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Original Research Article

Climate change vulnerability of Asia's most iconic megaherbivore: greater one-horned rhinoceros (*Rhinoceros unicornis*)

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A B S T R A C T

Climate change is an emerging threat for biodiversity conservation. It has already started impacting species assemblages and ecosystem dynamics. The greater one-horned rhinoceros (*Rhinoceros unicornis*) is an iconic and globally threatened megaherbivore. Once widespread across the northern part of the Indian subcontinent, there were fewer than 500 rhinoceros during the early 1960s, confined to isolated patches of suitable habitats in the southern part of Nepal and northern foothills of India, including Brahmaputra floodplains. Following both governments' successful conservation strategies, the species has been recovering, and its global population at present is over 3500. However, the likely impacts of climate change has not been adequately incorporated into conservation plans for the species and may challenge this success. In this study, we developed a set of 21 vulnerability indicators and assessed the vulnerability of rhinoceros to climate change in Nepal through a review of literature, site observations of prime rhinoceros habitat, key informant interviews, a two-day stakeholders' consultation workshop, and expert elucidation. Our findings suggest that rhinoceros in Nepal is likely to be 'moderately vulnerable' to the impacts of climate change, mainly due to (1) the likelihood of invasive plant species and severe floods in its prime habitat 'Chitwan National Park', and (2) fragmented habitat, small population size, droughts and forest fires in Bardia and Shuklaphanta National Parks. We further identified and recommended adaptation measures intended to enhance the resilience of rhinoceros to these likely threats.

1. Introduction

Climate change has emerged as a key threat for global biodiversity conservation over the last few decades (Hannah et al., 2005; Heller and Zavaleta, 2009; IPCC, 2014; Pacifici et al., 2017; Foden et al., 2019; Haight and Hammill, 2020) given that

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species assemblages and ecosystem dynamics have already started responding to the recent global climate shift (Morueta-Holme et al., 2010; Bellard et al., 2012; Ripple et al., 2017). Some of these responses include (1) shifts in spatial distributions of species, particularly along altitudinal gradients (Parmesan, 2006; Thuiller et al., 2011; Sunday et al., 2012; Corlett, 2015) (2) changes in phenology (Charmantier et al., 2008; Knudsen et al., 2011; Zhixia et al., 2020), (3) reductions in population size (Both et al., 2006; Hunter et al., 2010; Knudsen et al., 2011; Molnár et al., 2011; Gedir et al., 2015; Selwood et al., 2015), (4) increase in fire frequency (Flannigan et al., 2000; Couturier et al., 2014), diseases (Harvell et al., 2009; Pascual and Bouma, 2009), and invasive species (Hellmann et al., 2008; Taylor and Kumar 2013; Hulme, 2017), (5) loss of habitat (Leadley, 2010; Escobar et al., 2015); and (6) extinction of species (Thomas et al., 2004; Böhm et al., 2016; Fulton, 2017; Waller et al., 2017). Global biodiversity models suggest that changes in the distribution of species, loss of habitat, and species extinction will continue throughout this century if not addressed adequately (Hannah et al., 2020), while habitat alteration as a result of climate change will further jeopardise the biodiversity of the world (Leadley, 2010; Bellard et al., 2012; Segan et al., 2016; Pires et al., 2018).

Greater one-horned rhinoceros (*Rhinoceros unicornis*; hereafter referred to as rhinoceros) is a flagship wildlife species (Borthakur et al., 2016; Cédric et al., 2016; Rookmaaker et al., 2016). Until the middle of the 19th century, rhinoceros existed abundantly throughout the floodplains of the Ganges, Brahmaputra and Sindhu Rivers between the Indo-Myanmar border in the east and Pakistan in the west (Foose and van Strien, 1997). However, its population sharply declined due to rampant hunting and habitat loss to the point where there were fewer than 500 rhinoceros globally during the 1960s, confined to isolated patches of suitable habitats in the southern part of Nepal and northern foothills of India, including Brahmaputra floodplains (Rookmaaker et al., 2016; Ellis and Talukdar, 2019). Following the both governments' successful conservation strategies, its population has been recovering, and currently, there are more than 3500 individuals in the wild (Thapa et al., 2013; Rookmaaker et al., 2016; DNPWC, 2017). But whether or not this recovery can be sustained given projected climate change impact remains uncertain.

One of the most likely impacts of climate change is a spatial shift in suitable habitats for terrestrial species (Parmesan, 2006; Thuiller et al., 2011). Some species can simply move to suitable habitats, while others try to adapt to new habitat conditions or shift habitat preferences gradually over generations (Battin, 2004). But climate change is occurring rapidly, and most species may not be able to respond through local adaptation across landscapes (Olson et al., 2009). Rhinoceros is a habitat specialist and confined to a mosaic of tall grasslands and riverine forests on the alluvial floodplain in the Himalayan foothills (See Fig. 1), where water and green growth remains available throughout the year (Jnawali, 1995; Dinerstein, 2003; Kandel and Jhala, 2008; Sarma et al., 2012). As a result of habitat contraction and poaching, its distribution range and population has been reduced, and they now survive in a few protected areas of India and Nepal (Talukdar et al., 2008; DNPWC, 2017; Ellis and Talukdar, 2019). In Nepal, the rhinoceros population is likely to be affected by changing climate given that climate-induced hazards including flash floods and prolonged droughts are expected to increase in future (DNPWC, 2017). However, the predicted impacts of climate change on wildlife species, including rhinoceros, have not been well studied (DNPWC, 2017; Pant et al., 2019). While investigating the direct impacts of climate change requires long-term empirical data, climate change vulnerability assessment derived from available knowledge provides the basis for adaptation measures to species management until such information becomes available (Glick et al., 2011; Foden and Young, 2016).

Accurately predicting the impacts of climate change on biodiversity is a major scientific challenge (Pacifici et al., 2015). Understanding the life-history parameters, characteristics of the landscapes in which the species live, and a projected range of climatic changes provide a better understanding of the impacts of climate change on species (Akçakaya et al., 2006). Limited information exists on how the changing climate is going to impact wildlife and the exact mechanisms of climate change impacts on them (Foden and Young, 2016), and studies conducted so far have not documented the likely impacts of climate change to rhinoceros (Pant et al., 2019). However, a species conservation action plan for rhinoceros in Nepal (DNPWC, 2017)

Fig. 1. Greater one-horned rhinoceros (*Rhinoceros unicornis*) in grassland habitat of Chitwan National Park, Nepal.

has acknowledged that climate change is one of the emerging threats for rhinoceros and has identified this as a knowledge gap (DNPWC, 2017). Thus, assessing the vulnerability of rhinoceros to climate change is an important priority. In this study, we undertook a comprehensive climate change vulnerability assessment for the rhinoceros in Nepal. We first developed vulnerability indicators and then assessed climate change vulnerability following a participatory approach. Our aim was to determine the level of risk climate change poses to rhinoceros in Nepal and better inform the conservation of the species through the identification of potential adaptation strategies. Though we focus on rhinoceros in Nepal, our assessment likely informs similar issues for rhinoceros-bearing protected areas in India, especially Kaziranga National Park in Assam, a major rhinoceros habitat that holds nearly 70% of its global population (Rookmaaker et al., 2016; Talukdar, 2018).

2. Materials and methods

2.1. Description of the study area

We assessed climate change vulnerability for rhinoceros in all of the rhinoceros-bearing protected areas of Nepal, namely Parsa, Chitwan, Bardia and Shuklaphanta National Parks, including their buffer zones (Fig. 2, Table 1). Chitwan National Park (CNP; 95,200 ha) supports more than 90% of the total rhinoceros population in Nepal (DNPWC, 2017) while Parsa National Park (PNP; 62,700 ha) is a new home to rhinoceros given that 3–5 individuals recently migrated there from the adjoining CNP (Acharya and Ram, 2017). Given that these two national parks are contiguous, we have treated CNP and PNP, their buffer zones, and surrounding areas as a single unit in our study. In 2015, there were 608 rhinoceros in these parks, and another 29 in Bardia National Park (BNP; 96,800 ha) and 8 in Shuklaphanta National Park (ShNP; 30,500 ha), based on census data from the Department of National Parks and Wildlife Conservation (DNPWC, 2017). Rhinoceros in BNP and ShNP were translocated there from CNP between 1986 and 2017 (Thapa et al., 2013; DNPWC, 2018).

2.2. Climate change vulnerability assessment

This study utilized a review of relevant literature, site observations of prime rhinoceros habitat, key informant interviews (n = 53), a two-day stakeholders' consultation workshop (n = 1), and expert elucidation meeting (n = 1) as research methods for developing and validating indicators and assessing climate change vulnerability of rhinoceros in Nepal (Fig. 3). We

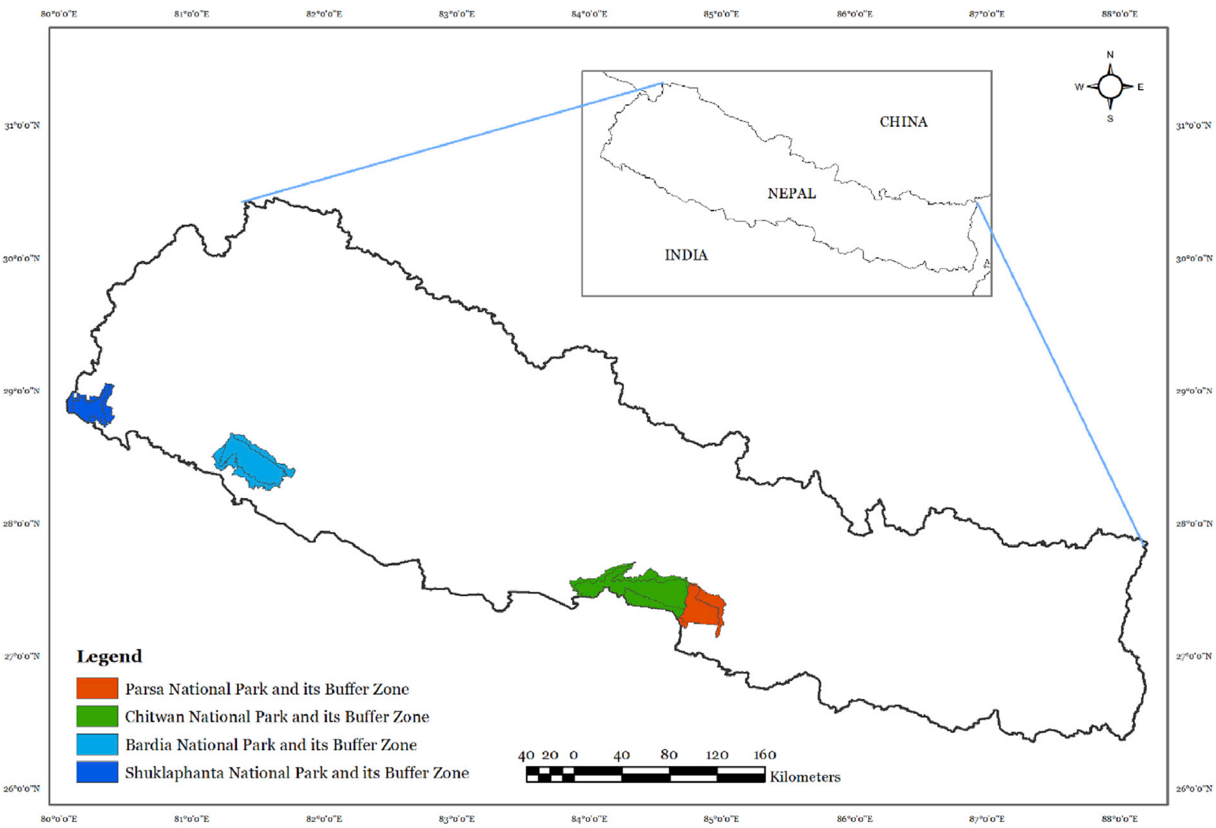

Fig. 2. The location of Parsa, Chitwan, Bardia and Shuklaphanta National Parks in Nepal.

Table 1
Distribution of greater one-horned rhinoceros (Rhinoceros unicornis) in protected areas of Nepal (DNPWC, 2017).

Protected Area	Core Area (km^2)	Buffer Zone (km^2)	No. of rhinoceros in 2015	Remarks
Chitwan National Park	952	729	605	The only source population of rhinoceros in Nepal.
Parsa National Park	627	285	3	Very small population migrating from adjoining CNP.
Bardia National Park	968	507	29	91 (43 males, 48 females) rhinoceros translocated from CNP between 1986 and 2017. But most of the rhinoceros in Babai floodplain were lost due to poaching during Maoist insurgency.
Shuklaphanta National Park	305	243	8	Nine (Two males and seven females) rhinoceros translocated from CNP in 2000 and 2017.
Total	2852	1764	645	

followed these methodologies as recommended by the IUCN SSC Guidelines for Assessing Species' Vulnerability to Climate Change (Foden and Young, 2016). These are commonly used methodologies for climate change vulnerability assessments (CCVA) of many species (Glick et al., 2011; Foden et al. 2013, 2019; Pacifici et al., 2015).

First, we developed a set of 20 proposed vulnerability indicators for rhinoceros in Nepal, primarily based on a literature review. We refined the list of indicators following the inputs from interview with key informants. We then finalized a set of 21 vulnerability indicators for rhinoceros through stakeholders' consultation workshop (Table 2). The participants of the workshop assigned scores to each of the indicators, which was further analyzed using the analytical framework (Fig. 4) to get the climate change vulnerability index (Table 3). We then validated the indicators and outcomes of the vulnerability assessment for rhinoceros through expert elucidation. In addition, we documented the perception of the key informants on level of likely climate change vulnerability to rhinoceros in Nepal (Fig. 5).

2.2.1. Literature review

Some CCVA methods are developed for specific taxa, such as birds, while most others are generic and applied to a wide range of species at various geographic scales (Gardali et al., 2012). CCVAs of the species generally follow the basic conceptual model of vulnerability assessments as suggested by the IPCC (2007), which describes climate change vulnerability as a function of exposure, sensitivity and adaptive capacity. Sensitivity is a measure of how strongly a species is likely to be affected by climate change; exposure is the extent to which species' physical environment will change; and adaptive capacity is a species' ability to overcome the negative impacts of climate change (Glick et al., 2011; Foden et al., 2013). A species with higher sensitivity and exposure to a changing climate, but lower adaptive capacity is likely to be more vulnerable to climate change than others. On the other hand, if the adaptive capacity of the species is higher, it is likely to be less vulnerable even under higher rates of exposure and sensitivity (Glick et al., 2011). Accordingly, we searched the literature for vulnerability indicators of sensitivity, exposure and adaptive capacity.

In general, three methodological approaches are used for CCVA of a species: trait-based, correlative and mechanistic (Pacifici et al., 2015; Foden and Young, 2016). The first approach is considered the most commendable, given that the response of a species to climate change is strongly influenced by its unique combination of biological traits (Foden et al., 2013). Thus, we

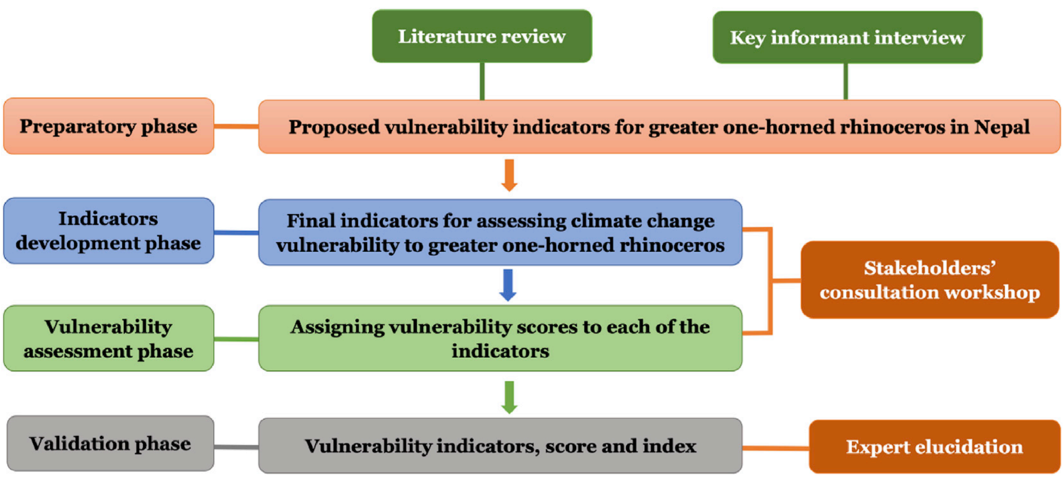

Fig. 3. Flowchart of the research methods for assessing climate change vulnerability of greater one-horned rhinoceros in Nepal.

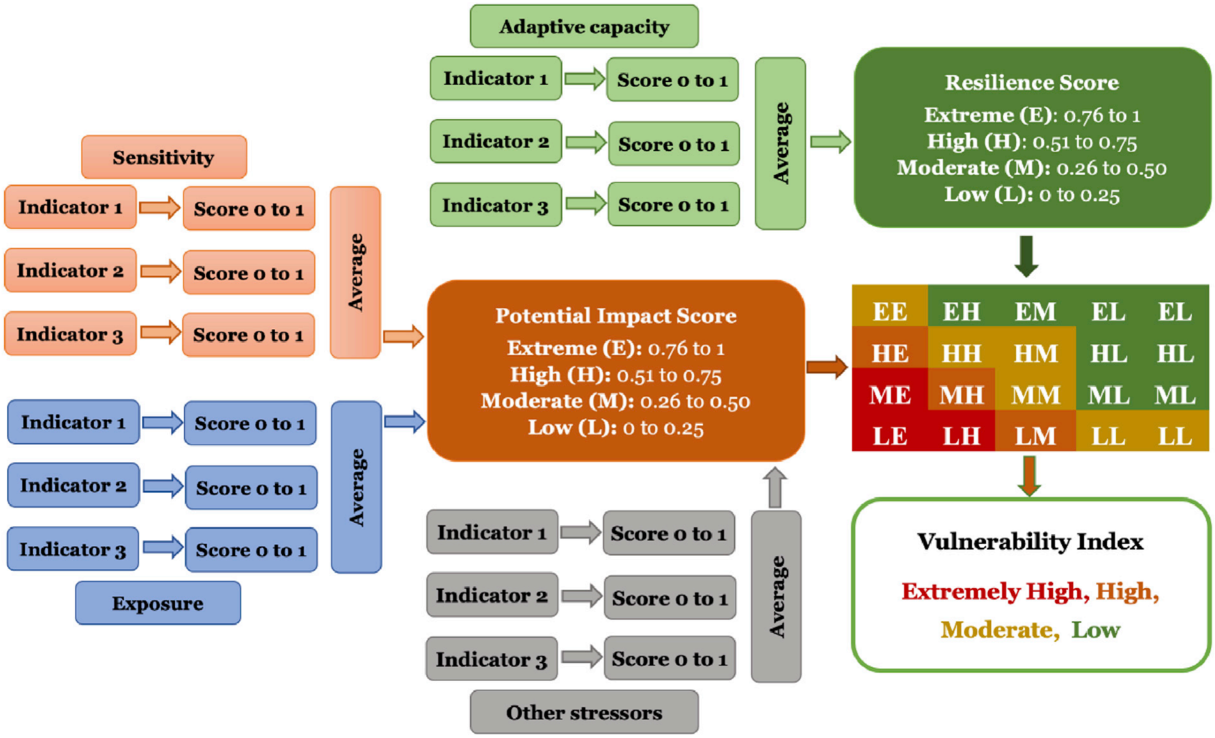

Fig. 4. The analytical framework for climate change vulnerability index adopted from Comer et al. (2019).

used a trait-based approach in this study. Vulnerability assessment is a theoretical concept, and it needs appropriate indicators for measuring it (Hinkel, 2011; Tonmoy et al., 2014). Hence, we first developed a set of vulnerability indicators for rhinoceros in Nepal, primarily based on a literature review, as reported in Pant et al. (2019). As there were no specific indicators developed for rhinoceros, we evaluated the generic indicators developed for a wide range of species (Young et al., 2011; Advani, 2014; Bagne et al., 2014; Lee et al., 2015; Foden and Young, 2016; Foden et al., 2019). After reviewing the available literature, we selected 20 indicators most relevant to rhinoceros.

2.2.2. Key informant interviews

Semi-structured interviews were conducted in person with 53 key informants, including protected area managers, rhinoceros experts and representatives from conservation agencies such as National Trust for Nature Conservation (NTNC), World Wide Fund for Nature (WWF), International Union for Conservation of Nature (IUCN), Zoological Society of London (ZSL), and members of the community-based organizations who have knowledge and experience in wildlife management, particularly rhinoceros conservation in the buffer zone community forests. We recorded their views about climate change vulnerabilities of rhinoceros in Nepal and, with their input, refined the 20 proposed vulnerability indicators identified in the literature review. Forty-eight interviewees were male (91%) and five were female (9%). The dominance of male interviewee is due to skewness in the gender representation in this field in Nepal. Of the 53 key informants, 29 (55%) were from government organizations, 12 (23%) were from non-government organizations and six (11%) each from community-based organizations and media. Most of the interviewees (>55%) had more than 15 years of experience in the biodiversity conservation sector in Nepal. Two more vulnerability indicators were added through these key informant interviews, which were then taken to a wider group of stakeholders for further evaluation.

2.2.3. Stakeholders' consultation workshop

A stakeholder workshop is an effective means for developing indicators and assessing climate change vulnerability because it brings together a wide range of knowledge and experience, promotes stimulating discussion and engages a wide variety of interested parties (Glick et al., 2011; Cross et al., 2012). Such workshops also enable instant communication of the outcomes to the relevant audience, paving the way for future implementation (Glick et al., 2011). We organized a two-day workshop in April 2019 in Chitwan National Park, Nepal. A total of 37 stakeholders participated, representing government organizations, non-governmental organizations, academic institutions, community-based organizations, and tourism entrepreneurs' organizations. The workshop began with introductory presentations, including an overview of the 22 proposed indicators obtained during the literature review and key informant interviews. The first session of the workshop involved a group exercise in discussing and refining the vulnerability indicators. In the plenary session of the workshop, each group presented their revised indicators, which were finalized by consensus with the entire group.

Out of the 22 indicators discussed, workshop participants agreed on 21 indicators with some slight modifications (Table 2). For example, under 'sensitivity', they accepted seven indicators, rejected three, moved one indicator to adaptive capacity and added 'niche breadth' as one more indicator. Under 'exposure', they accepted all the indicators. In adaptive capacity, they accepted three, rejected two indicators, and moved one indicator, i.e. 'feeding habit' from sensitivity. Other indicators, i.e. 'poaching', 'pollution', 'human-wildlife conflict' and 'interspecific interaction' were combined to create one more category of the indicators as 'other stressors'. The final set of 21 vulnerability indicators included eight that assessed sensitivity, five that assessed exposure, four that assessed adaptive capacity and four that assessed other stressors.

Using the final 21 indicators, the CCVA was performed separately for each of the three rhinoceros populations to improve the resolution of our vulnerability assessment: (1) Chitwan-Parsa population (Rhinoceros in CNP and PNP as well as their buffer zones and surrounding areas), (2) Bardia population (Rhinoceros in BNP and its buffer zone) and (3) Shuklaphanta population (Rhinoceros in ShNP and its buffer zone). Participants were divided into groups for this exercise, each group comprised of stakeholders having knowledge and experiences of the respective rhinoceros population that was allocated to them for assessment. They were asked to assign a vulnerability score ranging from 0 (least vulnerable) to 10 (most vulnerable) for each of the indicators of sensitivity, exposure and other stressors. They were also asked to score each of the adaptive capacity indicators from 0 (most vulnerable) to 10 (least vulnerable). In the plenary session, members of each group were asked to provide the reasoning for assigning a varying score for different indicators. Finally, all workshop participants unanimously agreed on assigned vulnerability scores after some further discussion and minor adjustments.

2.2.4. Expert elucidation

Validation of a CCVA is an important step that identifies how well assessments are performed (Foden et al., 2019). A meeting of relevant experts was held in Kathmandu, Nepal, later in April 2019 to share and validate the outcomes of the stakeholders' consultation workshop. Nine experts participated in the meeting, representing related government departments and INGOs including DNPWC, WWF, and ZSL. Among the experts, two were members of the IUCN Asian Rhino Specialist Group. During this meeting, the findings of the stakeholders' consultation workshop were presented and discussed, and potential reasons for higher-lower scores were explored. In addition, a brief report was prepared, including the key findings of the workshop, which was shared with officials at DNPWC and WWF, for their feedback. They considered the on-ground reality of the findings and suggested some measures to enhance the resilience of rhinoceros, given the likely impacts of climate change.

2.3. Data analysis

The quantitative data were analyzed using simple statistical tools. Mean scores for sensitivity, exposure and other stressors were derived to obtain potential impact score, whereas the mean for adaptive capacity was calculated to obtain a resilience score applying the equation proposed by Füssel and Klein (2006). The equation states that combined exposure and sensitivity compose the potential impact, while adaptive capacity is the resilience of a system to cope with these impacts. Thus, climate change vulnerability can be expressed as an equation

$$V = f\,(PI, AC)$$

where V is vulnerability, PI is a potential impact, and AC is adaptive capacity.

Based on these scores, the climate change vulnerability index (CCVI) for rhinoceros in Nepal was identified using an analytical framework (Fig. 4). This framework has also been used by a number of studies to derive the climate change vulnerability index (Young et al., 2009; Nelson et al., 2010; Comer et al. 2012, 2019; Tuberville et al., 2015; Nguyen et al., 2016).

The CCVI uses component indicator values to ultimately arrive at a four-level series of index, i.e., Extremely High, High, Moderate, and Low vulnerability, which is derived from relative measures of both resilience and potential impact. When using quantitative data for measurement, numerical scores are normalized to a 0–1 scale, with 0 indicating "most favourable" conditions, and 1 indicating "least favourable" conditions (Comer et al., 2019). Quartiles of each continuous measure are used as a starting point to determine the range falling into each of the Extremely High to Low categories (e.g., $\geq$0.75 = Extremely high, 0.5–0.75 = High, 0.25–0.50 = Moderate, and $\leq$0.25 = Low vulnerability). In this framework, all indicators are weighted equally, and we used the arithmetic mean for their combination. We followed the categories of CCVI as follows (Young et al., 2011; Comer et al., 2019).

- ***Extremely high climate change vulnerability*** results from combining high potential impact with low resilience. These are circumstances where climate change stress and its effects are expected to be most severe, and relative resilience is lowest.
- ***High climate change vulnerability*** results from combining either high or moderate potential impact with low or medium resilience. Under either combination, climate change stress is anticipated to have a considerable impact.

- ***Moderate climate change vulnerability*** results from a variety of combinations for potential impact and resilience; initially with circumstances where both are scored as moderate. However, this also results where resilience is scored high if combined with either high or medium exposure.
- ***Low climate change vulnerability*** results from combining low potential impact with high resilience. These are circumstances where climate change stress and its effects are expected to be least severe or absent, and relative resilience is highest.

3. Results

3.1. Climate change vulnerability indicators

Table 2 presents the final list of 21 indicators developed through a participatory approach in order to assess the climate change vulnerability of rhinoceros in Nepal.

3.2. Climate change vulnerability scores

The vulnerability scores for each of the indicators are given in Appendix-1, while the summary of the average vulnerability score under sensitivity, exposure, adaptive capacity and other stressors categories for rhinoceros in Nepal is presented in Table 3.

The largest variation in vulnerability scores for a single population was Chitwan-Parsa (Sensitivity—0.43, other stressors—0.68). Chitwan-Parsa had the lowest sensitivity score (0.43), and Shuklaphanta had the highest (0.60). Scores of exposure, adaptive capacity and other stressors were largely similar for each population and the rhinoceros population of Nepal as a whole.

3.3. Climate change vulnerability index

The potential impact score, calculated from the average of sensitivity, exposure and other stressors were ‘high’ for all populations (0.51—0.52), as was the resilience of each population (0.50—0.58). This resulted in a vulnerability index of

Table 2
Climate change vulnerability indicators for greater one-horned rhinoceros in Nepal and the explanation for their inclusion.

SN	Indicator	Rationale
Sensitivity		
1	Habitat component — Food	The changing climate is likely to impact the abundance of food resources that will be available for the species.
2	Habitat component — Water	The spatial and temporal availability of water could be affected due to climate change.
3	Special habitat requirements	Rhinoceros requires mud pools for wallowing to maintain its body temperature and the availability of the wallowing sites could be limited due to the effects of climate change.
4	Distribution range	Species with restricted distributions are more likely to be vulnerable to climate change.
5	Population size	Species that can quickly recover from low population numbers may be less vulnerable to climate change.
6	Niche breadth	Species with a narrow physiological niche are likely to be more vulnerable to climate change.
7	Susceptibility to disease	The increased spread of wildlife diseases is a likely impact of climate change.
8	Invasive species	The spread of invasive species is likely to increase due to climate change.
Exposure		
9	Change in temperature	The degree of observed and projected changes in temperature could affect the species and its habitat.
10	Change in precipitation	The degree of observed and projected changes in precipitation pattern could affect the species and its habitat.
11	Floods	Frequent and severe floods will cause habitat destruction and loss or decline in the species population.
12	Droughts	Prolonged and frequent drought can increase the likelihood of local extinction.
13	Forest fire	Increased fire frequency could have adverse effects on the species and its habitat.
Adaptive capacity		
14	Dispersal ability	Species with high dispersal ability are less vulnerable to climate change.
15	Dispersal opportunity	Species distributed in an area with limited dispersal opportunity are more vulnerable to climate change.
16	Genetic diversity	Species with low genetic variation are likely to be more vulnerable to climate change.
17	Feeding habit	Generalist species are likely to be less sensitive to climate change than specialists.
Other stressors		
18	Poaching	Poaching is likely to exacerbate vulnerability to climate change.
19	Human-wildlife interaction	The conflict between human and wildlife can worsen if wildlife enters human settlements in search of suitable habitat.
20	Pollution (water, waste)	Pollution of water sources in and around rhinoceros habitat can intensify climate change vulnerability.
21	Interspecific interaction	Climate change is likely to intensify interspecific interactions among wildlife species due to limited resources.

Table 3
Climate change vulnerability score and index for greater one-horned rhinoceros (Rhinoceros unicornis) in Nepal. HH in vulnerability index column means that both potential impact and resilience scores are high, resulting in a 'moderate vulnerability' index according to the analytical framework presented in Fig. 4.

Rhinoceros Population	Vulnerability Score				Combined vulnerability score		Vulnerability index
	Sensitivity	Exposure	Adaptive capacity	Other stressors	Potential impact	Resilience	
Chitwan-Parsa	0.43	0.46	0.58	0.68	0.52 (High)	0.58 (High)	**Moderate (HH)**
Bardia	0.55	0.44	0.53	0.55	0.51 (High)	0.53 (High)	**Moderate (HH)**
Shuklaphanta	0.60	0.44	0.50	0.53	0.52 (High)	0.50 (High)	**Moderate (HH)**
Overall (Nepal)	0.46	0.46	0.55	0.60	0.51 (High)	0.55 (High)	**Moderate (HH)**

'moderately vulnerable' for all populations (Table 3). This result was in accordance with the perception of the key informants given that the majority (>60%) of them believe that rhinoceros population in Nepal is likely to be moderately vulnerable due to the impacts of climate change (Fig. 5).

4. Discussion

Our results indicate that all populations of rhinoceros in Nepal are moderately vulnerable to the likely impacts of climate change (Table 3, Fig. 4). Relatively high sensitivity and exposure, as well as high adaptive capacity to climate change (Table 3), mean that vulnerability is consistent across populations of all sizes. A wide range of potential sources of vulnerability contributes to this finding (Table 2, Appendix-1).

4.1. Climate change vulnerability indicators

In this study, we have come up with a set of 21 indicators in four categories, i.e. sensitivity (n = 8), exposure (n = 5), adaptive capacity (n = 4) and other stressors (n = 4). The vulnerability indicators under first three categories deals with the biological traits of rhinoceros that are likely to make it more sensitive to climate change, anticipated exposure of rhinoceros and its habitat to changing climate and likely extreme events as well as the inherent capability of rhinoceros to withstand probable adverse impacts of climate change. The other pressures, such as poaching and pollution, are not directly related to the impacts of climate change. However, they are likely to increase the vulnerability of rhinoceros if they are left unaddressed. Thus, stakeholders have identified these factors as non-climatic stressors that need to be considered while conducting a CCVA for rhinoceros. We believe that our inclusion of indicators related to non-climatic stressors for assessing the climate change vulnerability of rhinoceros has helped in identifying the full range of pressures faced by rhinoceros in the context of climate change.

It is evident from other studies that the effect of climate change on species is likely to be exacerbated by the existence of non-climatic stressors (Glick et al., 2011). For example, interspecific competition for limited resources among megaherbivores increases their climate change vulnerability given that both rhinoceros and elephants largely depend on floodplain grass *Saccharum spontaneum*, particularly during monsoon season (Pradhan et al., 2008), and the floodplain grasslands have been shrinking due to invasive plant species (Subedi, 2012; Murphy et al., 2013). Likewise, megaherbivores such as African

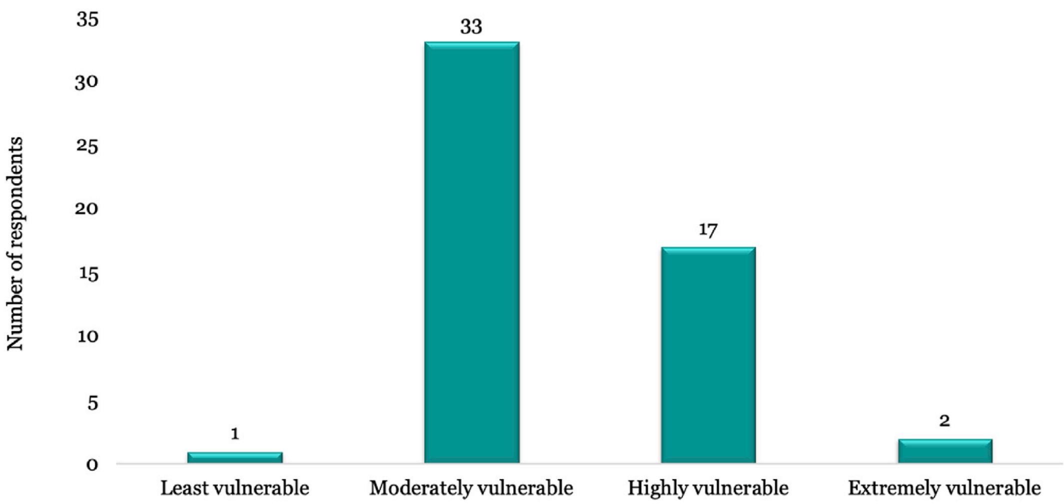

Fig. 5. Key informants' perception of the extent of climate change vulnerability of greater one-horned rhinoceros in Nepal (n = 53).

elephant, black and white rhino and hippopotamus are prone to habitat elements of vulnerability (Mawdsley et al., 2009; Owen-Smith, 2014), which can be exacerbated due to non-climatic stressors such as poaching (Owen-Smith, 2014). In accordance with the findings of such studies, our study has emphasized the need for reducing the pressures from non-climatic stressors such as poaching, human-rhinoceros conflict, pollution and interspecific competition to enhance the adaptive capacity of the rhinoceros to cope with the likely effects of the climate change.

The effectiveness of adaptation planning depends on our capacity to appropriately assess the vulnerability of a species to future climate (Glick et al., 2011). Current methods in quantifying the vulnerability of a species to climate change focus on appraising exposure to climatic changes and largely ignore the ecological differences between species that may significantly over or underestimate their climate change vulnerability (Foden et al., 2013). Since predicting the impact of climate change on species is a challenging task (Pacifici et al., 2015), identifying the full range of pressures, impacts and their associated mechanisms are very important for an effective CCVA (Foden et al., 2019). A substantial number of CCVAs to species has accounted for exposure, sensitivity and adaptive capacity (Glick et al., 2011; Foden et al., 2013; Böhm et al., 2016; Foden and Young, 2016), while some of these assessments have not considered even adaptive capacity as a component of the vulnerability assessment (Gardali et al., 2012; Garnett et al., 2013).

4.2. Climate change vulnerability scores

The findings of our study (Table 3) suggest that the rhinoceros population in Chitwan-Parsa complex is likely to be less sensitive to climate change than the Bardia and Shuklaphanta populations. In contrast, the Chitwan-Parsa population seems to be more exposed than the populations of Bardia and Shuklaphanta. The results also show that all of the populations are likely to be highly vulnerable to the other stressors. Adaptive capacity scored high for all of the populations. Based on the vulnerability score (Appendix−1), the population of rhinoceros in Chitwan-Parsa is likely to be more vulnerable due to invasive species, floods, human-rhinoceros conflict and pollution whereas populations of rhinoceros in Bardia and Shuklaphanta are more vulnerable because of the small size of the suitable habitat, small population size, lack of wallowing sites, prolonged drought and forest fire.

Stakeholders and experts believe that rhinoceros in Nepal can tolerate warmer temperatures projected by the climate models for the next 50 years, and climate change may not have severe impacts on their physiology. This is because rhinoceros in Shuklaphanta are thriving well, where the average annual temperature is more than 2 °C higher than Chitwan (CNP, 2013; DNPWC, 2018). This view is reinforced by other studies that mammals are capable of handling higher temperature if provided with an adequate supply of water (Mitchell et al., 2018). However, the predicted increase in extreme events associated with climate change is expected to compromise species' abilities to survive and reproduce (Kearney and Porter, 2009). It is likely that rhinoceros in Chitwan will be more vulnerable to flooding, which is one of the climate-induced extreme events experienced in the region. For example, at least ten rhinoceros from Chitwan were swept away by a severe flood in August 2017 across the Nepalese border into India; nine of them were rescued from India, and one was found dead (CNP, 2017). In India, 12 rhinoceros were found dead in Kaziranga National Park in the recent flood episode of July 2019 (Sharma, 2019). In addition, the rhinoceros population in CNP is likely to be affected by the invasion of *Mikania micarantha*, *Chromolaena odorata* and other invasive plant species into rhinoceros habitat. It is estimated that more than 15% of the prime rhinoceros habitat has been invaded by *Mikania micarantha* in CNP (Subedi, 2012; Murphy et al., 2013). Mikania can kill native flora such as grasses and trees, in which rhinoceros largely depend on. Rhinoceros population has already declined in areas with high mikania infestation (Murphy et al., 2013).

Species with restricted distributions are likely to be highly sensitive to climate change (Morueta-Holme et al., 2010). Likewise, occupied area is the most important predictor for CCVA because it provides a comprehensive measure of the breadth of climatic and habitat conditions under which a species can persist (Pearson et al., 2014). One reason that the rhinoceros population in Chitwan is less vulnerable than those in the other parks is they have abundant dispersal opportunities resulting from parks connectivity. CNP has landscape continuity with other protected areas of Nepal and India. The combined area of CNP, PNP, their buffer zones, and the forest corridor of Barandabhar as well as Valmiki Tiger Reserve of India is over 2500 km^2 and forms the largest protected area complex in this region. CNP, along with surrounding landscape, is ecologically inclusive (CNP, 2013), whereas rhinoceros populations in Bardia and Shuklaphanta are likely to be more vulnerable due to small and isolated patches of suitable habitat available for the species there (DNPWC, 2017).

Generalist species are likely to be less sensitive to climate change than specialist species (Brown, 1995). Species with specific diet and narrow habitat are likely to be more sensitive to climate change than others (Thuiller et al., 2005). The rhinoceros is a habitat specialist; however, it is a dietary generalist known to feed on more than 100 species of plants (Laurie, 1982; Dinerstein, 2003). Thus, rhinoceros in Nepal are likely to be highly adaptive in terms of its feeding ecology. Similarly, species with increasing and/or stable population are less vulnerable to the impacts of climate change (Glick et al., 2011; Foden et al., 2013). Due to their very small population size, rhinoceros in Shuklaphanta ($n = 8$) are likely to be highly sensitive to the impacts of climate change, in comparison to rhinoceros in Bardia ($n = 29$) and Chitwan-Parsa ($n = 608$) which would have moderate and low sensitivity, respectively.

Another observed impact of climate change is a rise in the incidence and spread of wildlife diseases, parasites and zoonosis, which is likely to further compromise already vulnerable species (Mackay, 2008; Harvell et al., 2009; Pascual and Bouma, 2009). The changing disease dynamics as a result of global warming has already been associated with the recent mass extinction of amphibians due to pathogen outbreaks (Pounds et al., 2006). Our CCVA indicates that rhinoceros in Nepal are likely to be moderately susceptible due to the spread of diseases resulting from climate change. Recent trends in the natural death of rhinoceros in Nepal is increasing, and 95 rhinoceros were found dead in CNP over the last three years, the reason behind most of these mortalities are not known (Mandal, 2019). Thus, the emergence of diseases and its redistribution due to climate change is a concern for rhinoceros conservation, which needs further investigation.

4.3. Climate change vulnerability index

It is believed that abundance and/or geographical extent of moderately vulnerable species are likely to decrease (Anacker et al., 2013), though they are not at immediate risk of climate-induced extinction (Glick et al., 2011; Young et al., 2015; Foden et al., 2019). However, given that rhinoceros recovery trends have been gradual and hard-won, this species needs to be monitored regularly to ensure that the likely adverse impacts of climate change do not overwhelm current conservation successes. Our study primarily relies on the subjective judgement of the experts and stakeholders directly involved in either the research or management of rhinoceros. In CCVA literature, uncertainty is acknowledged as a reality given that no one can know precisely how climate might change, and how species or ecosystems may respond to the changing climate (Glick et al., 2011; Foden and Young, 2016). Our study, therefore, provides general guidance for the adaptive management of the rhinoceros population in Nepal. National Park authorities in Nepal can utilize these findings to make choices and refine management decisions in the future through an adaptive management process based on the best available information (Holling, 1978; Walsh et al., 2012).

A similar approach to this CCVA can also be applied to other wildlife species in different geographical areas, and the vulnerability index developed through CCVA can also be used to compare the likely vulnerabilities across species. This research is more relevant to rhinoceros-bearing protected areas in India, particularly Kaziranga National Park, where rhinoceros habitat condition is comparable with CNP, and the challenges for rhinoceros conservation are similar (Talukdar, 2000; Basu et al., 2015; Puri and Joshi, 2018). In another study, Purnomo et al. (2011) developed indicators and assessed climate change vulnerability to Indonesia's Javan Rhino National Park. The stakeholders generally accepted that the natural adaptive capacity of the national park ecosystem is low, but no specific indicators were developed (Purnomo et al., 2011). In our study, we assigned vulnerability scores to each of the indicators and developed a vulnerability index. Similarly, some other studies have revealed that nature and extent of climate change impacts are species-specific. For instance, the recent drought in Kruger National Park has affected the two species of rhinoceros differently given that the natural mortality was increased, and the births decreased for white rhinoceros (*Ceratotherium simum*), with no such impacts on black rhinoceros (*Diceros bicornis*) (Ferreira et al., 2019). This suggests that the CCVA should be at a species level, and if possible, deeper into the sub-species level.

5. Conclusion

This study has developed species-specific vulnerability indicators and assessed the climate change vulnerability of the rhinoceros in Nepal. Based on the vulnerability index, the rhinoceros populations in Nepal are likely to be moderately vulnerable to the impacts of climate change. The potential impacts are likely to be high, but their adaptive capacity may offset these impacts. Climate change may not directly impact the physiology of the rhinoceros. However, it is likely to impact them indirectly through extreme events such as floods and droughts, limited availability of resources due to the prevalence of invasive plant species, and continued pressures from existing stressors such as poaching, human-wildlife conflict and pollution. Accounting for both climatic and non-climatic stressors can assist in developing adequate conservation plans for rhinoceros. Accordingly, we recommend the following adaptation measures for the persistence of rhinoceros well into the future.

a. Plan and manage wallowing sites for rhinoceros given that this is an essential component of rhinoceros habitat. Wallowing in mud pool helps rhinoceros for thermoregulation, and this could be an effective adaptation strategy against the likely impacts of climate change. Maintaining wallowing sites is fundamentally essential for Shuklaphanta, as this population of rhinoceros is likely to be highly vulnerable due to prolonged droughts and lack of wallowing sites.
b. Develop a comprehensive flood model to identify the rhinoceros habitat that is likely to be affected by various flood levels, and plan for climate refugia to maintain rhinoceros during the likely flood events in the future. Likewise, identify and create suitable corridors for rhinoceros and remove anthropogenic barriers to facilitate dispersal to higher and safe grounds during flood events. This is particularly important for rhinoceros in Chitwan, where they are likely to be highly affected by severe floods.
c. Build on active habitat management practices to provide a mosaic of grasslands and wetlands. This can be achieved by creating new grasslands and wetlands as well as maintaining the extant grasslands by removing invasive plant species. Controlling the spread of invasive weeds is particularly important for Chitwan, where the rhinoceros population is likely to be highly affected by the predicted increase in invasive species, especially *Mikania mikarantha* and *Chromolaena odorata* in grassland habitats.

d. Initiate long-term experimental research on rhinoceros ecology and its habitat dynamics, which can provide evidence-based insights on potential direct impacts of climate change on species, especially in the context of threats that arise from invasion of prime rhinoceros habitat by exotic weeds, and other likely threats on rhinoceros and its habitat.
e. Identify climate refugia and create additional suitable habitat to provide adequate habitat for rhinoceros in the region. This is particularly important for the rhinoceros in Bardia and Shuklaphanta as these populations are likely to be more vulnerable due to the small and fragmented habitat.
f. Initiate disease surveillance and health condition monitoring to provide an early warning system for potential disease outbreaks. This is particularly crucial for Chitwan, where natural death of rhinoceros is increasing, but the reasons behind surged mortality have not been thoroughly investigated.
g. Continue the ongoing best practices such as the implementation of zero poaching, pollution control and park-people partnership strategies given that such non-climatic stressors are likely to exacerbate the climate change vulnerability of rhinoceros in future.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix 1

Climate change vulnerability score for greater one-horned rhinoceros in Nepal.

SN	Indicators	Vulnerability Score			
		Nepal	Chitwan-Parsa	Bardia	Shuklaphanta
1. Sensitivity					
1.1	Habitat component-Food	4	3	4	5
1.2	Habitat component-Water	4	3	5	7
1.3	Special habitat requirements	5	5	7	8
1.4	Distribution range	5	4	7	7
1.5	Population size	4	3	7	8
1.6	Niche breadth	5	5	5	5
1.7	Susceptibility to diseases	5	5	5	5
1.8	Invasive species	5	6	4	3
2. Exposure					
2.1	Change in air temperature	3	3	3	3
2.2	Change in precipitation	2	2	2	2
2.3	Flood	6	7	4	3
2.4	Droughts	6	6	7	7
2.5	Forest fire	6	5	6	7
3. Adaptive capacity					
3.1	Dispersal ability	5	5	5	5
3.2	Dispersal opportunity	5	6	5	4
3.3	Genetic diversity	5	5	4	4
3.4	Feeding habit	7	7	7	7
4. Other stressors					
4.1	Poaching	6	6	6	7

(*continued on next page*)

(*continued*)

SN	Indicators	Vulnerability Score			
		Nepal	Chitwan-Parsa	Bardia	Shuklaphanta
4.2	Human-wildlife interaction	6	7	6	5
4.3	Pollution (Water, waste)	6	7	5	5
4.4	Interspecific interaction	6	7	5	4

Notes on vulnerability score: 0 is the lowest, and 10 is the highest level of vulnerability for sensitivity, exposure and other stressors, whereas 0 is the highest, and 10 is the lowest vulnerability for adaptive capacity.

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