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Drought vulnerability among China's ungulates and mitigation offered by protected areas

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Abstract

Ongoing perturbations in the global climate have triggered changes in the frequency or magnitude of extreme climatic events, including drought. Increasingly common or intense droughts have threatened ungulates. Intensifying trend of drought has been observed in China since the 1980s. We assessed drought vulnerability of 60 ungulate taxa distributed in China by synthesizing information on drought exposure and intrinsic vulnerability related to biological traits. In total, 27 taxa were identified as vulnerable to drought, which represent over half of the taxa assessed as threatened in the IUCN Red List and China's National Red List. We identified hotspots where a high number of drought-vulnerable taxa are concentrated, including Northeast Himalayan subalpine conifer forests, alpine conifer and mixed forests of Nujiang-Lancang Gorge, and Qionglai-Minshan conifer forests, which are all located in Southwest China. We also assessed conservation efforts that China has allocated to ungulate taxa vulnerable to drought. Drought-vulnerable taxa that are endemic to China have significantly lower coverage in China's National Nature Reserve system compared with nonvulnerable taxa. These findings reveal the gaps in existing conservation efforts and indicate possible improvements that might be needed to maintain species resistance in the face of increasing and intensifying drought impacts.

KEYWORDS

adaptive capacity, climate change, extreme climatic events, mammals, refuges, sensitivity

1 | INTRODUCTION

Climate change poses increasing threats to biodiversity by inducing major environmental changes and compounding other ongoing threats (Dawson, Jackson, House, Prentice, & Mace, 2011; Mantyka-pringle, Martin, & Rhodes, 2012). Aims to mitigate such threats have spurred the development of climate change vulnerability assessments that evaluate the predisposition of species and ecosystems being adversely affected by climatic variations. Along with the development, challenges to climate change vulnerability assessments have also been increasingly recognized (Butt et al., 2016). One challenge is the omission of an important component of climate change in species vulnerability assessments—changing

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frequency or magnitude of extreme climatic events (Chapman et al., 2014). Extreme climatic events (ECEs) refer to unusual, unpredictable, and/or unseasonal variations at the extremes of the historical distribution of climate events (IPCC, 2012), which can trigger demographic shifts, decline, or resource bottlenecks in populations of a variety of taxa (Maron, McAlpine, Watson, Maxwell, & Barnard, 2015).

Due to expanded and accelerated drying on land caused by globally increased temperature, drought, as a type of ECEs, has occurred in greater frequency, intensity, and/or duration since the 1970s (Dai, 2011; Trenberth et al., 2014). Between 1951 and 2010, a significant increase in drought was found in Africa, East Asia, Mediterranean region, and Southern Australia (Spinoni, Naumann, Carrao, Barbosa, & Vogt, 2014). During this period, changes in drought intensity and duration were also observed in China due to the reduction in regional precipitation (Zhai et al., 2017). From 1980 to 2015, observational data showed that drought became more widespread in Qinghai-Tibet Plateau and Southwest and Southeast China (Shao, Chen, Tan, & Gu, 2018). In the last decade, the entire country experienced an aggravation of drought severity, especially in South China—a region considered to be humid (Zhai et al., 2017; Zhou et al., 2017). Under intermediate future greenhouse gas emissions, scenarios from the Coupled Model Intercomparison Project phase 5 (CMIP5), coupled climate model simulations, suggest that decreased precipitation and/or increased evaporation will cause severe and widespread droughts in the next 30–90 years over many land areas (Dai, 2013); and most recent projections agree that the warming rate in China will be faster than the global mean (IPCC, 2013). Increasing intensity and areal coverage of drought was identified across the country at the 1.5°C and 2.0°C global warming, using 22 ensemble runs from 13 global climate models in CMIP5, which could double the current losses of gross domestic products from droughts (Huang et al., 2018; Su et al., 2018).

In a recent assessment of the impacts of extreme climatic events, mammals were one of the most responsive taxa to drought events, and one third of the 37 relevant observational studies across the world reported >25% population declines (Maxwell et al., 2019). Among these observations, drought has been frequently recorded threatening the persistence of ungulate species by altering availability of food, water, and shelter (Frank & McNaughton, 1992; Ogutu, Piepho, Dublin, Bhola, & Reid, 2010; Folks et al., 2014). For example, zebra (*Equus burchelli*) population die-offs were observed during a severe drought (Georgiadis, Hack, & Turpin, 2003), and lamb mortality of mouflon (*Ovis orientalis orientalis*) doubled due to drought impacts (Garel, Loison, Gaillard, Cugnasse, & Maillard, 2004). Besides these impacts, drought could also cause declines in conception rate by reducing ungulates' mating activities (Ismail, Kamal, Plath, & Wronski, 2011) and decrease reproductive rate (Saltz, Rubenstein, & White, 2006). In China, drought was also observed to depress ungulate populations. The food shortage caused by a serious drought in 1994 triggered a significant decline of Eld's deer (*Rucervus eldii*) population and ~40% reduction in its reproductive rate (Song, 1996). Drought is also one of the major factors affecting food resources and restricted population growth of sika deer (*Cervus nippon*) in Southwest China (Guo, 2002). In Central China, a 7-year survey on the isolated populations of alpine musk deer (*Moschus chrysogater*) showed that drought and snow cover had negative impacts on species abundance; populations have declined as a joint consequence of such impacts, deforestation and poaching (Liu & Sheng, 2008).

Land-use change and unsustainable exploitation of natural resources in China have caused many prevailing and/or urgent environmental issues that threaten persistence of its biodiversity (Zhang, Luo, Mallon, Li, & Jiang, 2017). However, potential solutions to these problems remain challenged by the country's strong demand of economic growth (Ma et al., 2019). In such a context, populations of some vulnerable species might not sustain elevated frequency and magnitude of ECEs given the witnessed dramatic impacts of these events on different species. The risk of ECEs on species survival in China is not a potential one, especially when an intensifying trend of some events, such as drought, was observed in the recent past and is predicted to increase. Estimations of how species would respond to future drought are restricted by uncertainties in predicting drought patterns on local scales (Ghil et al., 2011; Seneviratne, 2012) and uncertainties in variation of future species ranges. Despite this, accumulated historic exposure is found to be the major driver of potential drought risk (Carrão, Naumann, & Barbosa, 2016). This provides scope to assess current vulnerability of species by combining recent drought distribution and species ranges (Ameca, Mace, Cowlishaw, Cornforth, & Pettorelli, 2013; Zhang et al., 2019), which enables us to assess drought vulnerability of ungulates distributed in China.

Protected Areas (PAs) are a critical tool for reducing threats to species diversity and maintaining habitat integrity (Geldmann et al., 2013). By protecting natural habitats and maintaining intact ecosystems, PAs are also a viable option to increase habitat resilience and resistance to drought (WCPA/IUCN, 2018). In China, the past 40 years witnessed an explosion of PAs: 11 types of PAs have been established with conservation objectives varying from protecting biodiversity and geological features, preserving scenic landscapes and seascapes, to maintaining ecosystem services (Zhang et al., 2017). Among China's PAs, Nature Reserves are designated with a major goal of protecting endangered or endemic species and ecosystems, and now account for ~15% of the country's land territory (MEP of PRC, 2015). However, the extent to which these Nature Reserves could serve as a safety net for those ungulate species vulnerable to the increasing drought events remains unknown.

In this study, we assessed the drought vulnerability of ungulate taxa distributed in China, with the aim of identifying the taxa vulnerable to drought and the areas where these taxa are concentrated, namely, the hotspots of drought-vulnerable taxa. We also examined the extent of protection that China's Nature Reserve system provides to the drought-vulnerable ungulate taxa. Overall, our study is expected to facilitate national and regional conservation planning and climate change risk management for ungulate taxa in China.

2 | METHODS

2.1 | Assessing ungulates vulnerability to drought

Following the IUCN-SSC Guidelines for Assessing Species Vulnerability to Climate Change (Foden & Young, 2017), we adopted a trait-based approach to assess drought vulnerability of ungulates distributed in China. Trait-based vulnerability assessment is valuable for exploring species' sensitivity and adaptive capacity to climate change (Foden et al., 2019) and has been effectively used to prioritize species at risk (Ameca, Mace, Cowlishaw, & Pettorelli, 2019; Böhm et al., 2016; Zhang et al., 2019). We collected information on exposure and species biological traits associated with intrinsic vulnerability, referring to species ability to withstand (sensitivity) or adjust to drought impacts (adaptive capacity), to assess the risk of ungulate taxa being negatively affected by droughts that already took place. Conservation status of species as expressed through categories of extinction risk on the IUCN Red List of Threatened Species is a critical indictor of the health of biodiversity that synthesizes information on population size, trend, range, habitat, and ecology, and it has been widely used in informing necessary conservation actions (IUCN, 2017). In this study, we highlighted the ungulate taxa assessed in higher threat categories that are also assessed to be drought-vulnerable, to suggest priorities in risk mitigation for the target ECE (Small-Lorenz, Culp, Ryder, Will, & Marra, 2013).

2.2 | Quantifying exposure to drought

Our study focused on the 60 ungulate taxa (refer to species and subspecies, taxonomy according to the 3rd edition of Mammal Species of the World [Wilson & Reeder, 2005) with ≥5% of the range in China (Table S1). These taxa were further classified into "endemic" (>95% of the range is within China's borders) and "nonendemic" (5% ~95% of the range is within China's borders). The spatial data of ungulate taxa were downloaded from the IUCN Red List of Threatened species (Version 2017-2, accessed February 2017, IUCN, 2017). As the study was to assess current vulnerability of ungulate taxa to drought, we adopted the extant range where the taxa are most likely to occur to calculate exposure. Considering the strong geographic isolation of islands, we assessed exposure independently for the populations of *Muntiacus vaginalis*, *Rusa unicolor*, *Sus scrofa* in Hainan and *R. unicolor* and *S. scrofa* populations in Taiwan.

We created maps of precipitation pattern with WEATHER CLIMATE TOOLKIT 4.2.1 (NCEI/NOAA, 2020), using global monthly average Standardized Precipitation Index (SPI) data obtained from the Full Data Reanalysis Product of Global Precipitation Climatology Center (Schneider et al., 2017). The data set contains SPI values from January 1900 to March 2017 on a $1^\circ \times 1^\circ$ equally spaced longitude/latitude grid. SPI is a widely used index to characterize drought on a range of timescales. SPI values are interpreted as the number of *SDs* by which the observed anomalies deviate from the long-term mean, and so can be compared across biomes with markedly different climates (WMO (World Meteorological Organization), 2012). In this study, we used SPI of 12 months (SPI-12) to examine spatial and temporal patterns of drought that could affect survival of ungulates. SPI-12 is a comparison of the precipitation for 12 consecutive months (e.g., July 2001–June 2002) with that recorded in the same 12 consecutive months in all previous years of available data (July 2000–June 2001, July 1999–June 2000 … July 1900–June 1901). SPI-12 values below zero indicate a long-term distinctive dry trend tied to availability of water and food resources in ungulates' habitat (WMO, 2012; Zhang et al., 2019). Aiming at identifying the species that are currently vulnerable to drought due to recent exposure, we examined SPI-12 for the past 40 years to capture enough geographic variations of the spots of high drought reoccurrence (Yu, Li, Hayes, Svoboda, & Heim, 2014) to select the areas that are most likely to be recently affected. Prediction of drought or assessment of ungulate vulnerability to future drought was not involved in this study. Based on the classification system developed by (McKee, Doesken, & Kleist, 1993), drought was measured by (a) identifying grids with SPI-

TABLE 1 Traits used for assessing intrinsic vulnerability (high sensitivity and low adaptive capacity) of ungulate taxa to drought

	Traits	Variable type	Score calculation	Rationale	Reference
Sensitivity	Adult body mass	Continuous	$\frac{\max(x)-x_i}{\max(x)-\min(x)}$[a]	Small body mass associated with relatively low energy reserves increases sensitivity to food scarcity as a result of drought. Weakened individuals may ultimately die as a result of predation, starvation or disease.	Cromsigt, Prins, and Olff (2009); Cowlishaw, Pettifor and Isaac (2009)
	Small population[b]	Categorical	Yes—Score 1 No—Score 0	Taxa with small population sizes have inherent vulnerability to Allee effects, which reduces the capacity to recover from population decline caused by catastrophic events such as drought.	Dublin and Ogutu (2015); Foden et al. (2013)
	Litters per year	Continuous	$\frac{\max(x)-x_i}{\max(x)-\min(x)}$	Within the one-generation assessment (4~16 years) period, animals that produce a smaller number of litters per year may be less able to recover quickly from a reduction in population size following droughts	Garel et al. (2004); Purvis, Gittleman, Cowlishaw, and Mace (2000); Owen-Smith et al. (2012); Song (1996)
	Gestation length	Continuous	$\frac{x_i-\min(x)}{\max(x)-\min(x)}$	Droughts during gestation affect reproductive success. Longer gestation length indicates a higher possibility of encountering droughts during the time	Saltz et al. (2006)
Low-adaptive capacity	Diet breadth	Continuous	$\frac{\max(x)-x_i}{\max(x)-\min(x)}$	Ungulate taxa with narrow diet are restricted by the availability of limited types of resources. When the limited resources are depressed during severe droughts, these taxa are likely to be outcompeted by taxa utilizing a wide range of resources.	Folks et al. (2014); Macandza, Owen-Smith, and Cain (2012)
	Seasonal movement	Categorical	Sedentary—Score 1 Migratory—Score 0	Sedentary species are related to relatively low dispersal capacity, and thus are restricted to move to areas that are less affected by drought. Thus, they are associated with higher vulnerability to drought	Augustine (2010)
	Water dependency[c]	Categorical	Yes—Score 1 No—Score 0	Taxa that are more tightly coupled to specific requirements to water are likely to be less resilient during droughts, because they have a narrower range microhabitat options available to them.	Estrada, Delgado, Arroyo, Traba, and Morales (2016) ; Foden et al. (2013); Kay (1997)

(Continues)

TABLE 1 (Continued)

Traits	Variable type	Score calculation	Rationale	Reference
Drought-vulnerable habitat dependency	Categorical	If (1) the description of taxon behavior included “being fond of water,” “live close to water,” or (2) the description of habitat included “distributed (largely/mainly/mostly) in wetlands/marshes.” Yes—Score 1 No—Score 0	Taxa could be at relatively higher risk if they depend mainly on any of the following habitats known to be sensitive To drought: temperate broadleaf forests and conifer forests, subtropical dry forests, temperate scrublands and steppes	Frank and McNaughton (1992); Kay (1997); Vicente-Serrano et al. (2013)

[a] x_i is the value of the trait variable i, and min(x) and max(x) are the minimum and maximum value of i, respectively.

[b] Criterion D of the IUCN Red List of Threatened Species (IUCN, 2017) was adopted for the judgment of small population: (D) number of mature individuals ≤1,000 or (D2) (only applies to category “Vulnerable”) area of occupancy <20 km^2 or number of distribution of locations ≤5.

[c] We considered a taxon have dependence on water/wetland if (1) the description of taxon behavior had included “being fond of water”, “live close to water”, or (2) the description of habitat includes “distributed (largely/mainly/mostly) in wetlands/marshes”.

12 values lower than −1.0 indicating the occurrence of persisting dryness of moderate or higher levels, and (b) calculating the reoccurrence probability of such dryness for each 1° × 1° grid. We obtained geographic extent and probabilities of drought reoccurrence during January 1977 to March 2017 (483 months) as polygons in a shapefile format, within full ranges (median = 3.5×10^4 km^2) of all 60 ungulate taxa (Figure S1).

To quantify the exposure, we calculated the percentage of a taxon's extant range overlapping with polygons of different probabilities of drought reoccurrence. ARCGIS 10.3 (ESRI) was used to create these drought polygons and analyze exposure of ungulate taxa (ESRI (Environmental Systems Research Institute), 2014). Because different population turnover rates of taxa may influence risk of population decline under drought impacts, we used the length of one generation (IUCN, 2017; Pacifici et al., 2013) as a reference time frame to scale exposure for the comparison across taxa (O'Grady, Reed, Brook, & Frankham, 2008). Drought exposure score of each taxon was accordingly calculated with the formula:

$$\text{Exposure score} = (E\text{a} \times p\text{a} + E\text{b} \times p\text{b} + \cdots E\text{n} \times p\text{n}) \times T\text{gl},$$

where E_{a}, E_{b} ... E_{n} is the exposure of an ungulate taxon, quantified as the range percentage overlapping with drought polygon, to drought with reoccurrence probabilities p_{a}, p_{b}, ... p_{n} from January 1977 to March 2017; T_{gl} (months) is the generation length of the assessed ungulate taxon.

2.3 | Quantifying intrinsic vulnerability

Intrinsic vulnerability conferred by species biological traits was assessed by conducting a literature review, aiming to identify demographic, morphological, and behavioral traits of ungulate taxa that are likely to be associated with intrinsic sensitivity and adaptive capacity to drought. We performed a literature search in Web of Science in May 2018, searching the literature published between 1977 and 2018 with the topics relevant to “ungulate” and “drought.” The results (n = 290) were trimmed using the following criteria: (a) an observational study; (b) from wild populations; (3) recorded during or in the years following drought. In total, 27 peer-reviewed publications were identified (Data S2). We also considered the impacts of drought on habitats and food resources and likely mechanisms of how these impacts would affect ungulates for trait selection based on the studies on drought or other threats causing similar impacts. We chose the traits affecting intrinsic vulnerability through independent mechanisms (Zhang et al., 2019), for example, body size and mobility, affect intrinsic vulnerability through fat reserves and capacity of obtaining available resources, respectively. Eight key traits were then selected with the rationales explained in Table 1. These traits were described by either categorical or continuous variables, of which the data were gathered from peer-reviewed papers and online databases including IUCN Red List (IUCN, 2017), Encyclopedia of Life (EOL, 2018), PanTHERIA (Jones et al., 2009), and Animal Diversity

Web (Myers, Espinosa, Parr, Jones, & Hammond, 2017). Trait variables with data available were scaled to scores ranging from 0 to 1—a higher score is related to a higher intrinsic vulnerability (Table 1, Data S3). Intrinsic vulnerability of the taxa with data available for less than four traits was considered as "Data Deficient." The additive rule, which reflects situations where traits do not interact and can stand in for one another to enhance vulnerability or counter one another to reduce vulnerability (Graham et al., 2011), was adopted for intrinsic vulnerability calculation. This can be illustrated using the formula:

$$\text{Intrinsic vulnerability score} = \sum_{i=1}^{n} z_i / n$$

where z_i is the score of the trait variable i and n is the number of trait variables with available data.

2.4 | Assessing vulnerability to drought

We assessed drought vulnerability of ungulate taxa by combining exposure and intrinsic vulnerability. To classify these taxa in exposure and intrinsic vulnerability dimensions, we conducted sensitivity analysis to find the thresholds for classification among a series of threshold values by increasing or decreasing each value by 5%, and then adopted the value if the assessment results were least sensitive to its changes. Thirty-six taxa with exposure scores falling in the higher 80% of the value range were classified as "exposed"; the same threshold was used to identify 45 "intrinsically vulnerable" taxa (Step 1, Figure 1). We then subclassified these taxa into low, moderate, and high categories in each vulnerability dimension, using 20% and 80% of the score range as lower and upper thresholds (Steps 2 and 3, Figure 1; Appendix). Drought vulnerability of each taxon was then classified into minimal, low, moderate, and high categories based on the framework proposed by Thomas et al. (2011) (see Table S2). An ungulate taxon was considered as "drought-vulnerable" if it had been assessed to have moderate or high vulnerability.

We used the threat categories of ungulate taxa in China Biodiversity Red List—Mammals (Jiang et al., 2016, hereafter CBRL) to incorporate conservation status into the study. CBRL is an application of IUCN Red List of Threatened species (IUCN, 2017, hereafter RL) at the national level, which informs context-specific threats and conservation priority of mammal taxa (especially the subspecies endemic to China) within China's borders. Considering external threats across species full range for nonendemic taxa, we also referred to the threat categories of ungulate species in RL of IUCN (IUCN, 2017). Both lists have not included the risks of ECEs into the assessment of threat categories. We grouped the taxa classified as "Extinct in the Wild (EW)," "Critically Endangered (CR)," "Endangered (EN)," and "Vulnerable (VU)" as "Threatened," those classified as "Near Threatened (NT)" and "Least Concern (LC)" as "Nonthreatened," and highlighted drought-vulnerable taxa that are threatened in CBRL and/or RL.

2.5 | Estimating conservation efforts on drought-vulnerable ungulate taxa

We used ARCGIS 10.3 (ESRI) to estimate China's conservation efforts on the 60 ungulate taxa by calculating the areal percentages of taxa' ranges (ranges within China for nonendemic taxa) that are protected by China's 449 National Nature Reserves (NNRs) as one measure of China's conservation effort (Pimm, Clinton, & Li, 2018) (Figure S2). NNRs are protected areas designated to preserve natural features with significant conservation values, which represent one of the most important tools for biodiversity conservation in China (State Council of PRC, 2005; Zhang et al., 2017). Compared with provincial and county-level Nature Reserves, NNRs deliver better conservation outcomes because of more efficient management with more manpower and financial resources (Xu & Melick, 2007), as well as clearly defined and protected boundaries (Pimm et al., 2018). An ungulate taxon with a higher percentage of range protected was expected to be more capable of coping with drought impacts; drought-vulnerable taxa with low percentages of ranges protected were identified. Since the Nature Reserves system of Mainland China does not apply to Hong Kong SAR, Macau SAR, and Taiwan, the refuge analysis was not conducted for *Capricornis swinhoei*, *C. nippon taiouanus*, and the populations of *Muntiacus reevesi*, *R. unicolor*, and *S. scrofa* in Taiwan.

3 | RESULTS

3.1 | Ungulate taxa vulnerable to drought

Of 60 ungulate taxa distributed in China, 7% were highly exposed and 52% were moderately exposed to drought; 7% were associated with high intrinsic vulnerability and 73% with moderate intrinsic vulnerability to drought. Based on the assessments of exposure and intrinsic vulnerability, we identified 27 taxa with moderate

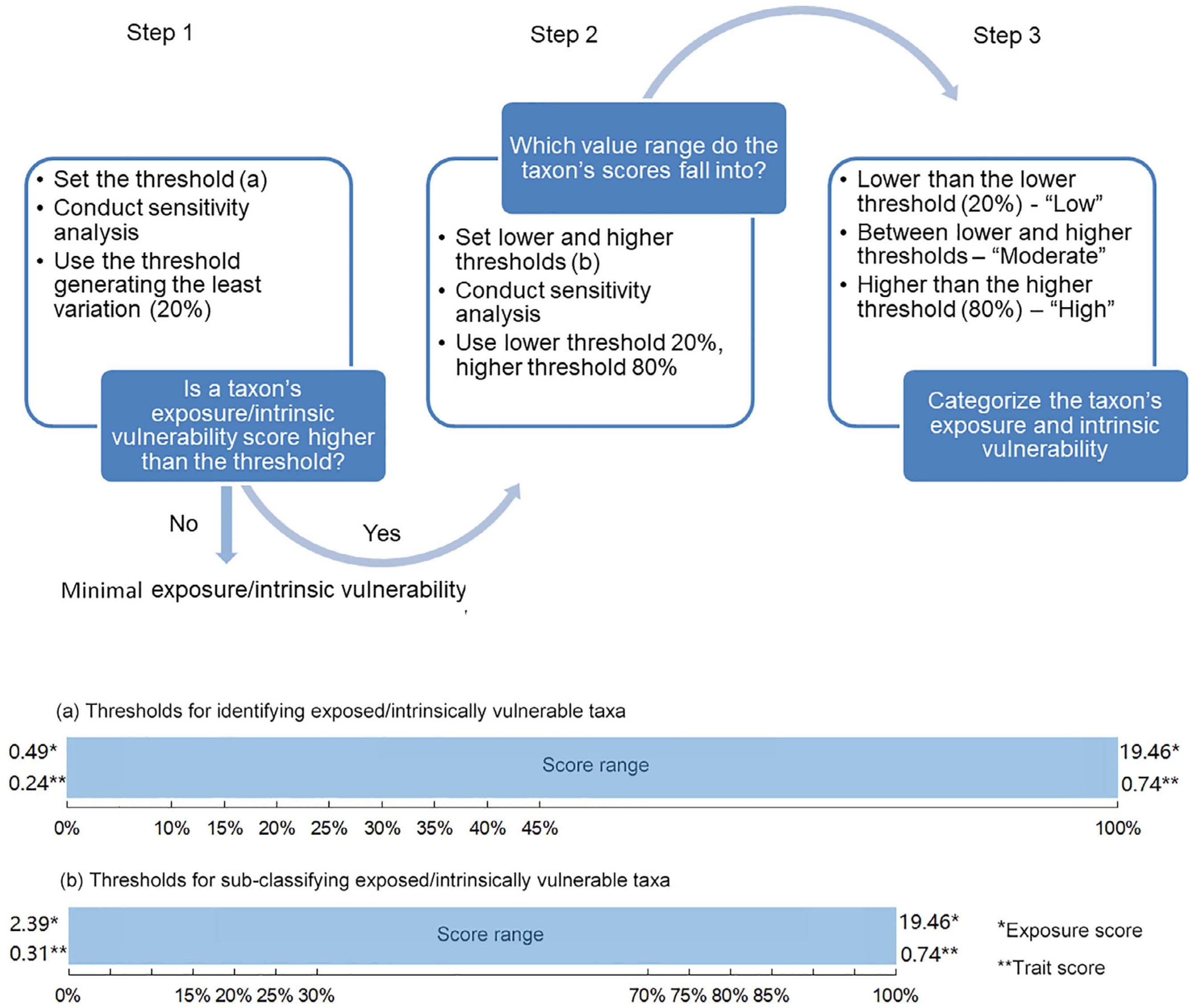

FIGURE 1 A flowchart demonstrating the steps of assessing exposure and intrinsic vulnerability for China's ungulate taxa. For the results of threshold sensitivity analysis, see Figure S4

vulnerability to drought, and no taxa with high vulnerability to drought (assessment result of all 60 taxa see Data S4).

During 1977 to 2017, drought (defined as SPI-12< -1) occurred more intensively over Northeast, South, and Southwest China, where reoccurrence probabilities of drought greater than 20% were widely witnessed (Figure S1). Ungulate taxa with moderate or high exposure to drought are relatively concentrated in the evergreen forests of South China and lower reaches of the Yangtze River (Southeast China), as well as in the conifer and evergreen forests of Southwest China (Figure 2a). A high number of ungulate taxa with moderate or high intrinsic vulnerability to drought was identified in the meadows and conifer forests in East Himalayas and Hengduan Mountains (Southwest China) (Figure 2a), where the highest richness of ungulate taxa in China is shown (Figure S3). Accordingly, hotspots of drought-vulnerable taxa are highlighted in Figure 2a, including the Northeast Himalayan subalpine conifer forests, alpine conifer and mixed forests of Nujiang-Lancang Gorge, and Qionglai-Minshan conifer forests, which are all located in Southwest China. These hotspots are not fully congruent with the areas with high proportions of taxa vulnerable to drought, which include the mixed forests of southern Hengduan Mountains in Southeast China and broadleaf evergreen forests of Wuyi and Nanling Mountains in South China (Figure 2b).

Twenty-five of 27 drought-vulnerable ungulate taxa are listed as "threatened" in CBRL (Table S1). By grouping the taxa by CBRL categories, we found that the ratio of vulnerable to nonvulnerable taxa was higher in the threatened groups (Figure 3a). Over 50% taxa in "CR," "EN," and "VU" are vulnerable to drought, while less than 30% of vulnerable taxa were found in "EW," "NT," and "LC." Fifteen drought-vulnerable ungulate taxa are listed as "threatened" by RL. By grouping the taxa by RL categories, we found ≥50% taxa in "EW," "CR," "VU," "NT," and "DD" are vulnerable to drought, and "EN" and "LC" groups had less than 50% of the taxa vulnerable to drought (Figure 3b). Despite insufficient trait data for the assessment, we additionally suggested to list *Muntiacus gongshanensis* (DD in RL) as "vulnerable" due to its moderate exposure to drought and "CR" category in CBRL.

3.2 | A measure of conservation efforts on the ungulate taxa vulnerable to drought

The extant ranges of 30 ungulate taxa endemic to China overlap with NNRs on average by 13.1 ± 16.1% (max = 70.4%, min = 1.8%, n = 28). Twelve of the endemic taxa were assessed as vulnerable to drought, and 4.9 ± 3.5% of their ranges is protected by NNRs. Such an average percentage is lower than 19.3 ± 18.5% of the endemic taxa that were not vulnerable to drought (F = 6.645, p = .016) (Figure 4a). In general, the protection within NNRs declined with the increase of endemic taxa's exposure and/or intrinsic vulnerability to drought, and the taxa of higher threat categories tend to have less of their ranges protected (Figure 4b).

For the 30 ungulate taxa nonendemic to China, their ranges in China overlap NNRs on average by 14.8 ± 20.1% (max = 94.1%, min = 0, n = 30). Fourteen nonendemic taxa were assessed as vulnerable to drought and 19.9 ± 27.2% of their ranges in China is protected by NNRs. The percentage of NNR-protected range of these taxa is not significantly different from the percentage of nonendemic taxa that are not vulnerable to drought (F = 1.705, p = .202) (Figure 4c). Drought-vulnerable species *Hydropotes inermis* and *Tragulus williamsoni* have less than 1%

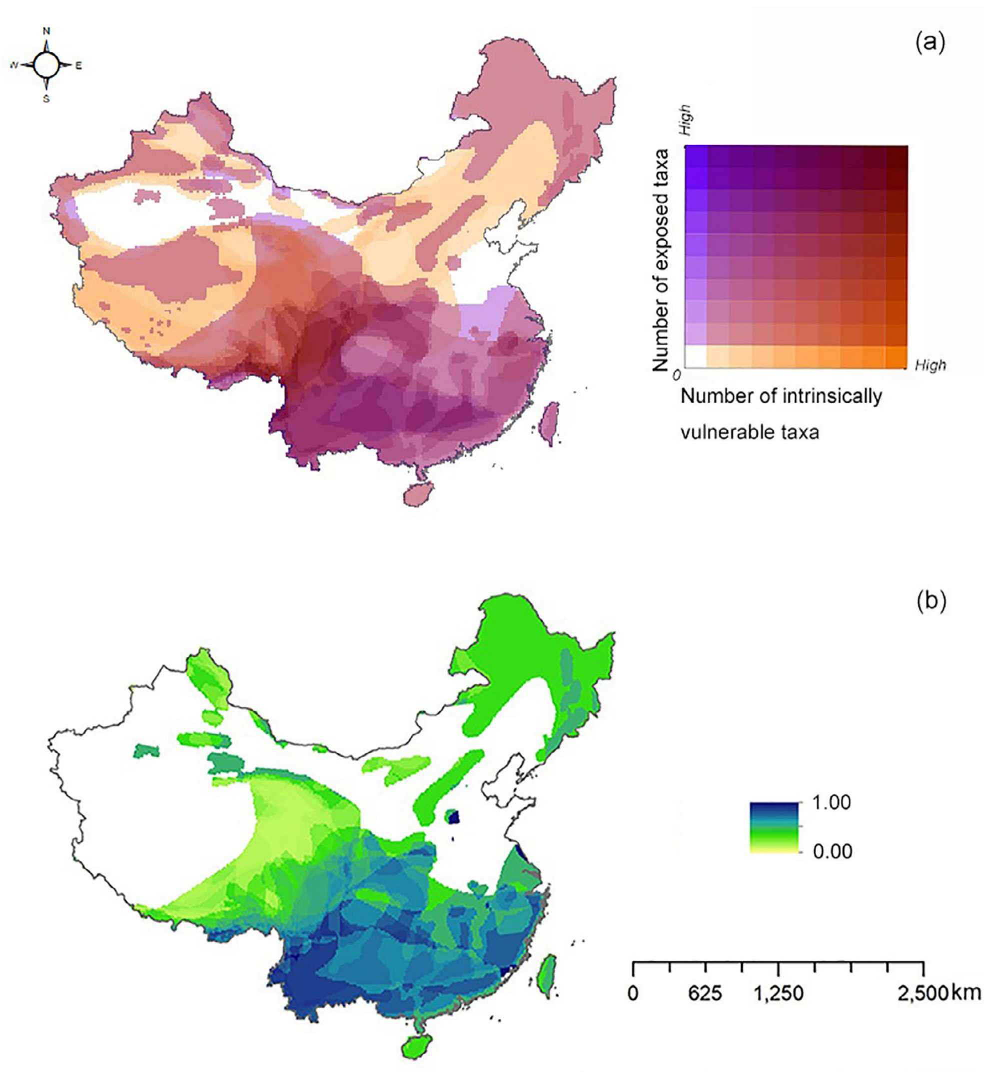

FIGURE 2 Richness of ungulate taxa assessed as (i) exposed to drought only (shown in purple), (ii) intrinsically vulnerable to drought only (shown in orange), and (iii) vulnerable to drought (the combination of the two variables, shown in maroon) (a). Proportion of ungulate taxa assessed as vulnerable to drought in China (b)

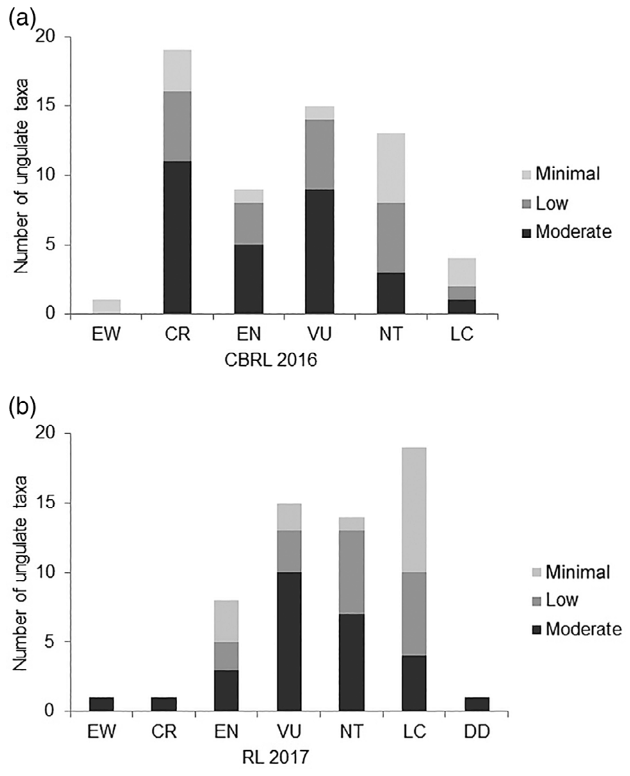

FIGURE 3 Number of ungulate taxa with different levels of drought vulnerability in each CBRL category (a) and RL category (b). *M. gongshanensis* (drought vulnerability unknown) is not included in the analysis

of the ranges in China protected by NNRs. We found no trend in NNR-protected range along with increasing exposure, intrinsic vulnerability, or threat category (Figure 4d).

4 | DISCUSSION

By examining exposure and intrinsic vulnerability, our study assessed drought vulnerability of ungulate taxa distributed in China and mapped hotspots of drought-vulnerable taxa, which would facilitate the management of relevant drought risks. Droughts are unpreventable climate events. It is therefore critical for species to maintain resistance and/or resilience to possible population decline caused by direct and indirect drought impacts, including habitat loss, resource shortage, and increasing interspecies conflicts. Drought-vulnerable taxa need to be highlighted within the framework of conservation prioritizing, as their biological traits and higher exposure are associated with a relatively higher drought risk. For these taxa, mitigation of anthropogenic threats is anticipated to reduce the risk that drought triggers population decline or die-offs when synergizing with these threats, which is especially recommended for the taxa listed as "threatened" in both CBRL and RL. For the "nonthreatened" taxa that are vulnerable to drought, further investigation would be needed when drought increases, as these taxa might deserve uplisting in threat status due to climatic impacts. In the hotspots of drought-vulnerable taxa, priority actions should focus on mitigating prevailing threats upon persistence of both populations and habitats of vulnerable taxa, such as hunting and expansion of plantations (Li, Bleisch, & Jiang, 2016; Liu et al., 2017; Yang, Meng, Xia, & Feng, 2003). For the taxa with higher exposure and lower intrinsic vulnerability, they are more likely to cope with drought impacts and hence have a lower priority in risk mitigation. Despite this, continuous monitoring on non-ECE stressors of ungulates' survival, such as habitat loss and fragmentation caused by urbanization and agriculture (Zhang, Ameca, & Jiang, 2018), is necessary in the regions where more taxa were exposed to drought. For the taxa with higher intrinsic vulnerability and lower exposure, they may confront latent risk due to possible variations in the pattern or intensity of future drought. Thus, efforts are recommended to prevent population decline of taxa that are severely threatened in CBRL or RL for exacerbated non-ECE stressors.

Drought is one of the main drivers of the reduction in aboveground vegetation, which affects ungulate survival, although land biomes differ in their response to water deficit (Knapp & Smith, 2001). Because of poor tolerance to water stress (Maherali, Pockman, & Jackson, 2004; McDowell et al., 2008), drought vulnerability of vegetation is considered to be higher in more humid biomes (Engelbrecht et al., 2007). At the drought timescale of this study, temperate forests and grasslands in sub-humid biomes and subtropical dry forests are relatively more sensitive to water stress for lacking tolerance and recovery capacity (Chaves, Maroco, & Pereira, 2003; Gazol et al., 2018; Vicente-Serrano et al., 2013). We thus assume that a decrease in habitat quality is more likely to happen in these habitat types when prolonged drought occurs frequently, which could pose a threat to ungulates' survival. However, drought vulnerability of vegetation is not only related to the sensitivity to water stress but also to its capability of recovering (resilience), which depends on plant traits and local environmental factors (Vicente-Serrano et al., 2013). Therefore, to account for the relationships between drought-induced vegetation changes and ungulates' survival, we suggest pre- and postdrought surveys on ungulate populations in a variety of habitat types of different biomes. These efforts would improve understanding the role of ungulates' primary habitat types in shaping their drought vulnerability.

For ungulate taxa endemic to China, our findings showed that drought-vulnerable taxa on average occurred

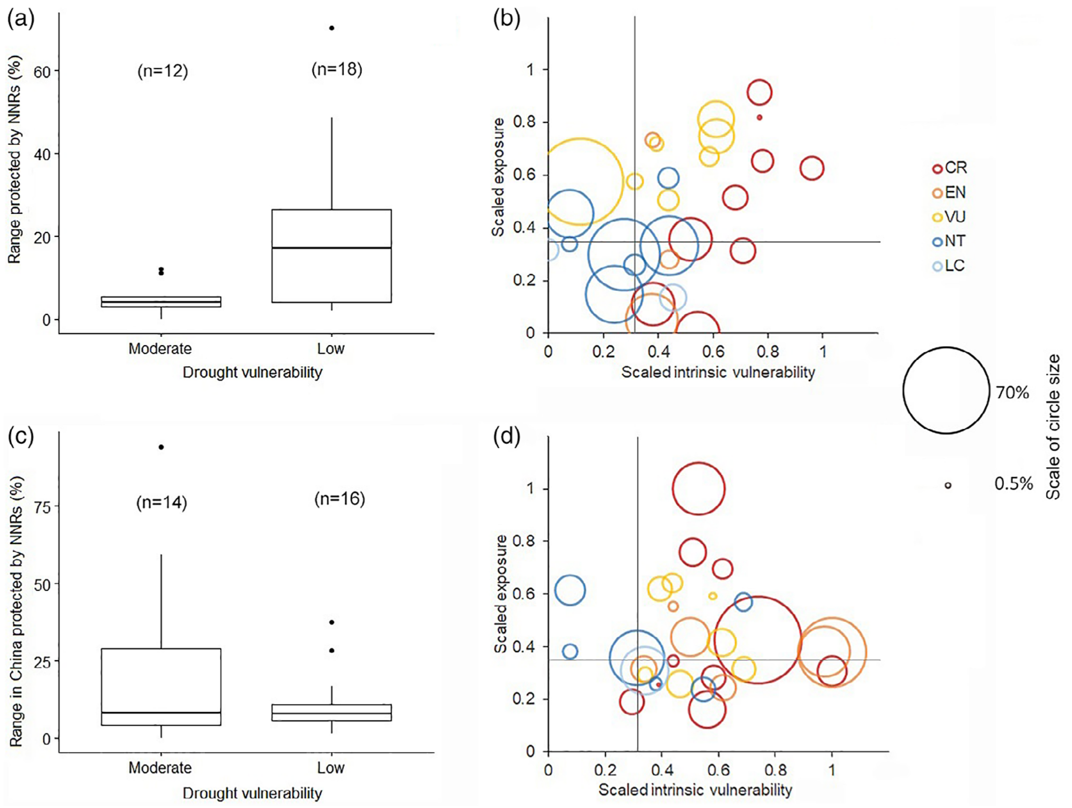

FIGURE 4 Average percentage of range within China that is protected by NNRs of ungulate taxa endemic (a) and nonendemic to China (c); exposure and intrinsic vulnerability (both scaled from 0 to1) of ungulate taxa that are endemic (b) and nonendemic to China (d). The color represents CBRL categories. Circle size represents the percentage of taxon range within China that is protected by NNRs. Gray lines show the thresholds of "moderate" exposure (0.36) and "moderate" intrinsic vulnerability (0.32). *Equus ferus* ("Extinct in the Wild"), *M. gongshanensis* (intrinsic vulnerability unknown) and four taxa distributed in Taiwan are not included in the analysis. CBRL, China Biodiversity Red List; NNRs, National Nature Reserves

in areas less well covered by NNRs than nonvulnerable taxa. NNRs of small size are unevenly distributed in East, Southwest, and Southeast China where drought reoccurred intensively (Figure S2). Associated with higher exposure, ungulate taxa in these regions are more likely to be vulnerable to drought, but have lower coverage by small NNRs. For ungulate taxa nonendemic to China, conservation efforts from NNRs show no significant difference between vulnerable and nonvulnerable taxa. Drought vulnerability of nonendemic taxa was assessed based on exposure of their full ranges, and thus it is less related to the spatial distribution of drought in China. Therefore, NNR coverage of drought-vulnerable taxa may be less affected by the uneven distribution pattern of NNRs in China. It is important to note, however, that we calculated the NNR-protected percentage for nonendemic taxa using their range within China, which only represents the conservation efforts they have received in China. For drought-vulnerable taxa with low percentage of range protected by NNRs, it is essential to assess the potential of other available conservation tools in mitigating the risk from drought, which could facilitate compensations for lacking protection of NNRs. For nonendemic taxa, information on how they are protected or managed in each country of occurrence needs to be shared and updated. Attention is needed for the vulnerable taxa protected by NNRs but whose range percentage within China is low, and the taxa whose threat categories are higher in RL than in CBRL.

NNR is the PA type with most strict control on human activities and receives high management investment (Zhang et al., 2017). Increasing the size of NNRs in the regions highly exposed to drought will be less meaningful, unless matching management can be ensured. We therefore suggest prioritizing management effectiveness of nature reserves to deliver expected conservation outcomes that would alleviate nonclimatic threats. Such an option is expected to prevent habitats from further degradation within current nature reserve networks. Besides NNRs, the role of other PA types in buffering nonclimatic threats needs to be enhanced based on their management goals. Initiatives, such as "National Park Pilots," should act in coordinating functions of different PA types in China and reduce conflicts caused by competition for conservation funding and resources. "National Park Pilots" is the plan designating the first group of NPs containing major habitats of six charismatic mammal species in China, with the aim of boosting the establishment of the country's national park system (Zhang et al., 2017). Assistance should be also provided for dispersion of vulnerable ungulates by optimizing connectivity and heterogeneity of suitable habitat (Prober, Doerr, Broadhurst, Williams, & Dickson, 2019), which would have good potential in enhancing species resilience to drought impacts. Other than PAs, efforts such as programs on species conservation, habitat preservation, and public education would also contribute to drought risk mitigation by increasing conservation output. However, we did not incorporate them into the analysis, since it is difficult to quantify and compare these contributions at a unified scale. We hope relevant approaches of scaling these contributions will be developed, as the data from standardized surveys increases. These efforts are especially important for the regions inhabited by dense human populations with little remaining natural habitat, such as the middle and lower reaches of Yangtze River and South China. In these regions, successful conservation is more likely to be achieved by adjusting human activities toward sustainable coexistence with nature, rather than restricting the efforts on a few small and isolated remains of natural habitat.

This study enables the comparison of drought vulnerability among ungulate taxa, but it is subject to the uncertainties from the trait-based framework. Although ecological responses to extreme climatic events have been recorded for species across the world, relevant case studies are still much less than the studies on well-known threats such as habitat loss (Maxwell et al., 2019). Insufficient observational responses of species to drought currently restrict us from relating responses of ungulate taxa to drought with potential determinants of vulnerability by a more quantitative approach. Subjective thresholds were chosen for classifying exposure and intrinsic vulnerability, which consequently generated relative results instead of the precise assessment accounting for the actual vulnerability induced by these factors (Hossain, Kujala, Bland, Burgman, & Lahoz-Monfort, 2019). For assessing intrinsic vulnerability, we assigned equal weights to biological traits, and so the results lack quantification of the different influence that traits pose on species vulnerability (Pacifici et al., 2015). We also assigned equal weight to exposure and intrinsic vulnerability for classifying drought vulnerability, as the empirical studies are insufficient to support weighting the two aspects differently. To build a robust evidence base for quantifying the trait-based vulnerability assessment, demographic and behavioral responses of ungulates to drought are needed to identify the different responses of species distributed in different biomes. The mechanism of drought affecting population dynamics should also be identified by designing surveys with controls on other threats. Despite the uncertainties, we think that the challenges should not restrict us from pursuing greater opportunities of shaping conservation actions, which address the full range of climate change impacts, given the observed and predicted trend of drought in China.

Our assessment combines information from drought occurrence pattern and intrinsic traits of ungulate taxa distributed in China, supplementing conservation status assessments by identifying taxa vulnerable to increasing drought intensity over time. It also identifies those regions with the greatest risk of drought-induced loss of ungulate populations and diversity. Overall, the study facilitates the prioritization of ungulate taxa and habitat locations for adaptive conservation planning, with the goal to maintain resilience and resistance of vulnerable taxa and affected habitats. To facilitate this goal, research efforts must elucidate the mechanism of population decline of ungulates affected by drought. Furthermore, existing conservation tools need to be improved to reduce nonclimatic threats to vulnerable ungulates, to mitigate catastrophic synergetic impacts that might accompany droughts. The approach used in our study could be potentially applied across terrestrial mammals in assessing their vulnerability to different ECEs on global and regional scales. We hope this study serves as a benchmark upon which enhanced and coordinated conservation actions can be made, ensuring the persistence of the diverse and important group of ungulates in China and beyond.

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CONFLICT OF INTEREST

The authors declare no conflicts of interest.

AUTHOR CONTRIBUTIONS

L.Z. designed the study and performed the analysis. L.Z. and L.G. wrote the manuscript. All authors contributed to the improvement and revisions of the manuscript.

ETHICS STATEMENT

All data were collected from online databases and literature, following research ethics. No ethical approval was required for the study.

DATA AVAILABILITY STATEMENT

The original data are available by contacting the corresponding author.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of this article.

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