure. Extinction risk was assessed using the IUCN Red List threat categories version 3.1 (Accessed December 2011). We refer species and subspecies currently recognized as Critically Endangered, Endangered, and Vulnerable as "Threatened," whereas Least Concern and Near Threatened species and subspecies are referred to as "Non-Threatened." Range polygons of Data Deficient mammals and/or without full Red List assessment were kept in the analyses if these have range polygons coded as "Extant." The resulting dataset contained 5,760 terrestrial mammals comprising species and subspecies.

Frequency and geographic distribution of cyclones, available as shapefiles, were extracted from the joint database DEWA/GRID-Geneva of the United Nations Environment Programme (Accessed November 2011) (UNEP 2005). This database includes geospatial data on cyclone tracks for the period 1980–2005. We restricted the analysis to the period 1992–2005 for which global coverage of cyclone occurrence is available. To generate the global distribution of areas currently prone to drought conditions, we used the Global Drought Monitor database (Accessed December 2011) (Lloyd-Hughes & Saunders 2011). This database uses the Standardized Precipitation Index (SPI), which is a probability index based on the cumulative rainfall data for a given period of time, to identify droughts occurrence (McKee *et al.* 1993; Trnka *et al.* 2003). We used the global monthly average SPI data available on a $1^\circ \times 1^\circ$ equally spaced longitude/latitude grid and used a running 9-month time window over the period 1980–2011 for each grid point. A mask was applied to the data to exclude grid points for the oceans as well as in locations/times of the year when it has not been possible to determine the SPI (e.g., Polar regions like Greenland or the Siberian Tundra and also deserts where totals are close to zero with very little variance). From the remaining grid points, drought areas were identified as those whose grid points had mean SPI scores below zero. This method is robust provided that computations are based on (1) a high-quality continuous precipitation record of at least 30 years, and (2) a reasonable SPI time scale to reflect impacts on water resources of interest (McKee *et al.* 1993; Lloyd-Hughes & Saunders 2002).

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Our SPI series spans a period of 31 years and different time windows were explored before determining the nine month scale at which the degree of dryness remained relatively consistent in agreement with general theory defining hydrological droughts (Seneviratne *et al.* 2012).

Quantifying exposure to cyclones and droughts

We defined exposure as the degree to which the spatial extent of a particular type of extreme climatic event overlays the geographic area within which a terrestrial mammal is most likely to occur. We, therefore, started by superimposing the extant geographic distribution of terrestrial mammals (using ArcGIS version 9.3, ESRI 2008) with the geographic distributions of the areas impacted by cyclones and drought conditions. In the second stage we identified mammals with "significant" and "high" exposure, defined as an overlap of at least 25% or 75%, respectively, of their extant geographic range with areas impacted by cyclones and droughts (see below). Cyclones are short-lived extreme climatic events (Landsea *et al.* 2010) and can have a high frequency of occurrence not always affecting the same extent of the environment (Lugo 2008). Taking this into account, we selected those mammal species in which at least 25% of their extant geographic ranges overlapped with the paths of cyclones. We initially assumed that exposure to at least 2 cyclones or more over a relatively short period of time could prevent species not only from recovering the individual numbers lost in the first event but also erode the resilience of survivors and drive more serious population losses in the future should a phenomenon of similar magnitude takes place. For mathematical accuracy, however, we used 2.6 cyclones as this figure represents the weighted mean of the frequency of cyclones experienced by each species for the period 1992–2005, which equates to at least two cyclones every 10 years within a species extant range. Compared to cyclones, droughts take a long time to develop and have large return periods making start/end times difficult to delineate especially when there is insufficient observational data (McKee *et al.* 1993; Chung & Salas 2000; Breshears *et al.* 2005). This is why frequency counts of drought events and future projections are more challenging for some areas of the world than others (Panu & Sharma 2002; Mishra *et al.* 2009; IPCC 2012). Recognizing the difficulties in quantifying the occurrence probabilities of individual events globally, we assessed exposure to droughts by focusing only on the spatial extent of those areas which, on average, have had drier than average conditions (SPI <0) over the period 1980–2011. Terrestrial mammals with significant exposure were identified as those with at least 25% overlap between their extant geographic range and the areas which have experienced such drought conditions (SPI <0). Finally, we identified mammals having high exposure defined as those whose extant geographic range exhibited $\geq$75% overlap with either cyclones or droughts with particular emphasis on those collectively termed as "Threatened" and "Non-Threatened" for which we also identified relative location using the WWF terrestrial ecoregions' classification (Olson *et al.* 2001). The 25% and 75% range overlaps used to characterize significant and high exposure for both types of extreme events are arbitrary cut-off levels because at present there is no objective basis on which to set the level. We use these values because they have been used previously in spatial ecology and conservation prioritization of mammals and other vertebrates at different scales (Argent *et al.* 2003; Orme *et al.* 2005; Morrison *et al.* 2007; Pompa *et al.* 2012). We believe that these proportions can be easily interpretable and decision-makers more likely to be familiar with them.

Results

Terrestrial mammals at significant exposure

Of the world's terrestrial mammals assessed ($n = 5{,}760$), 6.2% were determined at significant exposure to cyclones, 22.6% to droughts and 3.1% to both phenomena. Although the number of terrestrial mammals with significant exposure to droughts is over three times the number of those exposed to cyclones, the proportions of "Threatened," "Non-Threatened" and "Data Deficient" is similar (Figure 1). Long-term observational data indicates that geographical hotspots of cyclones are different from those where droughts are common. As a result, there were few examples of mammals exposed to both phenomena over the time periods assessed. Of the 6.2% ($n = 357$) of terrestrial mammals significantly exposed to cyclones, the greatest proportions of both "Threatened" and "Non-Threatened" mammals were located within the Caribbean region (36.7% and 41.7%, respectively). Of the 22.6% ($n = 1{,}301$) terrestrial mammals significantly exposed to droughts, the greatest proportions of both "Threatened" and "Non-Threatened" mammals (51.9% and 65.7%, respectively) were predominantly distributed in Africa south of the Sahara.

Terrestrial mammals at highest exposure

From the 5,760 terrestrial mammals assessed, our analysis of the highest exposure for the "Threatened" grouping yielded 100 (1.7%) species exposed exclusively to cyclones (Figure 2a and Table S1 in the online supplementary material) and 139 (2.4%) exposed exclusively

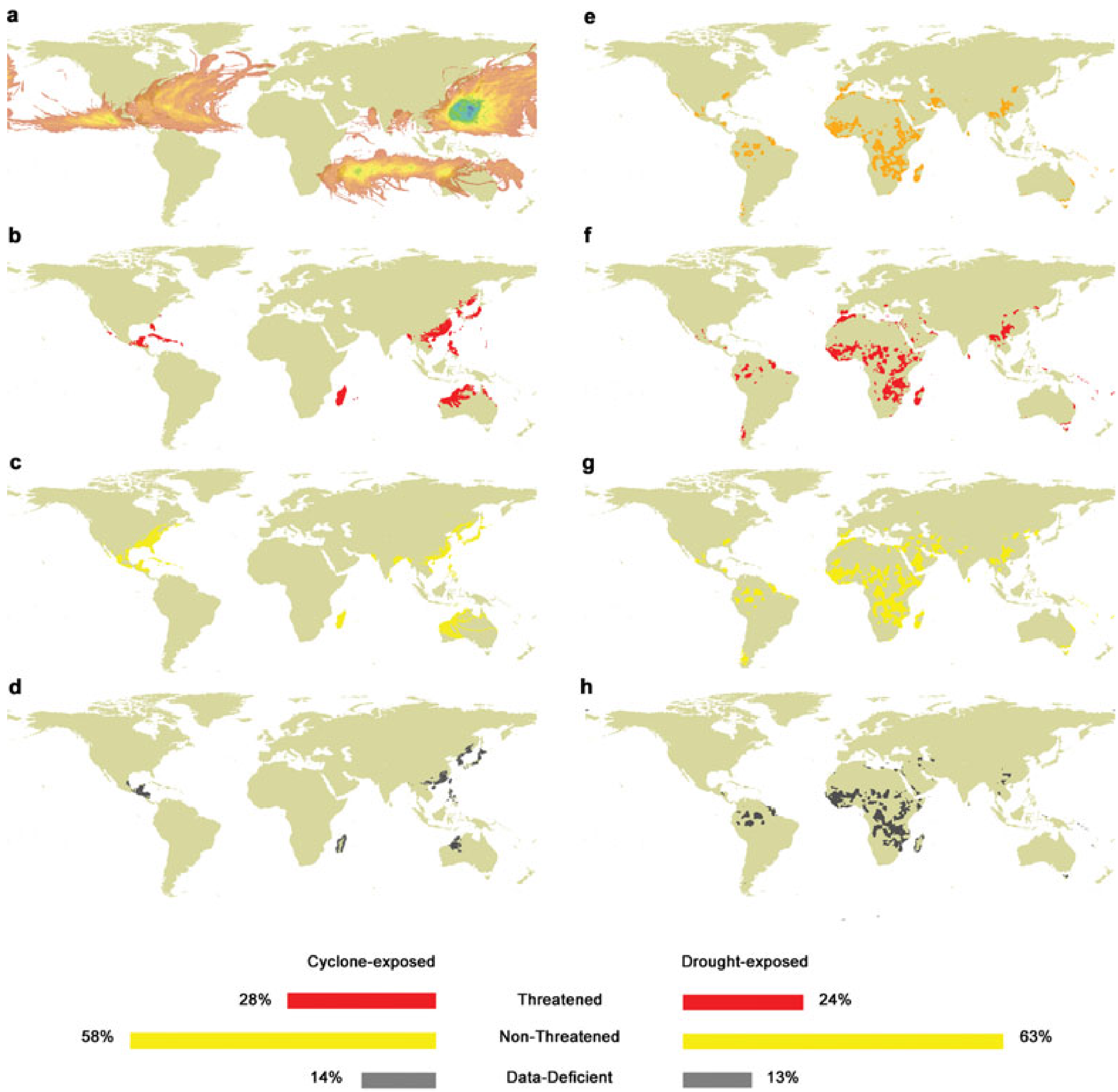

Figure 1 Global pattern of terrestrial mammals with significant exposure to cyclones (panel a) and droughts (panel e) classified by risk status following the IUCN Red List criteria. Mammals with significant exposure to cyclones, shown in panels: b, Threatened (Critically Endangered, Endangered, Vulnerable) c, Non-Threatened (Least Concern, Near Threatened), and d, Data Deficient, are those with at least 25% overlap between their 'extant' geographic range and areas experiencing a high cyclone frequency in the period 1992–2005. Mammals with significant exposure to droughts are those with at least 25% overlap between the 'extant' geographic range (panels: f, = Threatened, g, = Non-Threatened, and h, = Data Deficient) and areas experiencing drought conditions in the period 1980–2011. Details of methodology are provided in *Methods*.

to droughts (Figure 2b and Table S1) with 36 (0.6%) exposed to both phenomena. The greatest proportion of "Threatened" cyclone-exposed mammals ($n = 56$, 0.9%) was found in Madagascar, including species across five terrestrial ecoregions (spiny thickets, succulent woodlands, subhumid forests, lowland forests and dry deciduous forests) (See Figure 2a). The greatest proportion of "Threatened" drought-exposed mammals ($n = 43$, 0.7%) was found in West Africa, including species across the Sudanian savanna, Guinean and Congolian forest-savanna mosaic, Congolian coastal and swamp forests, and the Cameroonian Highlands forests (Figure 2b).

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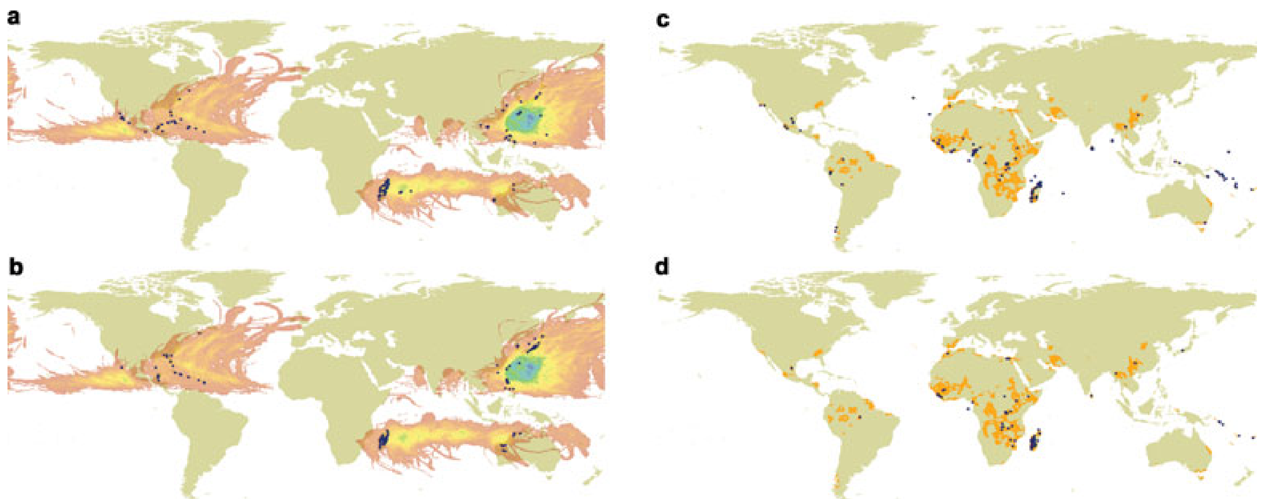

Figure 2. Global pattern of "Threatened" and "Non-Threatened" terrestrial mammals at high exposure to cyclones and droughts. For panel a, Threatened (Critically Endangered, Endangered, Vulnerable) and panel b, Non-Threatened (Least Concern, Near Threatened) mammals, dots represent the centroid area within each species' "extant" geographic range having a >25% and ≥75% overlap with a high cyclone occurrence, respectively: areas with the lowest frequency of cyclones are indicated in light brown whereas dark blue areas represent locations with the greatest cyclone frequency (period 1992–2005). Dots in panels c, (Threatened) and d, (Non-Threatened) represent the centroid area within each species' "extant" geographic range with >25% and ≥75% overlap (respectively) with areas affected by drought conditions, (light-brown shaded areas) for the period 1980–2011. Details of methodology are provided in *Methods*.

Table 1 "Threatened" and "Non-Threatened" terrestrial mammals at high exposure to cyclones and droughts by taxonomic Order

	Highly exposed to cyclones		Highly exposed to droughts	
	Threatened	Non-threatened	Threatened	Non-threatened
Afrosoricida	6	23	5	8
Carnivora	6	5	5	2
Cetartiodactyla	7	3	5	4
Chiroptera	29	44	31	22
Dasyuromorpha	1	5	0	0
Diprotodontia	2	1	6	0
Eulipotyphla	6	18	25	7
Lagomorpha	3	4	0	0
Peramelemorphia	1	0	0	0
Primates	40	9	55	15
Rodentia	35	53	43	20
Total	**136**	**165**	**175**	**78**

Globally, the taxonomic Order Primates comprised the greatest proportion of "Threatened" mammals at the highest exposure to either cyclones or droughts, followed by the Orders Rodentia and Chiroptera (Table 1).

In parallel, from the total 5,760 mammals assessed our analysis of highest exposure for "Non-Threatened" mammals yielded 135 (2.3%) species exposed exclusively to cyclones (Figure 2c and Table S1), 48 (0.8%) exposed exclusively to droughts (Figure 2d and Table S1) and 30 (0.5%) exposed to both phenomena (Table 1). The greatest proportion of "Non-Threatened" mammals exposed to cyclones (1.1%, $n = 65$,) and droughts (0.5%, $n = 33$) were located in Madagascar. Globally, the Order Rodentia comprised the greatest proportion of "Non-Threatened" mammals at highest exposure to cyclones, followed by the Chiroptera and Afrosoricida (Table 1). In contrast, the Chiroptera comprised the greatest proportion of such taxa at high exposure to droughts, followed by the Rodentia and Primates (Table 1).

Discussion

Two decades of research and international collaboration have been devoted to compiling and assessing the available information to advance our understanding of climate change impacts on Earth. On the basis of this work, it is now widely recognized that we need to accelerate our efforts for managing the potential impacts of extreme climatic events on natural and human systems (CCSP 2008; ICSU 2008; UNISDR 2011; UNEP 2012). According to the recently released report on Managing the Risk of Extreme Events and Disasters to Advance Climate Change Adaptation by the IPCC (IPCC 2012), there is solid evidence that the observed increments in global temperatures have been and will continue shaping activity patterns of extreme climatic events around the globe over the 21st century. Unfortunately, establishing the direction and magnitude of such patterns in terms of occurrence probabilities, frequency and intensity is challenging (Bader *et al.* 2008; Gutowski *et al.* 2008; Seneviratne *et al.* 2012). Less contentious, however, is the proposition that the severity of impacts strongly depends on (1) the level of exposure to extreme events, (2) the cumulative effects of similar such phenomena experienced in the past, and (3) the intrinsic vulnerability of the systems affected (Ostertag *et al.* 2005; Adger 2006; Murray *et al.* 2012; Seneviratne *et al.* 2012).

From a conservation perspective, recent research defines mechanisms through which climate change and extreme climatic events are expected to increase biodiversity loss (Dawson *et al.* 2011; Geyer 2011; Jiguet *et al.* 2011; Laurence & Useche 2012) and proposes frameworks to tackle negative impacts at both species and population levels (Williams *et al.* 2008; Ameca y Juárez *et al.* 2012). Studies identifying species' susceptibility and adaptive capacity to a broad spectrum of impacts derived from climate change are also underway (Foden *et al.* 2008; Scholss *et al.* 2012), yet exposure to extreme climatic events has not been explicitly addressed in any species' risk assessment. The well-established IUCN Red List does not, for example, include any explicit consideration of extreme climatic events. The IUCN Red List does record threat types (IUCN Threats Classification Scheme, Version 3.1, Accessed July 2012) and the category "climate change and severe weather" includes potential impacts derived from cyclones and droughts under two different sub-categories: "storms and floods" and "droughts." Yet the Red List records only 69 terrestrial mammal species affected by storms/floods, and 81 affected by droughts.

Given that there is limited information on the consequences of extreme climatic events for species, and that in any case there is not a mechanism to use any such information systematically in the risk assessment, there is a gap in identifying species which could benefit from conservation actions to mitigate impacts from such extreme phenomena. For example, strategies enhancing an exposed population's resilience to extreme climatic events might include the creation of a systematic network of waterholes where droughts are a high risk. Admittedly, the impacts of cyclones will be more difficult to mitigate; in this case, the options could include translocations of individuals at imminent risk. As presented here, a workable indicator to assess the contribution of exposure to the overall species' vulnerability can be formulated by quantifying the overlap between species occurrence and exposed areas to such extreme climatic events. Based on this, approximately 31.9% of the terrestrial mammals assessed under the IUCN Red List have experienced significant exposure to cyclones, droughts or both in combination, of which 4.7% faced extremely high exposure (Table S1). This could represent a substantial increase in the number of terrestrial mammals classified as threatened by the IUCN under the category "climate change and severe weather" (Table S2) provided that these species are found to possess high sensitivity and/or low adaptability to these phenomena (see below).

The historical exposure of a species to a given disturbance over evolutionary time is expected to shape its intrinsic adaptability to that disturbance, reducing its likelihood of extinction from this source (Lande *et al*. 2003). However, adaptations that have prevented species from becoming extinct due to recurrent exposure to extreme phenomena (in the order of thousands of years) might not be the same as those traits that prevent them from experiencing mass-mortality events. For example, populations of exposed species with early maturation, a large number of offspring and/or many reproductive events during a lifetime may bounce back from the brink of extinction caused by extreme climatic events; however these species might not have evolved the traits (dormancy, torpor, high dispersal capacity, diversified diet, etc.,) to avert immediate or near-term severe declines derived from exposure to disturbance. As a result, different taxa with similar levels of exposure might experience greater or lesser impacts due to species' intrinsic susceptibility and/or adaptability and the local habitat conditions (See below) (Recher *et al.* 2009; Bezuijen *et al.* 2011; Ameca y Juárez *et al.* 2012). From our analysis, the Order Primates exhibited the greatest proportion of taxa considered at highest exposure to cyclones and droughts, (Figure. 3a,b). Although it might be expected that some primate species will possess the behavioral and physiological flexibility to cope with conditions derived from these phenomena, it is also true that such flexibility will have its limitations: recent reports of cyclone and drought impacts on primate populations indicated losses far greater than the expected annual mortality rate. For example, a 46.8% loss in *Semnopithecus entellus* (Waite *et al.* 2007), a 50% loss in *Eulemur fulvus* (Tarnaud & Simmen 2002), and a 42% loss in *Alouatta pigra* (Pavelka *et al.* 2003). In addition, local habitats might have already experienced anthropogenic degradation that could enhance species exposure to extreme climatic events and/or compromise any intrinsic coping strategies for population persistence in the longer term. Studies have revealed that the interaction between anthropogenic stressors and exposure to extreme climatic events can be expected to outstrip species' adaptive capacity (if any), enhancing the risk of severe unanticipated impacts (Craig *et al.* 1994; Munson *et al.* 2008). Yet, other studies report that these stressors can mitigate each other (Verboom *et al.* 2010; Blaum *et al.* 2011). Similarly, some extreme climatic events might be a 'catastrophe' for some species (Pavelka *et al.* 2003) but create a bonanza for others (Widmer *et al*. 2004). These

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principles will need to be taken into account in vulnerability and viability analyses to contribute in revealing within species' symptoms of extinction risk and pinpointing overlooked taxa in need of conservation attention and/or reassure the efforts to those already of concern. The existing IUCN criteria have a wide range of mechanisms for calibrating threat levels across different life history and threat contexts, and this approach could be extended to deal with climate change impacts (Foden *et al.* 2008) including extreme events. Our method is comparable to existing classification systems in its potential for consistency and flexibility, which are fundamental features in the Red Listing process (Mace *et al.* 2008; Vié *et al.* 2008). Consequently, it has the potential to be applicable to other taxonomic groups.

Although many details concerning extreme climatic events remain to be fully understood, earth-system modellers have made significant progress in the treatment of uncertainties. In this way, and following the uncertainty guidance of the IPCC fifth report (Mastrandrea *et al.* 2010), there is evidence of medium confidence suggesting that increases in both duration and intensity of droughts have been in place through southern Europe and West Africa; this is also expected to occur in the next 100 years in Central Europe, the Mediterranean, Central North America and Mexico, northeast Brazil, and southern Africa. It is likely that the frequency of the most intense cyclones will increase substantially in some regions (Seneviratne *et al.* 2012). These observed and projected changes suggest that identifying species that are or might soon be subject to extreme climatic events merit more attention from conservation scientists and policy-makers alike, if effective and proactive strategies are to be designed and implemented. The IUCN Red List is widely accepted as a critical conservation tool for species' conservation against the escalating impacts of anthropogenic pressures. In this regard, assessing levels of exposure to extreme climatic events can complement existing guidelines and criteria for assessing species' extinction risk and develop more robust assessments because these phenomena are not well addressed by the current criteria (Foden *et al.* 2008). In particular, pinpointing areas where species have been exposed to extreme climatic events can help target species that possess a combination of traits that makes them highly vulnerable to such events while being associated with a degree of exposure for which such traits may become critical in shaping survival. With this study we intend to stress that incorporating the quantification of exposure to extreme climatic events, combined with information pertaining to species' intrinsic sensitivity and adaptability to such events, into existing risk assessments could contribute toward reducing the overall vulnerability of species to potential population losses and hence, ultimately, reducing their risk of extinction.

Acknowledgments

The authors thanks to James Duffy and Alienor Chauvenet for valuable comments on earlier stages of the manuscript. E.I.A.J. was funded by the Mexican Council for Science and Technology (Ref. 209160) and the World Wildlife Fund (Ref. RM60).

Supporting Information

Additional Supporting Information may be found in the online version of this article at the publisher's web site:

Table S1: a, Threatened and b, Non-Threatened terrestrial mammals with highest exposure to cyclones and droughts.

Table S2: Terrestrial mammals categorized at threat of a, storm/floods ($n = 69$) and b, droughts ($n = 81$) on the IUCN Threats Classification Scheme Version 3.0. (Data accessed July 2012).

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