UNIVERSITY OF SOUTHERN QUEENSLAND

GREATER ONE-HORNED RHINOCEROS (*RHINOCEROS UNICORNIS*) IN NEPAL IN THE CONTEXT OF CLIMATE CHANGE: VULNERABILITY ASSESSMENT AND ADAPTATION PLANNING

A Thesis submitted by

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ABSTRACT

Climate change has been identified as one of the most serious global concerns over the last few decades. The earth's temperature has increased by nearly 1^0C over the last 100 years. Likewise, the average global temperature is projected to increase by nearly 2^0C by the end of the 21st century, threatening biodiversity conservation. Species and ecosystems have already started responding to these changes in temperature and precipitation. Ecological studies have documented spatial and temporal shifts in species distributions in many parts of the world. The shift and contraction of suitable habitat are likely to intensify because of climate change, which may lead to further species extinctions.

Rhinoceros is a megafauna belonging to the family Rhinocerotidae. All five species of rhinoceros surviving in different parts of the world are threatened due to poaching and habitat loss. This includes greater one-horned rhinoceros, hereafter "rhinoceros" which has specialised habitat and food requirements. Until the middle of the 19th century, rhinoceroses were abundant throughout the Indian sub-continent. The global population of rhinoceros declined to fewer than 500 individuals during the early 1960s due to habitat loss and poaching. Following successful conservation initiatives, its population has been recovering and there are now nearly 3,700 rhinoceros, restricted to a few protected areas in Nepal and India. In Nepal, rhinoceroses were brought back from the brink of extinction during the 1960s and effective anti-poaching strategies have contributed to the increase in the population of this megaherbivore ever since. Whilst habitat loss and poaching remain serious threats to the survival of the rhinoceros, likely adverse impacts of climate change may jeopardise these conservation successes. However, climate change has not been incorporated well into management plans developed to ensure a viable population of rhinoceros in Nepal.

The overarching aim of this study was to assess the climate change vulnerability and explore the possible ways for initiating adaptation planning for rhinoceros conservation in Nepal. We used a combination of qualitative and quantitative research methods including (1) a review of the relevant literature, (2) key informant interviews, (3) stakeholders’ consultation workshop, (4) ensemble species distribution modelling, and (5) expert elucidation. First, we developed indicators of climate change vulnerability to the rhinoceros population in Nepal. Based on these indicators, the extent of climate change vulnerability was assessed, and key vulnerability factors were considered before identifying and prioritising adaptation actions. These were identified using available information on spatial distribution, biological traits, and climatic variables. In addition, habitat suitability modelling was performed for current and future climate and land use change scenarios.

The key findings of this research imply that rhinoceroses in Nepal will face a ‘moderate’ level of climate change vulnerability and over one-third of the current habitat is likely to become unsuitable by the year 2070. The ensemble habitat model estimated an area of 2,610 km^2 or 1.77 % of the total area of Nepal to be suitable for rhinoceros, and nearly 35% (924 km^2) of which is predicted to be lost under the highest emission scenarios by 2070. We identified 20 adaptation actions for rhinoceros conservation. Of these, identifying and protecting climate refugia, restoring existing habitats through wetland and grassland management, creating artificial highlands in floodplains, and translocating them to other suitable habitats were prioritised more highly over other actions. A variety of caveats to our results exist given the uncertainty inherent in climate models, and the relatively unpredictable responses of rhinoceros to global warming and adaptation interventions.

This research provides insights for protected area managers to implement adaptive management of rhinoceros in Nepal. Besides, it will provide a basis for policymakers to allocate scarce resources into prioritised areas, which will contribute towards ensuring its persistence well into the future. We also recommend further empirical research to provide better insights on the consequences of climate change so that our suggested adaptation actions can be refined in the future. This study is the first of its kind in Nepal, to our knowledge, and is anticipated to be instrumental for initiating climate change adaptation planning. Thus, this research is important not only for rhinoceros but also for sympatric wildlife species that are vulnerable to the likely impacts of climate change.

CERTIFICATION OF THESIS

I, Ganesh Pant, declare that the PhD Thesis entitled **Greater One-horned Rhinoceros (*Rhinoceros unicornis*) in Nepal in the Context of Climate Change: Vulnerability Assessment and Adaptation Planning** is not more than 100,000 words in length including quotes and exclusive of tables, figures, appendices, bibliography, references, and footnotes.

This Thesis is the work of **Ganesh Pant** except where otherwise acknowledged, with the majority of the contribution to the papers presented as a Thesis by Publication undertaken by the Student. The work is original and has not previously been submitted for any other award, except where acknowledged.

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STATEMENT OF CONTRIBUTION

This section provides details of the agreed share of contributions of the PhD candidate and respective co-authors (Supervisors) in the journal publications presented in this Thesis.

Article 1: Chapter 3 (Review article)

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Author	**Task Performed**
Ganesh Pant PhD Candidate	Establishing methodology, compiling and analysing data, preparing tables, graphs and figures, and writing the manuscript.
Professor Tek Maraseni Principal Supervisor	Supervising and assisting in finalising the methodology, technical inputs, editing and co-authoring the manuscript.
Professor Armando Apan Associate Supervisor	Technical inputs, editing and proofreading of the manuscript
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ADDITIONAL PUBLICATIONS, CONFERENCE PAPERS AND AWARDS DURING THE DOCTORAL RESEARCH PERIOD

Research articles

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Conference papers

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5. **Ganesh Pant,** Tek Maraseni, Armando Apan and Benjamin L. Allen (2018). Greater one-horned rhinoceros (*Rhinoceros unicornis*) in Nepal in the context of climate change: Vulnerability assessment and adaptation planning. Paper presented in **Spatial Planning for Protected Areas in Response to Climate Change (SPARC) Decision Support Tool Design Workshop** organised by Conservation International at the University of California, Santa Barbara, California, USA, 5–9 November 2018.

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ABBREVIATIONS

ACT	Adaptation for Conservation Targets
ANN	Artificial Neural Network
AUC	Area Under Curve
AWMS	Australasian Wildlife Management Society
BaNP	Banke National Park
BIO	Bioclimatic
BIOMOD	Biodiversity Modelling
BNP	Bardia National Park
BZ	Buffer Zone
CBD	Convention on Biological Diversity
CCVA	Climate Change Vulnerability Assessment
CCVI	Climate Change Vulnerability Index
CI	Conservation International
CNP	Chitwan National Park
CTA	Classification Tree Analysis
DEM	Digital Elevation Model
DNA	Deoxyribonucleic Acid
DNPWC	Department of National Parks and Wildlife Conservation
EbA	Ecosystem-based Adaptation
EROS	Earth Resources Observation and Science
FDA	Flexible Discriminant Analysis
FLUS	Future Land Use Simulation
GAM	Generalised Additive Model
GBIF	Global Biodiversity Information Facility
GBM	Generalised Boosting Model
GBRMP	Greater Barrier Reef National Park

GCM	Global Circulation Model
GeoSOS	Geographical Simulation and Optimisation System
GHG	Greenhouse Gas
GIS	Geographic Information System
GLM	Generalised Linear Model
GO	Government Organisation
GON	Government of Nepal
GPS	Global Positioning System
HDX	Humanitarian Data Exchange
INGO	International Nongovernmental Organisation
IPBES	Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services
IPCC	Intergovernmental Panel on Climate Change
IUCN	International Union for Conservation of Nature
KCA	Krishnasar Conservation Area
KNP	Kaziranga National Park
KTWR	Koshi Tappu Wildlife Reserve
MARS	Multiple Additive Regression Splines
MAXENT	Maximum Entropy
MFSC	Ministry of Forests and Soil Conservation
MIROC	Models for Interdisciplinary Research on Climate
MOCTCA	Ministry of Culture, Tourism and Civil Aviation
MODIS	Moderate Resolution Imaging Spectroradiometer
MOFE	Ministry of Forests and Environment
NACA	Nepali Academics in America
NGO	Nongovernment Organisation
NTNC	National Trust for Nature Conservation
ODMAP	Overview, Data, Model, Assessment and Prediction

PA	Protected Area
PHVA	Population and Habitat Viability Assessment
PNP	Parsa National Park
RF	Random Forest
ROC	Receiver Operating Characteristics
SDM	Species Distribution Modelling
SNIP	Source Normalised Impact per Paper
SNP	Shuklaphanta National Park
SPARC	Spatial Planning for Protected Areas in Response to Climate Change
SRE	Surface Range Envelope
SRTM	Shuttle Radar Topographic Mission
SSC	Species Survival Commission
SSP	Shared Socioeconomic Pathway
TSS	True Skill Statistics
UNEP	United Nations Environment Program
UN	United Nations
UNESCO	United Nations Educational, Scientific and Cultural Organisation
USAID	United States Agency for International Development
USDM	Uncertainty Analysis for Species Distribution Models
USGS	United States Geological Survey
USQ	University of Southern Queensland
VIF	Variance Inflation Factor
WGS	World Geodetic System
WWF	World Wide Fund for Nature
ZSL	Zoological Society of London

CHAPTER 1: INTRODUCTION

1.1 Background

Climate change is acknowledged as a serious global concern over the last few decades in response to the rising temperatures, changing precipitation patterns and increasing frequency and severity of extreme weather events (Nelson et al., 2010; Chapman et al., 2014; IPCC, 2014; IPBES, 2019; Perera et al., 2020). The earth's surface temperature has increased by at least 0.74^{0}C over the last 100 years and the climate models have predicted that the average global temperature would exceed 1.5^{0}C by the end of the 21st century, even under the most optimistic emission scenario (Almazroui et al., 2020; Newbold et al., 2020; IPCC, 2021).

In recent years, the rapidly changing climate is considered to be one of the key threats to biodiversity conservation (Hannah et al., 2005; Pacifici et al., 2017; Pires et al., 2018; Haight & Hammill, 2020) given that species assemblage and ecosystem dynamics have started impacting due to climate change (Walther et al., 2002; Morueta-Holme et al., 2010; Bellard et al., 2012). Some of these impacts include (i) changes in phenology (Parmesan & Yohe, 2003; Cohen et al., 2018; Zhixia et al., 2020), (ii) shifts in the distribution of floral and faunal species (Root et al., 2003; Thuiller et al., 2011; Corlett, 2015; Trisos et al., 2020), (iii) decrease in population size (Hunter et al., 2010; Molnár et al., 2011; Moritz & Agudo, 2013; Selwood et al., 2015; Soroye et al., 2020), (iv) increase in fire frequency (Flannigan et al., 2000; Couturier et al., 2014), the emergence of new diseases (Pounds et al., 2006; Harvell et al., 2009; Pascual & Bouma, 2009; Vezzulli et al., 2020), and proliferation of invasive species (Taylor & Kumar, 2013; Gong et al., 2020; Wallingford et al., 2020), (v) decline in suitable habitat

(Leadley, 2010; Escobar et al., 2015; Dar et al., 2021); and (vi) increased species extinction (Thomas et al., 2004; Pearson et al., 2014; Waller et al., 2017).

Global biodiversity models have indicated that shift in the spatial distribution of species, habitat loss, and species extinctions is likely to continue if climate change is not addressed adequately (Hannah et al., 2020). The decline in wildlife habitat due to climate change further jeopardises the biological diversity of the world (Leadley, 2010). Likewise, predictions on consequences of climate change on biodiversity suggest that more species will become imperilled with extinction (Bellard et al., 2012; Bagchi et al., 2013; Oliver et al., 2015; Román-Palacios & Wiens, 2020). For example, the Bramble Cay melomys (*Melomys rubicola*), a small rodent which lived exclusively on low-lying Great Barrier Reef islands, was the first mammal species to go extinct due to human-induced climate change when rising seas finally covered the islands in 2016 (Fulton, 2017).

Rhinoceros, commonly abbreviated to rhino, is the second largest terrestrial animal on earth and belongs to the Rhinocerotidae family of the taxonomic order Perissodactyala (Milliken et al., 2009; Mallet et al., 2019). Rhinoceros is a "megafauna", which refers to animals that have a body mass over 1,000 kg (Fariña et al., 2013). Currently, there are five species of rhinoceros surviving in the world. The javan rhinoceros (*Rhinoceros sondaicus*), greater one-horned rhinoceros (*Rhinoceros unicornis*), and sumatran rhinoceros (*Dicerorhinus sumatrensis)* are distributed in South Asia and South East Asia, whereas black rhinoceros (*Diceros bicorn) and* white rhinoceros (*Ceratotherium simum*) inhabit South and Western Africa (Foose & van Strien, 1997; Amin et al., 2006; DNPWC, 2017). Once abundant throughout Africa and Asia, all these rhinoceroses are threatened and are struggling for their existence due to continual poaching and the degradation of suitable habitats (Amin et al., 2006; Ellis & Talukdar, 2019).

Greater one-horned rhinoceros, hereafter "rhinoceros", is a specialist in terms of habitat and food requirements (Pradhan et al., 2008; Ellis & Talukdar, 2019). Until the middle of the 19th century, rhinoceroses were abundant throughout the Indian sub-continent (Foose & van Strien, 1997). The global population of rhinoceros declined to fewer than 500 individuals during the early 1960s due to habitat loss and poaching (Rookmaaker et al., 2016). Following successful conservation initiatives, its population has been recovering. Currently, there are more than 3,550 rhinoceros in the wild currently restricted to a few protected areas in the northern foothills of India and southern parts of Nepal (Rookmaaker et al., 2016; Ellis & Talukdar, 2019). In Nepal, rhinoceroses were brought back from the brink of extinction during the 1960s and effective antipoaching strategies have increased the population of this megaherbivore ever since (DNPWC, 2017; Acharya et al., 2020). But these conservation successes may now be threatened by climate change.

One of the most likely impacts of climate change is a shift in spatial and temporal patterns in the availability of suitable habitats for terrestrial species (Thuiller et al., 2011; Sunday et al., 2012; Kanagaraj et al., 2019). Some species can simply move to other suitable habitats, while other animals are forced to adapt to new habitat conditions or shift gradually over generations (Battin, 2004; Lister & Stuart, 2008). But given climate change is occurring rapidly, most species may not be able to respond through local adaptation or migration across landscapes (Olson et al., 2009; Roy et al., 2015; Butt et al., 2021). Rhinoceros, being a habitat specialist, is confined to the riverine grasslands in the foothills of the Himalayas where water and green growth remain relatively constant throughout the year (Laurie, 1982; Dinerstein & Price, 1991; Jnawali, 1995). As a result of habitat contraction due to anthropogenic land use changes, the rhinoceros population is now restricted to a small fraction of its historical range (DNPWC, 2017; Ellis & Talukdar, 2019).

The ecological impacts associated with climate change exacerbate the existing pressures on our natural systems (Glick et al., 2011). In Nepal, the rhinoceros population seems to be affected by commonly observed climate-induced stressors including torrential precipitation and flash floods, frequent forest fires and prolonged droughts. Whilst habitat loss and poaching remain serious threats to the survival of the rhinoceros, likely adverse impacts of climate change may also jeopardise its conservation success (DNPWC, 2017; Adhikari & Shah, 2020). Despite the perceived risk, the likely consequences of climate change on rhinoceroses and their habitat have not been well studied. In this context, understanding rhinoceros vulnerability to climate change and the availability of suitable habitat for rhinoceros under future climate scenarios appeared crucial to devise appropriate climate change adaptation measures.

1.2 Problem statement

The rate of vertebrate species extinction due to human activities over the last century is at least 20 times higher than the pre-human extinction rate (Pereira et al., 2010; Ceballos et al., 2015). Among the vertebrates, large mammalian species are at high risk of extinction due to vulnerability associated with biological traits such as low reproductive rate and large body size (Cardillo et al., 2005). Large herbivores in particular are facing a dramatic decline in population size and distribution such that 60% are threatened with extinction due to hunting and land-use changes (Ripple et al., 2015). The impact of climate change was a similarly serious issue for the survival of large mammals in prehistoric times given fossil records have confirmed that climate change was a key driver of the Pleistocene megafaunal extinction (Cooper et al., 2015). Members of the Rhinocerotidae family have a history of climate-induced extinction during the Late Quaternary period (Lorenzen et al., 2011).

Predicting the impacts of climate change on biodiversity is a major scientific challenge (Pacifici et al., 2015). Limited information exists on how the changing climate is going to impact wildlife species and the mechanisms underpinning this change (Foden & Young, 2016). Studies conducted so far have documented some of the likely adverse impacts of climate change on selected wildlife species including the snow leopard (*Panthera uncia*), the giant panda (*Ailuropoda melanoleuca*), the polar bear (*Ursus maritimus*), and the Asian elephant (*Elephas maximus*), but not for the rhinoceros (Aryal et al., 2016; CBD, 2018; WWF, 2018; Kanagaraj et al., 2019).

A species conservation action plan for rhinoceros in Nepal (DNPWC, 2017) has acknowledged that climate change is one of the prominent threats for rhinoceros (Adhikari & Shah, 2020). Climate-induced hazards including torrential rain, flash floods, prolonged droughts and frequent forest fires are expected to increase in the future (DNPWC, 2017). In recent years, the population of rhinoceros has been increasing in Nepal, as poaching has been halted, especially through the successful implementation of anti-poaching programs (Aryal et al., 2017; DNPWC, 2017). However, the question arises on how long the species can be conserved in the face of climate change impacts. Thus, this research has explored the likely impacts of climate change on rhinoceros through vulnerability assessment and identified the possible ways for adaptation planning.

Vulnerability assessment is regarded as a tool to understand potential impacts of climate change and inform adaptation planning (Füssel & Klein, 2006). Vulnerability assessment helps in identifying which species or systems are likely to be affected by projected changes and why these are vulnerable (Glick et al., 2011). Climate change adaptation is emerging as a primary lens for conservation planning and it requires an understanding of the likely impacts of climate change (Glick et al., 2009). The effectiveness of the adaptation plan depends on our capacity to appropriately assess the vulnerability of a species to future climate (Glick et al., 2011). The current methods in quantifying the vulnerability focus on appraising exposure to climatic change and largely ignore the ecological differences between species (Foden et al. 2013). Most of the methods for climate change vulnerability of the species are generic and used for both terrestrial and aquatic species, including plants (Foden & Young 2016). Vulnerability indicators for assessing the climate change impact are appropriate for the identification of vulnerable systems at a local scale (Hinkel, 2011). Thus, there was a need to develop vulnerability indicators in the local context to assess the climate change vulnerability of the rhinoceros population in Nepal.

Determining how vulnerable a species is to climate change provides valuable information for devising policies to reduce the climate-induced hazards (Füssel & Klein, 2006). The climatic (direct) and non-climatic (indirect; anthropogenic) factors collectively determine the vulnerability of a species given that climate change interacts with existing stressors and exacerbate the likely vulnerability (Jones et al., 2016). However, most of the research is based on a piecemeal approach and does not account for the complex interactions between climatic and anthropogenic factors (Gardali et al., 2012; Pacifici et al., 2017). In this study, we have followed a comprehensive approach (i) incorporating both direct and indirect factors for assessing vulnerability, (ii) linking biological traits of the species while determining the extent of the vulnerability, and (iii) identifying where the adaptation actions can be spatially integrated using the correlative approach of vulnerability assessment.

1.3 Aims and objectives

The overarching aim of this study was to assess the climate change vulnerability of greater one-horned rhinoceros under different greenhouse gas (GHG) emission scenarios and explore the possibilities for appropriate adaptation planning. Unless mentioned otherwise, the scope of this study is limited to rhinoceros populations in Nepal, with the following four objectives. Based on the review of relevant literature and the expert consultations, we assumed that rhinoceroses in Nepal are likely to be vulnerable due to the adverse impacts of climate change and needs adaptation planning for securing their persistence well into the future. This proposition was verified through systematic documentation of the evidence published in four Quartile 1 (Q1) journal articles, responding to each of the following specific objectives and one systematic review.

1.3.1 Develop indicators of climate change vulnerability. This objective was accomplished by developing a set of 21 climate change vulnerability indicators for the rhinoceros in Nepal (Chapter 4; Pant et al. 2020).

1.3.2 Assess the extent of climate change vulnerability. This objective was fulfilled by evaluating the level of vulnerability to rhinoceros in Nepal due to the likely adverse impacts of climate change (Chapter 4; Pant et al. 2020).

1.3.3 Examine the current and future habitat suitability, taking bioclimatic variables as the main predictor of suitable habitat. This objective was achieved through an ensemble modelling for current rhinoceros habitat suitability in Nepal and predicting the declines in current habitat in by the year 2070 due to combined effects of climate and land use changes (Chapter 5; Pant et al. 2021).

1.3.4 Identify appropriate adaptation measures. This objective was realised through the identification and prioritisation of adaptation actions for rhinoceros conservation in Nepal (Chapter 6; Pant et al. 2022).

The specific questions addressed by this research were:

1. What are the most relevant indicators of climate change vulnerability for rhinoceros in Nepal?
2. What is the level of vulnerability the rhinoceros population in Nepal is likely to face due to the impacts of climate change?
3. To what extent will suitable rhinoceros habitat in Nepal shift or decline due to the impacts of climate change?
4. Which adaptation actions are most likely to enhance the resilience of rhinoceros to climate change in Nepal?

1.4 Significance of the research

Responding to climate change involves two possible approaches: (i) reducing and stabilising the levels of greenhouse gas (GHG) emissions in the atmosphere, labelled “mitigation measures” and (ii) adjusting or adapting to actual or expected future climate, or “adaptation measures” (Smit et al., 2000; Morecroft et al., 2019). This study deals with the latter, and is important for safeguarding Nepal’s biodiversity given that rhinoceros is an umbrella species

(Amin et al., 2006) which, if adequately protected, also confers protection to a large number of sympatric species (Roberge & Angelstam, 2004; Karki et al., 2015). Rhinoceros is also an influential ecosystem engineer (Subedi, 2012) which helps to maintain ecosystem health so that other species may thrive (Waldram et al., 2008). Rhinoceros are also a flagship species (Subedi, 2012; Borthakur et al., 2016; Cédric et al., 2016), with high levels of public recognition and concern in Nepal.

In addition to being work on a flagship species, this study also particularly relevant for neighbouring countries like India, where the condition of the habitat and the issues associated with rhinoceros conservation are similar to those areas of Nepal which we focus on (Cédric et al., 2016; Rookmaaker et al., 2016; DNPWC, 2017). Rhinoceros is further listed as a vulnerable species on IUCN Red List (Ellis & Talukdar, 2019) and protected by national legislation in both the range countries of Nepal and India (Rookmaaker et al., 2016; DNPWC, 2017). Wildlife attracts substantial numbers of tourists, and iconic animals like rhinoceros are major attractions for tourists (Lubbe et al., 2017). In Nepal, more than 70% of tourists visited protected areas in 2017 (MOCTCA, 2018) and more than 40% of them visited protected areas with rhinoceros (DNPWC, 2018). Thus, rhinoceros also contributes to the national economy through tourism promotion. Two of the National Parks (namely Chitwan in Nepal and Kaziranga in India) with extant rhinoceros are also listed as World Heritage Sites. The preceding information demonstrates the value of conserving rhinoceros and undertaking our study on climate change vulnerability assessment and adaptation planning for the rhinoceros population in Nepal.

Climate change adaptation is evolving as the overarching framework for conservation that anticipates and prepares for an uncertain future climate (Glick et al., 2011). The rhinoceros conservation action plan of Nepal 2017–2021 has revealed that climate change is emerging as one of the prominent threats to rhinoceros (DNPWC, 2017). Thus, it is crucial to understand the extent of climate vulnerability to the rhinoceros and the associated vulnerabilities to initiate adaptation planning for its conservation in Nepal. This research has not only assessed the likely vulnerabilities of rhinoceros to climate change but also identified and prioritised the adaptation actions that are expected to contribute to enhancing the resilience of rhinoceros to withstand these adverse impacts. More specifically, this research has identified climate refugia for rhinoceros and recommended possible measures to safeguard both current and future potential habitat from fragmentation and conversion into other land uses. Thus, this study is of great significance to initiate adaptation planning for a threatened wildlife species, aiming to secure its persistence well into the future.

This study is also important from an ecosystem-based adaptation (EbA) perspective given that it has explored the possible ways for reducing climate change vulnerabilities of a flagship and umbrella species. EbA is a nature-based solution that harnesses biodiversity and ecosystem services to reduce vulnerability and build resilience to climate change (Scarano, 2017). It is also known as an ecosystem-based approach to climate change adaptation or nature-based solutions to climate change and involves a wide range of ecosystem management activities to increase resilience and reduce the vulnerability of people and the environment to climate change (Munang et al., 2013; Seddon et al., 2020). Thus, this study contributes to biodiversity conservation in the face of climate change through climate change vulnerability assessment and adaptation planning for a species, which is an integral part of ecosystem-based adaptation.

Likewise, this study is equally valuable for scholars and practitioners from around the world, given that it has contributed to academic knowledge related to climate change vulnerability of a threatened mammal species in a less-developed country. In recent years, climate change vulnerability of a species has been a well-researched topic, with over 743 peer-reviewed articles reported between 2000 and 2016 (de los Ríos et al., 2018). However, most of the studies were from North America, Europe and Australia, indicating a clear knowledge gap in less-developed countries, where greater numbers of threatened species and higher levels of biodiversity exist (Pacifici et al., 2015; Chambers et al., 2017). Out of 743 articles, >50% (n=372) studied plants whereas mammals were underrepresented with only <10% (n= 68), despite the status of mammals as one of the most threatened taxa (de los Ríos et al., 2018).

1.5 Structure of the Thesis

The research described in this Thesis has followed the conceptual framework presented in **Figure 1.1.** First, indicators for climate change vulnerability of the rhinoceros population in Nepal was developed following a participatory approach. Based on these indicators, the extent of climate change vulnerability was assessed using a trait-based approach of vulnerability assessment of species. Likewise, an ensemble species distribution modelling was used as a correlative approach of vulnerability assessment, which has predicted the current habitat and the change in future suitable habitats of rhinoceros in Nepal by the year 2070. Based on the findings of the research, we have recommended initiating adaptation planning for rhinoceros conservation. We also have identified and prioritised the adaptation actions for rhinoceros conservation in Nepal, details of which are presented in the subsequent chapters.

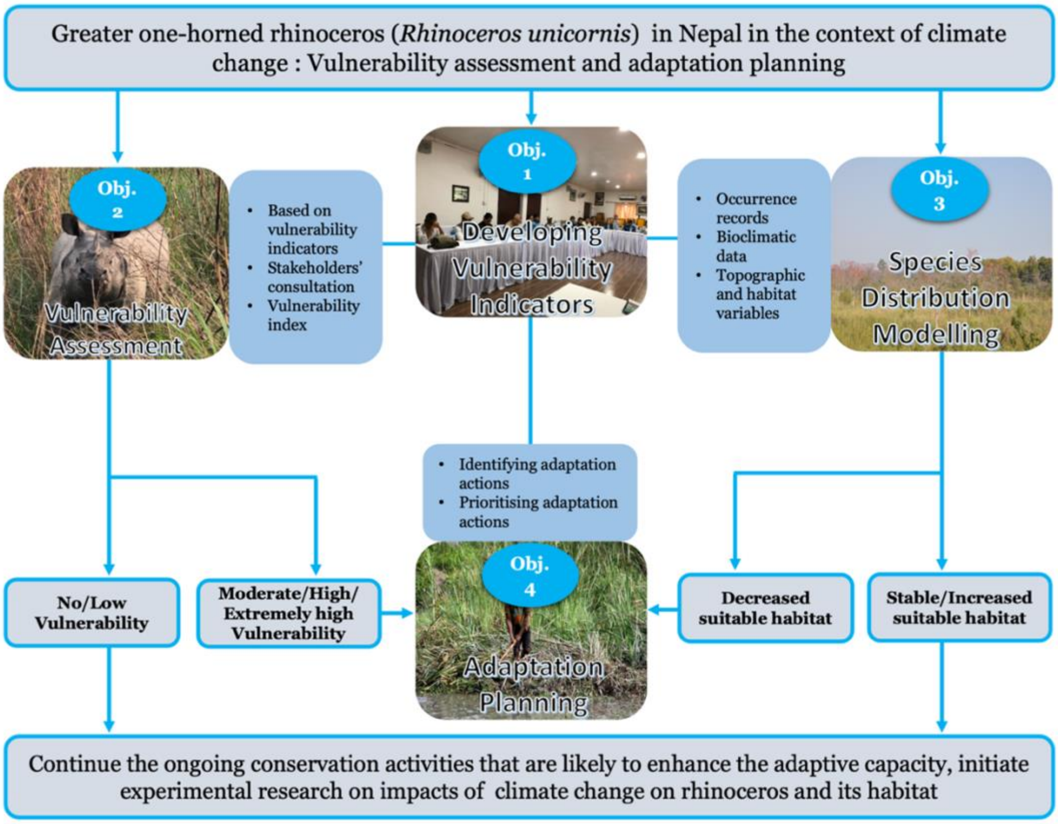

Figure 1.1 Conceptual framework of the research.

The articles published in international peer-reviewed journals within the scope of this research are presented in different chapters, given that the Thesis is prepared following a 'Thesis by Publication' protocol. More specifically, the Thesis has been organised in seven different chapters as follows:

Chapter 1: This chapter provides an overall context and background of the research including the problem statement, aim and objectives of the study, significance of the research and the structure of the Thesis.

Chapter 2: This chapter is a review of the literature relevant to our research topic. The first section sets the context of research under the framework of climate change vulnerability assessment to species. The second section is about a systematic review of the published literature between 1985 and 2018 on rhinoceroses and their conservation, which highlights the gaps in rhinoceros research.

Chapter 3: This chapter briefly describes the study area and the general methods used for this research. It provides the general methodological foundation for the following chapters which use more specific methods of data collection and analysis.

Chapter 4: This chapter covers two specific objectives of the research. The first part is on developing indicators of climate change vulnerability of rhinoceros and the second part uses these indicators to determine the extent of their climate change vulnerability in Nepal.

Chapter 5: This chapter builds on previous chapters and describes the projected changes in rhinoceros habitat suitability in Nepal under different greenhouse gas emission scenarios by the year 2070.

Chapter 6: With their vulnerability assessed and their projected available habitat described, this chapter identifies and prioritises climate change adaptation actions for rhinoceros conservation in Nepal. We further describe how the prioritised actions can be spatially integrated.

Chapter 7: This chapter summarises the key findings of the research and recommends management actions to initiate adaptation planning. The limitations of the study and areas for further research are also discussed in this chapter.

CHAPTER 2: LITERATURE REVIEW

This chapter has two sections. The first section comprises the overall literature review to contextualise the study under the framework of climate change vulnerability assessment (CCVA) to species. On top of that, it explores the different approaches currently in practice to assess the extent of vulnerability a species is likely to face in the context of predicted climate change scenarios. The second section is a review of published articles on greater one-horned rhinoceros (*Rhinoceros unicornis*) that identifies the research gap in the field of rhinoceros conservation. In addition to these two sections, each of the objective-wise published chapters has presented the reviewed literature relevant to their study focus.

2.1 Overall literature review

2.1.1 Climate change vulnerability assessment to species

Climate change vulnerability assessment (CCVA) to species has evolved as priority research in the biodiversity conservation sector aiming to aid for adaptation planning (Gardali et al., 2012; Garcia et al., 2014; Foden et al., 2019). Vulnerability is "the extent to which systems are susceptible to, and unable to cope with adverse impacts of climate change" (IPCC, 2014). Climate change vulnerability to a species can be defined as a function of three components: species' exposure to climate stimuli, the sensitivity of the species itself and its adaptive capacity as illustrated in the conceptual model (**Figure 2.1**), which forms the basis for CCVA (IPCC, 2007). Exposure is the climatic element that differs in the physical space of a species and sensitivity is how the species respond to change in climatic conditions, the potential impact is determined by combining these two components (Foden et al., 2013). Adaptive capacity refers to the species' ability to tolerate, adapt to or recover from the adverse impacts of climate change. Hence, evaluating each of these components is crucial for assessing the vulnerability of a species to climate change.

A species or an ecosystem having higher exposure and sensitivity to changing climate, but lower adaptive capacity is more vulnerable to climate change. In contrast, if the adaptive capacity of the species or ecosystem is higher, it is less vulnerable even under higher sensitivity and exposure (Glick et al., 2011). Climate change is not only in addition to other direct threats to species including poaching and land use change but also act synergistically with those threats (Benning et al., 2002; Hof et al., 2011). Thus, the combined effects of climate change and other direct threats pose the greatest risk to our natural systems including wildlife species (Glick et al., 2011; Poudyal et al., 2021). In this context, CCVA is an important tool to appraise the likely consequences of future climate on species and to initiate adaptation planning for safeguarding the species in the face of climate change (Wade et al., 2017; Foden et al., 2019).

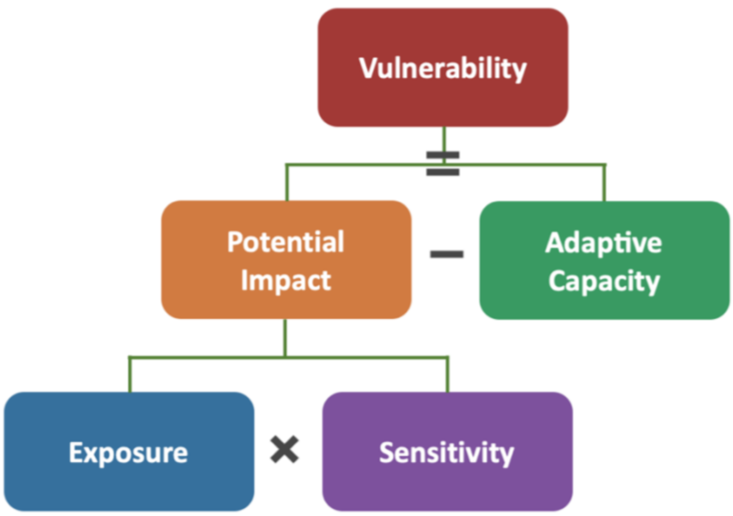

Figure 2.1 Conceptual framework of vulnerability assessment (IPCC, 2007).

There are three methodological approaches in practice for assessing species' climate change vulnerability: (i) trait-based, (ii) correlative, and (iii) mechanistic (Pacifici et al., 2015; Foden et al., 2019). Species distribution modelling as a correlative approach is the most used method for CCVA of species, especially for fauna (Willis et al., 2015; de los Ríos et al., 2018). The trait-based approach (TVA) uses selected biological features such as life-history traits to predict extinction risk, based on existing data and expert judgement calculating relative vulnerability score and index (Foden et al., 2013). The mechanistic or process-based approach involves biological processes, interactions, and thresholds, which is prevailed for CCVA of plants (de los Ríos et al., 2018). Data requirements, spatial and temporal scales of application and modelling methods greatly vary among approaches and each of the approaches has certain uncertainties and limitations (Pacifici et al., 2015). An integrated approach combining two or more approaches, selecting the least complex approach, and involving all stakeholders is likely to reduce uncertainty and gives the best possible results in CCVA of species (Pacifici et al., 2015; Foden & Young, 2016). Considering the available information, time and resources, we have integrated the trait-based and correlative approaches of CCVA in our study as suggested by Willis et al. (2015).

2.1.1.1 Trait-based approach

The climate change vulnerability of a species largely depends on the biological traits of the species. Thus, a framework using a trait-based approach is likely to perform better at assessing the vulnerability of a species (Foden et al., 2013). This approach considers the vulnerability of species to anticipated climate change based on the best available knowledge of the species' ecology and life history traits (Willis et al., 2015). The framework combines three components of climate change vulnerability, namely exposure, sensitivity, and adaptive capacity and explains four distinct classes of species vulnerable to climate change. Species of concern are in the 'highly vulnerable' category, if they are sensitive, exposed and have low adaptive capacity. Thus, these species are the priority for monitoring and adaptation planning (Foden et al., 2013). The trait-based approach was used in this study, given that the unique combination of biological traits strongly influence a species' response to climate change and this approach is considered most commendable (Foden et al., 2013). Vulnerability assessment, being a theoretical concept, requires indicators for measuring it (Hinkel, 2011; Tonmoy et al., 2014). Therefore, we developed a set of vulnerability indicators for rhinoceros in Nepal, primarily based on a literature review. In doing so, we first evaluated the generic indicators developed for a wide range of species given that there were no specific indicators developed for assessing climate change vulnerability to rhinoceros (Young et al., 2011; Advani, 2014; Lee et al., 2015; Foden et al., 2019).

2.1.1.2 Correlative approach

The species distribution model (SDM) as a correlative approach of climate change vulnerability assessment is a powerful tool for forecasting the future occurrences and distributions of species (Foden & Young, 2016). The SDM is considered to have a huge potential in conservation planning by widening our understanding of species distribution (Franklin, 2010; Jetz et al., 2012) through predicting the consequences of changing climate on species (Berry et al., 2002; Araújo et al., 2005; Elith et al., 2010). It also helps in projecting the distribution of species in time and space, which is crucial in analysing the risk of extinction (Elith & Leathwick, 2009). Over the last few decades, the species distribution modelling has been a widely used as a spatial modelling technique for habitat suitability analysis. However, the predictive performance differs among various techniques and consensus methods are used aiming to reduce the uncertainty of the models (Marmion et al., 2009). SDMs can be performed using a wide range of statistical modelling techniques. Among them, biodiversity modelling (BIOMOD) maximizes the predictive performance of current species distribution models and increases the reliability of future potential distributions using different types of statistical modelling methods. However, the relative performance of different techniques may be distinctive across species, indicating that even the most accurate model is likely to vary between species. Therefore, it would be more reliable to use a framework assessing different models for each species and selecting the most accurate one using both evaluation methods and expert knowledge (Thuiller, 2003; Thuiller et al., 2009).

Habitat suitability modelling for rhinoceros in the past has been performed using a geospatial tool based on habitat parameters such as land use/land cover, distance from a water body, grassland, guard post, road and settlement, for a particular area for current climatic condition (Kushwaha et al., 2000; Kafley et al., 2009; Sarma et al., 2011; Medhi & Saha, 2014; Rimal et al., 2018). A recent study has also predicted future suitable habitats throughout Nepal using bioclimatic and topographic data as predictor variables (Adhikari & Shah, 2020). In contrast, this study used an ensemble modelling approach to identify current suitable habitats and to predict future habitat suitability for rhinoceros in Nepal in the context of climate and land use changes. In this study, SDM was used as a correlative approach, given that it is an equally powerful tool as a complex mechanistic model and has been widely used for predicting suitable habitats for species (Fordham et al., 2018). More importantly, we combined SDM with TVA in this study, given that these approaches can complement through the exchange of information during the process and provide better results by minimising the uncertainty of the assessment (Willis et al., 2015; Foden & Young, 2016). The information on environmental tolerances and other biological traits from the TVA aided in selecting predictor variables for SDM. Likewise, SDM allowed more meaningful quantification of exposure to climate change through the identification of selected bioclimatic variables as the best predictors of current distribution and applying such exposure estimates to TVA. On top of that TVA was important in identifying key vulnerabilities and possible adaptation measures, whereas SDM provided the inputs on priority sites to implement the identified adaptation actions spatially. **Figure 3.2** has illustrated how two approaches of vulnerability assessment have been integrated for more effective climate change vulnerability assessment and adaptation planning for rhinoceros in Nepal.

2.1.2 Climate change adaptation planning

Climate change adaptation is receiving increasing attention, given that adaptation plans are being prepared and has been implemented at the local, sub-national and national levels (IPCC, 2014; Araos et al., 2016). Climate change adaptation has been emerging as a primary lens for conservation planning (Glick et al., 2009) and vulnerability assessment is a key tool for informing adaptation planning (Glick et al., 2011). Climate change adaptation is defined as "adjusting to moderate or avoid the harm that is likely to arise from a current or projected change in climate and associated effects" (Smit et al., 2000). The priorities for adaptation of different systems may be different depending on the magnitude of change a system has been experiencing or is likely to experience in the future due to climatic changes (Watson et al., 2013). Therefore, the effectiveness of conservation strategies in the face of climate change relies not only on enhancing our understanding of the observed changes on species and ecosystem dynamics but also on predicting the likely response of humans to these changes (Watson et al., 2013; Morecroft et al., 2019). Successful conservation requires to encompass numerous approaches to climate change adaptation; however, most of these are not delivered in an integrated way for conservation planning and implementation of the prioritised actions in the context of the likely uncertainty associated with future climatic changes (Smit et al., 2000). Similarly, the current management practices are likely to be irrelevant under the projected changes in climatic conditions, and ecologists needs go beyond exploring the probable impacts of climate change and initiate devising the possible solutions (Hulme, 2005). In these circumstances, developing adaptation actions for the species that are at most risk due to climate change should receive higher priority (Abrahms et al., 2017; Morecroft et al., 2019). Adaptation efforts are mostly directed towards building resistance to climate-related stressors and enhancing resilience to provide species and systems with a better chance for accommodating the rapid climatic changes (Glick et al., 2009).

Climate change adaptation is accepted as an overarching framework for conservation planning over the last few decades (Glick et al., 2011; Stein et al., 2013) and the current adaptation measures for biodiversity conservation, more specifically wildlife management are largely focused on biological corridors, protected areas, ecosystem services, invasive species, adaptive management, and assisted migration (LeDee et al., 2021). There are numerous examples of how adaptation actions for species conservation and ecosystem management can be formulated and implemented. For instance, the climate adaptation strategy for national fish, wildlife and plants of the United States (Burns et al., 2021), Greater Barrier Reef National Park climate change strategy and action plan in Australia (GBRMP, 2012), climate change adaptation actions for Australian birds (Garnett et al., 2013), and adaptation actions for the seabirds of the Albatross Island in Tasmania (Alderman & Hobday, 2017) have been developed. Recently, a national adaptation plan has been prepared in Nepal, which has included 11 priority adaptation programs for biodiversity conservation (GON, 2021). However, there are no specific adaptation actions developed for a specific wildlife species conservation in Nepal. Thus, this research was conducted to identify and prioritise the adaptation actions as a basis for initiating adaptation planning for rhinoceros in the face of climate change.

2.2 Review article

This section is an exact copy of a review article entitled "Trends and current state of research on greater one-horned rhinoceros (*Rhinoceros unicornis*): A systematic review of the literature over a period of 33 years (1985-2018)" published in an international peer-reviewed journal, *Science of the Total Environment*, vol. 710 (2020), pp. 1-14. https://doi.org/10.1016/j.scitotenv.2019.136349.

Synopsis

This article attempts to draw the attention of scholars from around the world and policymakers, particularly in the biodiversity conservation sector on research needs for the effective conservation of an iconic wildlife species, the greater one-horned rhinoceros. The review article outlines the status and the growth in peer-reviewed publications related to various aspects of rhinoceros conservation over the last three decades. More specifically, this study has thoroughly documented the patterns and trends of the research on both captive and free-ranging rhinoceros. In this paper, we used a systematic review approach to investigate the knowledge gap in the field of rhinoceros research. After reviewing the themes discussed in 215 peer-reviewed journal articles on rhinoceros between 1985 and 2018, we concluded that no studies are addressing the likely effects of climate change on rhinoceroses and their habitat, and limited research has been done related to population genetics, diseases, and habitat dynamics. The primary focus of the studies to date remains the biological aspects of the rhinoceros including morphology, anatomy, physiology, and behaviour. This article recommends initiating long-term experimental research on rhinoceroses and their habitat dynamics including density-dependent effects that can provide valuable information required for securing the future of rhinoceros; predominantly in the context of threats that arise from invasion of prime grassland habitat by invasive plants and drying up of wetlands in rhinoceros habitat, and other emerging threats associated with the impacts of climate change on rhinoceros habitat.

CHAPTER 3: METHODOLOGY

This chapter presents a brief description of the study area, an overview of the research design, and methods used for data collection and analysis. Each of the following chapters is presented as published articles in international peer-reviewed journals and contain detailed research methods in each of those papers. Thus, this chapter summarises the overall methodological approach used for the entire Thesis. The following sections portray an overview of the study area and a synopsis of the research methods used for collecting and analysing the data for this study.

3.1 Study area

The study area of this research covers the entire country of Nepal, with a particular focus on regions within and around four protected areas of the country where rhinoceros occur: Chitwan, Bardia, Shuklaphanta and Parsa National Parks **(Figure 3.1).** Nepal is a small mountainous country in South Asia, and is endowed with rich biological diversity because of its extreme altitudinal range (from 60 m to 8,848 m) and associated heterogeneous topography and climatic variation (Paudel et al., 2012; Bhattacharjee et al., 2017). There are 118 ecosystems (Dobremez, 1970) and 35 forest types (Stainton, 1972) in Nepal, and although it constitutes only about 0.1% of the landmass of the world (MFSC, 2002), Nepal is ranked 25th for its biodiversity wealth (Parajuli & Pokhrel, 2002). Nepal is home to 3.2% of the flowering plant species, 9.5% of the bird species and 5.2% of the mammal species known in the world (MFSC, 2014). The history of biodiversity conservation in Nepal dates back to the early 1970s. Chitwan National Park (CNP) was the first protected area in the country, established in 1973. Now, more than

23% of the country's land is managed under a protected area system (DNPWC, 2018).

Rhinoceroses in Nepal are confined to flood plain grasslands in the southern lowlands (DNPWC, 2017). 'Lowland' in Nepal lies south of the foothills of the Himalayas, and are characterised by tall grasslands, scrublands, sal forests and clay-rich swamps. There are seven protected areas (PAs) in the lowlands of Nepal, namely Shuklaphanta National Park (SNP), Bardia National Park (BNP), Banke National Park (BaNP), Krishnasar Conservation Area (KCA), Chitwan National Park (CNP), Parsa National Park (PNP), and Koshi Tappu Wildlife Reserve (KTWR). Of these seven PAs, rhinoceros are present in SNP, BNP, CNP and PNP.

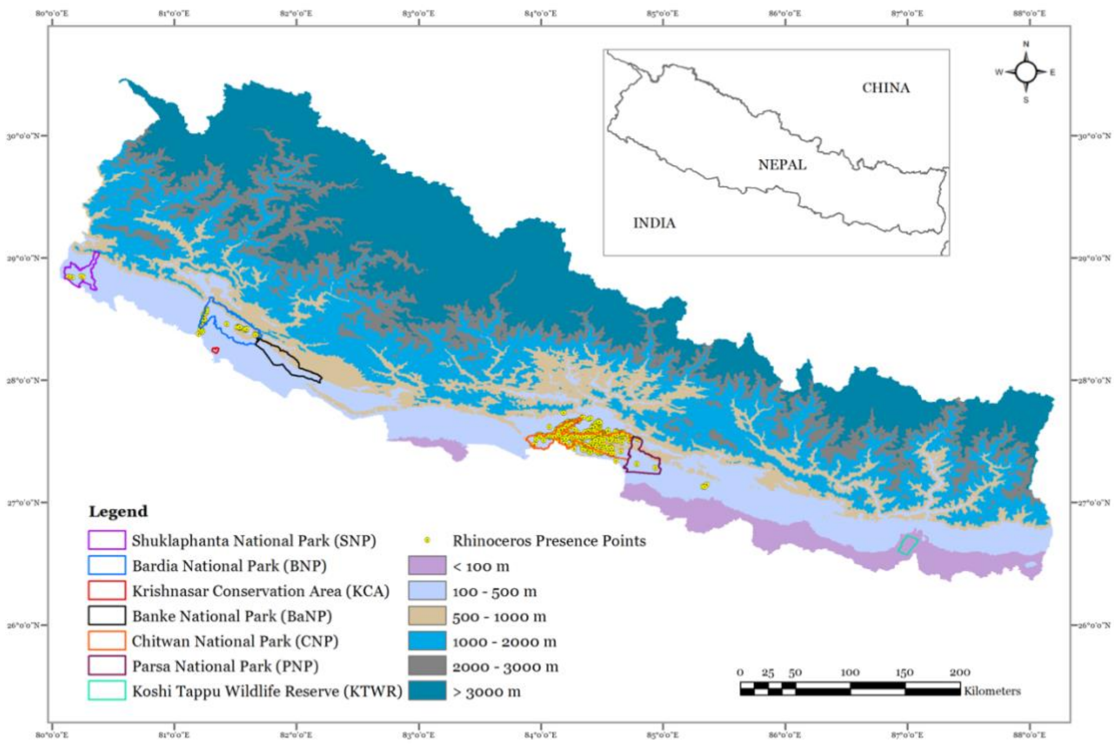

Figure 3.1 Map of the study area depicting current rhinoceros distribution in different protected areas and the elevation range in Nepal.

Nepal is the fourth most vulnerable country in the world to climate change (MFSC, 2014). Chitwan district, which encompasses more than 70% of CNP (CNP, 2016), has further been ranked as a high-risk category district of Nepal, having a vulnerability index between 0.60 and 0.78 (MOE, 2010). CNP is the second most important home to the greater one-horned rhinoceros (*Rhinoceros unicornis*) in the world after the Kaziranga National Park in India (Ellis & Talukdar, 2019); CNP supports about 20% of the global population and more than 90% of Nepal's population (CNP, 2013; DNPWC, 2017).

2.2 Research methods

2.2.1 Research design and approach

We did a literature review to determine what was studied about the likely impacts of climate change for rhinoceros in Nepal, and not much was known. To address this research gap, we followed the recommended approach to developing vulnerability indicators. We then conducted a vulnerability assessment using those indicators, following the approach recommended by Foden and Young (2016). We further used the ensemble modelling approach to assess the current habitat and predict future habitat suitability. With these tasks completed, we again consulted the stakeholders and the experts to identify and prioritise adaptation measures. This section provides an overview of the methodological approach used for assessing climate change vulnerability and identifying and prioritising adaptation actions for rhinoceros conservation in Nepal, which is presented in **Figure 3.2**.

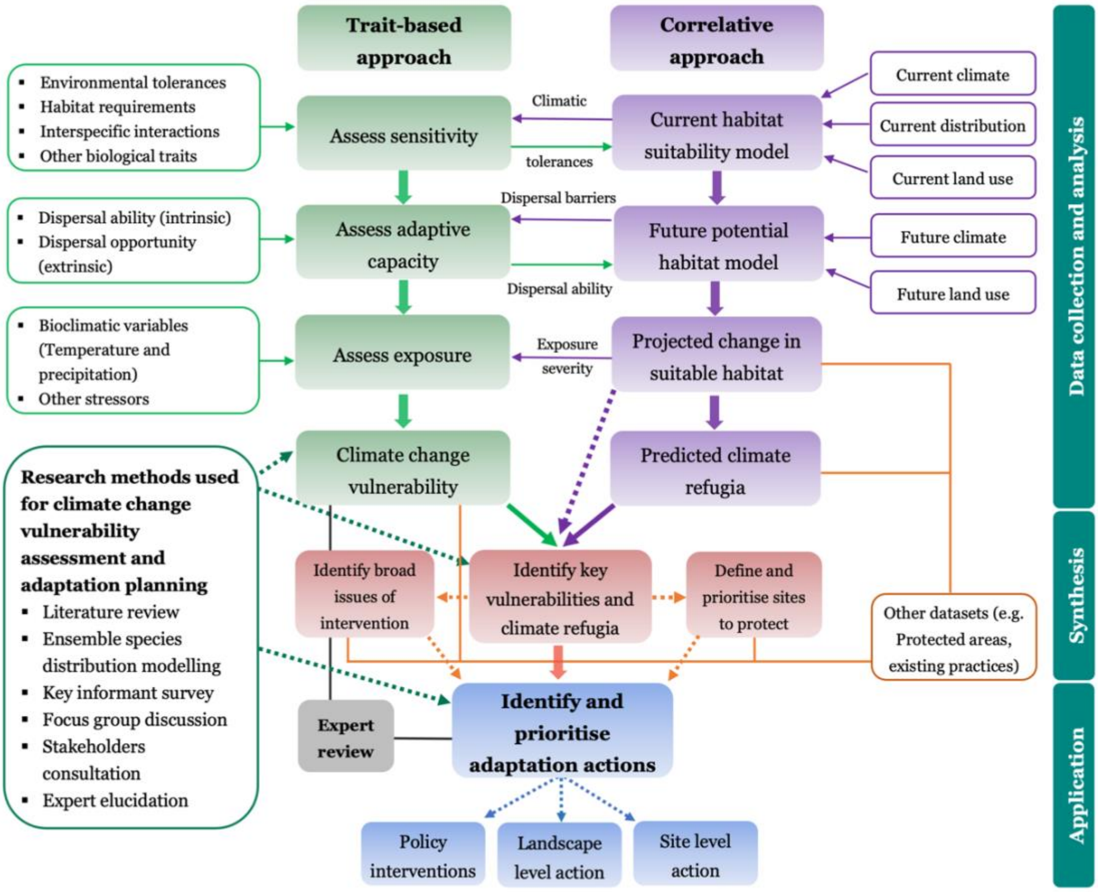

Figure 3.2 Overview of the research methods for climate change vulnerability assessment and adaptation planning for rhinoceros conservation in Nepal.

In this research, two major techniques of climate change vulnerability assessment to species, trait-based and correlative approaches, were integrated as illustrated in the **Figure 3.2** (Willis et al., 2015; Foden & Young, 2016; Foden et al., 2019). Likewise, a mixed approach was used combining both qualitative and quantitative techniques. For the trait-based approach of CCVA, mostly qualitative methods were used to develop vulnerability indicators, given that vulnerability assessment is a theoretical concept and needs indicators for measuring it (Hinkel, 2011; Tonmoy et al., 2014). On the other hand, the quantitative approach was used through an ensemble species distribution modelling for the correlative approach of CCVA.

3.2.2 Data collection

In this Thesis, both primary and secondary data were collected using a combination of different data collection techniques. Some of the common techniques to systematically collect data include direct observation, using available information, face to face interviews, questionnaire surveys and focus group discussions (Morgan & Harmon, 2001; Chaleunvong, 2009). Primary data were both qualitative and quantitative in nature, collected following a mixed approach acknowledging the strengths and weaknesses of both quantitative and qualitative techniques (Axinn & Pearce, 2006; Längler et al., 2019). We found this approach relevant in our case given that this study aimed to answer both quantitative and qualitative research questions.

Qualitative data were collected through key informant interviews, focus group discussions, and stakeholder consultation. Likewise, quantitative data on rhinoceros presence/absence and environmental variables were collected through direct observation and other available sources that held such data. Most of the data for this study were therefore obtained from primary sources, while additional information was gathered from relevant literature and other secondary sources. The information collected and used in this study was cross-validated through expert elucidation and verification based on relevant literature to increase the validity and credibility of the research findings (Heale & Forbes, 2013; Noble & Heale, 2019). The individuals directly involved in rhinoceros research and/or management are considered expert in this study.

3.2.3 Data analysis

The qualitative data generated from key informant interviews, focus group discussions and stakeholder consultation was analysed using qualitative techniques such as content analysis, after transcribing the interviews and field notes, documenting key messages and responses, and coding and categorising the data. Quantitative techniques were used to analyse rhinoceros presence data and environmental variables in ArcMap 10.8.1 (ESRI, 2020), and the ensemble models for determining habitat suitability were generated using the BIOMOD2 package (Thuiller et al., 2020). We further used statistical tools in R (R Development Core Team, 2020) to test for multicollinearity of the environmental variables and analyse the metrics for model evaluation.

To sum up, this chapter has briefly described the study area and provided an overview of the research methods used to answer the research questions. As noted, a detailed explanation of research methods and the justification of selecting those methods have been provided in the specific chapters presented in the form of published peer-reviewed journal articles.

CHAPTER 4: CLIMATE CHANGE VULNERABILITY ASSESSMENT

This chapter is presented as an exact copy of an original research article entitled "Climate change vulnerability of Asia's most iconic megaherbivore: greater one-horned rhinoceros (*Rhinoceros unicornis*)" published in *Global Ecology and Conservation*, vol. 23 (2020), pp. 1-14. https://doi.org/10.1016/j.gecco.2020.e01180.

Synopsis

This article provides the details on how a trait-based approach of climate change vulnerability assessment to species can be applied in evaluating the extent of climate change vulnerability to the rhinoceros population in Nepal. After reviewing the relevant literature, key informant interviews and stakeholders' consultation, a set of 21 vulnerability indicators were developed and vulnerability scores were assigned to each of the indicators to determine the level of vulnerability the rhinoceros population in Nepal is likely to face in the context of climate change. The key climate change vulnerabilities to rhinoceros in Nepal as outlined in the paper include susceptibility to flash floods, habitat loss due to invasive plant species, increased forest fire and drying up of wetlands due to increased droughts. Likewise, this article shows that rhinoceros in Nepal is likely to be 'moderately vulnerable' due to the impacts of climate change. This paper mentions that climate change may not directly impact the physiology of the rhinoceros, but it is likely to impact them indirectly through extreme weather events such as floods and droughts, the decline in habitat due to the prevalence of invasive plant species, and continued pressures from existing stressors such as poaching, human-wildlife conflict and pollution. Finally, the paper has suggested a few interventions to address the identified climate change vulnerabilities to enhance the resilience of the rhinoceros in the context of likely adverse impacts of climate change.

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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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Adaptive capacity
Climate refugia

ABSTRACT

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

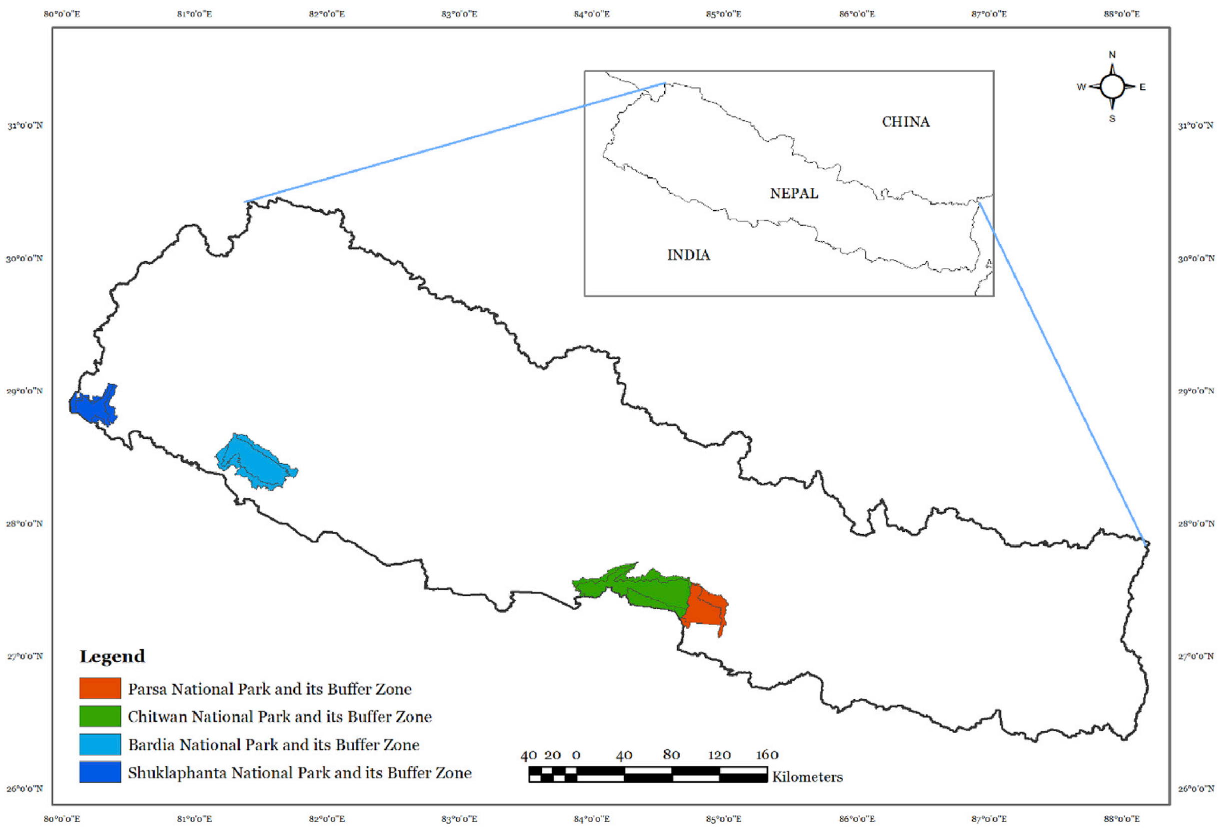

Fig. 2. The location of Parsa, Chitwan, Bardia and Shuklaphanta National Parks in Nepal.

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

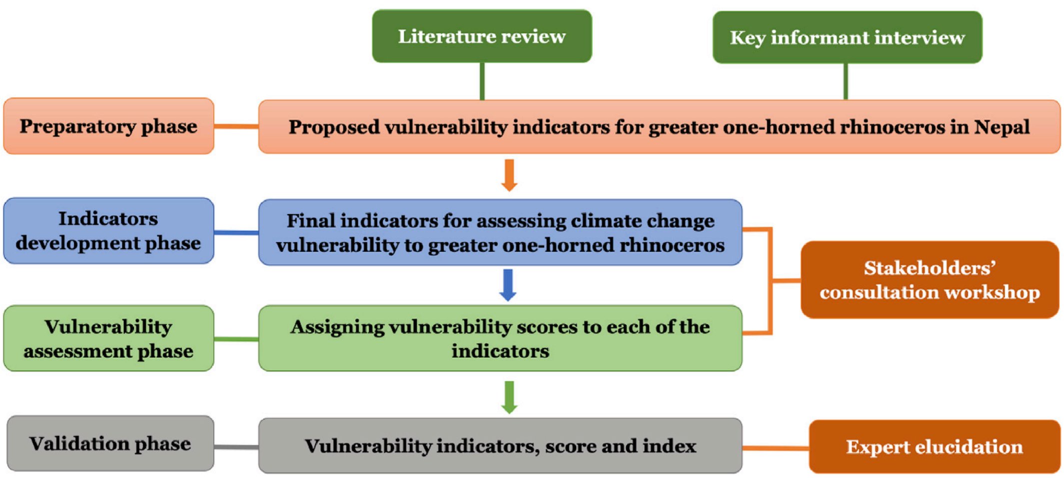

Fig. 3. Flowchart of the research methods for assessing climate change vulnerability of greater one-horned rhinoceros in Nepal.

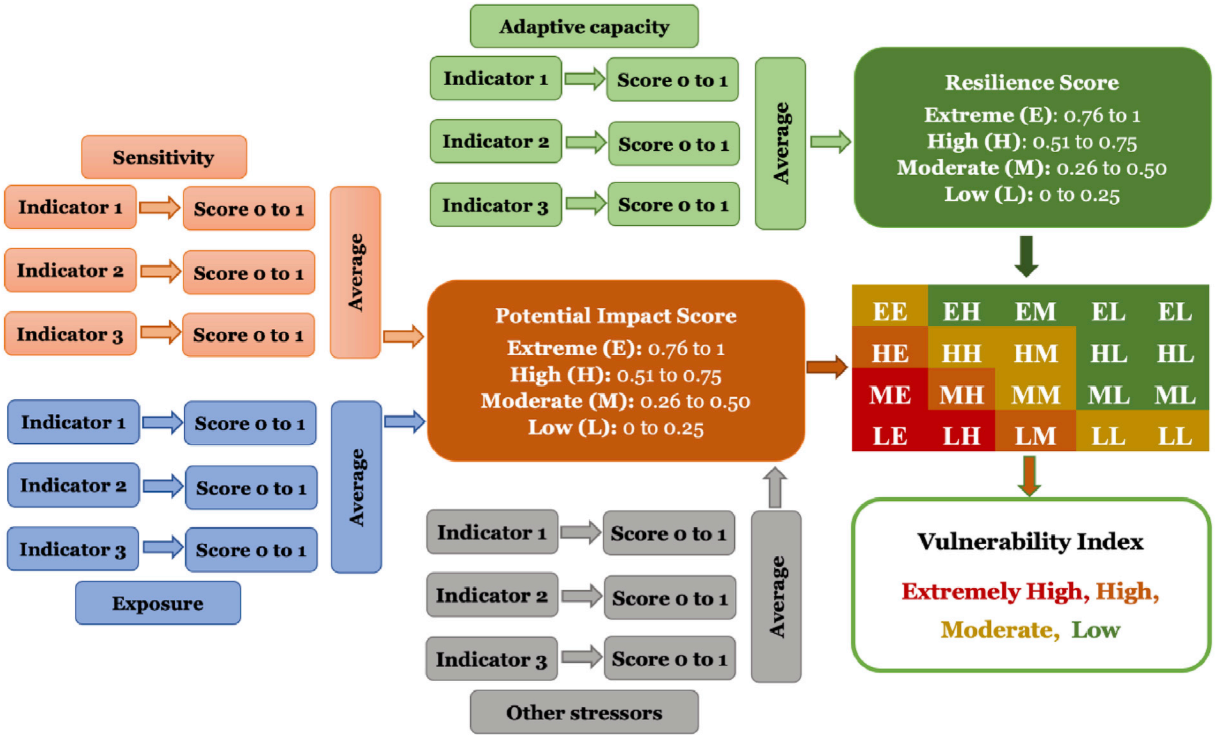

Fig. 4. The analytical framework for climate change vulnerability index adopted from Comer et al. (2019).

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

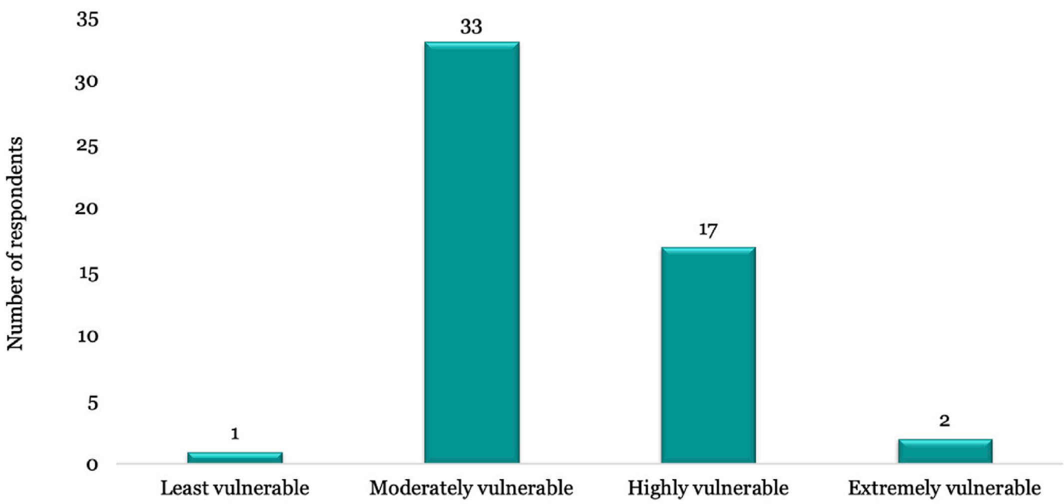

Fig. 5. Key informants' perception of the extent of climate change vulnerability of greater one-horned rhinoceros in Nepal ($n = 53$).

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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CHAPTER 5: HABITAT SUITABILITY MODELLING

This chapter is an exact copy of a published original research article "Predicted declines in suitable habitat for greater one-horned rhinoceros (*Rhinoceros unicornis*) under future climate and land use change scenarios" in *Ecology and Evolution*, vol. 11 (2021), pp. 18288-18304. https://doi.org/10.1002/ece3.8421.

Synopsis

This article has envisaged the possible scenario for rhinoceros habitat suitability in Nepal by the year 2070 considering the likely impacts arising from climate and land use changes. Using an ensemble species distribution modelling as a correlative approach of climate change vulnerability assessment to species, this paper has identified the current suitable habitat and future climate refugia for rhinoceros in Nepal. The ensemble model has estimated the current suitable habitat of rhinoceros to be 2,610 km^2, which is 1.77% of the total area of Nepal. This article reveals that over 35% of the current suitable habitat is likely to become unsuitable by 2070 under the highest greenhouse gas emission scenario due to the combined effects of climate and land use changes. Moreover, the study suggests that the predicted decline will be influenced to a greater degree by climatic changes than land use changes. This article presents a relatively more optimistic modelling scenario compared to other research on different threatened species in this region and indicates that the rhinoceros population in Nepal is likely to experience a moderate level of vulnerability to climate change considering the predicted decline in suitable habitat. This paper has highlighted the need for safeguarding the potential rhinoceros habitat outside protected areas against further fragmentation and conversion into other land use, expanding the protected areas to include potential rhinoceros habitat and future climate refugia, and initiating experimental on-ground research to better elucidate the ecological mechanisms associated with predicted decline in rhinoceros habitat suitability.

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RESEARCH ARTICLE

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Predicted declines in suitable habitat for greater one-horned rhinoceros (*Rhinoceros unicornis*) under future climate and land use change scenarios

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Abstract

Rapidly changing climate is likely to modify the spatial distribution of both flora and fauna. Land use change continues to alter the availability and quality of habitat and further intensifies the effects of climate change on wildlife species. We used an ensemble modeling approach to predict changes in habitat suitability for an iconic wildlife species, greater one-horned rhinoceros due to the combined effects of climate and land use changes. We compiled an extensive database on current rhinoceros distribution and selected nine ecologically meaningful environmental variables for developing ensemble models of habitat suitability using ten different species distribution modeling algorithms in the BIOMOD2 R package; and we did this under current climatic conditions and then projected them onto two possible climate change scenarios (SSP1-2.6 and SSP5-8.5) and two different time frames (2050 and 2070). Out of ten algorithms, random forest performed the best, and five environmental variables—distance from grasslands, mean temperature of driest quarter, distance from wetlands, annual precipitation, and slope, contributed the most in the model. The ensemble model estimated the current suitable habitat of rhinoceros to be 2610 km^2, about 1.77% of the total area of Nepal. The future habitat suitability under the lowest and highest emission scenarios was estimated to be: (1) 2325 and 1904 km^2 in 2050; and (2) 2287 and 1686 km^2 in 2070, respectively. Our results suggest that over one-third of the current rhinoceros habitat would become unsuitable within a period of 50 years, with the predicted declines being influenced to a greater degree by climatic changes than land use changes. We have recommended several measures to moderate these impacts, including relocation of the proposed Nijgad International Airport given that a considerable portion of potential rhinoceros habitat will be lost if the airport is constructed on the currently proposed site.

KEYWORDS
BIOMOD2, climate change refugia, correlative approach, ensemble modeling, habitat loss, land use change, species distribution modeling

1 | INTRODUCTION

Climate plays an important role in determining the distribution of species over space and time, and the species thrive only in a particular environment because they are adapted to a certain climatic condition in their geographical range (Araújo & Pearson, 2005; Choudhury et al., 2016). The earth's temperature has increased by about 0.74°C in the last 100 years, and the global average temperature is projected to rise further by 4.3 ± 0.7°C by 2100 (Almazroui et al., 2020; IPCC, 2014). Such climate warming is anticipated to have many far-reaching consequences for global biodiversity and associated ecosystem functions (Hannah et al., 2005; IPBES, 2019; Pacifici et al., 2017) including (1) increased rates of species extinction (Fulton, 2017; Pearson et al., 2014; Thomas et al., 2004), (2) population decline (Both et al., 2006; Moritz & Agudo, 2013; Soroye et al., 2020), (3) changes in phenology (Cohen et al., 2018; Menzel et al., 2020; Zhixia et al., 2020), (4) increased invasion by alien species (Gong et al., 2020; Hulme, 2017; Wallingford et al., 2020), and (5) range shifts and decline in habitat suitability of species (Corlett, 2015; Thuiller et al., 2011; Trisos et al., 2020). More specifically, climate change may push some species to higher elevations and the species adapted to live on mountains are particularly vulnerable to the likely impacts of climate change (Aryal et al., 2016; Chen et al., 2011; Elsen et al., 2020). It is predicted that loss of habitat, changes in species distribution, and increased extinction of species will continue if we fail to address the likely consequences of the changing climate (Hannah et al., 2020), while climate-induced habitat alteration will further endanger global biodiversity (Bellard et al., 2012; Erdelen, 2020; Pires et al., 2018). On the other hand, habitat loss and fragmentation due to land use changes are likely to exacerbate the effects of climate change on species and ecological dynamics across the globe (Kaszta et al., 2020; Oliver et al., 2015).

Greater one-horned rhinoceros (*Rhinoceros unicornis*, hereafter "rhinoceros") is a threatened megaherbivore, currently surviving in a few protected areas in the northern foothills of India and the southern parts of Nepal (Ellis & Talukdar, 2019; Pant et al., 2020b). In Nepal, Chitwan National Park is a prime habitat for rhinoceros (Figure 1) and a small population of which was translocated to Bardia and Shuklaphanta National Parks from Chitwan (DNPWC, 2017). Rhinoceroses were abundant until the nineteenth century (Foose & Strien, 1997), before the population in the wild sharply declined to approximately 500 individuals during the early 1960s (Rookmaaker et al., 2016). Following intensive conservation efforts since then the rhinoceros population in both India and Nepal has been gradually recovering, and there are approximately 3550 rhinoceros today (Ellis & Talukdar, 2019). Rhinoceroses are habitat specialists and prefer a mosaic of grassland patches dominated by *Saccharum spontaneum* and the riverine forests on alluvial floodplains along the foothills of the Himalayas, where green growth and water remain available all year round (Dinerstein & Price, 1991; Jnawali, 1995; Laurie, 1982; Pradhan et al., 2008). The inadequacy of currently available habitat is identified as a challenge for rhinoceros conservation (Pant et al., 2020b), and the decrease in both quality and quantity of rhinoceros habitat has been observed in protected areas in both countries, which is likely to deteriorate in future and is thus likely to affect its survival (Medhi & Saha, 2014; Sarma et al., 2009; Subedi, 2012). Despite its population recovery, rhinoceros is facing conservation challenges due to habitat loss in terms of fragmentation and encroachment and the problem is likely to be intensified in future due to the impacts of climate change (DNPWC, 2017; Pant et al., 2020b). Although a few researchers have recently begun studying rhinoceros in relation to climate change (Adhikari & Shah, 2020; Mukherjee et al., 2020; Pant et al., 2020a), the likely consequences of the changing climate on rhinoceroses and their habitat are not well understood (DNPWC, 2009; Pant et al., 2020b).

Species distribution modeling (SDM), which is also known as ecological niche modeling, establishes a species–environment relationship to explain and predict the probable distribution of a species (Elith & Leathwick, 2009; Thuiller et al., 2009). It can be used as a correlative approach of assessing vulnerability of a species to climate change, which provides spatial information regarding the potential climate change impacts on species (Foden & Young, 2016). The SDM has the potential to achieve conservation planning goals by helping to widen our knowledge of species distribution (Franklin, 2010; Jetz et al., 2012; Raymond et al., 2020) and predicting the impacts of climate change on species (Araújo et al., 2005; Berry et al., 2002; Elith et al., 2010). Likewise, SDM helps in projecting species distribution in space and time, which is central to extinction risk analysis (Elith & Leathwick, 2009). SDMs for predicting future events are an especially useful tool for prioritizing biodiversity conservation (Araújo et al., 2005; Bellard et al., 2012). However, the predictive performance of modeling techniques differs, and the uncertainty of predictions could be substantially reduced by using consensus methods (Marmion et al., 2009). These ensemble techniques of SDM systematically evaluate the species distribution models and its potential variations under future climate change, and BIOMOD serves as a suitable platform to such modeling (Thuiller et al., 2009). Using an ensemble approach, SDM can combine predictions from many modeling techniques and the predictive performance is believed to be improved considerably (Hao et al., 2020).

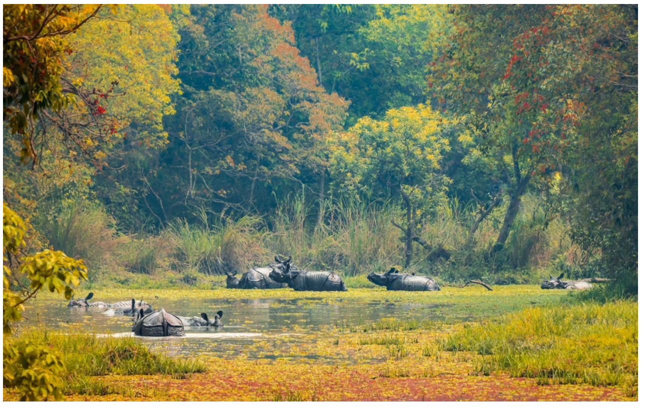

FIGURE 1 Greater one-horned rhinoceros (*Rhinoceros unicornis*) in Chitwan National Park, Nepal (Photo credit: Sagar Giri)

Here, we explored the likely vulnerability of rhinoceros in Nepal due to the combined effects of climate and land use changes using ensemble SDM techniques. Our specific objectives included (1) identifying the ecological niche of rhinoceros in Nepal, (2) investigating the impacts of different climate and land use change scenarios on future habitat suitability of rhinoceros, and (3) identifying the climate change refugia to secure the future persistence of rhinoceros in a changing climate. Previous studies on rhinoceros habitat suitability (Kafley et al., 2009; Rimal et al., 2018; Thapa et al., 2014) identified only current habitat at selected sites, while Adhikari and Shah (2020) has also predicted future suitable habitat throughout Nepal using bioclimatic and topographic data as predictor variables. In contrast, our study identified current suitable habitat for rhinoceros and predicted future habitat for all of Nepal under two different climate and land use change scenarios using bioclimatic, topographic, habitat, and anthropogenic data as predictor variables.

2 | METHODS

2.1 | Study area

Nepal extends over 147,516 km^2 in South Asia between latitudes of 26°22′ to 30°27′ north and longitudes of 80°04′ to 88°12′ east. It is endowed with rich biodiversity because of its varied climate and topography along a sharp altitudinal gradient ranging from 60 to 8848 m above mean sea level (Figure 2) within a north–south span of about 140 km (Bhattacharjee et al., 2017; Paudel et al., 2012). Nepal is divided into three major physiographical regions: (1) lowland (Terai and Siwalik) (2) mid-hills, and (3) high mountain (Shrestha & Aryal, 2011). The climate is dominated by the south-easterly monsoon, and most of the precipitation occurs during the rainy summer months between June and September (Shrestha & Aryal, 2011; Shrestha et al., 2000). The annual mean temperature is 18°C and the average annual precipitation is 1768 mm (Shrestha et al., 2000). Rhinoceroses in Nepal are confined to alluvial flood plains in the southern lowlands (DNPWC, 2017). There are seven protected areas (PAs) in the lowlands of Nepal namely Shuklaphanta National Park (SNP), Bardia National Park (BNP), Banke National Park (BaNP), Krishnasar Conservation Area (KCA), Chitwan National Park (CNP), Parsa National Park (PNP), and Koshi Tappu Wildlife Reserve (KTWR). Of these seven PAs, SNP, BNP, CNP, and PNP have rhinoceros at present.

2.2 | Rhinoceros presence data

Records of rhinoceros presence modeled in our study were obtained mostly from national census and periodic monitoring data held by the Department of National Parks and Wildlife Conservation (DNPWC),

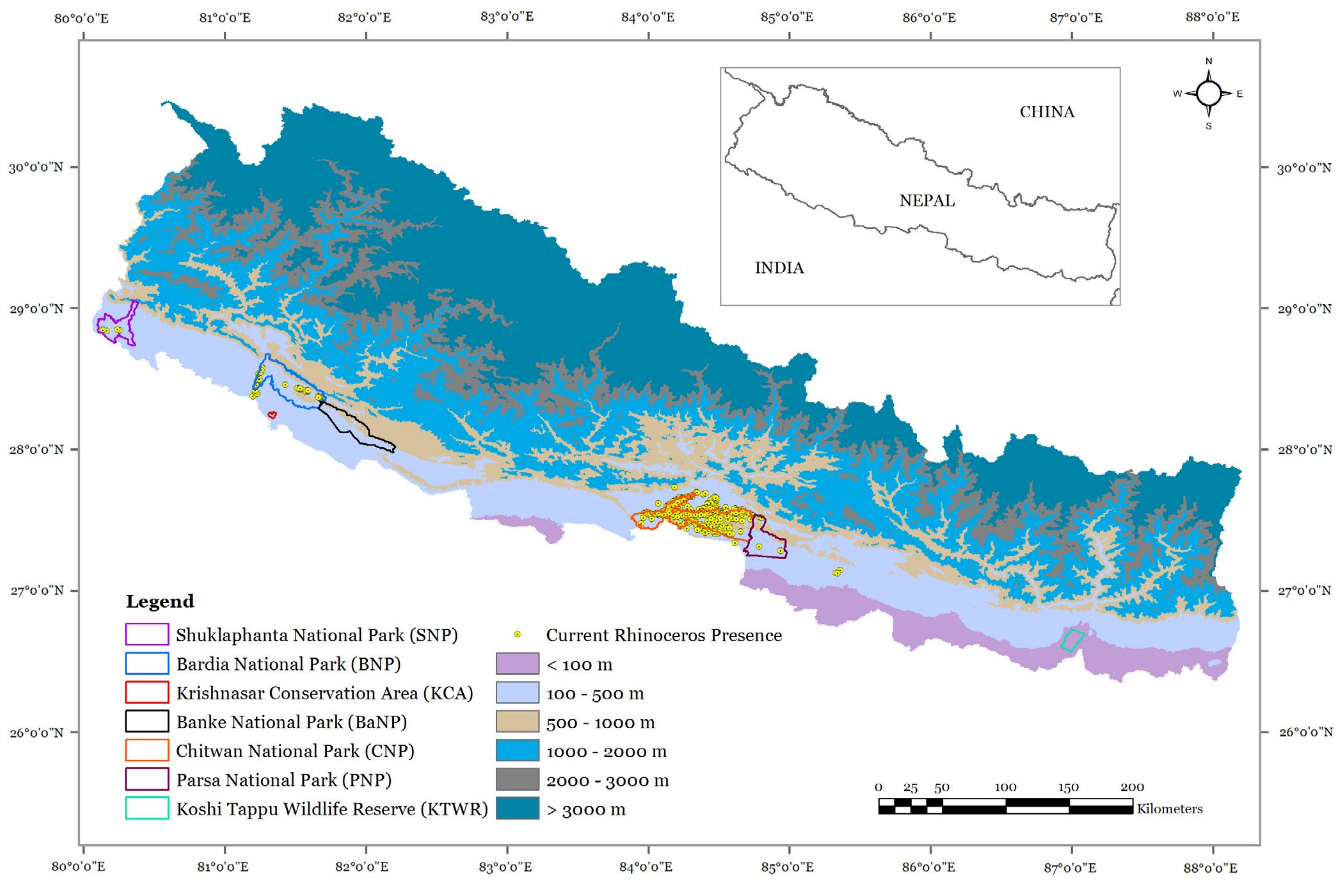

FIGURE 2 Study area map showing the current distribution of greater one-horned rhinoceros and elevation range in Nepal

Nepal, between 2008 and 2017 (Table 1). We also collected a small number of additional opportunistic rhinoceros presence records from fieldwork conducted specifically for this research in April 2019, as well as from an online database, the Global Biodiversity Information Facility (GBIF). In summary, we compiled an extensive database of 2739 current rhinoceros presence points. In the next step, we cleaned the presence data removing the duplicates and the points appeared outside the known distribution range of the species.

We used the SpThin package in R to spatially rarefy the occurrence dataset to ensure that no two points were within a grid of 1 × 1 km (Aiello-Lammens et al., 2015), given that the spatial resolution of the environmental variables used in this modeling was 1 km. Hence, we retained only one presence point in each grid cell to reduce spatial autocorrelation and avoid the inflated measures of accuracy (Veloz, 2009). Spatial filtering also reduces the effects of sample bias and helps to improve the predictive performance of the models (Boria et al., 2014). After filtering, a set of 495 spatially independent locations of rhinoceros presence were retained and used for modeling. We did not use historical presence records of rhinoceros given that most of the environmental variables we used have substantially changed when compared to historical periods. Besides, our focus was to identify current and future suitable habitat that are available for rhinoceros conservation, not the historical range of the species. Historical period in the case of rhinoceros in Nepal is before 1970s as its habitat was almost entirely lost to agriculture during the early 1960s and occurring only in a few isolated protected areas from the 1970s onward (DNPWC, 2017; Subedi et al., 2017).

2.3 | Environmental variables

We used a combination of bioclimatic, topographic, habitat, and anthropogenic variables to predict current and future suitable habitat for rhinoceros in Nepal. We endeavored to include meaningful predictor variables given that variable selection is considered a vital step in SDM (Araujo & Guisan, 2006). First, we identified a set of 28 variables (Appendix S1) primarily based on literature suggesting the significance of these variables for rhinoceros habitat suitability (Dinerstein, 2003; Dinerstein & Price, 1991; Jnawali, 1995; Laurie, 1982; Pant et al., 2020b; Pradhan et al., 2008; Subedi, 2012). We then excluded those environmental variables with correlation coefficients >0.8 and variance inflation factor (VIF) >5 after testing the multicollinearity among environmental variables using the USDM (Uncertainty Analysis for Species Distribution Models) package in R to avoid model overfitting (Gareth et al., 2013; Naimi et al., 2014), retaining 14 variables for further analysis (Appendix S2). Finally, we selected nine of these as ecologically meaningful variables and used them as predictor variables in habitat suitability modeling for rhinoceros (Table 2) following a reiterative process of model formation and stepwise removal of the least contributing variables, as suggested by Zeng et al. (2016). The main purpose of reducing the number of environmental variables is to enhance the predictive performance of the model given that ensemble models avoid overfitting without losing explanatory power through reducing the number of predictor variables (Breiner et al., 2015). We projected all variables to WGS84 and resampled these raster data in ArcMap 10.8.1 (ESRI, 2020) using bilinear interpolation method at a spatial resolution of 1 km, given that data from various sources were in different grain size ranging from ~10 m to ~1 km resolution.

2.3.1 | Bioclimatic variables

Bioclimatic variables are widely used for spatial modeling given that these are ecologically meaningful and describe annual trends, seasonality, and extremes of temperature and precipitation (Hijmans et al., 2005; Hijmans, 2012). Rhinoceroses prefer moist habitats with moderate climate (Subedi, 2012), and their occurrence was recorded from areas having >1500 mm average annual rainfall and >22°C annual mean temperature (Dinerstein & Price, 1991; DNPWC, 2017; Laurie, 1982). We downloaded 19 bioclimatic variables for the current climate (1970–2000) from WorldClim— Global Climate Data (Fick & Hijmans, 2017). Rhinoceros shows affinity toward higher rainfall and moderate temperature (Pant et al., 2020b; Subedi, 2012).

2.3.2 | Topographic and habitat variables

The current distribution of rhinoceros is recorded from 100 to 500 m elevation in and around four protected areas located in the southern part of Nepal (DNPWC, 2009; Pant et al., 2020b). It is evident from other studies that the topographic variables, such as elevation, and slope have an influence on habitat suitability of megaherbivores (Sarma et al., 2020). Thus, we included topographic data as one of the predictor variables in our models. We derived elevation data from Shuttle Rader Topographic Mission (SRTM) Digital Elevation Model (DEM) of 30 m spatial resolution downloaded from the United States Geological Survey database (USGS, 2020) from which aspect and slope data were computed using ArcMap 10.8.1 (ESRI, 2020).

Rhinoceros, primarily a grazer, is a grassland dependent species, it prefers riverine forests, and it further requires waterholes to wallowing for thermoregulation (Dinerstein & Price, 1991; Laurie, 1978). Thus, grasslands, riverine forests, and wetlands play a fundamental role in determining the habitat suitability of this species. Therefore, we extracted the layers containing grasslands, forests, and wetlands of the study area from Esri 2020 Land Cover (Karra & Kontgis, 2021). We generated raster data layers containing proximity to grasslands, forests, and wetlands using Euclidean Distance tool in ArcMap 10.8.1 (ESRI, 2020).

2.3.3 | Anthropogenic variables

Anthropogenic activities influence the species distribution and have been identified as a threat to rhinoceros (DNPWC, 2017; Pant et al., 2020b), and these were also incorporated into our model.

TABLE 1 Records of species presence compiled from various sources and used for species distribution modeling for greater one-horned rhinoceros in Nepal

Data	Year	Presence points	Source
National rhinoceros census	2008	423	Department of National Parks and Wildlife Conservation
	2011	503	
	2015	645	
Rhinoceros monitoring in Babai Valley, Bardia	2016	183	Bardia National Park
GPS points from collared rhinoceros in Chitwan	2017	844	Chitwan National Park
Fieldwork for this study	2019	56	Self
GBIF Database	2020	85	GBIF website
Total		2739	

Abbreviations: GBIF, Global Biodiversity Information Facility; GPS, Global Positioning System.

TABLE 2 Environmental variables used for habitat suitability modeling for greater one-horned rhinoceros in Nepal

Category	Source	Selected variables	Resolution	Type
Bioclimatic	WORLDCLIM	BIO7—Temperature annual range	~1 km	Continuous
		BIO9—Mean temperature of driest quarter	~1 km	Continuous
		BIO12—Annual precipitation	~1 km	Continuous
Topographic and habitat	SRTM	Slope	~ 30 m	Continuous
	ESRI 2020 Land Cover	Distance from grasslands	~10 m	Continuous
		Distance from wetlands	~10 m	Continuous
		Distance from forests	~10 m	Continuous
Anthropogenic	MODIS Land Cover	Croplands	~500 m	Continuous
	HDX	Population density	~1 km	Continuous

Abbreviations: HDX, Humanitarian Data Exchange; MODIS, Moderate Resolution Imaging Spectroradiometer;SRTM, Shuttle Radar Topographic Mission.

Anthropogenic variables used were croplands and human population density. To include the land use change scenarios, we extracted the combined class of croplands and cropland/natural vegetation mosaics from Moderate Resolution Imaging Spectroradiometer (MODIS) Land Cover Type (MCD12Q1) Version 6 (Friedl & Sulla-Menashe, 2019). Likewise, human population density data were downloaded from the Humanitarian Data Exchange Dataset (HDX, 2020).

2.3.4 | Future climate and land use change scenarios

We used the future bioclimatic variables from Models for Interdisciplinary Research on Climate (MIROC), particularly MIROC6, to model the response of rhinoceros to future climate. MIROC6 is the recently updated version of MIROC5 (Michibata et al., 2019), and the overall reproducibility of mean climate and internal variability in MIROC6 is better than that in its previous version (Tatebe et al., 2019). The MIROC5 is a consistent global circulation model (GCM) for rainfall projection in the Indian subcontinent (Babar et al., 2015) which simulates extreme and summer precipitation better than other GCMs for the South Asian region (Mishra et al., 2014). MIROC5 is also capable of capturing the distribution and variability of temperature in this region (Yu et al., 2015). Thus, MIROC6 was selected for this study considering the better performance of this model in predicting future climate over the geographical range of rhinoceros. Data are available for four Shared Socioeconomic Pathways (SSPs), where SSP1-2.6 is based on a lower emission scenario, which anticipates a mean warming of well below 2°C by 2100, while SSP5-8.5 is based on the highest emission scenario, with a mean warming of 5.5°C by the end of this century (Hausfather, 2018). In this study, we have chosen SSP1-2.6 and SSP5-8.5 to model the suitable habitat for rhinoceros to capture the full range of predicted climate change scenarios.

We used data on global land use and land cover change simulation for years 2050 and 2100 from the GeoSOS global database to project the future scenarios for human land use changes (Li et al., 2017). This simulation has combined MODIS land cover categories into six classes and predicted the changes from 2010 to 2100 under four scenarios of the Intergovernmental Panel on Climate Change (IPCC, 2014) Special Report on Emission Scenarios using Future Land Use Simulation (FLUS) system. We extracted the land use category "farmland" of Li et al. (2017) which has combined two categories: (i) croplands and (ii) cropland/natural vegetation mosaics from MODIS land cover. We included two land use change scenarios: A1B (moderate increase in land use across all resources) and A2 (high emphasis on development with adverse impact on the environment). We grouped SSP1-2.6 with A1B scenario and SSP5-8.5

with A2 scenario while predicting the rhinoceros habitat suitability for 2050 and 2070 due to the combined effects of climate and land use changes.

2.4 | Species distribution modeling methodology

We followed the overview, data, model, assessment, and prediction (ODMAP) protocol proposed by Zurell et al. (2020) in developing habitat suitability models for rhinoceros in Nepal (Appendix S3). Combining several models generated from different modeling techniques into an ensemble map is highly acknowledged in recent SDM exercises given its better predictive accuracy (Hao et al., 2019). Thus, we used an ensemble modeling approach to develop habitat suitability models for rhinoceros in Nepal. We generated ensemble models based on ten algorithms: artificial neural network (ANN), classification tree analysis (CTA), flexible discriminant analysis (FDA), generalized additive model (GAM), generalized boosting model (GBM), generalized linear model (GLM), multiple adaptive regression splines (MARS), maximum entropy (MAXENT), random forest (RF), and surface range envelope (SRE) using the BIOMOD2 package (Thuiller et al., 2020) in R (R Development Core Team, 2020), as shown in Figure 3. First, data layers were prepared in ArcMap 10.8.1 (ESRI, 2020) and the multicollinearity among bioclimatic variables was tested. After selecting the appropriate data layers, the models were calibrated to generate suitability maps. Rhinoceros presence and pseudo-absence data were split into training (80%) and testing data sets (20%). With the training dataset, we randomly generated 10,000 pseudo-absence points as suggested by Barbet-Massin et al. (2012), in which we assigned equal weight for the presence and pseudo-absence datasets, and we repeated the pseudo-absence generation three times to avoid random bias. This modeling, comprising ten algorithms, three pseudo-absence selection, and three evaluation runs resulted into a total of 90 model runs. We generated ensemble models using the ensemble modeling function in BIOMOD2. Finally, we employed range size function within the BIOMOD2 package when calculating the range shifts for rhinoceros under different climate and land use change scenarios in Nepal.

2.5 | Model evaluation and validation

Model evaluation and validation in SDM examine the accuracy of the model prediction. It assesses the predictive performance of a model based on various evaluation statistics and is generally performed using response curves, variable importance, and model coefficients. The area under the receiver operating characteristics (ROC) curve known as area under the curve (AUC) is a standard method to assess the accuracy of predictive distribution models (Lobo et al., 2008). Likewise, true skill statistics (TSS) is a common method to evaluate the predictive performance of such models (Allouche et al., 2006). These two methods are independent, but it is desirable to execute both methods for cross checking (Thuiller et al., 2009). We therefore used TSS to evaluate the predictive performance while we analyzed

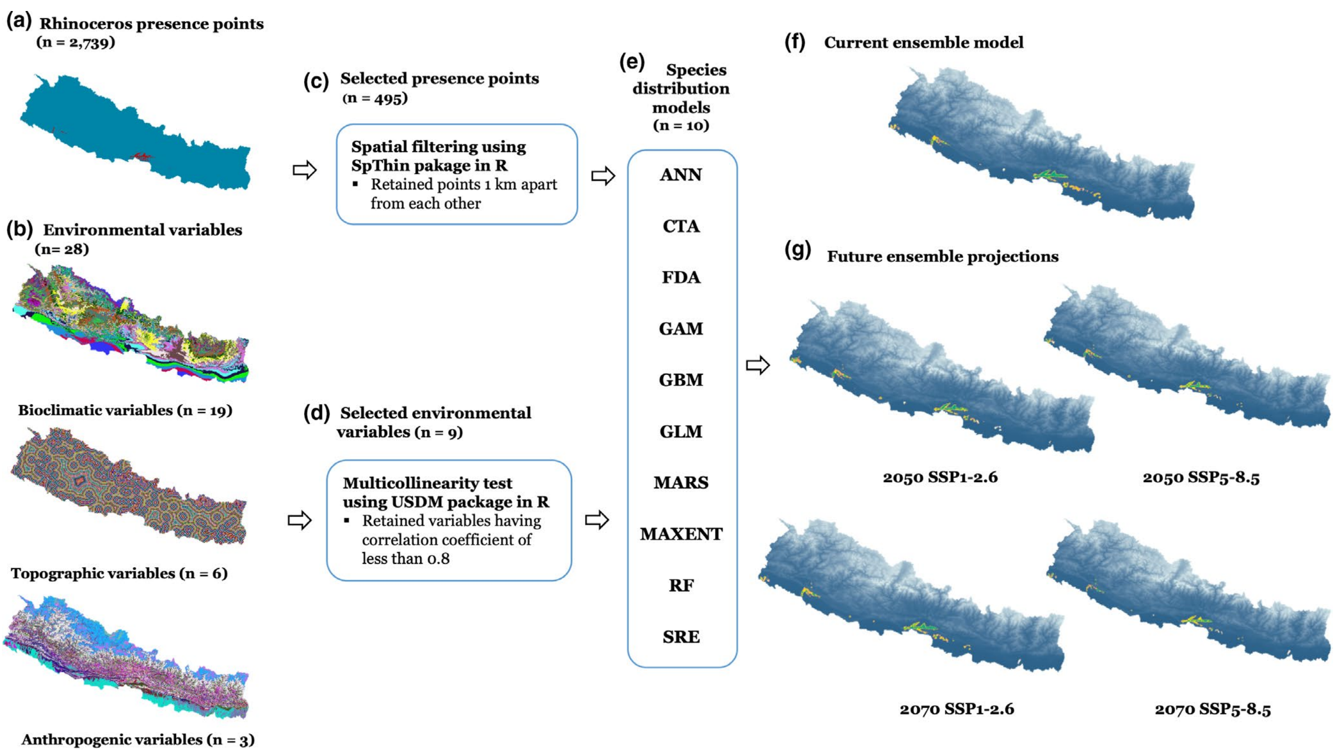

FIGURE 3 Methods used for ensemble species distribution modeling for greater one-horned rhinoceros in Nepal using BIOMOD2 package in R (a–e); current ensemble model (f), ensemble projections into future greenhouse gas (GHG) emission scenarios (g). SSP1-2.6 and SSP5-8.5 are two different climate change scenarios that anticipate a mean warming of 2 and 5.5°C by 2100, respectively

AUC for cross-comparison of our models. The TSS value accounts for both omission as well as commission errors, which ranges from +1 to −1 (Allouche et al., 2006). The model is considered perfect if the TSS value is +1, whereas the TSS value between 0.7 and 0.9 indicates a good model (Allouche et al., 2006; Thuiller et al., 2009). In addition, we employed cross validation techniques such as the Boyce index to further assess the predictive performance of the models (Boyce et al., 2002; Engler et al., 2004), which is the most appropriate evaluation metric in the case of presence-only models (Hirzel et al., 2006). We selected all models having a TSS value >0.85 for building ensemble model using the weighted mean approach. Consensus method based on weighted mean approach increases the model accuracy (Marmion et al., 2009). The weighted mean approach creates the final model based on the selected threshold of the TSS value and generates the binary map which is also known as the presence–absence map.

We classified the output map into three suitability classes: low (<60%), moderate (60–80%), and high (>80%) using the reclassify function in ArcMap 10.8.1 (ESRI, 2020). In addition, we further validated the on-ground reality of the current habitat suitability model for rhinoceros in Nepal through expert consultation. For this, we shared the current habitat suitability model we generated to five field biologists each having more than 10 years of professional experience in research and management of rhinoceros in Nepal. All of them agreed that the current suitability model has captured not only the areas currently occupied by rhinoceros but also the potential habitat having similar environmental conditions at present that are likely to support rhinoceros populations in Nepal.

3 | RESULTS

3.1 | Model performance and contribution of predictor variables

The predictive performance of our ensemble model was excellent, with a TSS value of 0.986. Likewise, all the ten algorithms had an average TSS value of >0.750. SRE had the lowest TSS value (0.763), while RF had the highest TSS value (0.983) (Figure 4). Similarly, AUC value of the ensemble model was 0.999 whereas RF had the highest (0.998) and SRE had the lowest (0.882) AUC value. Environmental variables contributed differently to our models (Figure 5), but the variables that contributed the most were distance from grasslands, mean temperature of driest quarter (BIO9), distance from wetlands, annual precipitation (BIO12), and slope. As expected, distance from grasslands had the highest contribution (25.94%) to our model, followed by the mean temperature of driest quarter (21.49%) (Figure 5b,f). The distance from wetlands contributed 12.42% in our model and the habitat suitability decreased with increasing distance from wetlands (Figure 5g). Response curves showed that areas with >1500 mm of annual rainfall were suitable for rhinoceros and this covariate contributed 10.57% in the model (Figure 5c). The fifth most contributing variable was slope (10.33%), indicating that slopes of <10° were most suitable for rhinoceros (Figure 5e). The remaining four variables collectively contributed 19.25% in the model (Figure 4a,e,h,i).

3.2 | Rhinoceros habitat suitability

The extent of habitat suitability for rhinoceros in Nepal under current and future climate change scenarios is presented in Figure 6. The estimated current suitable habitat for rhinoceros is 2610 km^2, which is 1.77% of the total area of Nepal. Of current suitable habitat, 2044 km^2 (78%) is inside protected areas (PAs) while the remaining 566 km^2 (22%) lies outside PAs (Appendix S7 and S8). Among the five PAs and their buffer zones that are suitable for rhinoceros, CNP and KTWR have the highest (1063 km^2) and the lowest suitable area (67 km^2), respectively. The current suitable habitat of rhinoceros in BNP, PNP, and SNP is 447 km^2, 291 km^2, and 176 km^2, respectively. At present, the model does not reveal any suitable rhinoceros habitat in KCA and BaNP. Most of the current suitable habitat of rhinoceros outside protected areas extends over Bara, Rautahat, Sarlahi, and Kapilbastu districts, although suitable rhinoceros habitat is distributed across 16 districts of Nepal. Of these 16 districts, Chitwan has the highest (904 km^2) whereas Kailali, Surkhet, and Jhapa have negligible current suitable habitat (Appendix S9 and S10).

A summary of suitable habitat areas for rhinoceros in Nepal under current and future climate and land use change scenarios estimated by the ensemble models is presented in Table 3. Under the SSP1-2.6 scenario for 2050, a net loss of 285 km^2 in suitable habitat is likely to occur and the highest reduction in suitable habitat (924 km^2) is predicted under the SSP5-8.5 scenario for 2070. The predicted change in habitat suitability of rhinoceros in Nepal under different climate and land use change scenarios by the end of 2070 is presented in Figures 7 and 8. In 2070, we predicted a net loss of 12.39% (323 km^2) in current suitable habitat under SSP1-2.6 climate scenario based on the predicted loss of 20.30% (539 km^2) and a gain of 7.91% (206 km^2) Likewise, 27.04% (706 km^2) of the current suitable habitat of rhinoceros will be lost owing to a predicted loss of 33.42% (872 km^2) and a gain of 6.39% (167 km^2) under SSP5-8.5 climate scenario in 2050.

4 | DISCUSSION

4.1 | Model performance and contribution of predictor variables

The AUC and TSS values of the ensemble model were 0.986 and 0.999, respectively, indicating that our model was statistically robust, and the predictive performance was near perfect (Allouche et al., 2006). We endeavored to minimize the effects of uncertainties by spatially rarefying the presence points, use of minimum number of environmental variables and applying cross-validation

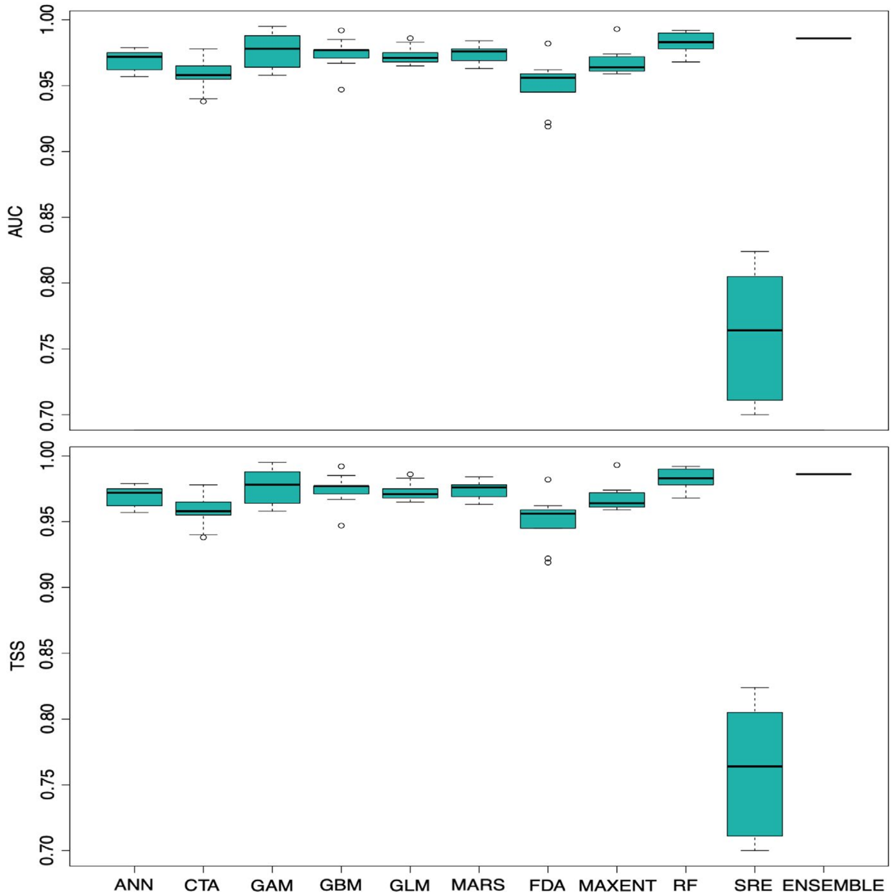

FIGURE 4 Predictive performance of different modeling techniques used for species distribution modeling of greater one-horned rhinoceros in Nepal, based on area under curve (AUC) and true skill statistics (TSS) value. The AUC and TSS values of the ensemble model are also shown for comparison

techniques (Breiner et al., 2015; Hijmans, 2012). For instance, we used 80% of the presence and pseudo-absence datasets for model calibration and the remaining 20% of data was used for model evaluation, generated evaluation metrics from independently divided testing and evaluating datasets, and used the Boyce index for cross-validation. Lobo et al. (2008) suggested that AUC value of over 0.8 is likely to be an indication of overparameterization. However, the AUC and TSS values from testing and evaluating data indicated the consistent predictive performance of our models (Appendix S4 and S5). Likewise, we compared the AUC values of our models to the Boyce index (Appendix S6) which also showed that all these models are performing well. For example, the RF model which performed the best in our data had the AUC and the Boyce index of 0.998 and 0.994, respectively. The suitability map generated has captured the current habitat of rhinoceros well and all the models are consistently performing in different presence–absence data and various model runs. Hence, we believe that our model has not been affected from overfitting.

Our ensemble approach identified suitable rhinoceros habitat that was mainly concentrated in the central and western lowland of Nepal, indicating that its distribution was constrained by topographic variables. Suitable habitat ranges of many terrestrial species have shifted toward higher elevations in response to changing climate (Chen et al., 2011; Dar et al., 2021; Moritz et al., 2008). Rhinoceros habitat suitability is limited by topographic factors given that slope contributed strongly to our models (Figure 4e). We excluded the elevation data in our model due to its high correlation with other variables, but instead used slope as a proxy for elevation in interpreting the results given that slope increases with increasing elevation in Nepal. Currently, the known distribution of rhinoceros in Nepal extends between the elevation range of 100 and 500 m (DNPWC, 2009; Pant et al., 2020b), consistent with our findings. Rhinoceroses are not likely to shift into higher elevations like some other species but instead appear trapped in small patches of suitable habitat at lower elevations.

The distance from grasslands, mean temperature of driest quarter, distance from wetlands, annual precipitation, and slope were the predictor variables with the strongest influence in our model, whereas human population density and changes in croplands as an anthropogenic variable had only a slight contribution (Figure 5h,i). Even though temperature and precipitation patterns are strong determinants of rhinoceros habitat suitability, the coarse spatial resolution of these covariates may obscure the interplay between these climatic factors and the actual suitability of the habitat for rhinoceros. Given that a finer resolution is likely to increase model accuracy (Connor et al., 2018), the inclusion of site-specific climate characteristics, terrain attributes, and anthropogenic data at finer grain sizes for model building possibly results in better accuracy in prediction of rhinoceros habitat suitability. Regardless, any such refinements to our model are unlikely to produce wholesale differences to the gross species distribution predictions we have made, and rhinoceros will still be trapped in small habitat patches in lower elevations.

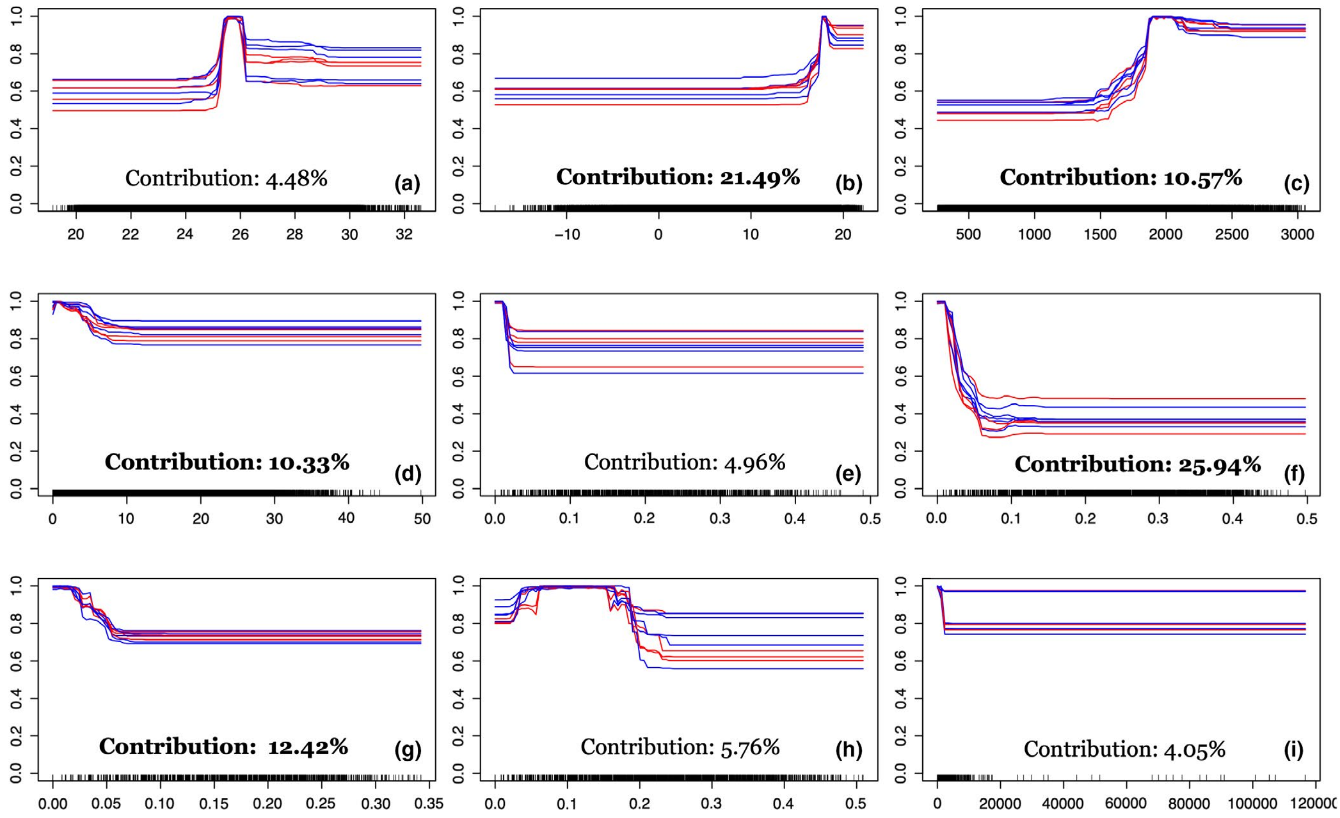

FIGURE 5 Response curve of environmental variables used to model habitat suitability of greater one-horned rhinoceros in Nepal (a) temperature annual range (BIO7), (b) mean temperature of driest quarter (BIO9), (c) annual precipitation (BIO12), (d) slope, (e) distance from forests, (f) distance from grasslands, (g) distance from wetlands, (h) croplands, and (i) population density

4.2 | Rhinoceros habitat suitability

Our results show that 35% of the current suitable habitat will be lost by 2070 due to the combined effects of climate and land use changes under the highest GHG emission scenario. Such a change in climate is likely to modify environmental elements such as temperature and precipitation, which may considerably affect habitat suitability for many species (Allen et al., 2018; Walther et al., 2002; Watson et al., 2012). Even a small change in annual average temperature can have a profound effect upon ecosystem dynamics (Saulnier-Talbot et al., 2014). The geographical range of the rhinoceros in the past mainly declined due to habitat loss associated with anthropogenic land use changes (Ellis & Talukdar, 2019; Rookmaaker et al., 2016), but our study indicates that future land use change is likely to contribute less to habitat loss than climate change (Appendix S11). Grasslands, which are a vital component of rhinoceros habitat, will substantially decrease globally (Chen et al., 2020). The data on land use change we used in our model also indicate that the extent of farmlands and urban areas will increase and the area of forest and grassland will decrease by the end of this century (Li et al., 2017). The reason behind the comparatively less contribution of land use change in predicted habitat decline is possibly because a majority of alluvial floodplain has already been converted into croplands. Similar studies conducted in India and Nepal for Asian elephant and Himalayan brown bear also suggested that the likely effects of climate change on habitat decline is greater than human land use changes (Dar et al., 2021; Kanagaraj et al., 2019).

The current distribution of rhinoceros based on our ensemble model matched the known occurrence records and is also consistent with the findings of recent research by Jhala et al. (2021). However, a study by Adhikari and Shah (2020) reported that approximately 5% (7240 km^2) of the country is suitable for rhinoceros, which is greater than our findings. The reason behind this difference is that their model considers a substantial portion of land outside protected areas as suitable rhinoceros habitat, despite these patches being already occupied by human settlements or croplands that will never be converted back to grasslands for rhinoceros conservation. However, their predicted suitable habitat within protected areas seems convincing. For instance, they estimated an area of 659 km^2 to be suitable for rhinoceros in CNP, similar to our model that estimated 638 km^2 of suitable habitat within the park. A previous study by Thapa et al. (2014) suggested that 516 km^2 is currently suitable for rhinoceros in CNP. Ours and each of these studies consistently indicate that suitable rhinoceros habitat is limited to only around 500–700 km^2 in CNP. Our future ensemble projection also suggests that these parts of CNP are likely to remain prime habitat for rhinoceros in Nepal.

Ecological studies have shown that the rhinoceros population has been gradually shifting to the western parts of CNP in Nepal (Subedi et al., 2013), possibly attributable to a shift in suitable

FIGURE 6 Extent of suitable habitat for greater one-horned rhinoceros in Nepal under current and future climate and land use change scenarios

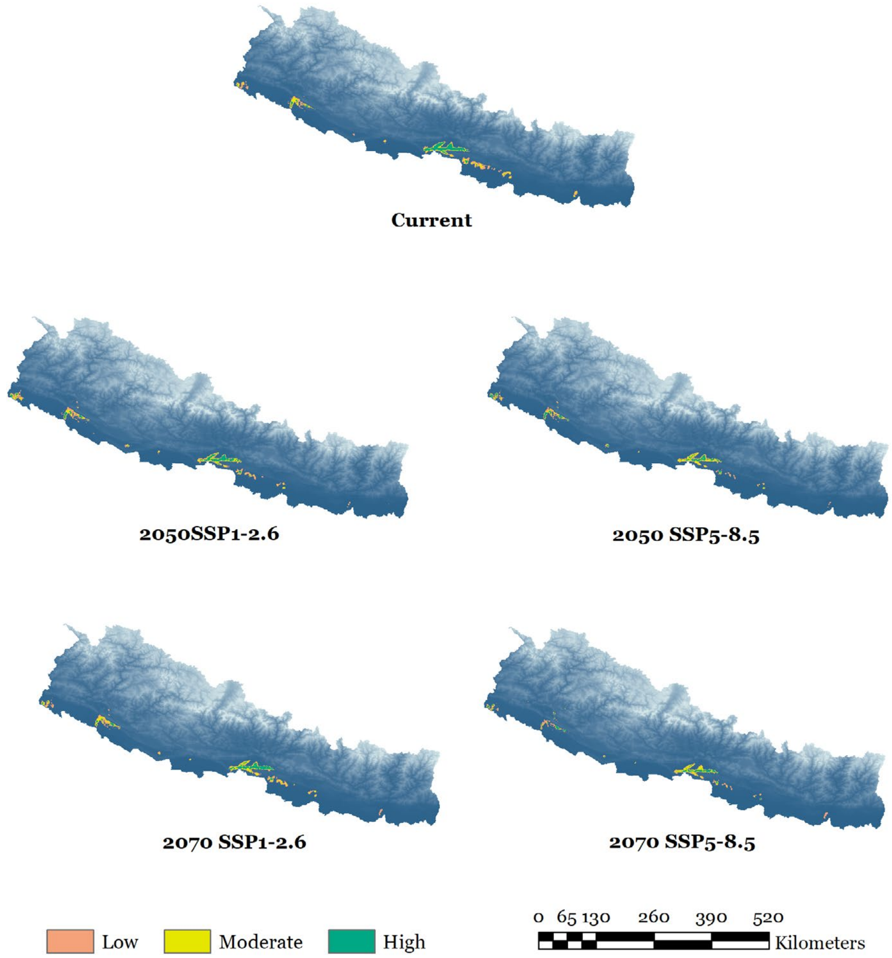

TABLE 3 Estimated area of suitable habitat for greater one-horned rhinoceros in Nepal under current and future climate and land use change scenarios

Climate scenario	Suitable habitat area (km^2) Low	Moderate	High	Total	Percentage (%) of Nepal's area
Current	1129	726	755	2610	1.77
2050 SSP1-2.6	1082	651	592	2325	1.58
2050 SSP5-8.5	832	616	456	1904	1.29
2070 SSP1-2.6	1007	741	539	2287	1.55
2070 SSP5-8.5	781	550	355	1686	1.14

Abbreviation: SSP, Shared Socioeconomic Pathways.

habitat. Our study also indicates a westward expansion of habitat suitability for rhinoceros (Figure 8), given that the extent of predicted loss is more in the central and eastern parts and possible gain in suitable habitat is likely to be more in the western lowlands of Nepal. Our model does show a considerable shift in suitable habitat of rhinoceros within the current distribution range given that 1016 km^2 of suitable habitat will be lost and 92 km^2 of new habitat will appear by 2070 under the highest GHG emission scenario. The climate model suggests that annual mean temperature and precipitation are projected to increase in South Asia during the twenty-first century and the intensity of predicted changes will differ spatially (Almazroui et al., 2020; IPCC, 2014; Jayasankar et al., 2015). One of the possible reasons behind the predicted habitat shift is that the availability and quality of grasslands and wetlands, which are essential components of rhinoceros habitat, are likely to be impacted due to fluctuations in temperature and rainfall. Experimental research on habitat dynamics and fine resolution data on environmental variables in habitat suitability modeling may provide better insights on exact mechanisms of what will make the current suitable habitat unsuitable in future, which is a critical issue for future research.

Our results indicate that the rhinoceros population in Nepal is likely to experience a moderate level of vulnerability to climate change given the predicted loss in suitable habitat under highest

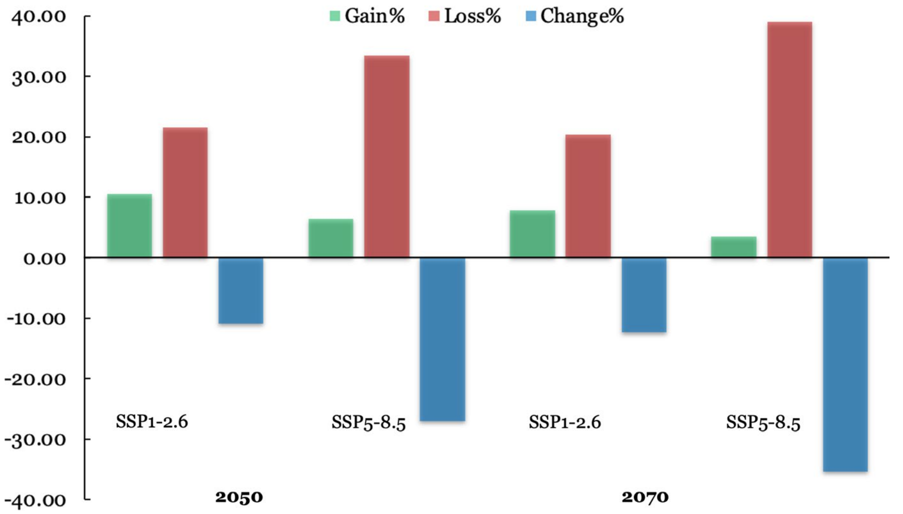

FIGURE 7 Percentage change in suitable habitat of greater one-horned rhinoceros in Nepal predicted by the ensemble model under future climate and land use change scenarios

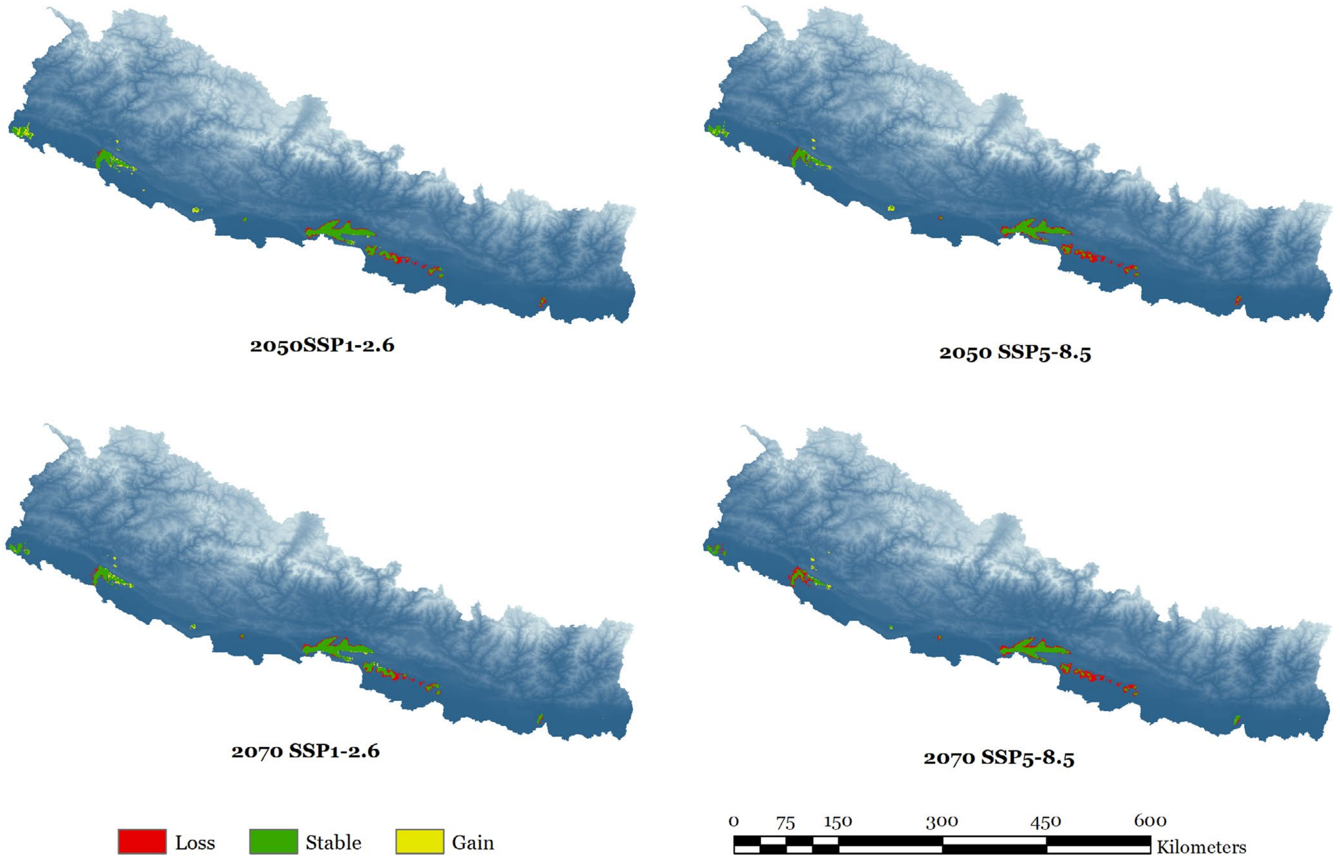

FIGURE 8 Extent of the predicted changes in suitable habitat for greater one-horned rhinoceros in Nepal

GHG emission scenario is 35% by 2070 due to the combined effects of climate and land use changes (Anacker et al., 2013). This result is consistent with the earlier findings of Pant et al. (2020a) on assessing climate change vulnerability to rhinoceros. Thus, our study presents a more optimistic modeling scenario compared to studies on different threatened species in this region. Kanagaraj et al. (2019) predicted that around 42% of currently available habitat for Asian elephants in India and Nepal will be lost due to the combined effects of climate change and human pressure by the end of 2070. Likewise, Dar et al. (2021) suggested that high emission scenarios with land use change may result in a decline of brown bear habitat of >90% by 2070. Mukul et al. (2019) sadly indicated that there will be no suitable habitat for tigers due to the combined effects of sea-level rise and climate change by 2070 in the Bangladesh Sundarbans.

Despite the habitat constraints faced by rhinoceros in Nepal, the Government of Nepal has proposed the construction of

Nijgadh International Airport in an area of 80.50 km^2 in Kohalbi municipality of Bara district (Shah, 2019)—a place where our model suggests that nearly 33% (26 km^2) of the area occupied by the proposed airport is currently suitable for rhinoceros. Most of the proposed airport area (94.20%) is forest land including nearly 3 km^2 of floodplains (Shah, 2019). This area is an important wildlife corridor adjacent to the extended area of PNP, a feeding ground for many mammals and an area frequently utilized by several threatened species including tigers (*Panthera tigris*) and leopards (*Panthera pardus*). Our study also suggests that approximately 27 km^2 of Rautahat district is suitable habitat for rhinoceros. This area is being used by rhinoceros venturing out from PNP (Acharya & Ram, 2017), and three to four rhinoceroses were recently found in Rautahat district (Rimal et al., 2018). Thus, our model has identified a considerable extent of ecological niche for rhinoceros in Bara and Rautahat districts to the eastern part of PNP, which could serve as additional habitat for rhinoceros conservation. However, threats such as poaching and potential conflict with humans should be addressed while managing this area as an important habitat for rhinoceros and other wildlife species.

In our study, current suitable habitat of 67 km^2 was detected in KTWR, while the ensemble projection showed that there will be 57 km^2 of suitable habitat by the end of 2070. The action plan of Nepal Government for rhinoceros conservation (2017–2021) has recommended a feasibility study for translocating rhinoceros in KTWR (DNPWC, 2017). Rhinoceros being a megaherbivore requires large areas of habitat to support viable population (Amin et al., 2006). The average home range size of rhinoceros ranges between 3.5 and 27 km^2 depending on habitat quality (Dinerstein, 2003; Subedi, 2012). A medium-sized population of more than 50 is considered a viable population for rhinoceros given that it is less susceptible to extinction and possibly withstand some poaching if supplemented or managed as a metapopulation (Jhala et al., 2021). Considering the habitat suitability as predicted by our ensemble model, KTWR has the potential to support a population of ~45 rhinoceros, but there is no possibility of managing rhinoceros as a metapopulation because the closest suitable habitat as predicted by our model is in Sarlahi district, which is nearly 130 km west from KTWR. It is also important to note that a recent study by Jhala et al. (2021) has suggested that KTWR can hold a minimum of 50 rhinoceros but has not included this protected area as a priority reintroduction site for rhinoceros in Nepal.

We used ensemble SDM to predict the habitat suitability for rhinoceros in Nepal given that it is equally powerful tool as a complex mechanistic model and has been widely used for predicting suitable habitat for species (Fordham et al., 2018). However, SDM is not without limitations. It assumes that species maintain equilibrium with the environment, which may not always be true. Similarly, it does not account for interactions among species which may affect the model accuracy. Thus, these limitations of SDM should be acknowledged while interpreting the findings of this study. In addition, there are uncertainties related to climate and land use change projections. Despite these inherent uncertainties associated with the correlative spatial modeling approach, the present study provides a broad perspective on current ecological niche for rhinoceros in Nepal and where the species is likely to persist in future in the context of likely impacts of climate and land use changes.

5 | CONCLUSIONS

Our results indicate that rhinoceros in Nepal is likely to face a considerable decrease in habitat suitability over the next 50 years. With an estimated 35% decline in suitable habitat under the highest GHG emission scenario, rhinoceros in Nepal is likely to experience a moderate level of vulnerability due to the combined effects of climate and land use changes, with predicted decline in habitat being influenced to a greater degree by climatic changes than land use changes. Based on the insights provided by our models, literature review, and expert consultation, we have suggested the following conservation measures to moderate the likely impacts arising from climate and land use changes:

a. Expand protected areas to secure the predicted climate change refugia for rhinoceros in Nepal. Priority should be given to protect the suitable rhinoceros habitat in Bara, Rautahat, and Sarlahi districts toward the eastern part of Parsa National Park, which could be either managed as an extended area of the existing protected area or declared and managed as a separate protected area.
b. Investigate the actual ecological mechanism driving the reduction in currently suitable rhinoceros habitat. Land use changes and the impacts of changing temperature and rainfall on grasslands and wetlands seem particularly obvious, but we were unable to confidently identify other likely mechanisms with our models. We therefore encourage the initiation of experimental on-ground research and the generation of finer resolution data on environmental variables for further analysis of the habitat suitability to better elucidate these mechanisms and inform rhinoceros conservation interventions.
c. Consider the findings of this study while assessing the feasibility of Koshi Tappu Wildlife Reserve as an additional future site for rhinoceros introduction, given that the suitable habitat predicted by our model may not support a viable population of rhinoceros there in long run. In this regard, this research is expected to provide basis for the Department of National Parks and Wildlife Conservation for further assessment and to set priorities for managing the available rhinoceros habitat in the country.
d. Avoid suitable rhinoceros habitats when selecting sites for development projects such as airports, railway tracks, and highways given that the current suitable rhinoceros habitat in Nepal is already <2% of the country, and nearly 35% of this current habitat is likely to become unsuitable within a period of 50 years due to the combined effects of climate and land use changes.

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CONFLICT OF INTEREST

None.

AUTHOR CONTRIBUTIONS

Ganesh Pant: Conceptualization (equal); Data curation (lead); Formal analysis (lead); Methodology (equal); Software (lead); Validation (supporting); Visualization (lead); Writing – original draft (lead); Writing – review & editing (equal). **Tek Maraseni:** Conceptualization (equal); Formal analysis (supporting); Methodology (equal); Supervision (lead); Validation (supporting); Visualization (supporting); Writing – review & editing (lead). **Armando Apan:** Conceptualization (equal); Data curation (supporting); Formal analysis (supporting); Methodology (equal); Supervision (supporting); Validation (lead); Writing – review & editing (supporting). **Benjamin L. Allen:** Conceptualization (equal); Formal analysis (supporting); Methodology (equal); Supervision (supporting); Writing – review & editing (supporting).

OPEN RESEARCH BADGES

This article has earned an Open Data and Open Materials Badges for making publicly available the digitally-shareable data necessary to reproduce the reported results. The data is available at https://doi.org/10.5061/dryad.wpzgmsbnw.

DATA AVAILABILITY STATEMENT

Dataset and R Markdown File related to ensemble modeling used in this study are deposited in Dryad Digital Repository and are available via the following link. https://doi.org/10.5061/dryad.wpzgmsbnw.

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SUPPORTING INFORMATION

Additional supporting information may be found in the online version of the article at the publisher's website.

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CHAPTER 6: ADAPTATION PLANNING

This chapter is presented as an exact copy of an original research article entitled "Identifying and prioritising climate change adaptation actions for greater one-horned rhinoceros (*Rhinoceros unicornis*) conservation in Nepal" published in *PeerJ*, vol. 10 (2022), pp. 1-23. https://doi.org/10.7717/peerj.12795.

Synopsis

This article has devised the basis for initiating adaptation planning for rhinoceros conservation in Nepal, given that climate change adaptation actions for rhinoceros have been identified and prioritised in this study. After reviewing the relevant literature, key informant interviews and focus group discussions, a suite of 20 possible adaptation actions for rhinoceros conservation in Nepal were identified and these actions were prioritised through expert consultation. The paper states that identifying and protecting climate refugia, restoring the existing habitats through wetland and grassland management, creating artificial highlands in floodplains to provide rhinoceros with refuge during severe floods, and translocating them to other suitable habitats received higher priority out of the 20 adaptation actions identified. This article argues that the implementation of these adaptation actions will contribute to reducing the vulnerability of rhinoceros to the likely adverse impacts of climate change. Moreover, this paper has emphasised the need to integrate likely climate change impacts while planning for rhinoceros conservation and initiating experimental research and monitoring programs to better inform adaptation planning in the future.

Identifying and prioritising climate change adaptation actions for greater one-horned rhinoceros (*Rhinoceros unicornis*) conservation in Nepal

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ABSTRACT

Climate change has started impacting species, ecosystems, genetic diversity within species, and ecological interactions and is thus a serious threat to conserving biodiversity globally. In the absence of adequate adaptation measures, biodiversity may continue to decline, and many species will possibly become extinct. Given that global temperature continues to increase, climate change adaptation has emerged as an overarching framework for conservation planning. We identified both ongoing and probable climate change adaptation actions for greater one-horned rhinoceros conservation in Nepal through a combination of literature review, key informant surveys ($n = 53$), focus group discussions ($n = 37$) and expert consultation ($n = 9$), and prioritised the identified adaptation actions through stakeholder consultation ($n = 17$). The majority of key informants (>80%) reported that climate change has been impacting rhinoceros, and more than 65% of them believe that rhinoceros habitat suitability in Nepal has been shifting westwards. Despite these perceived risks, climate change impacts have not been incorporated well into formal conservation planning for rhinoceros. Out of 20 identified adaptation actions under nine adaptation strategies, identifying and protecting climate refugia, restoring the existing habitats through wetland and grassland management, creating artificial highlands in floodplains to provide rhinoceros with refuge during severe floods, and translocating them to other suitable habitats received higher priority. These adaptation actions may contribute to reducing the vulnerability of rhinoceros to the likely impacts of climate change. This study is the first of its kind in Nepal and is expected to provide a guideline to align ongoing conservation measures into climate change adaptation planning for rhinoceros. Further, we emphasise the need to integrating likely climate change impacts while planning for rhinoceros conservation and initiating experimental research and monitoring programs to better inform adaptation planning in the future.

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INTRODUCTION

Climate change is increasingly acknowledged as a critical threat for conserving global biodiversity, which is impacting almost every level of biological diversity including species, ecosystems, ecological interactions, and genetic diversity within species (*Foden et al., 2019*; *IPBES, 2019*). It is triggering changes in phenology, range shifts and species composition (*Chen et al., 2011*; *Rasmussen et al., 2017*; *Haight & Hammill, 2020*). These adverse impacts on biodiversity are likely to intensify in the future, given that the global average temperature is predicted to exceed 1.5 °C by 2100 even under the lowest greenhouse gas emission scenario (*IPCC, 2018*; *Newbold et al., 2020*). Biodiversity continues to decline globally, and many species will possibly become extinct due to the synergetic effects of climate change and land use changes if adequate adaptation measures are not implemented (*Da Silva et al., 2019*; *IPBES, 2019*; *Hannah et al., 2020*).

Climate change adaptation is defined as adjusting to moderate or avoid the harm that is likely to arise from a current or projected change in climate and associated effects (*Smit et al., 2000*). Adaptation priorities of different systems may be different based on the magnitude of change a system has been experiencing or is projected to experience due to climatic stressors (*Watson, Iwamura & Butt, 2013*). Thus, the effectiveness of species conservation strategies relies not only on enhancing knowledge of species and ecosystem responses to these changes but also on envisaging the likely response of humans (*Watson, Iwamura & Butt, 2013*; *Morecroft et al., 2019*). Successful conservation needs to embrace multiple approaches to climate adaptation; however, these are seldom delivered in an integrated way to assist in conservation planning and implementation in the context of the inherent uncertainty associated with future climate conditions (*Smit et al., 2000*). Likewise, the management practices of today may not be relevant under future climate scenarios, and ecologists must go beyond finding the likely climate change impacts and start devising probable solutions (*Hulme, 2005*). In this context, priority should be given to developing adaptation options for the species that are most susceptible to changing climate (*Abrahms et al., 2017*; *Morecroft et al., 2019*).

Greater one-horned rhinoceros (*Rhinoceros unicornis*; hereafter "rhinoceros") is one of the five remaining species of rhinoceros in the world and is currently distributed in a few protected areas in southern Nepal and the northern foothills of India (*Rookmaaker et al., 2016*; *Ellis & Talukdar, 2019*). Rhinoceroses were widespread throughout the Indian subcontinent until the middle of the nineteenth century, but the population sharply declined to only 500 rhinoceros during the 1960s due to poaching and habitat loss (*Rookmaaker et al., 2016*; *Pant et al., 2020b*). However, the rhinoceros population in the wild has been gradually increasing in both India and Nepal over the last two decades following effective conservation initiatives, and the global rhinoceros population at present is more than 3,500 individuals (*DNPWC, 2017*; *Ellis & Talukdar, 2019*). Despite its population recovery from the brink of extinction, rhinoceros is still considered to be at high risk due to poaching and habitat alteration induced by climate change (*Dinerstein, 2003*; *DNPWC, 2017*; *Pant et al., 2020b*). However, the probable impacts of changing climate on rhinoceroses and their habitat have not been well documented (*Pant et al., 2020b*).

Rhinoceros is a habitat specialist and prefers a mosaic of grassland and the riverine forests on alluvial floodplains along the foothills of the Himalayas, where green growth and water remain available throughout the year (*Laurie, 1982*; *Dinerstein & Price, 1991*; *Jnawali, 1995*; *Pradhan et al., 2008*). The insufficiency of suitable habitat is one of the limiting factors for rhinoceros conservation (*Pant et al., 2020b*), and the decline in both quality and quantity of rhinoceros habitat has been documented in rhinoceros-bearing protected areas in both India and Nepal (*Sarma et al., 2009*; *Subedi, 2012*; *Medhi & Saha, 2014*). In Nepal, the rhinoceros population has been gradually shifting westwards, which indicates the change in habitat suitability (*Subedi et al., 2013*) and climate change has been recently acknowledged as an emerging challenge for rhinoceros conservation (*DNPWC, 2017*). The decline in rhinoceros habitat is likely to be intensified in the future due to the impacts of climate change, given that over one-third of the current suitable habitat is predicted to become unsuitable in the next 50 years under the highest greenhouse gas emission scenario (*Pant et al., 2021*).

Over the last few decades, climate change adaptation has been acknowledged as an overarching framework for biodiversity conservation (*Glick, Stein & Edelson, 2011*; *Stein et al., 2013*) and the adaptation actions currently in practice for wildlife management are broadly focused on protected areas, invasive species, ecosystem services, adaptive management, biological corridors, and assisted migration (*LeDee et al., 2021*). There are several examples of adaptation planning for species conservation and ecosystem management from around the globe. For example, national fish, wildlife and plant climate adaptation strategy of the United States (*Burns et al., 2021*), climate change strategy and action plan for Greater Barrier Reef National Park, Australia (*GBRMP, 2012*), climate change adaptation actions for Australian birds (*Garnett et al., 2013*), and climate change adaptation actions for vulnerable seabirds on Albatross Island in Tasmania (*Alderman & Hobday, 2017*) have been formulated. In Nepal, national adaptation plan has been prepared that proposed 11 priority adaptation programs for forests, biodiversity and watershed conservation (*GON, 2021*). However, no specific adaptation actions have been developed to date for particular wildlife species conservation in Nepal.

The aim of this study was to identify, describe and prioritise adaptation actions to moderate the likely effects of climate change on rhinoceros in Nepal. The specific objectives included (1) documenting the ongoing conservation interventions that possibly contribute to climate change adaptation planning, (2) identifying the probable climate change adaptation actions, and (3) guiding the future course of actions to align ongoing conservation measures into adaptation planning. Climate change has been acknowledged as an emerging threat for rhinoceros conservation given that the decline in rhinoceros habitat due to invasive plant species and drying up of wetlands has been documented, and climate-induced hazards including flash floods, prolonged droughts and forest fires are predicted to increase in those areas (*Medhi & Saha, 2014*; *DNPWC, 2017*; *Pant et al., 2020b*; *Pant et al., 2021*). Likewise, *Pant et al. (2020a)* recently reported that rhinoceroses in Nepal are likely to experience a 'moderate' level of climate change vulnerability owing to susceptibility to flash floods, habitat loss due to invasive plant species, increased forest fires and drying up of wetlands due to increased droughts. The findings of the present

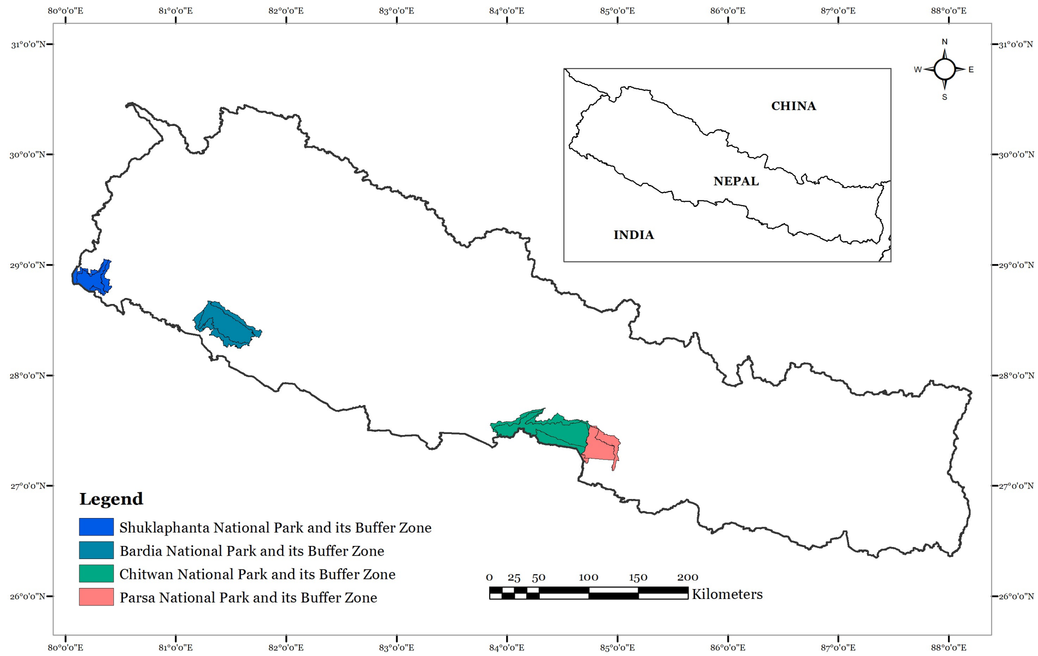

Figure 1 Location of National Parks (Shuklaphanta, Bardia, Chitwan and Parsa) with extant rhinoceros population in Nepal.

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study, if converted into action, are expected to reduce these vulnerabilities to rhinoceros in the era of rapid climate change. Although our focus is on rhinoceros conservation, this study is equally important for adaptation planning for other wildlife species given that rhinoceros is a flagship as well as an umbrella species, its conservation could support in the protection of other naturally co-occurring species (*Roberge & Angelstam, 2004*; *Amin et al., 2006*; *Cédric et al., 2016*).

MATERIALS & METHODS

Study area

Nepal extends over 147,516 km^2 in South Asia between longitudes of 80°04′ to 88°12′ east and latitudes of 26°22′ to 30°27′ north. We focused our study on all of the protected areas in Nepal with extant rhinoceros populations, namely Shuklaphanta, Bardia, Chitwan and Parsa National Parks, and their surrounding landscapes (Fig. 1). Chitwan National Park (CNP; 95,000 ha) is a stronghold of rhinoceros, and the only source population of rhinoceros in the country (*DNPWC, 2017*). Recently, Parsa National Park (PNP; 62,700 ha) has been colonised by rhinoceros where 3-5 animals have migrated from adjacent CNP (*Acharya & Ram, 2017*). Nearly 100 rhinoceroses were translocated between 1986 and 2017 from CNP to Bardia National Park (BNP; 96,800 ha) and Shuklaphanta National Park (SNP; 30,500 ha) (*DNPWC, 2018*; *Thapa et al., 2013*). Based on the census conducted in 2015 *DNPWC, 2017*, there were 645 rhinoceroses in four National Parks in Nepal, *i.e.*, CNP (605), BNP (29), SNP (8) and PNP (3).

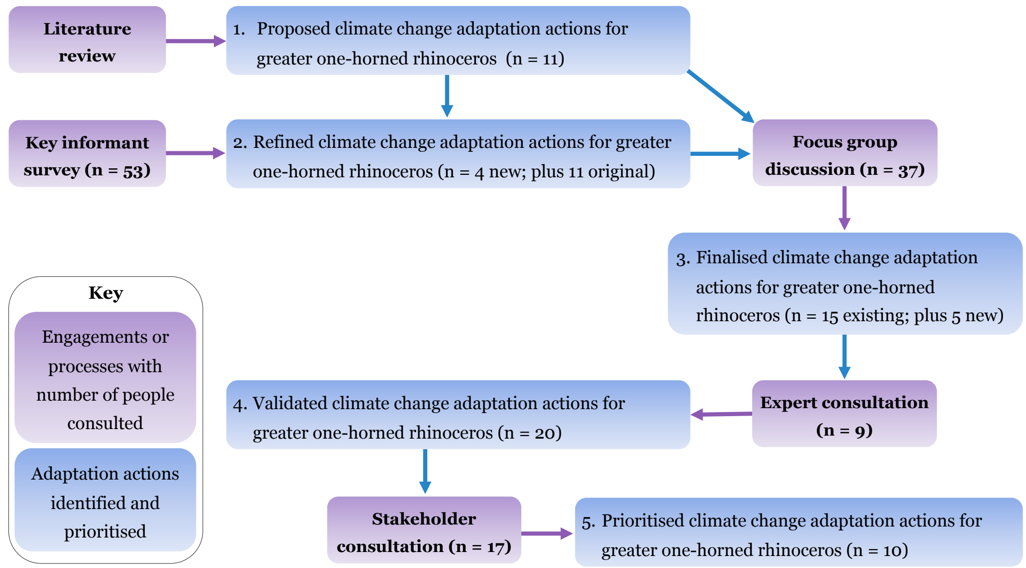

Figure 2 The methodological approach for identifying and prioritising climate change adaptation actions for rhinoceros conservation in Nepal.

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Methods

This study was conducted with the research permission (075/76 ECO- 2124) from the Department of National Parks and Wildlife Conservation, Nepal and the University of Southern Queensland, Australia has also granted ethical clearance (H19REA001) for the research. We used a combination of literature review, key informant surveys ($n = 53$), focus group discussions ($n = 37$), expert consultation ($n = 9$), and stakeholder consultation for priority ranking ($n = 17$) as methods to identify and prioritise adaptation actions to conserve rhinoceros in the face of climate change (Fig. 2). We collected primary data for this research between February and April 2019. We first developed a set of 11 proposed adaptation actions through a literature review. Later, we refined these actions with inputs from key informants and then finalised a list of 20 adaptation actions through focus group discussions during a stakeholder consultation workshop, where we grouped these actions into nine adaptation strategies. Further, we evaluated and validated the identified adaptation actions through expert consultation. We also documented key informants' insights related to climate change impacts on rhinoceros habitat including the shift in habitat suitability. Finally, we prioritised the identified adaptation actions based on priority ranking by stakeholders and experts.

Review of relevant literature

Climate change adaptation consists of planned actions aimed at reducing the risks and capitalises on the possible opportunities linked with climate change, which is emerging as a key framework for biodiversity conservation globally (*Füssel, 2007*; *Glick, Stein & Edelson, 2011*). Adaptation planning is regarded as a means to reduce the likely vulnerabilities to climate change and the projected climate scenarios in the future (*Thomas et al., 2019*).

Increasing resilience is an overarching objective of adaptation strategies and principles (*Morecroft et al., 2012*). Decisions on climate change adaptation to biodiversity primarily rely on expert judgement, with supplementary information generated from climate models. This approach also considers managing biodiversity in-situ followed by landscape-level interventions and finally ex-situ conservation through translocation (*Oliver et al., 2012*). Adaptation is characterised by flexible management as a component of well-designed adaptation strategies because of the uncertainties associated with predicted climate change impacts on ecosystems and species (*Glick, Stein & Edelson, 2011*).

Several adaptation approaches are used to incorporate climate change into conservation planning and translating these principles and strategies of climate change adaptation into action. Although various analytical techniques are used for adaptation planning, most of them follow similar steps, including assessing vulnerabilities to the species in relation to the predicted climate change scenarios, determining predicted range shifts for species, identifying promising adaptation options, and then appraising and choosing adaptation actions (*Stein et al., 2013*; *Abrahms et al., 2017*). We followed the participatory adaptation for conservation targets (ACT) framework, as suggested by *Cross et al. (2012)*, which considers the effect of climate change in deciding conservation measures for species, ecosystem and ecological function. This framework is founded on the principle that effective adaptation planning relies predominantly on indigenous knowledge related to ecosystems, and there is no need for detailed forecasts of changing climate or its impacts. We first appraised the generic adaptation actions proposed for biodiversity and wildlife (see *Mawdsley, O'malley & Ojima, 2009*; *Oliver et al., 2012*; *Abrahms et al., 2017*), given that there were no specific adaptation actions already developed for rhinoceros. On the basis of the literature review, including those described in *Pant et al. (2020b)*, we identified 11 adaptation actions relevant to rhinoceros conservation in Nepal.

Key informant survey

We interviewed 53 key informants in person, including rhinoceros experts, managers of the protected areas, academics, participants from conservation agencies such as the International Union for Conservation of Nature (IUCN), Zoological Society of London (ZSL), World Wide Fund for Nature (WWF), National Trust for Nature Conservation (NTNC), and members of relevant community-based organisations. We purposely selected participants who were directly involved in rhinoceros conservation in Nepal and they were familiar about the ongoing changes in rhinoceros habitat over the years. We documented their understanding of the probable climate change impacts on rhinoceros habitat, and with their input, we identified interventions that are likely to serve as suitable climate change adaptation actions. Five interviewees (9%) were female, and 48 (91%) were male. The fewer number of female interviewees is attributed to the gender imbalance in the biodiversity conservation sector in Nepal. The majority of the participants ($n = 29$; 54%) were government officials and 12 (23%) each from non-government organisations and community organisations. Most of the key informants (>55%) each had 15 years of experience or more in the environmental management sector. These key informants identified four more adaptation actions which were discussed with focus groups.

Figure 3 Participants discussing on climate change vulnerability and adaptation planning for rhinoceros in Nepal.

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Focus group discussion

We conducted focus group discussions on climate change adaptation planning for rhinoceros during a two-day workshop in Chitwan National Park, Nepal on 5-6 April 2019, which was attended by 37 stakeholders representing the department and protected area offices from the government sector, non-governmental organisations, universities and community-based organisations involved in rhinoceros conservation (Fig. 3). The discussion on identifying the adaptation actions was conducted immediately after the vulnerability assessment, the details on assessing climate change vulnerability to rhinoceros in Nepal is presented in *Pant et al. (2020a)*. The information on the existing practices for species-specific adaptation planning and adaptation actions relevant for rhinoceros conservation identified through literature review and key informant survey were provided to the workshop participants. In this session, participants were engaged in a group exercise for identifying the possible adaptation actions, primarily based on the identified climate change vulnerabilities for rhinoceros conservation in Nepal. During the plenary session, each group presented the details of adaptation actions that are expected to reduce the vulnerability of rhinoceros considering predicted climate change impacts, which were then finalised by consensus among all workshop participants. The participants finally agreed on 15 adaptation actions, though five additional potential adaptation actions were added for further discussion with experts.

Expert consultation

We consulted a cohort of nine experts face-to-face to validate the outcomes of our climate change adaptation focus group exercise for rhinoceros. In doing so, we invited all of the known rhinoceros conservation experts in Nepal from the Department of National

Parks and Wildlife Conservation (DNPWC) and NGOs, including the IUCN, WWF, NTNC and ZSL. Two of the experts were members of the IUCN Asian Rhino Specialist Group. In this face-to-face interaction with experts, adaptation actions identified for rhinoceros conservation were discussed and evaluated. We further prepared a summary report containing the key outcomes of the adaptation planning, which was sent to DNPWC officials and rhinoceros experts for their review and endorsement. Thus, the outcomes of the adaptation workshop were basically validated by nine experts from a range of GOs and NGOs in a series of face-to-face meetings.

Stakeholder consultation for priority ranking

In a subsequent engagement, we involved key stakeholders having more than ten years of experience in the biodiversity conservation sector in Nepal to assign a rank against each of the 20 adaptation actions on a scale of 0 to 9 (0–Not in priority and 9–highest priority). Out of 23 invitees, 17 stakeholders completed priority ranking individually. Of these 17 participants, 15 (88%) were male, and two (12%) were female. We compiled the assigned ranking score for each of the adaptation actions and calculated the overall score of each adaptation action using the following formula adopted from *Maraseni (2008)*.

$i = 17, j = 9$

Overall priority score $= \sum$ (Wi * Rj)/N

$i = 1, j = 0$

where,

Wi = Number of participants selecting a particular adaptation action W (i =1–17) corresponding to a particular rank R (j = 0–9)

Rj = Assigned a rank (j = 0–9) of a particular adaptation action

N = Total number of participants

RESULTS

Climate change impacts on rhinoceros and its habitat

The majority of the key informants (>80%) believed that climate change has already started impacting rhinoceroses and their habitat in Nepal (Fig. 4A). Of the 53 key informants, only 6 (9%) had the opinion that the observed changes in rhinoceroses and their habitat dynamics are due to other natural processes over time, though four key informants (7%) were not aware of such changes. Likewise, more than 65% of the key informants considered that rhinoceros habitat suitability in Nepal has been shifting westwards due to climate change (Fig. 4B). However, 11 key informants (20%) felt that the reasons behind this habitat shift were uncertain. Seven key informants (13%) did not know whether there has been a shift in rhinoceros habitat suitability in Nepal or not.

Climate change adaptation actions for rhinoceros conservation

After reviewing the relevant literatures including *Mawdsley, O'malley & Ojima (2009)*; *Oliver et al. (2012)*, *Watson et al. (2012)*, *Stein et al. (2013)*, *Abrahms et al. (2017)*, we identified a preliminary set of 11 climate change adaptation actions for rhinoceros conservation under nine adaptation strategies that are expected to contribute in reducing

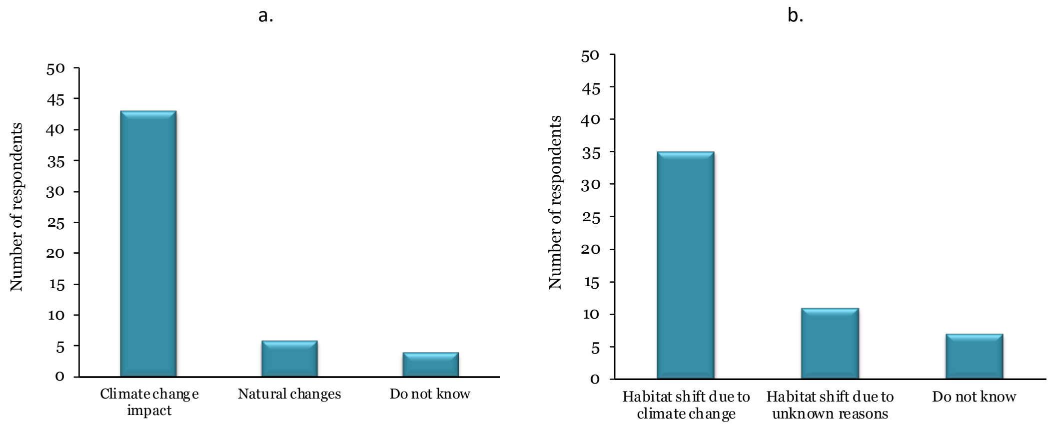

Figure 4 The perception of key informants about the likely impacts of climate change on rhinoceros habitat in Nepal (n = 53). (A) Key informants' perception of rhinoceros habitat dynamics in Nepal, (B) Key informants' perception on shift in rhinoceros habitat suitability in Nepal.

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likely climate change vulnerabilities. These adaptation actions include (i) expanding the existing protected areas, (ii) managing grasslands, (iii) managing wetlands, (iv) controlling invasive species, (v) restoring corridor and connectivity, (vi) conserving biodiversity at the landscape level, (vii) preparing species conservation action plan, (viii) translocating species to other suitable habitats, (ix) strengthening anti-poaching operation, (x) controlling water pollution, and (xi) mitigating human-wildlife conflict. Similarly, four more adaptation actions identified by key informants are (i) establishing new protected areas, (ii) practicing controlled burning, (iii) managing buffer zone, and (iv) conducting periodic census and ID-based monitoring.

In addition, five potential adaptation actions were explored through focus group discussion, which include (i) identifying and protecting climate refugia, (ii) designing and constructing earthen mounds in floodplain grasslands, (iii) integrating climate change impacts in species conservation action plan, (iv) translocating species to future suitable habitats, and (v) initiating experimental research and monitoring of climate change effects. The final set of 20 adaptation actions under nine strategies for rhinoceros conservation in Nepal identified through literature review, key informant survey and focus group discussion, and validated through expert consultation is presented here in Table 1. Of the 20 adaptation actions, 15 (75%) are currently in practice for rhinoceros conservation in Nepal, but these are part of ongoing rhinoceros conservation activities and are not directly linked to climate change.

Prioritisation of climate change adaptation actions

Out of the 20 identified climate change adaptation actions, ten actions prioritised through stakeholder consultation have been presented in Fig. 5 along with their respective overall score. The adaptation action with an overall score <1 was no longer considered as priority action. Among the others, 'identifying and protecting climate refugia' received the highest

Table 1 Climate change adaptation actions for rhinoceros conservation in Nepal grouped into different adaptation strategies. 'Ongoing' refers to the existing conservation interventions that are likely to contribute to increasing the resilience of rhinoceros and "Probable' refers to the potential adaptation actions for managing rhinoceros in an era of rapid climate change.

Strategy No.	Adaptation strategy	Adaptation actions		
			Ongoing	Probable
1	Increasing the extent of protected areas	a. Expand the existing protected areas	✓	
		b. Establish new protected areas	✓	
2	Improving management and restoring the existing protected areas	c. Manage grasslands	✓	
		d. Manage wetlands	✓	
		e. Practice controlled burning	✓	
		f. Control invasive species	✓	
3	Protecting biological corridors, stepping stones and refugia	g. Restore corridor and connectivity	✓	
		h. Identify and protect climate refugia		✓
		i. Design and construct earthen mounds in floodplain grasslands		✓
4	Managing and restoring ecosystem function rather than focusing on specific components	j. Conserve biodiversity at landscape-level	✓	
5	Increasing the matrix by expanding landscape permeability to species movement	k. Manage buffer zone	✓	
6	Focusing conservation resources on species that might become extinct	l. Prepare species conservation action plan	✓	
		m. Integrate climate change impacts in species conservation action plan		✓
7	Translocating species at risk of extinction	n. Translocate species to other suitable habitats	✓	
		o. Translocate species to future suitable habitats		✓
8	Reducing pressures on species from non-climatic sources	p. Strengthen anti-poaching operation	✓	
		q. Control water pollution	✓	
		r. Mitigate human-wildlife conflict	✓	
9	Evaluating and enhancing monitoring programs	s. Conduct periodic census and ID-based monitoring	✓	
		t. Initiate experimental research and monitoring of climate change effects		✓

priority, with an overall priority score of >6, followed by 'managing wetlands', 'constructing earthen mounds', 'managing grasslands', and 'translocating rhinoceros to suitable areas'.

DISCUSSION

The result of our study imply that climate change has already started impacting rhinoceros habitat in Nepal. In recent years, climate change has been acknowledged as an emerging threat to rhinoceros (*DNPWC, 2017*). Another study by *Pant et al. (2020a)* has revealed that rhinoceros in Nepal is likely to face a moderate level of vulnerability due to climate change because of severe floods, fragmented habitat, invasive plant species, droughts, small population size and forest fires. We considered these vulnerability factors while identifying the adaptation strategies and actions most likely to enhance its resilience against the impacts

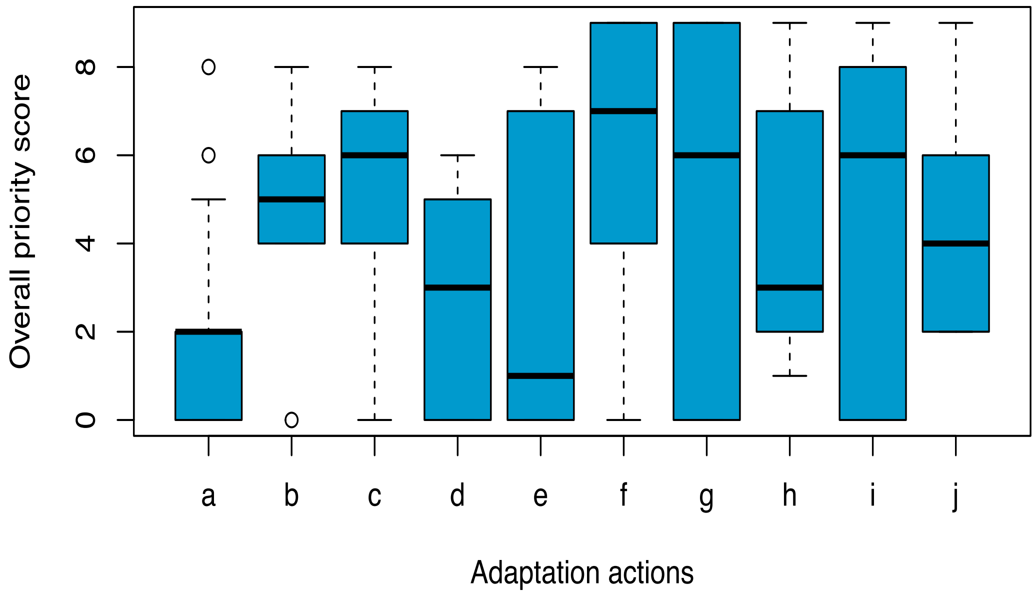

Figure 5 The prioritised climate change adaptation actions for greater one-horned rhinoceros conservation in Nepal based on priority ranking by stakeholders ($n = 17$). (A) Expand protected areas, (B) Manage grasslands, (C) Manage wetlands, (D) Control invasive species, (E) Restore corridor and connectivity, (F) Identify and protect climate refugia, (G) Design and construct earthen mounds in floodplain grasslands, (H) Develop climate-smart species conservation action plan, (I) Translocate rhinoceros to suitable habitats, (J) Initiate experimental research and monitoring of climate change effectsThe overall priority score '0' denotes least priority and the score '9' is the highest priority.

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of climate change. Adaptation strategies and actions need to be revised regularly and should be considered a continual process and not a static endpoint (*Stein et al., 2013*), so our study provides a foundation for the integration of adaptation actions into conservation planning for rhinoceros in Nepal. These findings can be utilised to guide management interventions on the basis of the best information available today and refine these decisions in the future following the principle of adaptive management (*Walsh et al., 2012*).

Those engaged in our study reported a shift in suitable rhinoceros habitat in Nepal, and they considered it a likely climate change impact on rhinoceros. The rhinoceros population has been gradually moving to the western parts of CNP (*Subedi et al., 2013*), and a recent study supports the view that suitable rhinoceros habitat is likely to experience a considerable decrease and shift westwards due to the impacts of climate change (*Pant et al., 2021*). In general, suitable habitat of wildlife species with a moderate level of vulnerability due to climate-induced changes is likely to decline substantially (*Anacker et al., 2013*) but will not be at risk of immediate extinction (*Foden et al., 2019*). Thus, our findings suggest that rhinoceros will have a better chance of persistence through adaptation planning if we can protect both current and future suitable habitat for rhinoceros conservation.

Identifying and protecting climate refugia has been prioritised as one of the most important adaptation actions in this study. Climate refugia, or areas that may serve as a shelter in facilitating the persistence of species amidst climate change impacts are increasingly acknowledged as an important adaptation strategy (*Morelli et al., 2020*). The increased risk of flooding is an extreme event induced by climate change, which is likely to jeopardise conservation success (*King, 2005*). The entire Terai region is fed by rivers originating in the snow-covered Himalayan mountains, and increasing temperatures lead to increased river flow. Chitwan National Park in Nepal is highly susceptible to this kind of climate-induced flash flooding (*Pant et al., 2020a*). For example, thousands of wild animals were reported dead, including two rhinoceros, during a severe flood episode in August 2017 (*Chitwan National Park, 2017*; *WWF, 2020*). Ten rhinoceros were also swept away through the Indian border and were transported back to the park (*Chitwan National Park, 2017*). In response, a raised soil mound with dimensions of 40 m × 30 m × 2 m was constructed in the buffer zone community forest as an experiment to see whether this type of structure can provide a safe refuge for rhinoceros and other wild animals during severe floods (*WWF, 2020*). We observed the site during our fieldwork in April 2019 and found that the area has been used by rhinoceros and other wild animals, however the effectiveness of these earthen mounds is yet to be evaluated. However, stakeholders and experts believe that such structures could provide safe high grounds for rhinoceros and other animals during flood events. Hence, the construction of earthen mounds in floodplain grasslands was considered to be one potential adaptation action for rhinoceros conservation in Nepal. This strategy is equally important for rhinoceros conservation in India, more specifically in Kaziranga National Park (KNP), given that an estimated 141 rhinoceros have been killed due to severe floods in KNP up until 2019 and 12 rhinoceros were found dead in the recent flood episode of July 2019 alone (*Sharma, 2019*). KNP and the surrounding landscape supports two-thirds of the global population of rhinoceros in the wild (*Pant et al., 2020b*) and the habitat condition and the conservation challenges in Nepal's Chitwan National Park are similar to those in Kaziranga National Park in India (*DNPWC, 2017*; *Puri & Joshi, 2018*).

The findings of our study indicate that improving management and restoring existing protected areas are regarded as essential adaptation strategies for rhinoceros conservation. This could be achieved, in part, through active management of grasslands and wetlands to improve their resilience. Some of the climate change effects in protected landscapes are possible to offset through intensive management of habitat components (*Mitchell et al., 2007*). Grassland management and wetland restoration are key ongoing management activities for rhinoceros conservation in Nepal (*DNPWC, 2017*). Rhinoceros is primarily a grazer and prefers the habitat mosaic of grasslands, riverine forests and wetlands (*Dinerstein, 2003*). But the quality of grasslands in the entire rhinoceros habitat in CNP is degrading due to invasive plants such as *Mikania micarantha* (Murphy et al., 2013). The degradation of wetlands is another serious concern expected to intensify in the future as a result of climate change (*DNPWC, 2017*). Likewise, climate change favours the proliferation of invasive plants (*Hellmann et al., 2008*). Thus, the changes triggered by changing climate should be considered while restoring and maintaining the grassland and wetland habitats to be an effective adaption action for rhinoceros conservation.

Translocation of rhinoceros to other suitable habitat was another prioritised adaption action in our study. Climate change can substantially reduce the availability of suitable habitat and species with low dispersal capacity will be at higher risk. In such cases, increasing landscape connectivity may not help for dispersal, so translocation of species should be considered as a better option (*Hulme, 2005*). Translocating species to places where they are not present is considered a 'last resort' if unassisted migration to suitable future habitat is very unlikely (*Oliver et al., 2012*). In Nepal, rhinoceroses were only present in CNP during the early 1980s (*Thapa et al., 2013*; *DNPWC, 2017*). To reduce the risk of losing rhinoceros from the likely catastrophic events, poaching and natural calamities, more than 90 rhinoceros were translocated to BNP and SNP between the late 1980s and 2017 (*Thapa et al., 2013*). Habitat suitability models suggest that BNP and SNP are suitable for rhinoceros, and the future suitable habitat is likely to increase (*Pant et al., 2021*). Therefore, continued translocation of rhinoceros to BNP and SNP is a recommended climate change adaptation action for rhinoceros conservation in Nepal.

Expanding protected areas coverage is one of the core strategies for conserving biodiversity, thereby reducing extinction threats (*Dinerstein et al., 2019*). Nepal has made a remarkable achievement in expanding the extent of protected areas (*Acharya et al., 2020*), such that Banke National Park (BaNP; 55,000 ha) and an extended area of PNP (12,800 ha) are recent additions (*DNPWC, 2018*). The extended area of PNP encompasses the suitable habitat of rhinoceros and is currently occupied by rhinoceros (*Acharya & Ram, 2017*). However, BaNP does not have rhinoceros at present and there will be no habitat suitability for rhinoceros in the future either (*Oli et al., 2018*; *Pant et al., 2021*). Thus, increasing the extent of protected areas may not serve as an effective adaptation action if we fail to include suitable habitat for a particular species. In this regard, a few patches of habitat suitable for rhinoceros have been identified in Bara and Rautahat districts to the eastern part of Parsa National Park, which has been used by the rhinoceros straying out from the protected areas (*Acharya & Ram, 2017*; *Rimal et al., 2018*; *Pant et al., 2021*). This area is likely to serve as an additional rhinoceros habitat for protected area expansion. However, further analysis is needed to ensure that poaching and conflict with humans will not jeopardise the conservation of rhinoceros and other wildlife species in those extended areas. Despite being a key adaptation option for biodiversity conservation, stakeholders did not rank the expansion of protected areas in top priority given that only a few patches of potential rhinoceros habitat remain outside the protected areas, >23% of the country is already under protected area system and most of the historical range of the rhinoceros outside protected areas are converted into human settlements (*DNPWC, 2018*; *Pant et al., 2020b*; *Pant et al., 2021*).

This study also acknowledges that corridor connectivity is an integral part of adaptation planning for rhinoceros. Landscape connectivity has also been regarded as a frequently cited adaptation strategy for biodiversity conservation. However, most of the connectivity planning does not directly account for climate-driven range shifts (*Littlefield et al., 2019*). In Nepal, landscape-level conservation has been practised for the last two decades to facilitate the movement of large mammals, including rhinoceros. The forest corridor in western terai between Bardia and Shuklaphanta National Parks is important for rhinoceros conservation given that it connects four rhinoceros-bearing protected areas in a transboundary landscape shared by both India and Nepal that collectively support at least 70 rhinoceros (*Pant et al.,* 2020b). Landscape connectivity in this region is vital for rhinoceros conservation given that movement of rhinoceros from one protected area to another has been recorded (*Talukdar & Sinha, 2013*). Maintaining corridors for landscape connectivity can be an important adaptation action for rhinoceros conservation if it accounts for the likely shifts indicated by habitat suitability models.

In practice, it is not possible to develop separate adaptation actions for every wildlife species. However, a number of adaptation actions developed for rhinoceros conservation are expected to benefit other species sharing the same ecosystem given that rhinoceros, like other megaherbivores, require large areas to support viable populations, and their conservation requirements encompass the habitat components required for many other species (*Amin et al., 2006*). For instance, rhinoceros, tiger, and elephant are key wildlife species in Chitwan National Park (*Chitwan National Park, 2013*). Maintaining grasslands and wetlands is a common strategy for conserving these wildlife species given that grassland is a key habitat component for rhinoceros, elephants, and the prey species of the tigers (*Chitwan National Park, 2013*; *Aryal et al., 2016*; *DNPWC, 2017*). In addition, elephants are basically browsers and they require a large volume of fodder and plenty of water for drinking (*Pradhan et al., 2008*). On the other hand, rhinoceros require waterholes for wallowing to regulate their body temperature (*Dinerstein, 2003*). Thus, some of the adaptation actions identified for rhinoceros conservation can serve as adaptation actions for other wildlife species and more specific actions can be further developed based on ecological requirements of these wildlife species occurring in this region.

The implementation of the adaptation actions identified in this study is expected to ensure a greater chance of persistence for rhinoceros well into the future. However, there are a number of factors that are likely to hinder the effective implementation of these adaptation actions for rhinoceros conservation in Nepal. For example, expansion of protected areas and maintaining a functional corridor and connectivity are ideal options for rhinoceros conservation, but very limited suitable habitat for rhinoceros outside protected areas minimises the potential for such intervention (*DNPWC, 2018*; *Pant et al., 2020b*; *Pant et al., 2021*). In this regard, restoring and maintaining the habitat components within protected areas and available biological corridor are among the most feasible options for conserving rhinoceros in the face of likely impacts of climate change that would also help in safeguarding other wildlife species in this region against the adverse impacts of changing climate. Thus, best possible efforts should be made in implementing the adaptation actions, acknowledging that the ideal situation may not be possible for managing large mammals in a human-dominated landscape.

In adaptation planning, uncertainty is regarded as a reality given that many sources of uncertainty exist in ecological processes, including the uncertainties in predicting climate change, possible responses of the species to global warming, and consequences of adaptation actions (*Stein et al., 2013*). Our study, therefore, provides only general guidance in aligning the available adaptation options to adaptation planning for rhinoceros conservation in Nepal. Effective adaptation planning needs to be continually adjusted in such a way that even without having thorough clarity about impacts and consequences, some adaptation options could be implemented and assessed. This approach of 'learning while doing' is consistent with adaptive management principles (*Gillson et al., 2019*), based on the premise that complete understanding of natural systems is rarely possible, so it is wise to monitor the responses for learning from diversified management interventions (*Williams & Brown, 2016*). Because of its flexible approach and dynamic nature, adaptive management as a fundamental component of adaptation planning should be implemented with as much experimental rigour as possible (*Abrahms et al., 2017*). We expect that the findings of our study will be utilised by protected area managers to make choices based on current information and to refine management actions following an iterative learning process, and we hope that management authorities invest the necessary resources to undertake proper experimental approaches when implementing management activities for rhinoceros conservation.

Adaptation strategies and actions to climate change for other wildlife species in different geographical areas can be formulated following a similar approach, and our research is particularly relevant for Kaziranga National Park in India, where the condition of the habitat and the issues associated with rhinoceros conservation are similar to Chitwan National Park in Nepal (*DNPWC, 2017*; *Puri & Joshi, 2018*; *Ellis & Talukdar, 2019*). Adaptation planning at the species and ecosystem levels are successfully implemented around the world. For instance, *Alderman & Hobday (2017)* developed a set of 24 climate change adaptation actions for vulnerable seabirds on Albatross Island in Tasmania. Likewise, the climate change strategy and action plan for the Great Barrier Reef National Park has been prepared and implemented (*GBRMP, 2012*). Such climate change adaption strategies and actions for wildlife species have not yet been formulated in Nepal. Our study is the first of its kind in Nepal and is expected to assist a vulnerable species to withstand the likely negative impacts of climate change. We focused on a single species given that the nature and degree of the impacts associated with changing climate are species-specific, even amongst closely related species. For example, two species of rhinoceros were affected differently by climate change in Kruger National Park –while births decreased and mortality increased for white rhinoceros, there were no such impacts on black rhinoceros due to the recent severe drought events (*Ferreira, Roex & Greaver, 2019*).

CONCLUSIONS

This study has identified, shortlisted, selected and ranked a suite of 20 plausible adaptation actions under nine adaptation strategies that are expected to enhance the resilience of rhinoceros to the likely adverse impacts of climate change. Of these, 75% of adaptation actions are already being implemented. However, these actions are implemented in different contexts without explicitly assessing the likely climate change impacts on the species and its habitat. Based on our findings on identifying and prioritising adaptation actions and analysis of the results from vulnerability assessment (*Pant et al., 2020a*), we recommend the following conservation interventions for effective climate change adaptation planning for rhinoceros in Nepal:

a. Protect identified climate refugia for rhinoceros conservation, particularly in western Nepal around Bardia and Shuklaphanta National Parks and further evaluate the habitats that are likely to become suitable for rhinoceros in the future, aiming to prioritise and spatially integrate these climate refugia. The priority should be given to restore biological corridors and maintain landscape connectivity to facilitate natural dispersal of rhinoceros between suitable habitats.

b. Identify areas in floodplain grasslands with the help of comprehensive flood modelling to create elevated refuges for rhinoceros during climate-induced flood episodes. This is particularly relevant for rhinoceros conservation in Chitwan National Park, which is highly susceptible to heavy rainfall and flash flooding.
c. Improve and restore the existing protected areas through active management of grasslands and wetlands including controlled burning, and invasive plant species control. This is particularly important in Chitwan National Park, which is likely to experience more climate-induced habitat alteration.
d. Translocate rescued rhinoceros to other suitable areas in the future. Where rescues are required, serious consideration should be given to releasing rescued rhinoceros into Bardia and Shuklaphanta National Parks rather than bringing them back to Chitwan National Park.
e. Increase the extent of protected areas, by either creating new protected areas or expanding existing ones. Priority should be given to including forest patches in Bara and Rautahat districts to the eastern part of Parsa National Park which is likely to serve as an additional habitat for rhinoceros conservation.
f. Revise the conservation action plan developed for rhinoceros conservation in Nepal, integrating the identified climate change adaptation actions that are expected to reduce the likely vulnerabilities to rhinoceros due to climate change.
g. Initiate experimental research related to aspects of rhinoceros ecology with the best chance of informing future climate change adaptation planning. This is expected to provide better insights on the likely consequences of climate change so it can be utilised in refining adaptation actions in the future following adaptive management principles.

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Author Contributions

- Ganesh Pant conceived and designed the experiments, performed the experiments, analyzed the data, prepared figures and/or tables, authored or reviewed drafts of the paper, and approved the final draft.
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CHAPTER 7: SYNTHESIS AND CONCLUSION

While climate change vulnerability assessment to species and adaptation planning for their conservation is an emerging field of research, the direct impacts of climate change on wildlife species have not been well documented. With the overall objective of advancing the knowledge on the likely climate change vulnerabilities to wildlife species and the possible ways to address such challenges, this study has developed vulnerability indicators, assessed the climate change vulnerabilities, and explored the possible adaptation actions using a case of rhinoceros in Nepal. This Thesis is related to two goals out of 17 UN sustainable development goals (a) Goal 13: Take urgent action to combat climate change and its impacts, and (b) Goal 15: Protect, restore, and promote sustainable use of terrestrial ecosystems, sustainably mange forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss. Therefore, this study is expected to contribute towards ensuring environmental sustainability through strengthening the resilience and adaptive capacity of key wildlife species to climate-related hazards and integrating climate change adaptation measures into conservation planning.

This chapter is a synthesis of the whole Thesis and puts forward some implications for policy and practice in managing wildlife species in the face of climate change, highlights the key research contributions and finally suggests a few important areas for further research.

7.1 Summary

The overarching goal of this Thesis was to assess the climate change vulnerability of the rhinoceros population in Nepal and to explore the possibilities for adaptation planning. There were four specific objectives and their corresponding research questions to address the aim of the research. Each chapter on the findings of the study (Chapter 4 to 6) has collectively fulfilled the objective of the research as a nested chapter. While many conclusions were drawn in each chapter, this section summarises some of the key findings of the research.

Climate change vulnerability indicators: This study illustrated how a set of specific climate change vulnerability indicators can be developed for a particular species in the local context. Likewise, this research emphasised the need for identifying the full range of impacts and their associated mechanisms for effectively appraising the climate change vulnerability of a species. Most of the current methods in assessing the vulnerability of a species focus on evaluating exposure to climatic changes and generally ignore the ecological differences among species. This study not only incorporated sensitivity, exposure, and adaptive capacity in developing vulnerability indicators but also considered non-climatic stressors to identify the full range of pressures faced by rhinoceros due to the impacts of climate change.

Climate change vulnerability score: The vulnerability score in this study suggested that the rhinoceros population in Chitwan is less sensitive to climate change than the Bardia and Shuklaphanta populations. In contrast, the Chitwan population seems to be more exposed than the populations of Bardia and Shuklaphanta. The results also showed that all the populations are likely to be highly vulnerable to the other stressors whereas the adaptive capacity is high for all the populations.

Climate change vulnerability index: Based on the vulnerability index, the potential impact from all components e.g., sensitivity, exposure and other stressors was high, and the resilience of the rhinoceros was also high. Thus, this study indicates that rhinoceros populations in Nepal are likely to face high levels of potential impacts from climatic changes, but their high adaptive capacity may offset these impacts.

Extent of climate change vulnerability: The analyses in chapter four indicated that rhinoceros populations in Nepal are moderately vulnerable to the likely impacts of climate change. While the geographical extent and abundance of the moderately vulnerable species are considered to decrease, this study revealed that the rhinoceros population in Nepal is not at immediate risk of climate-induced extinction.

Key vulnerability factors: This study indicated that the physiology of the rhinoceros may not be directly impacted due to climate change. However, it is likely to affect them indirectly by extreme weather events such as flash floods and severe droughts, the decline in habitat due to climate-induced proliferation of invasive plant species and persistent pressures from the existing stressors such as human-wildlife conflict, poaching, and pollution.

Current suitable habitat: The ensemble model presented in chapter five estimated that 1.77% of the total area of the country is currently suitable for rhinoceros in Nepal. Nearly 80% of the current suitable habitat is inside protected areas (PAs) whereas slightly more than 20% of the remaining suitable habitat lies outside PAs. Chitwan National Park and Koshi Tappu Wildlife Reserve have the highest and the lowest suitable area, respectively.

Predicted decline in suitable habitat: The results of this research on species distribution modelling indicated that the suitable habitat of rhinoceros in Nepal will considerably decrease by the year 2070. The suitable habitat under the highest GHG emission scenario is predicted to decline over 35% and rhinoceros in Nepal is likely to experience a moderate level of vulnerability due to the combined effects of climate and land use changes. The predicted decline in rhinoceros habitat in Nepal seems to be influenced to a greater degree by climatic changes than land use changes.

Climate change adaptation actions: In this study, we have identified a set of 20 possible adaptation actions under nine adaptation strategies, which are anticipated to contribute to enhancing the resilience of rhinoceros to the adverse impacts of climate change. Besides, we have prioritised these adaptation actions following a priority ranking and found that identifying and protecting climate refugia, restoring the existing habitats through wetland and grassland management, creating artificial highlands in floodplains to provide rhinoceros with refuge during severe floods, and translocating them to other suitable habitats are the adaptation actions in the highest priority.

As mentioned a set of 21 climate change vulnerability indicators for rhinoceros in Nepal were developed, the extent of vulnerabilities to rhinoceros in Nepal due to the impacts of climate change was assessed based on these indicators, the decline in suitable rhinoceros habitats due to the combined effects of climate and land use changes by the year 2070 was predicted, and a suite of 20 plausible adaptation actions was identified and prioritised aiming to enhance the resilience of rhinoceros to the likely adverse impacts of climate change, which has been discussed in the relevant chapters of this Thesis.

7.2 Implications for conservation

This research has laid the foundation for adaptation planning for rhinoceros conservation in Nepal through assessing the likely climate change vulnerabilities and identifying and prioritising the adaptation actions. However, these actions should be carefully evaluated considering the site-specific circumstances for effectively integrating these adaptation actions spatially. This section consists of the recommendations on how the findings of this study can be incorporated in policy and practice for managing the rhinoceros population in the context of likely impacts of climate change.

Climate refugia: Based on the findings of this study, identifying and protecting climate refugia received the highest priority as an adaptation action for rhinoceros conservation in Nepal. Climate refugia are the areas that will remain suitable for and enable the persistence of species in the face of climate change over time. In our study, habitat suitability models suggested that most of the climate refugia for rhinoceros in Nepal lies within the protected areas. Thus, effective management of these protected areas through restoration and improvement of grassland and wetland habitats is likely to benefit rhinoceros to withstand the climate change vulnerabilities. In doing so, priority should be given to the areas that have already witnessed climate-induced habitat alterations and the current rhinoceros habitats within protected areas, which are predicted to be unsuitable in near future as indicated by the habitat suitability models.

It is equally important to increase the extent of protected areas to preserve current suitable habitat as well as future climate refugia, given that over 20% of the potential rhinoceros habitat in Nepal lies outside protected areas as suggested by the ensemble model.

Protected areas are considered a core strategy to safeguard biodiversity with climate mitigation and adaptation co-benefits. However, expansion of protected areas as an adaptation action for rhinoceros conservation did not receive higher priority from the stakeholders and the experts in our study. One of the likely reasons behind this would be >23% of the country is already under a protected area system and most of the historical range of the rhinoceros outside protected areas are converted into human settlements or agricultural lands. Thus, the best possible efforts should be made in implementing the identified adaptation actions, acknowledging that the ideal situation may not always be possible for managing large mammals in a human-dominated landscape, as in the case of rhinoceros conservation in Nepal.

Elevated refuge during a climate-induced flood: Rhinoceros being a habitat specialist prefers the floodplain grasslands that are prone to flash flooding. Whilst increased flood events especially during the monsoon season has already threatened the survival of the rhinoceros, extreme weather events such as flash floods are predicted to increase in this region in the future due to global warming. In our study, creating artificial highlands in floodplains to provide rhinoceros with refuge during severe floods has been ranked as one of the top priority adaptation actions. Thus, this research highlighted the need for identifying suitable areas in floodplain grasslands with the help of comprehensive flood modelling to create an elevated refuge for rhinoceros during climate-induced flood episodes. This is particularly important for rhinoceros conservation in and around Chitwan National Park, which is highly susceptible to heavy rainfall and flash flooding.

Suitable rhinoceros habitat: Unlike some other wildlife species, the habitat suitability of rhinoceros is not likely to shift towards the higher altitude, given that our habitat models suggest that rhinoceros habitat suitability is constrained by topographic factors such as elevation and slope. Hence, the rhinoceros appears to be trapped in small patches of suitable habitat at lower elevations. Despite such habitat constraints, the scattered patches of potential rhinoceros habitat outside the protected areas are under constant pressure from fragmentation and conversion into other anthropogenic land use. For instance, a considerable portion of potential rhinoceros habitat will be lost if the Nijgad International Airport is constructed in the currently proposed site. In the given context, rhinoceros in Nepal will have a better chance of persistence if the potential rhinoceros habitat can be safeguarded from further fragmentation and loss through avoiding the potential rhinoceros habitat while selecting sites for development projects. This is probably a valuable insight for adaptation planning for rhinoceros conservation in Nepal, given that the current rhinoceros habitat is less than 2% of the country and nearly 35% of which is likely to be unsuitable by the year 2070 due to the combined effects of climate and land use changes.

Rhinoceros translocation: Another adaptation action prioritised in this research was translocating rhinoceros to other suitable habitats and the habitat suitability model suggested that rhinoceros habitat suitability is likely to increase in Bardia and Shuklaphanta National Parks in the future. Therefore, supplementing the rhinoceros population in these protected areas through the translocation of more rhinoceros from Chitwan National Park would help in securing a viable population of rhinoceros there. While continued translocation of a few rhinoceros to other suitable areas within the protected areas has been recommended, translocation of rhinoceros into the suitable habitats outside the protected areas has not been suggested at this stage. Instead, these areas should be protected as additional habitat for rhinoceros and other wildlife species, so that animals from adjoining protected areas would colonise in future if these areas will be kept free of anthropogenic pressures such as poaching and human-wildlife conflict.

Additional rhinoceros habitat: In this study, we also identified a potential habitat patches for rhinoceros in Koshi Tappu Wildlife Reserve. The Government of Nepal has considered this protected area in the eastern part of the country as an additional site for rhinoceros conservation. However, the suitable habitat patches as predicted by our model is not likely to support a viable population of rhinoceros in and around this reserve. Keeping this in view, this study is anticipated to provide guidance for further assessment of rhinoceros habitat suitability in this area and to prioritising the available rhinoceros habitat in the country.

This study has provided insights for policymakers and protected area managers for developing policy and plans to integrate the climate change adaptation actions into rhinoceros conservation planning and to allocate scarce resources to the prioritised actions. Thus, the findings of this research have implications for both policy and practice regarding rhinoceros conservation in the face of changes arising from climatic and land use changes as discussed above. Besides, the adaptation actions developed for rhinoceros conservation is likely to benefit other species sharing the ecosystem, given that rhinoceroses are umbrella species and their conservation requirements encompass the habitat components required for many other species. This study is the first of its kind in Nepal, to our knowledge, which is expected to be instrumental for initiating adaptation planning not only for rhinoceros conservation but also for other key wildlife species that are vulnerable to the likely impacts of climate change.

7.3 Contributions of the research

The primary aim of the study was to assess the climate change vulnerability and explore the possible adaptation actions for rhinoceros conservation. The key strength of this research is its extensiveness, given that it has considered a wide range of pressures while developing indicators for assessing the climate change vulnerability. This research contributes new knowledge in climate change vulnerability assessment and adaptation planning for wildlife species as follows.

- This research has illustrated how a comprehensive set of vulnerability indicators for a species can be developed to incorporate the full range of impacts. This is a valuable contribution in this field, given that most of the climate change vulnerability assessments for species have largely neglected the indirect impacts associated with anthropogenic factors and their interactions.
- This study has demonstrated how multiple approaches of climate change vulnerability assessment can be integrated to better inform the likely vulnerability of species to climate change. This approach has contributed to minimising the uncertainty of the results in two stages: (i) enhancing the model predictive performance through ensemble approach, and (ii) combining trait-based and correlative approaches for more reliable results.
- Another valuable contribution of this study is academic knowledge on likely vulnerability and adaptation planning of a mammalian species in one of the least developed countries, given that research on climate change vulnerability assessment is biased towards plant species in developed countries including North America, Europe, and Australia.
- This study has not only identified and prioritised the adaptation actions for rhinoceros conservation in Nepal but has also provided

insights on how these actions can be spatially integrated. Thus, this research provides a basis for initiating adaptation planning for rhinoceros conservation in the face of likely impacts of climate change.

- This study also contributes to ecosystem-based adaptation given that it has explored the possible ways of reducing climate change vulnerabilities to an iconic wildlife species. Thus, it is important in managing biodiversity in the context of changing climate, which forms an integral part of ecosystem-based adaptation.
- This research is equally important for other wildlife in different geographical areas, given that adaptation strategies and actions can be formulated following a similar approach, and this research is particularly relevant for Kaziranga National Park in India, where the habitat condition and the issues associated with rhinoceros conservation are similar to Chitwan National Park in Nepal.

7.4 Limitations of the study and further research

In this study, we endeavoured to scan the horizon for planning rhinoceros conservation in the face of climate change, which provides a perspective on the likely consequences of climate change on rhinoceros. Besides, it portrays a broader picture of where rhinoceros are likely to persist in the future considering the likely impacts associated with climate and land use changes. However, there are certain caveats associated with this study due to the inherent uncertainty of the climate models, and other sources of uncertainty exist in ecological processes, possible responses of the species to global warming and the consequences of the adaptation actions. To overcome the above-stated shortcomings, we have recommended the following research, which is likely to provide better insights on rhinoceros ecology in relation to the likely impacts of climate change, so that adaptation actions can be refined in the future following adaptive management principles.

a. Conduct empirical research on rhinoceroses and their habitat dynamics, predominantly in the context of the ecological mechanisms that are likely to influence the decline in current suitable habitat. The likely impacts of changing temperature and rainfall on grasslands and wetlands and the land use changes seem apparent, but we were unable to confidently identify other mechanisms with our models. We, therefore, recommend initiating experimental on-ground research and the generation of finer resolution ecological data for further analysis of the habitat suitability to better elucidate these mechanisms and inform adaptive management of rhinoceroses and their habitat.

b. Initiate habitat monitoring and experimental research related to aspects of rhinoceros ecology with the best chance of informing future climate change adaptation planning. This is particularly important, given that we have very limited information on the direct impacts of climate change on rhinoceroses and their habitat such as likely changes in water quality, the emergence of diseases and the health condition and physiology of rhinoceros itself.

c. Evaluate the effectiveness of the biological corridor in western Terai for the movement of rhinoceros between protected areas. Previous studies have suggested that the forest corridor in this region is important for rhinoceros conservation as it connects four rhinoceros-bearing protected areas in a transboundary landscape shared by India and Nepal that collectively support metapopulation management of at least 70 rhinoceros. However, the ensemble model in our study did not show adequate habitat patches that support the dispersal of rhinoceros between the suitable habitats in this transboundary landscape.

d. Identify suitable sites in alluvial grasslands preparing a comprehensive flood model to construct the elevated shelters for rhinoceros during the event of climate-induced flood episode. This research is especially relevant for the conservation of rhinoceros in Chitwan National Park, which is likely to be more susceptible in future due to intense rainfall and flash flooding exacerbated by climate change.

e. Initiate the monitoring program in relation to the response of rhinoceros to adaptation actions. For example, the construction of artificial highlands in floodplain grasslands to provide safe refuge for rhinoceros during severe flood episodes is recommended as a priority adaptation action. However, the likely response of rhinoceros and other wildlife in utilising such structures and the ability of such elevated grounds to provide safe refuge for these wildlife species is not understood. Thus, this is one of the important aspects of further research.

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APPENDICES

Appendix A: Supplementary materials for Chapter 3 (Review article)

Table A1 – Trends in population of greater one-horned rhinoceros in protected areas of India and Nepal between 1985 and 2015

SN	Protected Areas	Area (km²)	Year of Designation	Rhinoceros population size						
				1985	**1990**	**1995**	**2000**	**2005**	**2010**	**2015**
1	Kaziranga National Park	430	1908	1,080	1,129	1,200	1,552	1,855	2,048	2,401
2	Katerniaghat Wildlife Sanctuary	400	1975	4	4	4	2	2	2	2
3	Jaldapara National Park	217	1941	14	27	35	55	96	126	200
4	Gorumara National Park	80	1949	8	12	18	19	22	35	50
5	Pobitora Wildlife Sanctuary	39	1987	40	54	68	74	81	84	92
6	Orang National Park	79	1985	65	97	90	46	68	64	100
7	Manas National Park	500	1928	75	85	4	3	3	19	32
8	Dudhwa National Park	490	1977	7	10	13	16	21	29	32
India sub-total				***1,293***	***1,418***	***1,432***	***1,767***	***2,148***	***2,407***	***2,909***
9	Chitwan National Park	952	1973	310	358	466	544	372	408	605
10	Bardia National Park	968	1976	0	0	0	63	30	22	29
11	Suklaphanta National Park	305	1976	0	0	0	5	7	5	8
12	Parsa National Park	627	1984	0	0	0	0	0	0	3
Nepal sub-total				***310***	***358***	***466***	***612***	***409***	***435***	***645***
TOTAL				**1,603**	**1,776**	**1,898**	**2,379**	**2,557**	**2,842**	**3,554**

Table A2 – Details of the articles review

Wild: Nepal (1), India (2), Both countries (3), Not applicable (0); ***Captive***: Nepal (1), India (2), Other countries (3), Not applicable (0). ***Thematic areas***: Biology (I), Habitat (II), Genetics (III), Impact on species (IV), Population (V), Capture and handling (VI), Poaching (VII), Conflict (VIII), Disease (IX), Climate change (X) and Primary theme of the article (1), Secondary theme of the article (2). ***Source of the article***: Web of Science (WoS), Scopus (S) and Google Scholar (Google Scholar). ***Research type***: Primary (1) – Experimental, field-based, lab-based, primary data, and Secondary (2) – Analysis of secondary data or literature. ***Research duration***: One to six months (1), Seven months to one year (2), One year to two years (3), Two years to three years (4), or More than three years (5).

SN	First Author	Country of first author	Year	Journal	Title	Wild	Captive	Thematic area										Source	Citation	Type	Duration
								I	II	III	IV	V	VI	VII	VIII	IX	X				
1	O'Connor, L	United Kingdom	2018	Journal of Zoo and Wildlife Medicine	A survey of gastrointestinal parasites of wild and orphan Greater One-horned Rhino (*Rhinoceros unicornis*) in Kaziranga National Park, Assam, India	2	0	2	0	0	0	0	0	0	0	1	0	WoS, S, GS	2	1	1
2	Wojtusik, J	United States	2018	Theriogenology	Comparison of soy lecithin, coconut water, and coconut milk as substitutes for egg-yolk in semen cryodiluent for black rhinoceros (*Diceros bicornis*) and Indian rhinoceros (*Rhinoceros unicornis*)	0	3	1	0	0	0	0	0	0	0	0	0	WoS, S, GS	1	1	1
3	Gimmel, A	Switzerland	2018	Journal of Zoo and Wildlife Medicine	Milk composition of Indian Rhinoceros (*Rhinoceros unicornis*) and change over lactation	0	3	1	0	0	0	0	0	0	0	0	0	WoS, S, GS	0	1	1
4	Gross, EM	Germany	2018	Biodiversity Conservation	Seasonality, crop type and crop phenology influence crop damage by wildlife herbivores in Africa and Asia	3	0	0	0	0	0	0	0	0	1	0	0	WoS, S, GS	9	1	5
5	Hermes, R	Germany	2018	Plos One	Cryopreservation in rhinoceros—setting a new benchmark for sperm cryosurvival	0	3	1	0	0	0	0	0	0	0	0	0	S, GS	3	1	1
6	Roth, TL	United States	2018	Theriogenology	Monitoring and controlling ovarian function in the rhinoceros	0	3	1	0	0	0	0	0	0	0	0	0	WoS, GS	4	2	1

SN	First Author	Country of first author	Year	Journal	Title	Wild	Captive	Thematic area										Source	Citation	Type	Duration
								I	II	III	IV	V	VI	VII	VIII	IX	X				
7	Stoops, MA	United States	2018	Molecular Reproduction and Development	Early fetal sexing in the rhinoceros by detection of male-specific genes in maternal serum	0	3	2	0	1	0	0	0	0	0	0	0	WoS, S, GS	4	1	1
8	Filoux, A	Thailand	2018	Geobios	A late Pleistocene skeleton of *Rhinoceros unicornis* (Mammalia, Rhinocerotidae) from western part of Thailand (Kanchanaburi Province)	0	0	1	2	0	2	0	0	0	0	0	0	WoS, S, GS	0	1	1
9	Udelsman, R	United States	2018	World Journal of Surgery	Parathyroid, Thyroid and Recurrent Laryngeal Nerve Anatomy in an Indian Rhinoceros (*Rhinoceros unicornis*)	0	3	1	0	0	0	0	0	0	0	0	0	WoS, S, GS	1	1	1
10	Puri, K	India	2018	Nebio	A case study of Greater One Horned Rhinoceros (*Rhinoceros unicornis*) in Kaziranga National Park of Assam, India	2	0	0	1	0	0	0	0	1	0	0	0	GS	0	2	1
11	Dutta, DK	India	2018	The Indian Forester	Studies on Greater one Horned Rhinoceros Behaviour and Ecology with Special References to Wild to Wild Translocated Rhinoceros: A Review	3	0	1	0	0	0	0	0	0	0	0	0	GS	0	2	1
12	Rimal, S	Nepal	2018	Journal of Threatened Taxa	Habitat suitability and threat analysis of Greater One-horned Rhinoceros *Rhinoceros unicornis Linnaeus*, 1758 (Mammalia: Perissodactyla: Rhinocerotidae) in Rautahat District, Nepal	1	0	0	1	0	2	0	0	2	0	0	0	S, GS	1	1	1
13	Mahatara, D	Nepal	2018	Banko Jankari	Impact of anti-poaching approaches for the success of Rhino Conservation in Chitwan National Park, Nepal	1	0	0	0	0	0	0	0	1	0	0	0	GS	0	2	1
14	Lamichhane, BR	Nepal	2018	Plos One	Spatio-temporal patterns of attacks on human and economic losses from wildlife in Chitwan National Park, Nepal	1	0	0	0	0	0	0	0	0	1	0	0	GS	9	1	1
15	Subedi, N	Nepal	2017	Global Ecology and Conservation	Demography and viability of the largest population of greater one-horned rhinoceros in Nepal	1	0	0	0	0	0	1	0	2	0	0	0	WoS, S, GS	1	1	2

SN	First Author	Country of first author	Year	Journal	Title	Wild	Captive	Thematic area										Source	Citation	Type	Duration
								I	II	III	IV	V	VI	VII	VIII	IX	X				
16	Bouts, T	Belgium	2017	Journal of Zoo and Wildlife Medicine	Detomidine and butorphanol for standing sedation in a range of zoo-kept ungulate species	0	3	0	0	0	0	0	1	0	0	0	0	S, GS	0	1	1
17	Basumatary, SK	India	2017	Review of Palaeobotany and Palynology	Pollen and non-pollen palynomorph preservation in the dung of the Greater One-horned Rhino (*Rhinoceros unicornis*), and its implication to palaeoecology and palaeodietary analysis: A case study from India	2	0	1	0	0	0	0	0	0	0	0	0	WoS, S, GS	5	1	1
18	Acharya, KP	Nepal	2017	Ecological Indicators	Can forest fragmentation and configuration work as indicators of human-wildlife conflict? Evidences from human death and injury by wildlife attacks in Nepal	1	0	0	2	0	0	0	0	0	1	0	0	WoS, S, GS	9	2	1
19	Miller, M	South Africa	2017	Transboundary and Emerging Diseases	Tuberculosis in Rhinoceros: An Underrecognized Threat?	0	3	0	0	0	0	0	0	0	0	1	0	S, GS	14	1	1
20	Samera, O	Germany	2017	International Journal of Systematic and Evolutionary Microbiology	*Arcanobacterium wilhelmae sp nov*., isolated from the genital tract of a rhinoceros (*Rhinoceros unicornis)*	0	3	1	0	0	0	0	0	0	0	0	0	WoS, S, GS	3	1	1
21	Basumatary, SK	India	2017	Quaternary Research	Coprophilous fungi from dung of the Greater One-Horned Rhino in Kaziranga National Park, India and its implication to paleoherbivory and paleoecology	2	0	0	0	0	0	0	0	0	0	1	0	WoS, S, GS	8	1	1
22	Pluhacek, J	Czech Republic	2017	Current Zoology	Interbirth intervals are associated with age of the mother, but not with infant mortality in Indian rhinoceroses	2	3	1	0	0	0	0	0	0	0	0	0	WoS, S, GS	1	2	1

SN	First Author	Country of first author	Year	Journal	Title	Wild	Captive	Thematic area										Source	Citation	Type	Duration
								I	II	III	IV	V	VI	VII	VIII	IX	X				
23	Chen, X	China	2017	International Journal of General and Molecular Microbiology	*Enterovirga rhinocerotis gen. nov., sp nov*., isolated from *Rhinoceros unicornis* faeces	0	3	1	0	0	0	0	0	0	0	0	0	WoS, S, GS	2	1	1
24	Silwal, T	Nepal	2017	Oryx	When, where and whom: assessing wildlife attacks on people in Chitwan National Park, Nepal	1	0	0	0	0	0	0	0	0	1	0	0	WoS, S, GS	10	2	1
25	Aryal, A	Nepal	2017	Conservation Biology	Global lessons from successful rhinoceros conservation in Nepal	1	0	0	0	0	0	0	0	1	0	0	0	GS	18	2	1
26	Dutta, DK	India	2017	Pachyderm	Behavior of post released translocated greater one-horned rhinoceros (*Rhinoceros unicornis*) at Manas National Park, Assam, India	2	0	1	0	0	0	0	0	0	0	0	0	S, GS	2	1	2
27	Choudhury, MR	India	2016	Ecological Engineering	Predicting the probable distribution and threat of invasive *Mimosa diplotricha Suavalle* and *Mikania micrantha Kunth* in a protected tropical grassland	2	0	0	1	0	0	0	0	0	0	0	0	WoS, S, GS	23	1	2
28	Dutta, DK	India	2016	Journal of Threatened Taxa	Seasonal variations in food plant preferences of reintroduced Rhinos *Rhinoceros unicornis* (Mammalia: Perrissodactyla: Rhinocerotidae) in Manas National Park, Assam, India	2	0	1	0	0	0	0	0	0	0	0	0	S, GS	2	1	5
29	Acharya, KP	Nepal	2016	Plos One	Human-Wildlife Conflicts in Nepal: Patterns of Human Fatalities and Injuries Caused by Large Mammals	1	0	0	0	0	0	0	0	0	1	0	0	WoS, S, GS	51	2	1
30	Heidegger, EM	Switzerland	2016	Zoo Biology	Body condition scoring system for greater one-horned rhino (*Rhinoceros unicornis):* Development and application	0	3	1	0	0	0	0	0	0	0	0	0	WoS, S, GS	3	1	1
31	Stoops, MA	United States	2016	Animal Reproduction Science	Enhancing captive Indian rhinoceros genetics via artificial insemination of cryopreserved sperm	0	3	2	0	1	0	0	0	0	0	0	0	WoS, S, GS	10	1	1

SN	First Author	Country of first author	Year	Journal	Title	Wild	Captive	Thematic area										Source	Citation	Type	Duration
								I	II	III	IV	V	VI	VII	VIII	IX	X				
32	Hermes, R	Germany	2016	Plos One	Ovarian down Regulation by GnRF Vaccination Decreases Reproductive Tract Tumour Size in Female White and Greater One-Horned Rhinoceroses	0	3	1	0	0	0	0	0	0	0	0	0	WoS, S, GS	5	1	1
33	Cedric, G	France	2016	Ecological Indicators	Assessing and managing the rising rhino population in Kaziranga (India)	2	0	0	0	0	0	1	0	0	0	0	0	WoS, S, GS	0	2	1
34	Borthakur, U	India	2016	Oryx	Noninvasive genetic census of greater one-horned rhinoceros *Rhinoceros unicornis* in Gorumara National Park, India: a pilot study for population estimation	2	0	0	0	1	0	1	0	0	0	0	0	WoS, S, GS	1	1	1
35	Dutta, DK	India	2016	Pachyderm	Behaviour of post released translocated greater one-horned rhinoceros (*Rhinoceros unicornis*) at Manas National Park, Assam, India	2	0	1	0	0	0	0	0	0	0	0	0	WoS, GS	2	1	2
36	Roth, TL	United States	2016	Animal Reproduction Science	Factors impacting the success of post-mortem sperm rescue in the rhinoceros	0	3	1	0	0	0	0	0	0	0	0	0	WoS, S, GS	7	1	1
37	Li, G	China	2016	International Journal of Systematic and Evolutionary Microbiology	*Tessaracoccus rhinocerotis sp nov*., isolated from the faeces of *Rhinoceros unicornis*	0	3	1	0	0	0	0	0	0	0	0	0	WoS, S, GS	8	1	1
38	Thapa, J	Nepal	2016	Emerging Infectious Diseases	Mycobacterium orygis–Associated Tuberculosis in Free-Ranging Rhinoceros, Nepal, 2015	1	0	0	0	0	0	0	0	0	0	1	0	WoS, GS	10	1	1
39	Thapa, R	Nepal	2016	International Journal of Applied and Natural Sciences	Poaching Statistics of *Rhinoceros unicornis* in Chitwan National Park: A Review	1	0	0	0	0	0	0	0	1	0	0	0	GS	1	2	1

SN	First Author	Country of first author	Year	Journal	Title	Wild	Captive	Thematic area										Source	Citation	Type	Duration
								I	II	III	IV	V	VI	VII	VIII	IX	X				
40	Kundu, S	India	2016	Pachyderm	Possible sighting of a twin Greater one-horned Rhinoceros (*Rhinoceros unicorns*) in Jaldapara National Park, India	2	0	1	0	0	0	2	0	0	0	0	0	GS	0	1	1
41	Houwald, F Von	Switzerland	2016	International Zoo Yearbook	Causes and prevention of foot problems in Greater one-horned rhinoceros *Rhinoceros unicornis* in zoological institutions	0	3	0	0	0	0	0	0	0	0	1	0	S, GS	2	1	1
42	Houwald, F Von	Switzerland	2016	International Zoo Yearbook	Husbandry, management and breeding of the Greater one-horned rhinoceros *Rhinoceros unicornis* at Zoo Basel	0	3	1	0	0	0	0	0	0	0	0	0	S, GS	1	1	1
43	Zhigang, J	China	2016	Biodiversity Science	Where are the suitable introduction sites of greater one-horned rhinoceros *Rhinoceros unicornis* in China?	0	0	0	1	0	0	0	0	0	0	0	0	GS	0	2	1
44	Zschokke, S	Switzerland	2016	Indian Journal of History of Science	Genetic structure of the wild populations of the Indian rhinoceros (*Rhinoceros unicornis)*	2	0	2	0	1	0	0	0	0	0	0	0	GS	0	2	2
45	Kafley, H	Nepal	2015	Zoology and Ecology	Analysis of rhino (*Rhinoceros unicornis*) population viability in Nepal: impact assessment of antipoaching and translocation strategies	1	0	0	0	0	0	0	0	1	0	0	0	S, GS	3	2	1
46	Das, PK	India	2015	European Journal of Wildlife Research	Population genetic assessment of extant populations of greater one-horned rhinoceros (*Rhinoceros unicornis*) in India	2	0	2	0	1	0	0	0	0	0	0	0	WoS, S, GS	4	1	1
47	Li, G	China	2015	International Journal of General and Molecular Microbiology	*Sphingobacterium rhinocerotis sp nov*., isolated from the faeces of *Rhinoceros unicornis*	0	3	1	0	0	0	0	0	0	0	0	0	WoS, S, GS	2	1	1

SN	First Author	Country of first author	Year	Journal	Title	Wild	Captive	Thematic area										Source	Citation	Type	Duration
								I	II	III	IV	V	VI	VII	VIII	IX	X				
48	Deka, RJ	India	2015	Indian Journal of Animal Research	Studies on feeding behaviour and daily activities of *Rhinoceros unicornis* in natural and captive condition of Assam	2	2	1	0	0	0	0	0	0	0	0	0	WoS, S, GS	0	1	1
49	Li, X	China	2015	Ecography	Human impact and climate cooling caused range contraction of large mammals in China over the past two millennia	0	0	0	0	0	1	0	0	0	0	0	1	WoS, S, GS	24	2	1
50	Grigson, C	United Kingdom	2015	Archives of Natural History	New information on Indian rhinoceroses (*Rhinoceros unicornis*) in Britain in the mid-eighteenth century	0	3	1	0	0	0	0	0	0	0	0	0	WoS, S, GS	1	1	1
51	Dutta, DK	India	2015	Journal of Threatened Taxa	A study on the behavior and colonization of translocated Greater One-horned Rhinos Rhinoceros unicornis (Mammalia: Perissodactyla: Rhinocerotidae) during 90 days	2	0	1	0	0	0	0	0	0	0	0	0	GS	0	1	1
52	Ojah, S	India	2015	The Clarion-International Multidisciplinary Journal	Habitat suitability of Laokhowa Burhachapori wildlife sanctuary complex of Assam, India for *Rhinoceros unicornis* Linn.	2	0	0	1	0	0	0	0	0	0	0	0	GS	1	1	2
53	Bapodra, P	United States	2014	Journal of Zoo and Wildlife Medicine	Baseline assessment of opthalmic parameters in the Greater One-horned Rhinoceros (*Rhinoceros unicornis*)	0	2	1	0	0	0	0	0	0	0	0	0	WoS, S, GS	3	1	1
54	Bapodra, P	United States	2014	Zoo Biology	Evaluation of Season-Related Dietary Changes on the Serum Profiles of Fat-Soluble Vitamins, Mineral, Fatty Acids, and Lipids in the Captive Greater One-Horned Rhinoceros (*Rhinoceros unicornis*)	0	2	1	0	0	0	0	0	0	0	0	0	WoS, S, GS	0	1	2
55	Lopes, AA	United States	2014	Ecological Economics	Civil unrest and the poaching of rhinos in the Kaziranga National Park, India	2	0	0	0	0	0	0	0	1	0	0	0	WoS, S, GS	15	2	1

SN	First Author	Country of first author	Year	Journal	Title	Wild	Captive	Thematic area										Source	Citation	Type	Duration
								I	II	III	IV	V	VI	VII	VIII	IX	X				
56	Hermes, R	Germany	2014	Plos One	Reproductive Tract Tumours: The Scourge of Woman Reproduction Ails Indian Rhinoceroses	0	3	0	0	0	0	0	0	0	0	1	0	WoS, S, GS	18	1	1
57	Bapodra, P	United States	2014	Journal of Zoo and Wildlife Medicine	Comparison of Butorphanol-Detomidine versus Butorphanol-Azaperone for the standing sedation of captive Greater One-horned Rhinoceros *(Rhinoceros unicornis)*	0	3	0	0	0	0	0	1	0	0	0	0	WoS, S, GS	6	1	1
58	Stoops, MA	United States	2014	Zoo Biology	Use of urinary biomarkers of ovarian function and altrenogest supplementation to enhance captive breeding success in the Indian rhinoceros (*Rhinoceros unicornis*)	0	3	1	0	0	0	0	0	0	0	0	0	WoS, S, GS	8	1	1
59	Capiro, JM	United States	2014	Zoo Biology	Effects of management strategies on glucocorticoids and behavior in Indian rhinoceros (Rhinoceros unicornis): Translocation and operant conditioning	0	3	1	0	0	0	0	0	0	0	0	0	WoS, S, GS	14	1	1
60	Devkota, R	Nepal	2014	Journal of Helminthology	Sharing schistosomes: the elephant schistosome *Bivitellobilharzia nairi* also infects the greater one-horned rhinoceros (*Rhinoceros unicornis*) in Chitwan National Park, Nepal	1	0	0	0	0	0	0	0	0	0	1	0	WoS, S, GS	15	1	1
61	Barman, R	India	2014	Pachyderm	Rehabilitation of greater one-horned rhinoceros calves in Manas National Park, a World Heritage Site in India	2	0	0	0	0	0	0	0	0	0	0	0	WoS, S, GS	5	1	2
62	Thakur, S	Nepal	2014	International Journal of Applied Sciences and Biotechnology	Nutrient Analysis of Grass Species Consumed by Greater One-Horned Rhinoceros (*Rhinoceros Unicornis*) in Chitwan National Park, Nepal	1	0	1	0	0	0	0	0	0	0	0	0	GS	2	1	1
63	Taylor, LA	United Kingdom	2014	Contributions to Zoology	Tooth wear in captive rhinoceroses (*Diceros, Rhinoceros, Ceratotherium*: Perissodactyla) differs from that of free-ranging conspecifics	0	3	1	0	0	0	0	0	0	0	0	0	WoS, S, GS	12	1	1

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								I	II	III	IV	V	VI	VII	VIII	IX	X				
64	Medhi, A	India	2014	Climate change and biodiversity	Land Cover Change and Rhino Habitat Mapping of Kaziranga National Park, Assam	2	0	0	1	0	0	0	0	0	0	0	0	GS	3	2	1
65	Thapa, V	Nepal	2014	Journal of Threatened Taxa	An analysis of the habitat of the Greater One-horned Rhinoceros *Rhinoceros unicornis* (Mammalia: Perissodactyla: Rhinocerotidae) at the Chitwan National Park, Nepal	1	0	0	1	0	0	0	0	0	0	0	0	GS	2	2	1
66	Taylor, LA	United Kingdom	2013	Plos One	Detecting Inter-Cusp and Inter-Tooth Wear Patterns in Rhinocerotids	0	3	1	0	0	0	0	0	0	0	0	0	WoS, S, GS	18	1	1
67	Regnault, Sophie	United Kingdom	2013	Journal of Zoo and Wildlife Medicine	Osteopathology in the feet of Rhinoceroses: Lesipon type and distribution	0	3	2	0	0	0	0	0	0	0	1	0	WoS, S, GS	11	1	1
68	Menargues, A	Spain	2013	Animal Welfare	Seasonal pattern of salivary cortisol secretion in the greater one-horned rhino (*Rhinoceros unicornis*)	0	3	1	0	0	0	0	0	0	0	0	0	WoS, S, GS	3	1	2
69	Galateanu, G	Germany	2013	Plos One	One Small Step for Rhinos, One Giant Leap for Wildlife Management- Imaging Diagnosis of Bone Pathology in Distal Limb	0	3	0	0	0	0	0	0	0	0	1	0	WoS, S, GS	10	1	1
70	Talukdar, BK	India	2013	Pachyderm	Challenges and opportunities of transboundary rhino conservation in India and Nepal	3	0	0	1	0	0	0	0	1	0	0	0	WoS, S, GS	8	2	1
71	Subedi, N	Nepal	2013	Oryx	Population status, structure and distribution of the greater one-horned rhinoceros *Rhinoceros unicornis* in Nepal	1	0	0	1	0	0	1	0	0	0	0	0	WoS, S, GS	29	1	2
72	Thapa, K	Nepal	2013	Oryx	Past, present and future conservation of the greater one-horned rhinoceros *Rhinoceros unicornis* in Nepal	1	0	0	0	0	0	1	0	0	0	0	0	S, GS	23	2	1
73	Murphy, ST	United Kingdom	2013	Oryx	Invasive mikania in Chitwan National Park, Nepal: the threat to the greater one-horned rhinoceros *Rhinoceros unicornis* and factors driving the invasion	1	0	0	1	0	0	0	0	0	0	0	0	WoS, S, GS	28	2	1

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74	Martin, E	Kenya	2013	Oryx	Successful reduction in rhino poaching in Nepal	1	0	0	0	0	0	0	0	1	0	0	0	GS	11	2	1
75	Williams, NL	United Kingdom	2013	Oryx	Fate riding on their horns and genes	1	0	2	0	0	0	0	0	1	0	0	0	GS	5	2	1
76	Tripathi, AK	India	2013	International Journal of Pharmacology and Life Sciences	Social and Reproductive Behaviour of Great Indian One-horned Rhino, *Rhinoceros unicornis* in Dudhwa National Park, U.P., India	2	0	1	0	0	0	0	0	0	0	0	0	GS	1	1	2
77	Ghosh, SK	India	2013	Journal of Environment and Socio-biology	Development of species specific DNA marker as barcode sequence of greater Indian rhinoceros (*Rhinoceros unicornis*) from Northeast India	0	2	0	0	1	0	0	0	0	0	0	0	GS	1	1	2
78	Deka, RJ	India	2013	Indian Journal of Animal Production and Management	Grazing habits of one horned rhinoceros (*Rhinoceros unicornis*) in Pobitora Wildlife Sanctuary of Assam.	2	0	1	0	0	0	0	0	0	0	0	0	GS	0	1	2
79	Bhattacharya, A	India	2013	International Journal of Science and Research	Study on group size and group composition of great indian one horned rhinoceros (*R. unicornis, Linn.*) at Gorumara, Jaldapara and Kaziranga National Parks, India	2	0	1	0	0	0	0	0	0	0	0	0	GS	0	1	2
80	Regnault, S	United Kingdom	2013	Journal of Zoo and Wildlife Medicine	Osteopathology in the feet of rhinoceroses: lesion type and distribution	0	3	1	0	0	0	0	0	0	0	0	0	S, GS	11	1	1
81	Pal, P	India	2013	Indian Journal of Ecology	Rhino fate in trouble: Study on conservation and management issues of Kaziranga National Park, Assam	2	0	0	1	0	1	0	0	0	0	0	0	S	0	2	1
82	Sarma, PK	India	2012	Pachyderm	Assessment of habitat utilization pattern of rhinos (*Rhinoceros unicornis*) in Orang National Park, Assam, India	2	0	0	1	0	0	0	0	0	0	0	0	WoS, S, GS	6	1	1

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								I	II	III	IV	V	VI	VII	VIII	IX	X				
83	Hazarika, BC	India	2012	International Scholary Research Network	Food Habit and Feeding Patterns of Great Indian One-Horned Rhinoceros (*Rhinoceros unicornis*) in Rajiv Gandhi Orang National Park, Assam, India	2	0	1	0	0	0	0	0	0	0	0	0	GS	6	1	4
84	Martin, E	Kenya	2012	Pachyderm	Successful rhino conservation continues in West Bengal, India	2	0	0	0	0	0	1	0	0	0	0	0	GS	8	2	1
85	Tripathi, AK	India	2012	International Journal of Pharmacology and Life Sciences	Habitat and population ecology of *Rhinoceros unicornis* in Dudhwa National Park, Uttar Pradesh	2	0	0	1	0	0	1	0	0	0	0	0	GS	3	1	2
86	Dutta, DK	India	2012	Journal of Natural Sciences Research	How many locations do we need per day to reliably describe the habitat use of translocated rhinos in Manas NP?	2	0	0	1	0	0	0	0	0	0	0	0	GS	1	1	4
87	Zschokke, S	Switzerland	2011	Biological Conservation	Genetic differences between the two remaining wild populations of the endangered Indian rhinoceros (*Rhinoceros unicornis*)	3	1,2	2	0	1	0	0	0	0	0	0	0	WoS, S, GS	18	1	5
88	Schaftenaar, W	Netherland	2011	Reproduction in Domestic Animals	Dystocia and Fetotomy Associated with Cerebral Aplasia in a Greater One-horned Rhinoceros (*Rhinoceros unicornis*)	0	3	0	0	0	0	0	0	0	0	1	0	WoS, S, GS	3	1	1
89	Lahkar, BP	India	2011	Pachyderm	Invasive species in grassland habitat: an ecological threat to the greater one-horned rhino (*Rhinoceros unicornis*)	3	0	0	1	0	0	0	0	0	0	0	0	WoS, S, GS	21	2	1
90	Bhatta, R	India	2011	Nebio	Determining Population size and Demography of Great Indian One-horned Rhino-*Rhinoceros unicornis* in Pobitora Wildlife Sanctuary, Assam India	1	0	0	0	0	0	1	0	0	0	0	0	GS	0	1	3
91	Sarma, PK	India	2011	ISRN Ecology	Evaluation of Habitat Suitability for Rhino (*Rhinoceros unicornis*) in Orang National Park Using Geo-Spatial Tools	2	0	0	1	0	0	0	0	0	0	0	0	GS	6	1	3

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92	Sinha, SK	India	2011	Current Science	Nature-assisted re-establishment of Greater one-horned rhinoceros, *Rhinoceros unicornis* in its historical distribution range	2	0	0	0	0	0	1	0	0	0	0	0	S, GS	1	2	1
93	Sarmah, PC	India	2011	Journal of Veterinary Parasitology	A note on the occurrence of *Strongylus muller*, 1780 in a free ranging one horned rhino (*Rhinoceros unicornis*) from Kaziranga National Park, Assam, India	2	0	0	0	0	0	0	0	0	0	1	0	S, GS	0	1	1
94	Roth, TL	United States	2010	Theriogenology	Alkaline phosphatase as an indicator of true ejaculation in the rhinoceros	0	3	1	0	0	0	0	0	0	0	0	0	WoS, S, GS	5	1	1
95	Felger, EA	United States	2010	World Journal of Surgery	The Death of an Indian Rhinoceros	0	3	0	0	0	0	0	0	0	0	1	0	WoS, S, GS	7	1	1
96	Stoops, MA	United States	2010	Theriogenology	Semen cryopreservation in the Indian rhinoceros (Rhinoceros unicornis)	0	3	1	0	0	0	0	0	0	0	0	0	WoS, S, GS	34	1	1
97	Wack, AN	United States	2010	Journal of Zoo and Wildlife Medicine	Melanocytic Neoplasms in a black rhinoceros (Diceros bicornis) and an Indian rhinoceros (Rhinoceros unicornis)	0	3	1	0	0	0	0	0	0	0	0	0	WoS, S, GS	8	1	1
98	Martin, E	Kenya	2010	Pachyderm	Enhanced community support reduces rhino poaching in Nepal	1	0	0	0	0	2	0	0	1	0	0	0	GS	18	2	1
99	Hazarika, BC	India	2010	Nebio	A study on the behaviour of Great Indian One-horned Rhino (*Rhinoceros unicornis Linn.*) in the Rajiv Gandhi Orang National Park, Assam, India	2	0	1	0	0	0	0	0	0	0	0	0	GS	10	1	3
100	Endo, H	Japan	2009	Mammal Study	The morphological basis of the armor-like folded skin of the greater Indian rhinoceros as a thermoregulator	0	3	1	0	0	0	0	0	0	0	0	0	WoS, S, GS	4	1	1
101	Poudyal, M	Nepal	2009	Ecological Applications	Ecological and economic analysis of poaching of the greater one-horned rhinoceros (*Rhinoceros unicornis*) in Nepal	1	0	0	0	0	0	0	0	1	0	0	0	WoS, S, GS	26	2	1

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102	Sarma, PK	India	2009	Pachyderm	Assessment of habitat change and threats to the greater one-horned rhino (*Rhinoceros unicornis*) in Pabitora Wildlife Sanctuary, Assam, using multi-temporal satellite data	2	0	0	1	0	2	0	0	2	0	0	0	WoS, S, GS	6	1	3
103	Willerslev, E	Denmark	2009	BMC Evolutionary Biology	Analysis of complete mitochondrial genomes from extinct and extant rhinoceroses reveals lack of phylogenetic resolution	0	3	2	0	1	0	0	0	0	0	0	0	WoS, S, GS	103	1	1
104	Behr, B	Germany	2009	Reproduction in Domestic Animals	Germany/Australia Index of Sperm Sex Sortability in Elephants and Rhinoceros	0	3	1	0	0	0	0	0	0	0	0	0	WoS, S, GS	15	1	1
105	Endo, H	Japan	2009	Mammal Study	Absence of the guttural pouch in a newborn Indian rhinoceros demonstrated by three-dimensional image observations	0	3	1	0	0	0	0	0	0	0	0	0	WoS, S, GS	4	1	1
106	Martin, E	Kenya	2009	Pachyderm	Recent political disturbances in Nepal threaten rhinos: lessons to be learned	1	0	0	0	0	0	0	0	1	0	0	0	GS	12	2	1
107	Thapa, K	Nepal	2009	Pachyderm	Observations on habitat preference of translocated rhinos in Bardia National Park and Suklaphanta Wildlife Reserve, Nepal	1	0	0	1	0	0	0	1	0	0	0	0	GS	4	1	1
108	Konwar, P	India	2009	Journal of Threatened Taxa	Abundance of food plant species and food habits of *Rhinoceros unicornis Linn.* in Pobitora Wildlife Sanctuary, Assam, India	2	0	1	0	0	0	0	0	0	0	0	0	GS	7	1	4
109	Wolf, TM	United States	2008	Journal of Zoo and Wildlife Medicine	Serological response to west nile virus vaccination in the Greater One-horned Rhinoceros (*Rhinoceros unicornis*)	0	3	1	0	0	0	0	0	0	0	0	0	WoS, S, GS	4	1	5
110	Haffey, MB	United States	2008	Journal of Zoo and Wildlife Medicine	Urinalysis in three species of captive rhinoceros (*Rhinoceros unicornis, Dicerorhinus sumatrensis,* and *Diceros bicornis*)	0	3	1	0	0	0	0	0	0	0	0	0	WoS, S, GS	6	1	4

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								I	II	III	IV	V	VI	VII	VIII	IX	X				
111	Menargues, A	Spain	2008	Animal Welfare	Welfare assessment of captive Asian elephants (Elephas maximus) and Indian rhinoceros (*Rhinoceros unicornis*) using salivary cortisol measurement	0	3	1	0	0	0	0	0	0	0	0	0	WoS, S, GS	28	1	1
112	Pradhan, NMB	Nepal	2008	Wildlife Biology	Feeding ecology of two endangered sympatric megaherbivores: Asian elephant *Elephas maximus* and greater one-horned rhinoceros *Rhinoceros unicornis* in lowland Nepal	1	0	1	0	0	0	0	0	0	0	0	0	WoS, S, GS	43	1	3
113	Kandel, RC	Nepal	2008	Journal of Bombay Natural History Society	Demographic structure, activity patterns, habitat use and food habits of *Rhinoceros unicornis* in Chitwan National Park, Nepal	1	0	2	2	0	0	1	0	0	0	0	0	GS	9	1	2
114	Roth, T L	United States	2007	Journal of Zoo and Wildlife Medicine	Corticosteroid-induced suppression of in vitro lymphocyte proliferation in four captive rhinoceros species	0	3	1	0	0	0	0	0	0	0	0	0	WoS, S, GS	1	1	1
115	Kalita, SN	India	2007	Indian Veterinary Journal	Anatomical study on the femur of adult one-horned rhinoceros	0	2	1	0	0	0	0	0	0	0	0	0	WoS, GS	0	1	1
116	Pluhacek, J	Czech Republic	2007	Biological Conservation	Parity as a major factor affecting infant mortality of highly endangered Indian rhinoceros: Evidence from zoos and Dudhwa National Park, India	2	2	0	0	0	0	0	0	0	0	1	0	WoS, S, GS	17	2	1
117	Hermes, R	Germany	2007	Reproduction in Domestic Animals	Assisted reproduction in female Rhinoceros and elephants - Current status and future perspective	0	3	1	0	0	0	0	0	0	0	0	0	WoS, S, GS	48	2	1
118	Talukdar, BK	India	2007	Current Science	Tracing straying routes of rhinoceros in Pabitora Wildlife Sanctuary, Assam	2	0	0	0	0	0	1	0	0	0	0	0	WoS, S, GS	6	1	5
119	Ghosh, C	India	2007	Our Nature	Rhino-Fodders in Jaldapara Wildlife Sanctuary in Duars of West Bengal, India	2	0	1	0	0	0	0	0	0	0	0	0	GS	3	1	3
120	Wegge, P	Norway	2006	Ecological Research	Dry season diets of sympatric ungulates in lowland Nepal: competition and facilitation in alluvial tall grasslands	1	0	1	0	0	0	0	0	0	0	0	0	WoS, S, GS	68	1	1

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								I	II	III	IV	V	VI	VII	VIII	IX	X				
121	Talukdar, BK	India	2006	Pachyderm	Assam leads in conserving the greater one-horned rhinoceros in the new millennium	2	0	0	0	0	0	1	0	0	0	0	0	GS	6	2	1
122	Esson, DW	United States	2006	Veterinary Ophthalmology	Surgical management of a malacic corneal ulcer in a greater one-horned Asian rhinoceros (*Rhinoceros unicornis*) using a free island tarsoconjunctival graft	0	3	0	0	0	0	0	0	0	0	1	0	WoS, S, GS	11	1	1
123	Amin, R	United Kingdom	2006	International Zoo Yearbook	An overview of the conservation status of and threats to rhinoceros species in the wild	3	0	0	2	0	0	1	0	2	2	0	0	GS	61	2	1
124	Foose, TJ	United States	2006	International Zoo Yearbook	Population management of rhinoceros in captivity	0	3	1	0	0	0	0	0	0	0	0	0	S, GS	36	2	1
125	Martin, E	Kenya	2006	Pachyderm	Insurgency and poverty: recipe for rhino poaching in Nepal	1	0	0	0	0	0	0	0	1	0	0	0	GS	13	2	1
126	Martin, E	Kenya	2006	Pachyderm	Policy that work for rhino conservation in West Bengal	2	0	0	0	0	0	0	0	1	0	0	0	GS	5	2	1
127	Holden, MD	United Kingdom	2006	International Zoo Yearbook	Operant-conditioning programme for White rhinoceros, Black rhinoceros and Indian or Greater one-horned Asian rhinoceros *Ceratotherium simum, Diceros bicornis and Rhinoceros unicornis* at Whipsnade Wild Animal Park, Dunstable, UK	0	3	1	0	0	0	0	0	0	0	0	0	S, GS	13	1	1
128	Roth, TL	United States	2006	International Zoo Yearbook	A review of the reproductive physiology of rhinoceros species in captivity	0	3	1	0	0	0	0	0	0	0	0	0	S, GS	47	2	1
129	Pandit, PK	India	2006	Indian Forester	Anthrax Incidence and its Control by Vaccinating Greater One Horned Rhino (*Rhinoceros unicornis*) against Anthrax in Jaldapara Wildlife Sanctuary, West Bengal, India	2	0	0	0	0	0	0	0	0	0	1	0	GS	0	1	1
130	Hutchins, M	United States	2006	International Zoo Yearbook	Rhinoceros behaviour: implications for captive management and conservation	0	3	1	0	0	0	0	0	0	0	0	0	S, GS	45	2	2

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131	Roth, TL	United States	2005	Journal of Zoo and Wildlife Medicine	Semen collection in rhinoceroses (*Rhinoceros unicornis, Diceros bicornis, Ceratotherium simum*) by electroejaculation with a uniquely designed probe	0	3	1	0	0	0	0	0	0	0	0	0	WoS, S, GS	28	1	2
132	Clauss, M	Germany	2005	Journal of Animal Physiology and Animal Nutrition	Studies on digestive physiology and feed digestibilities in captive Indian rhinoceros (*Rhinocerosunicornis*)	0	3	1	0	0	0	0	0	0	0	0	0	WoS, S, GS	43	1	1
133	Steinheim, G	Norway	2005	Journal of Zoology	Dry season diets and habitat use of sympatric Asian elephants (*Elephas maximus*) and greater one-horned rhinoceros (*Rhinocerus unicornis*) in Nepal	1	0	1	1	0	0	0	0	0	0	0	0	WoS, S, GS	54	1	2
134	Borthakur, S	India	2005	Indian Veterinary Journal	Craniometry in Indian one horned Rhinoceros	0	2	1	0	0	0	0	0	0	0	0	0	WoS, GS	0	1	1
135	Clauss, M	Germany	2005	Comparative Biochemistry and Physiology	Tannin-binding salivary proteins in three captive rhinoceros species	0	3	1	0	0	0	0	0	0	0	0	0	WoS, S, GS	66	1	1
136	Rawat, GS	India	2005	National Academy Science Letters	Vegetation dynamics and management of Rhinoceros habitat in Duars of West Bengal: An ecological review	2	0	0	1	0	0	0	0	0	0	0	0	WoS, S, GS	4	2	1
137	Clauss, M	Germany	2005	Zoo Biology	Energy and mineral nutrition and water intake in the captive Indian rhinoceros (*Rhinoceros unicornis*)	0	3	1	0	0	0	0	0	0	0	1	0	WoS, S, GS	39	1	1
138	Dierenfeld, ES	United States	2005	Zoo Biology	Mineral concentrations in serum/plasma and liver tissue of captive and free-ranging rhinoceros species	0	3	1	0	0	0	0	0	0	0	0	0	WoS, S, GS	42	1	1
139	Choudhary, A	India	2005	Pachyderm	Threats to the greater one-horned rhino and its habitat, Pabitora Wildlife Sanctuary, Assam, India	2	0	0	1	0	2	2	0	2	0	0	0	GS	4	1	2

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140	Kalita, PC	India	2004	Indian Veterinary Journal	Anatomy of the scapula of rhinoceros calf	0	2	1	0	0	0	0	0	0	0	0	0	WoS, GS	0	1	1
141	Vance, CK	United States	2004	Journal of Zoo and Wildlife Medicine	Comparative studies of mitogen- and antigen-induced lymphocyte proliferation in four captive rhinoceros species	0	3	1	0	0	0	0	0	0	0	1	0	WoS, S, GS	12	1	1
142	Stoops, MA	United States	2004	Reproduction	Follicular, endocrine and behavioural dynamics of the Indian rhinoceros (*Rhinoceros unicornis*) oestrous cycle	0	3	1	0	0	0	0	0	0	0	0	0	WoS, S, GS	44	1	1
143	Kalita, PC	India	2004	Indian Veterinary Journal	Anatomy of the mandible of rhinoceros calf	0	2	1	0	0	0	0	0	0	0	0	0	WoS, GS	0	1	1
144	Bertelsen, MF	Canada	2004	Journal of Zoo and Wildlife Medicine	Surgical management of rectal prolapse in an Indian rhinoceros (*Rhinoceros unicornis*)	0	3	1	0	0	0	0	0	0	0	1	0	WoS, S, GS	8	1	1
145	Sharma, K	India	2004	Indian Veterinary Journal	Morphological and biometrical observations on the orbits of Indian one horned Rhinoceros	0	2	1	0	0	0	0	0	0	0	1	0	WoS, S, GS	0	1	1
146	Gomez, A	United States	2004	Zoo Biology	Use of salivary steroid analyses to assess ovarian cycles in an Indian rhinoceros at the National Zoological Park	0	3	1	0	0	0	0	0	0	0	0	0	WoS, S, GS	28	1	1
147	Martin, E	Kenya	2004	Pachyderm	Rhino poaching in Nepal during an insurgency	1	0	0	0	0	0	0	0	1	0	0	0	GS	14	2	1
148	Rothley, KD	Canada	2004	Pachyderm	Population model for the greater one-horned rhinoceros (*Rhinoceros unicornis*) in Royal Chitwan National Park, Nepal	1	0	0	0	0	0	1	0	0	0	0	0	GS	5	2	1
149	Bairagee, A	India	2004	Tiger Paper	A study on the population status and conservation approach for *Rhinoceros unicornis* in Pabitora Wildlife Sanctuary, Assam, India	2	0	0	0	0	0	1	0	2	0	0	0	S	2	1	3
150	Hsieh, HM	Taiwan	2003	Forensic Science International	Species identification of rhinoceros horns using the cytochrorne b gene	0	3	2	0	1	0	0	0	0	0	0	0	WoS, S, GS	120	1	1

SN	First Author	Country of first author	Year	Journal	Title	Wild	Captive	Thematic area										Source	Citation	Type	Duration
								I	II	III	IV	V	VI	VII	VIII	IX	X				
151	Zschokke, S	Switzerland	2003	Molecular Ecology Notes	Polymorphic microsatellite loci in the endangered Indian rhinoceros, *Rhinoceros unicornis*	0	1,2	2	0	1	0	0	0	0	0	0	0	WoS, S, GS	17	1	2
152	Kapur, V	India	2003	Molecular and Cellular Probes	Development of a DNA marker by minisatellite associated sequence amplification (MASA) from the endangered Indian rhino (*Rhinoceros unicornis*)	0	2	2	0	1	0	0	0	0	0	0	0	WoS, S, GS	3	1	1
153	Deka, RJ	India	2003	Zoo's Print Journal	Nutritional evaluation of the principal forages/feed consumed by Indian rhino (*Rhinoceros unicornis*) in Pobitora Wildlife Sanctuary and Assam State Zoo-cum ...	2	2	1	0	0	0	0	0	0	0	0	0	S, GS	5	1	2
154	Zschokke, S	Switzerland	2002	Canadian Journal of Zoology	Inbreeding, Outbreeding, infant growth and size dimorphism in captive Indian rhinoceros (*Rhinoceros unicornis*)	0	3	0	0	1	0	0	0	0	0	0	0	WoS, S, GS	34	2	1
155	Atkinson, MW	United States	2002	Journal of Zoo and Wildlife Medicine	Repeated Chemical Immobilization of a Captive Greater One-Horned Rhinoceros (*Rhinoceros unicornis*), Using Combinations of Etorphine, Detomidine, and Ketamine	0	3	0	0	0	0	0	1	0	0	0	0	WoS, S, GS	15	1	5
156	Clauss, M	Germany	2002	Journal of Wildlife Diseases	Fat soluble vitamins in blood and tissues of free-ranging and captive rhinoceros	0	3	1	0	0	0	0	0	0	0	0	0	WoS, S, GS	19	1	5
157	Talukdar, BK	India	2002	Pachyderm	Dedication leads to reduced rhino poaching in Assam in recent years	2	0	0	0	0	0	0	0	1	0	0	0	GS	8	2	1
158	Baishya, G	India	2001	Indian Veterinary Journal	Anatomy of the distal sesamoid of Indian one-horned rhinoceros	0	2	1	0	0	0	0	0	0	0	0	0	WoS, S	3	1	1
159	Schaffer, NE	United States	2001	Journal of Zoo and Wildlife Medicine	Clinical implications of rhinoceros reproductive tract anatomy and histology	0	3	1	0	0	0	0	0	0	0	0	0	WoS, S, GS	13	1	2

SN	First Author	Country of first author	Year	Journal	Title	Wild	Captive	Thematic area										Source	Citation	Type	Duration
								I	II	III	IV	V	VI	VII	VIII	IX	X				
160	Schwarzenberger, F	Austria	2000	General and Comparative Endocrinology	Fecal Progesterone, Estrogen, and Androgen Metabolites for Noninvasive Monitoring of Reproductive Function in the Female Indian Rhinoceros, *Rhinoceros unicornis*	0	3	1	0	0	0	0	0	0	0	0	0	WoS, S, GS	73	1	2
161	Gandolf, AR	United States	2000	Journal of Zoo and Wildlife Medicine	Melting corneal ulcer management in a greater one-horned rhinoceros (*Rhinoceros unicornis*)	0	3	2	0	0	0	0	0	0	0	1	0	WoS, S, GS	11	1	1
162	Talukdar, BK	India	2000	Pachyderm	The current state of rhino in Assam and threats in the 21st century	2	0	0	0	0	0	1	0	2	2	0	0	GS	16	1	1
163	Kuswaha, SPS	India	2000	Tiger Paper	Land area change and rhino habitat suitability analysis in Kaziranga National Park, Assam	2	0	0	1	0	0	0	0	0	0	0	0	GS	47	1	1
164	Rookmaker, LC	South Africa	2000	Pakistan Journal of Zoology	Records of the Rhinoceros in Pakistan and Afghanistan	0	0	0	1	0	0	0	0	0	0	0	0	GS	4	2	1
165	Yadav, VK	India	2000	Indian Forester	Male-male Aggression in *Rhinoceros unicornis*- Case study from North Bengal, India	2	0	1	0	0	0	0	0	0	0	0	0	S, GS	7	1	1
166	Ali, S	India	1999	Gene	Characterization of a species-specific repetitive DNA from a highly endangered wild animal, *Rhinoceros unicornis*, and assessment of genetic polymorphism by microsatellite associated sequence amplification (MASA)	0	2	2	0	1	0	0	0	0	0	0	0	WoS, S, GS	24	1	1
167	Martin, E	Kenya	1999	Pachyderm	West Bengal: committed to rhino conservation yet a major entrepot for endangered wildlife products	2	0	0	0	0	0	2	0	1	0	0	0	GS	4	2	1
168	Talukdar, BK	India	1999	Tigerpaper	Status of *Rhinoceros unicornis* in Pabitora Wildlife Sanctuary, Assam	2	0	0	0	0	0	1	0	0	0	0	0	GS	5	2	1
169	Schaffer, N	United States	1998	Journal of Zoo and Wildlife Medicine	Ultrasonographic monitoring of artificially stimulated ejaculation in three rhinoceros species (*Ceratotherium*	0	3	1	0	0	0	0	0	0	0	0	0	WoS, S, GS	28	1	1

SN	First Author	Country of first author	Year	Journal	Title	Wild	Captive	Thematic area										Source	Citation	Type	Duration
								I	II	III	IV	V	VI	VII	VIII	IX	X				
					simum, Diceros dicornis, Rhinoceros unicornus)																
170	Schaffer, NE	United States	1998	Zoo Biology	Cage restraints for rhinoceros	0	3	2	0	0	0	0	1	0	0	0	0	WoS, S, GS	13	1	2
171	Vigne, L	Kenya	1998	Pachyderm	Dedicated field staff continue to combat rhino poaching in Assam	2	0	0	0	0	0	0	0	1	0	0	0	GS	10	2	1
172	Borthakur, S	India	1997	Indian Veterinary Journal	Gross anatomical study on the skull of adult rhino (*Rhinoceros unicornis*)	0	2	1	0	0	0	0	0	0	0	0	0	WoS, S	4	1	1
173	Xu, XF	Sweden	1997	Molecular Phylogenetics and Evolution	The complete mitochondrial DNA sequence of the white rhinoceros, Ceratotherium simum, and comparison with the mtDNA sequence of the Indian rhinoceros, *Rhinoceros unicornis*	0	3	2	0	1	0	0	0	0	0	0	0	WoS, S, GS	69	1	1
174	Xu, XF	Sweden	1996	Molecular Biology and Evolution	The complete mitochondrial DNA sequence of the greater Indian rhinoceros, *Rhinoceros unicornis*, and the Phylogenetic relationship among Carnivora, Perissodactyla, and Artiodactyla (plus Cetacea).	0	3	2	0	1	0	0	0	0	0	0	0	WoS, S, GS	122	1	1
175	Endo, H	Japan	1996	Journal of Veterinary Medical Science	Testicular morphology of a greater Indian rhinoceros (*Rhinoceros unic ornis*)	0	3	1	0	0	0	0	0	0	0	0	0	WoS, S, GS	6	1	1
176	Martin, E	Kenya	1996	Pachyderm	The importance of park budgets, intelligence networks and competent management for successful conservation of the greater one-horned rhinoceros	3	0	0	0	0	0	0	0	1	0	0	0	GS	11	2	1
177	Martin, E	Kenya	1996	Pachyderm	Smuggling routes for West Bengal's rhino horn and recent successes in curbing poaching	2	0	0	0	0	0	0	0	1	0	0	0	GS	5	2	1
178	Talukdar, SR	India	1996	Indian Veterinary Journal	Gross and histological study on the thyroid gland of a week-old rhino calf (*Rhinoceros unicornis*)	0	2	1	0	0	0	0	0	0	0	0	0	WoS, S, GS	1	1	1

SN	First Author	Country of first author	Year	Journal	Title	Wild	Captive	Thematic area										Source	Citation	Type	Duration
								I	II	III	IV	V	VI	VII	VIII	IX	X				
179	Martin, E	Kenya	1996	Pachyderm	Nepal's rhinos-one of the greatest conservation success stories	1	0	0	0	0	0	1	0	0	0	0	0	GS	28	2	1
180	Choudhary, A	India	1996	Pachyderm	The greater one-horned Rhino outside Protected Areas in Assam, India	2	0	0	0	0	0	1	0	0	0	0	0	GS	2	2	1
181	Ghosh, DK	India	1996	Indian Forester	Crop depredation around Jaldapara sanctuary by *Rhinoceros unicornis* an indicative trend	2	0	0	0	0	0	0	0	0	1	0	0	S, GS	1	2	1
182	Nepal, SK	Nepal	1995	Environmental Management	The quandary of local people-park relations in Nepal's Royal Chitwan National Park	1	0	0	0	0	0	0	0	0	1	0	0	WoS, S, GS	78	2	1
183	Bordoloi, CC	India	1995	Indian Veterinary Journal	Mandible of the Great Indian One horned Rhinoceros (*Rhinoceros unicornis*)	0	2	1	0	0	0	0	0	0	0	0	0	WoS, GS	3	1	1
184	Studsrod, JE	Norway	1995	Environmental Conservation	Park-people relationships- The case of damage caused by park animals around the Bardia National Park, Nepal	1	0	0	0	0	0	0	0	0	1	0	0	WoS, S, GS	156	2	1
185	Lott, DF	United States	1995	Biological Conservation	Asian rhinos *Rhinoceros unicornis* on the run? Impact of tourist visits on one population	1	0	0	0	0	1	0	0	0	0	0	0	WoS, S, GS	93	1	2
186	Baur, B	Switzerland	1995	International Zoo Yearbook	Inbreeding in captive indian rhinoceros *Rhinoceros unicornis*	0	3	0	0	1	0	0	0	0	0	0	0	S, GS	10	2	1
187	Talukdar, BK	India	1995	Journal of Nature Conservation	Rhino poaching in Orang Wildlife Sanctuary, Assam, India	2	0	0	0	0	0	0	0	1	0	0	0	GS	2	2	1
188	Vigne, L	Kenya	1994	Pachyderm	The Greater One-horned Rhino of Assam is threatened by poachers	2	0	0	0	0	0	0	0	1	0	0	0	GS	10	2	1
189	Morales, JC	United States	1994	Molecular Biology and Evolution	Molecular Systematics of the Living Rhinoceros	3	0	0	0	1	0	0	0	0	0	0	0	GS	35	1	2
190	Nath, NC	India	1993	Journal of Zoo and Wildlife Medicine	Milk characteristics of a captive Indian rhinoceros (*Rhinoceros unicornis*)	0	2	1	0	0	0	0	0	0	0	0	0	GS	4	1	1
191	Bordoloi, CC	India	1993	Indian Veterinary Journal	Scapula of the Great Indian Rhino (*Rhinoceros unicornis*)	0	2	1	0	0	0	0	0	0	0	0	0	WoS, GS	0	1	1

SN	First Author	Country of first author	Year	Journal	Title	Wild	Captive	Thematic area										Source	Citation	Type	Duration
								I	II	III	IV	V	VI	VII	VIII	IX	X				
192	Bhattacharya, A	India	1993	Tiger Paper	The status of the Kaziranga rhino population	2	0	0	0	0	0	1	0	2	0	0	0	GS	7	2	1
193	Dinerstein, E	United States	1992	Ecology	Effects of *Rhinoceros unicornis* on riverine forest structure in lowland Nepal	1	0	1	0	0	0	0	0	0	0	0	0	GS	18	1	2
194	Martin, E	Kenya	1992	Oryx	The poisoning of rhinos and tigers in Nepal	1	0	0	0	0	0	0	0	1	0	0	0	S, GS	14	2	1
195	Dinerstein, E	United States	1991	Journal of Mammalogy	Sexual Dimorphism in Greater One-horned Rhinoceros (*Rhinoceros unicornis*)	1	0	1	0	0	0	0	0	0	0	0	0	WoS, S, GS	38	1	2
196	Dinerstein, E	United States	1991	The Journal of Wildlife Management	Demography and habitat use by greater one-horned rhinoceros in Nepal	1	0	0	1	0	0	1	0	0	0	0	0	WoS, S, GS	87	1	3
197	Vigne, L	Kenya	1991	Oryx	Assam's rhinos face new poaching threats	2	0	0	0	0	0	0	0	1	0	0	0	GS	7	2	1
198	Dinerstein, E	United States	1991	Mammalia	Seed dispersal by greater one-horned rhinoceros *(Rhinoceros unicornis)* and the flora of *Rhinoceros* latrines	1	0	1	0	0	0	0	0	0	0	0	0	WoS, S, GS	36	1	2
199	Dinerstein, E	United States	1990	Conservation Biology	Endangered greater one-horned rhinoceros carry high levels of genetic variation	1	0	2	0	1	0	0	0	0	0	0	0	WoS, S, GS	141	1	1
200	Dinerstein, E	United States	1990	Wildlife Society Bulletin	Capture, chemical immobilization and radio-collar life for greater one-horned rhinoceros	1	0	0	0	0	0	0	1	0	0	0	0	WoS, GS	12	1	2
201	Stratil, A	Czechoslovakia	1990	Comparative Biochemistry	Serum proteins of rhinoceroses: inter- and intra-specific variation	0	3	1	0	0	0	0	0	0	0	0	0	S, GS	17	1	1
202	Schaffer, NE	United States	1990	Zoo Biology	Methods of semen collection in an ambulatory greater one-horned rhinoceros (*Rhinoceros unicornis)*	0	3	1	0	0	0	0	0	0	0	0	0	WoS, S, GS	29	1	1
203	Dinerstein, E	United States	1989	Biotropica	The foliage-as-fruit hypothesis and the feeding behavior of South Asian ungulates	1	0	1	0	0	0	0	0	0	0	0	0	S, GS	45	1	3
204	Merenlender, AM	United States	1989	Journal of Heredity	Allozyme variation and differentiation in African and Indian Rhinoceros	0	3	2	0	1	0	0	0	0	0	0	0	WoS, S, GS	53	1	1
205	Dinerstein, E	United States	1988	Ecology	Fruits Rhinoceros Eat: Dispersal of Trewia Nudiflora (Euphorbiaceae) in Lowland Nepal	1	0	1	2	0	0	0	0	0	0	0	0	S, GS	149	1	5

SN	First Author	Country of first author	Year	Journal	Title	Wild	Captive	Thematic area										Source	Citation	Type	Duration
								I	II	III	IV	V	VI	VII	VIII	IX	X				
206	Dinerstein, E	United States	1988	Behavioural and Neural Biology	Adoption in Greater One-horned Rhinoceros *(Rhinoceros unicornis)*	1	0	1	0	0	0	0	0	0	0	0	0	GS	18	1	3
207	Maluf, NSR	United States	1987	American Journal of Anatomy	Kidney of the Great Indian Rhino *Rhinoceros unicornis, Linnaeus*	0	3	1	0	0	0	0	0	0	0	0	0	WoS, GS	10	1	1
208	Abbasi, A	Germany	1987	Biological Chemistry Hoppe-Seyler	Molecular Basis for ATP/2,3-Bisphosphoglycerate Control Switch-Over (Poikilotherm/Homeotherm) An Intermediate Amino-Acid Sequence in the Hemoglobin of the Great Indian Rhinoceros (*Rhinoceros unicornis*, Perissodactyla)	0	3	1	0	0	0	0	0	0	0	0	0	WoS, S	7	1	1
209	Bhattacharya, M	India	1987	Journal of Zoo Animal Medicine	Gross-anatomy of the heart of the Indian One-horned Rhinoceros (*Rhinoceros unicornis*)	0	2	1	0	0	0	0	0	0	0	0	0	WoS, S	2	1	1
210	Martin, E	Kenya	1987	Oryx	Conservation crisis —the rhinoceros in India	2	0	0	0	0	0	1	0	0	0	0	0	GS	14	2	1
211	Sale, JB	India	1987	Oryx	Reintroduction of greater Indian rhinoceros into Dudhwa National Park	2	0	0	0	0	0	2	1	0	0	0	0	S, GS	27	2	1
212	Choudhury, A	India	1987	Oryx	Railway threat to Kaziranga	2	0	0	0	0	1	0	0	0	0	0	0	S, GS	10	2	1
213	Kasman, LH	United States	1986	Zoo Biology	Urinary steroid evaluations to monitor ovarian function in exotic ungulates: III. Estrone sulfate and pregnanediol-3-glucuronide excretion in the Indian rhinoceros (*Rhinoceros unicornis*)	0	3	1	0	0	0	0	0	0	0	0	0	WoS, S, GS	48	1	1
214	Sale, JB	India	1986	Oryx	Reintroduction of greater Indian rhinoceros into Dudhwa National Park	2	0	0	0	0	0	2	1	0	0	0	0	GS	27	2	1
215	Martin, E	Kenya	1985	Oryx	Religion, royalty and rhino conservation in Nepal	1	0	0	0	0	0	1	0	0	0	0	0	GS	12	2	1

Appendix B: Supplementary materials for Chapter 5 (Research article)

Table B1. List of environmental variables that are possibly determining the habitat selection of greater one-horned rhinoceros (*Rhinoceros unicornis*).

Category	Source	Selected variables	Resolution	Type
Bioclimatic	WORLDCLIM	BIO1– Annual mean temperature	~1 km	Continuous
		BIO2– Mean Diurnal Range (Mean of monthly (Maximum temperature – minimum temperature))	~1 km	Continuous
		BIO3– Isothermality (BIO2/BIO7) (×100)	~1 km	Continuous
		BIO4– Temperature seasonality (Standard deviation x 100)	~1 km	Continuous
		BIO5– Maximum temperature of warmest month	~1 km	Continuous
		BIO6– Minimum temperature of coldest month	~1 km	Continuous
		BIO7– Temperature annual range (BIO5 – BIO6)	~1 km	Continuous
		BIO8–Mean temperature of wettest quarter	~1 km	Continuous
		BIO9 - Mean temperature of driest quarter	~ 1 km	Continuous
		BIO10– Mean temperature of warmest quarter	~1 km	Continuous

Category	Source	Selected variables	Resolution	Type
		BIO11– Mean temperature of coldest quarter	~1 km	Continuous
		BIO12 - Annual precipitation	~1 km	Continuous
		BIO13– Precipitation of wettest month	~1 km	Continuous
		BIO14 - Precipitation of the driest month	~1 km	Continuous
		BIO15– Precipitation seasonality (Coefficient of variation)	~1 km	Continuous
		BIO16– Precipitation of wettest quarter	~1 km	Continuous
		BIO17– Precipitation of driest quarter	~1 km	Continuous
		BIO18– Precipitation of warmest quarter	~1 km	Continuous
		BIO19– Precipitation of coldest quarter	~1 km	Continuous
Topographic and habitat	SRTM	Elevation	~ 30 m	Continuous
		Aspect	~ 30 m	Continuous
		Slope	~ 30 m	Continuous
	ESRI 2020 Land Cover	Distance from grasslands	~10 m	Continuous
		Distance from wetlands	~10 m	Continuous
		Distance from forests	~10 m	Continuous
Anthropogenic	MODIS Land Cover	Croplands	~500 m	Continuous
	HDX	Population density	~1 km	Continuous
	GEOFABRIK	Distance from roads	~1 km	Continuous

Table B2. List of environmental variables retained after collinearity test.

Category	Source	Selected variables	Resolution	Type
Bioclimatic	WORLDCLIM	BIO2– Mean Diurnal Range (Mean of monthly (Maximum temperature – minimum temperature))	~1 km	Continuous
		BIO3– Isothermality (BIO2/BIO7) (×100)	~1 km	Continuous
		BIO9 - Mean temperature of driest quarter	~ 1 km	Continuous
		BIO12 - Annual precipitation	~1 km	Continuous
		BIO14 - Precipitation of the driest month	~1 km	Continuous
		BIO15– Precipitation seasonality (Coefficient of variation)	~1 km	Continuous
		BIO18– Precipitation of warmest quarter	~1 km	Continuous
		BIO19– Precipitation of coldest quarter	~1 km	Continuous
Topographic and habitat	SRTM	Slope	~ 30 m	Continuous
	Esri 2020 Land Cover	Distance from grasslands	~10 m	Continuous
		Distance from wetlands	~10 m	Continuous
		Distance from forests	~10 m	Continuous
Anthropogenic	MODIS Land Cover	Croplands	~ 500 m	Continuous
	HDX	Population density	~1 km	Continuous

Table B3. Checklist for ODMAP (Overview, data, model, assessment, and prediction) protocol while developing habitat suitability models for greater one-horned rhinoceros (*Rhinoceros unicornis*) in Nepal.

ODMAP element	Contents
OVERVIEW	
Authorship	▪ **Authors:** Ganesh Pant, Tek Maraseni, Armando Apan and Benjamin L. Allen ▪ **Contact e-mail:** ganeshpant@yahoo.com, ganesh.pant@usq.edu.au ▪ **Title:** Predicted declines in suitable habitat for greater one-horned rhinoceros (*Rhinoceros unicornis*) under future climate and land use change scenarios
Model objective	▪ **Objective:** Predict habitat suitability ▪ **Target outputs:** Current and future habitat suitability maps
Taxon	Greater one-horned rhinoceros, *Rhinoceros unicornis*, Rhinocerotidae, Perissodactyla, Mammalia
Location	Nepal, Asia
Scale of analysis	▪ **Spatial extent (Lon/Lat):** 80°04’ - 88°12’ E, 26°22’ - 30°27’ N, covering 1,47,516 km² ▪ **Spatial Resolution:** 1 km ▪ **Temporal extent/time period:** Species occurrence data- 2008 to present; environmental data - 1970 to present, and future projection (2050 and 2070) ▪ **Type of extent boundary:** Political (the Federal Democratic Republic of Nepal)
Biodiversity data overview	▪ **Observation type:** Standard monitoring, field survey, GPS tracking ▪ **Response/Data type:** Presence-only
Type of predictors	Bioclimatic, anthropogenic, topographic and habitat variables

ODMAP element	Contents
Conceptual model / hypothesis	▪ **Hypothesis about species-environment relationships:** Species maintain equilibrium with their environment. The distribution of rhinoceros is determined by climatic factors (temperature and precipitation) and the presence of a specific habitat component (grasslands and wetlands), constrained by topographic factors (elevation, aspect, and slope), and influenced by anthropogenic disturbances (land use land cover and population density).
Assumptions	▪ Species are at equilibrium with their environment and do not occur elsewhere. ▪ Species occurrence data are free from observational bias and any biases are accounted for or corrected. ▪ Key predictor variables of the species are available and incorporated in the model. ▪ Predictor variables are measured or estimated without error
SDM algorithms	▪ **Algorithms:** We used ten SDM algorithms available in BIOMOD2 as follows a. Artificial Neural Network (ANN) b. Classification Tree Analysis (CTA) c. Flexible Discriminant Analysis (FDA) d. Generalised Additive Model (GAM) e. Generalised Boosting Model (GBM) f. Generalised Linear Model (GLM) g. Multiple Adaptive Regression Splines (MARS) h. Maximum Entropy (MAXENT) i. Random Forest (RF) j. Surface Range Envelope (SRE) ▪ **Model complexity:** We chose ten different modelling algorithms to yield complex response surfaces but prevent overfitting. ▪ **Model averaging:** We selected all models from ten SDM algorithms having a True Skill Statistics (TSS) value >0.85

ODMAP element	Contents
	for building ensemble model using the weighted mean approach.
Model workflow	▪ We compiled rhinoceros presence data from all possible sources. ▪ We used spThin package in R (Aiello-Lammens et al., 2015) to spatially rarefy presence data to reduce sample bias (Boria et al., 2014) and used a dataset of 495 selected rhinoceros presence points. ▪ We identified a set of 28 environmental variables primarily based on literature suggesting the significance of these variables for rhinoceros habitat suitability (Laurie, 1982; Dinerstein & Price, 1991; Jnawali, 1995; Dinerstein, 2003; Pradhan et al., 2008; Subedi, 2012). ▪ We then excluded the variables with correlation coefficients >0.8 and variance inflation factor (VIF) >5 after testing the multicollinearity among environmental variables using the USDM (Uncertainty Analysis for Species Distribution Models) package in R to avoid model overfitting (Gareth et al., 2013; Naimi et al., 2014), retaining 14 variables for further analysis. ▪ We selected nine of these as ecologically meaningful variables following a reiterative process of model formation and stepwise removal of the least contributing variables, as suggested by Zeng et al. (2016). ▪ We generated pseudo-absence data (n=10,000) and repeated pseudo-absence generation three times to avoid random bias (Barbet-Massin et al., 2012). ▪ We divided rhinoceros presence and pseudo-absence data into training (80%) and testing data (20%). ▪ After preparing appropriate data layers, we ran a total of 90 models comprising ten SDM algorithms, three pseudo-absence selection and three evaluation runs.

ODMAP element	Contents
	▪ We generated ensemble model using the ensemble modelling function in BIOMOD2. We included all the models having TSS value >0.85 for building ensemble model. ▪ We projected the ensemble models for two different climate scenarios for 2050 and 2070. ▪ Finally, we employed range size function within the BIOMOD2 package for calculating the range shifts. ▪ The model workflow is also depicted in Figure **3** in the paper.
Software, codes, and data	▪ **Modelling platform:** R (Version 4.1.1) with package BIOMOD2 ▪ **Code:** Code is shared in specified data repository ▪ **Data:** Data is shared in specified data repository
DATA	
Biodiversity data	▪ **Taxon names:** *Rhinoceros unicornis* ▪ **Taxonomic reference system:** N/A ▪ **Ecological level:** Species level ▪ **Data source:** a. Rhinoceros presence records from Government Department: Compiled from rhinoceros census and monitoring of individual rhinoceros using GPS collar between 2008 and 2017. b. Field work for this research: Rhinoceros presence points recorded in April 2019 using handheld GPS unit. c. GBIF website: Downloaded in February 2020. ▪ **Sampling design:** N/A ▪ **Sample size:** We compiled the rhinoceros presence data from entire Nepal. ▪ **Absence data:** We used presence-only data for modelling given that we did not have true absence data for rhinoceros. Pseudo-absence data were generated for running models in BIOMOD2.

ODMAP element	Contents
	▪ **Data cleaning and filtering:** We used the SpThin package in R to spatially rarefy the occurrence dataset (Aiello-Lammens et al., 2015). Spatial filtering reduces the effects of sample bias and helps to improve the predictive performance of the models (Boria et al., 2014).
Data partitioning	▪ Rhinoceros presence and pseudo-absence data were split into training (80%) and testing data sets (20%).
Predictor variables	▪ **Predictor variables:** a. Bioclimatic variables — Temperature annual range (BIO7), mean temperature of driest quarter (BIO9), and annual precipitation (BIO12) b. Topographic variables — Slope c. Habitat variables — Distance from grasslands, distance from wetlands, and distance from forests d. Anthropogenic variables — Croplands and population density ▪ **Data source:** a. https://www.worldclim.org/ b. https://www.usgs.gov/science-explorer-results?es=SRTM c. https://www.arcgis.com/home/item.html?id=d6642f8a4f6d4685a24ae2dc0c73d4ac d. https://doi.org/10.5067/MODIS/MCD12Q1.006, http://www.geosimulation.cn/flus.html, https://data.humdata.org/dataset ▪ **Data processing:** ▪ We downloaded the data layers from free online sources and standardised these data using various functions in ArcMap 10.8.1 (ESRI, 2017). ▪ We extracted the grass, water and trees layers of the study area from Esri 2020 Land Cover Raster Dataset in ArcMap 10.8.1 (ESRI, 2017). We converted the raster data into

ODMAP element	Contents
	polygon and generated data layers containing proximity to grasslands, wetlands and forests using Euclidean Distance tool in ArcMap 10.8.1 (ESRI, 2017). ▪ We resampled raster data of the environmental variables in ArcMap 10.8.1 (ESRI, 2017) at a spatial resolution of 1 km. We used bilinear interpolation method as environmental variables we used were continuous data. ▪ **Spatial resolution of raw data:** 10m, 30 m, 300 m, 500 m, 1 km ▪ **Projection:** WGS84
MODEL	
Variable pre-selection	▪ We identified a set of 28 environmental variables primarily based on literature suggesting the significance of these variables for rhinoceros habitat suitability (Laurie, 1982; Dinerstein & Price, 1991; Jnawali, 1995; Dinerstein, 2003; Pradhan et al., 2008; Subedi, 2012). ▪ After multicollinearity test among environmental variables, we excluded the variables with correlation coefficients >0.8 and variance inflation factor (VIF) >5 and retained 14 variables for further analysis. ▪ We selected nine of these as ecologically meaningful variables following a reiterative process of model formation and stepwise removal of the least contributing variables, as suggested by Zeng et al. (2016).
Multicollinearity	▪ We tested multicollinearity among environmental variables using the USDM (Uncertainty Analysis for Species Distribution Models) package in R to avoid model overfitting (Gareth et al., 2013; Naimi et al., 2014)
Model settings	▪ We used default settings for BIOMOD2 to run models using ten SDM algorithms.

ODMAP element	Contents
Model estimates	▪ **Model coefficient:** We used TSS to evaluate the predictive performance while we analysed ROC for cross-comparison. In addition, we used Boyce index for cross validation. ▪ **Variable importance:** We calculated the variable importance of the ensemble model and found that five environmental variables — distance from grasslands, annual precipitation, mean temperature of driest quarter, distance from wetlands, and slope, contributed the most in the model.
Model averaging / ensembles	▪ We selected all models from ten SDM algorithms having a True Skill Statistics (TSS) value >0.85 for building ensemble model using the weighted mean approach.
Non-independence	▪ We did not perform any test for checking non-independence of the models.
Threshold selection	▪ Binary predictions were derived by using the TSS maximisation threshold.
ASSESSMENT	
Performance statistics	▪ **Performance statistics estimated on training data:** We assessed model performance based on TSS value from 90 model runs.
Plausibility checks	▪ **Response plots:** We generated the response curves of the best performing model and analysed it for ecological plausibility. For instance, areas with >1500 mm of average annual rainfall was suitable for rhinoceros as indicated by the response curve.
PREDICTION	
Prediction output	▪ We used continuous predictions of occurrence probability for rhinoceros further analysis of habitat suitability as well as predicted presence generating the binary map (presence-

ODMAP element	Contents
	absence map) using the optimal prediction value threshold of 0.376 identified automatically based on TSS value.
Uncertainty quantification	▪ **Algorithmic uncertainty:** Ensemble forecasting can reduce model-based uncertainty in prediction from SDMs (Araújo & New, 2007). Thus, we accounted for algorithmic uncertainty by developing an ensemble model from all ten SDM algorithms based on consensus method for combining output of single models (Marmion et al., 2009). ▪ **Reality check:** We further endeavoured to validate the on-ground reality of the current habitat suitability model for rhinoceros in Nepal through expert consultation. For this, we shared the current habitat suitability model we generated to five field biologists each having more than ten years of professional experience in research and management of rhinoceros in Nepal. All of them agreed that the current suitability model has captured both currently occupied and other possible habitat of rhinoceros in Nepal.

Figure B1. Predictive performance of different algorithms using testing data for modelling habitat suitability of greater one-horned rhinoceros (*Rhinoceros unicornis*) in Nepal.

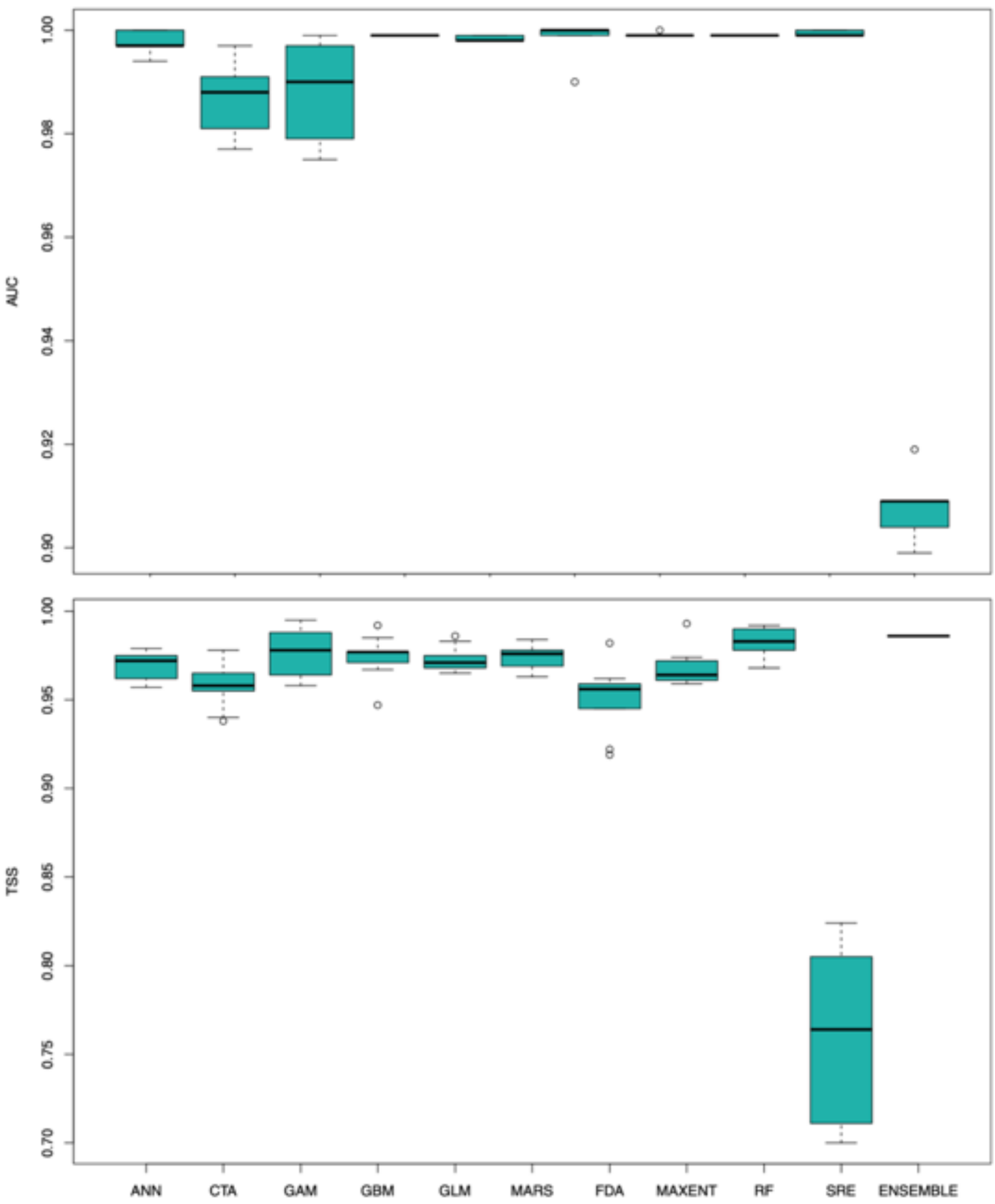


Figure B2. Predictive performance of different algorithms using evaluating data for modelling habitat suitability of greater one-horned rhinoceros (*Rhinoceros unicornis*) in Nepal.

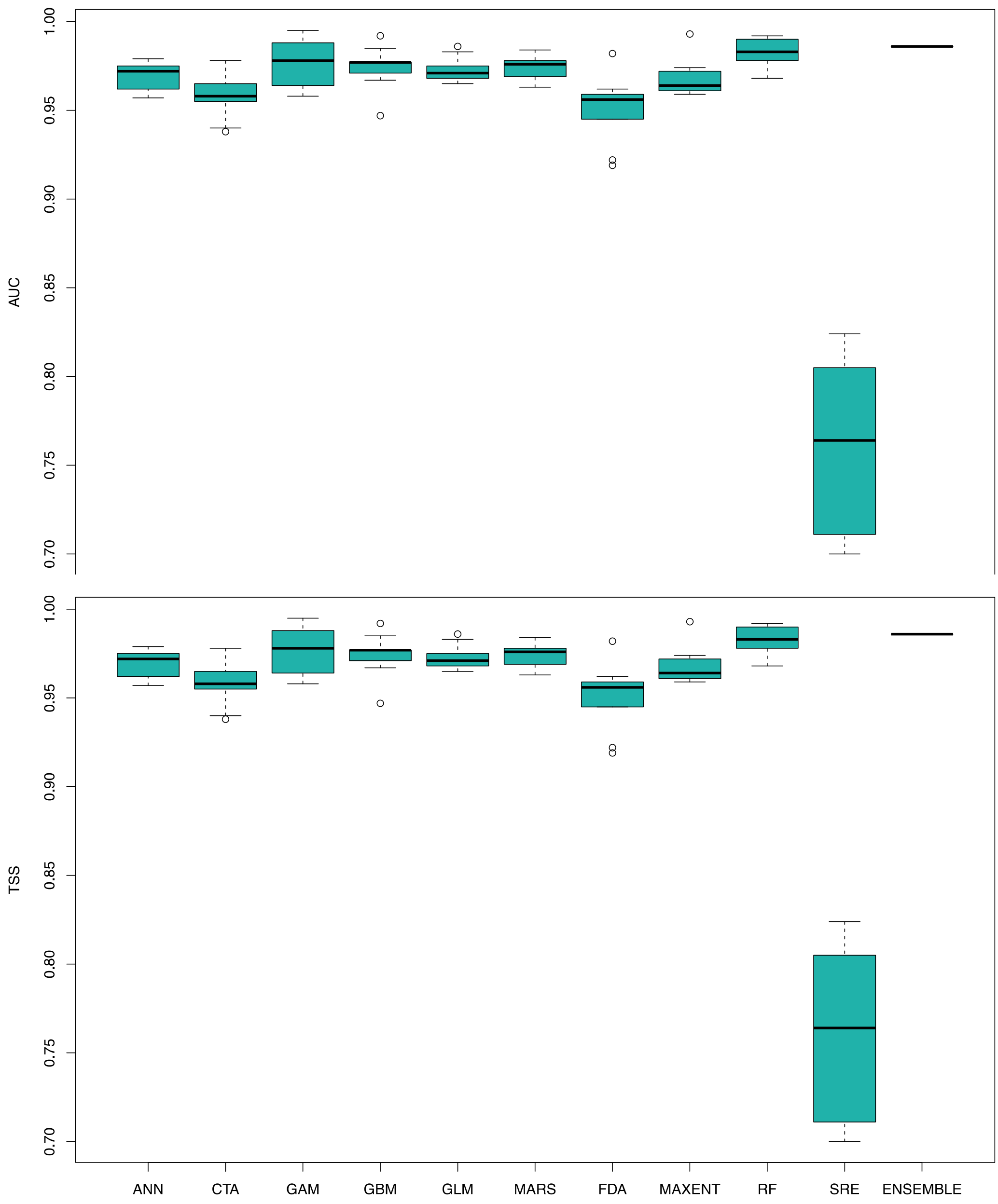


Figure B3. Predictive performance of the models included in the ensemble model based on Area Under Curve (AUC) value and the Boyce index for modelling habitat suitability of greater one-horned rhinoceros (*Rhinoceros unicornis*) in Nepal.

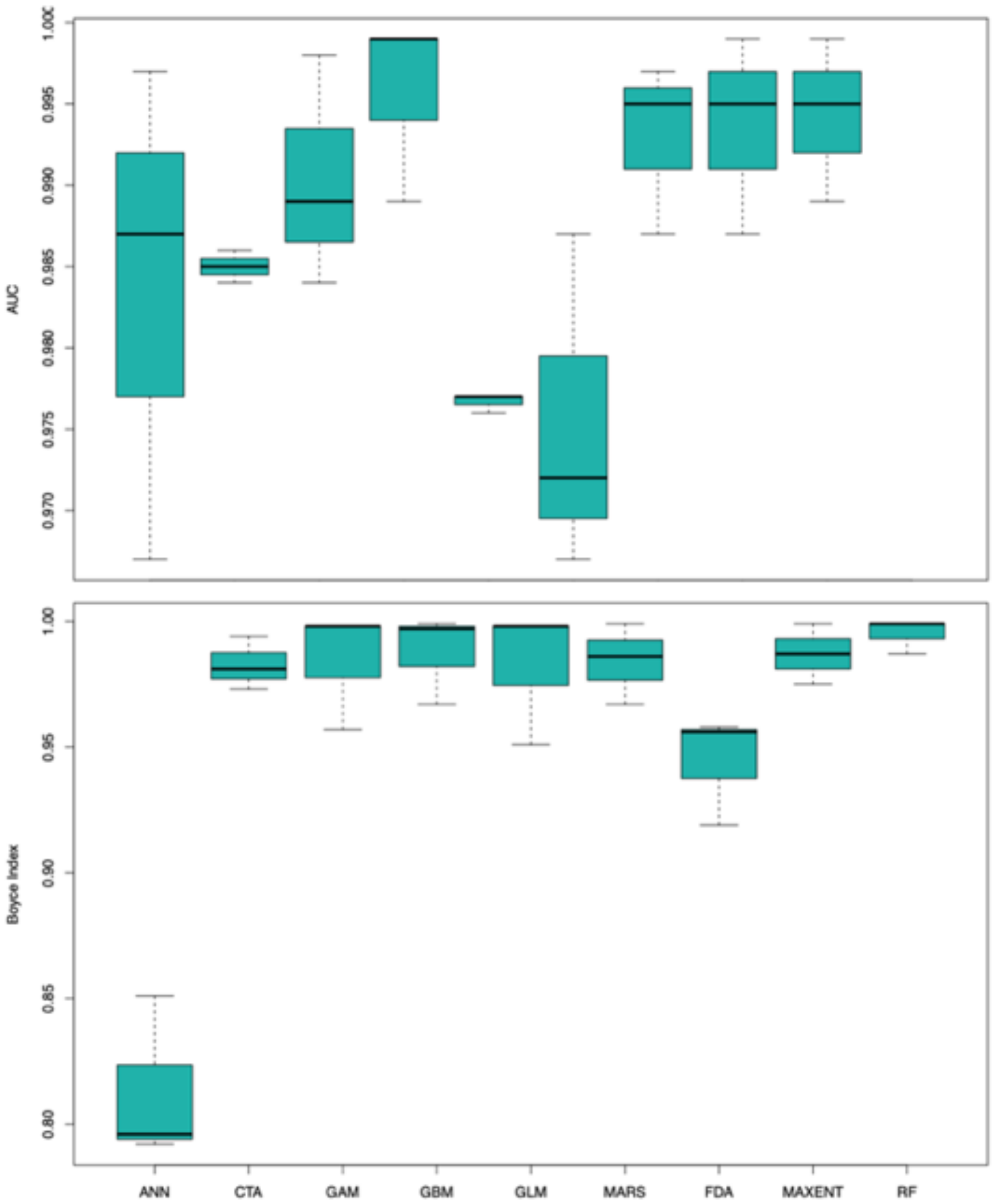


Figure B4. Distribution of current suitable habitat for greater one-horned rhinoceros (*Rhinoceros unicornis*) in and outside protected areas (PAs) of Nepal.

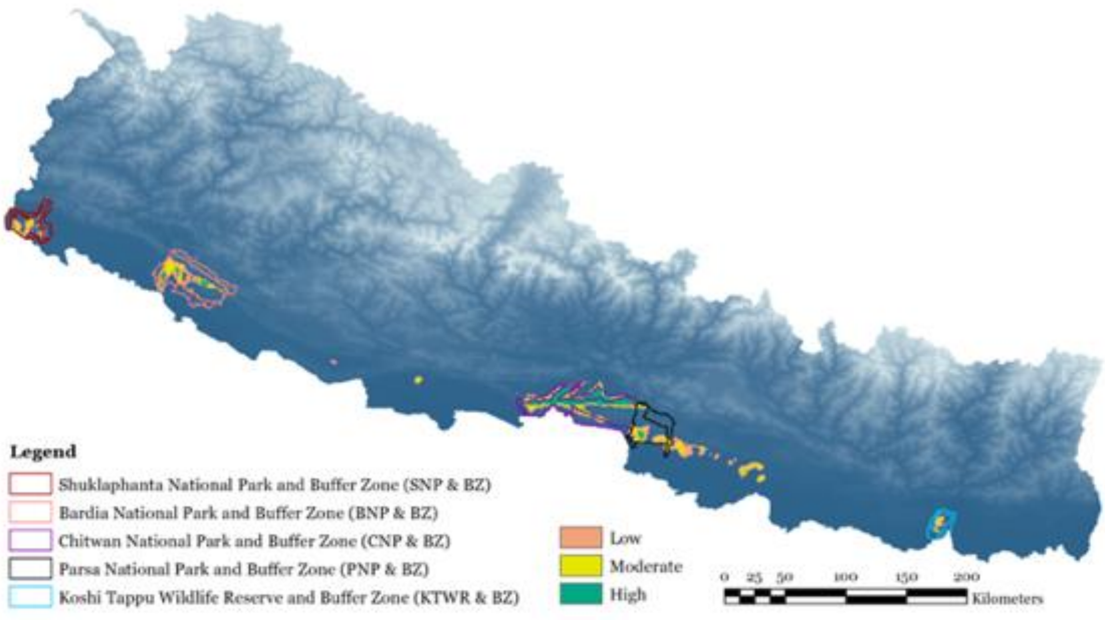
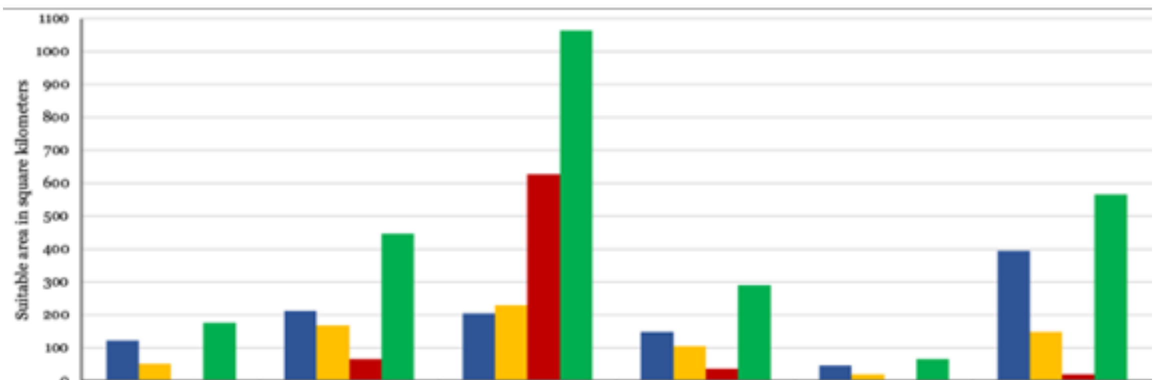


Figure B5. Estimated area of current suitable habitat for greater one-horned rhinoceros (*Rhinoceros unicornis*) in and outside protected areas (PAs) of Nepal.



	SNP & BZ	BNP & BZ	CNP & BZ	PNP & BZ	KTWR & BZ	Outside PAs
Low	122	212	205	148	46	396
Medium	52	168	230	106	21	149
High	2	67	628	37	0	21
Total	176	447	1063	291	67	566

Figure B6. Distribution of current suitable habitat for greater one-horned rhinoceros (*Rhinoceros unicornis*) in different districts of Nepal.

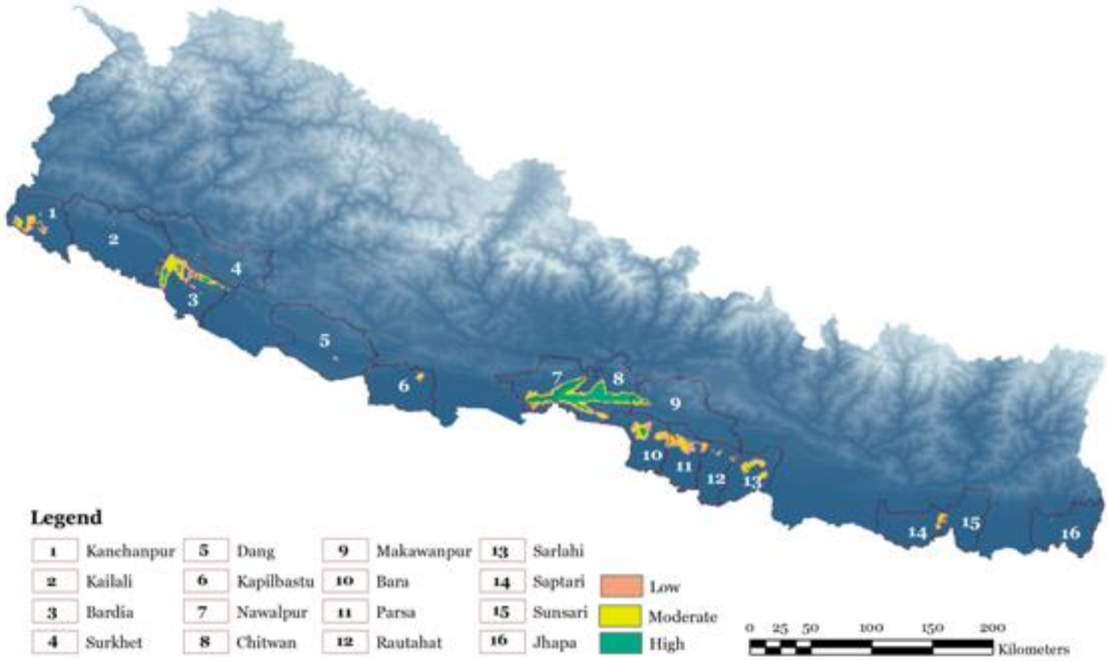
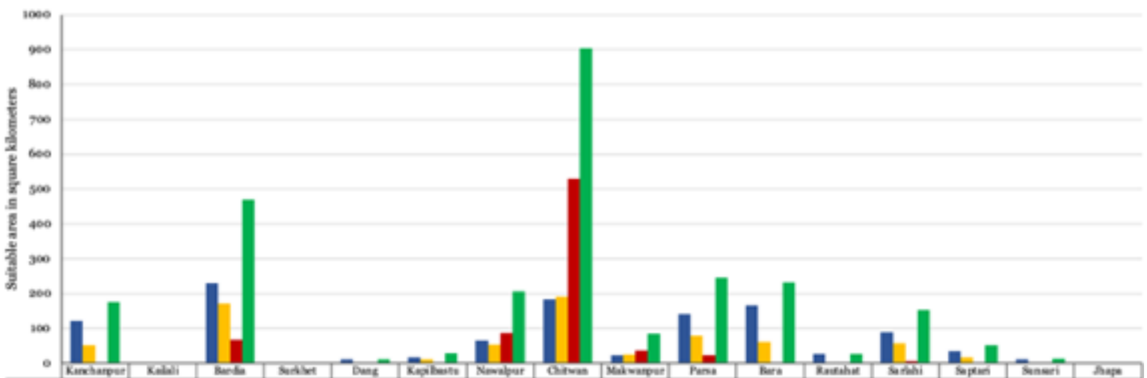


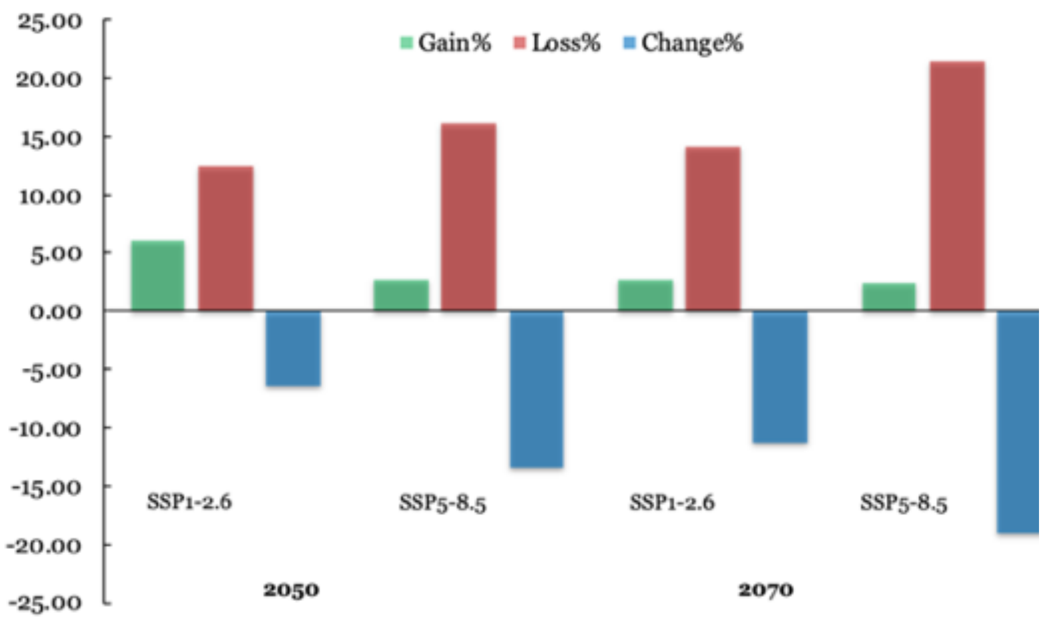
Figure B7. Estimated area of current suitable habitat for greater one-horned rhinoceros (*Rhinoceros unicornis*) in different districts of Nepal.



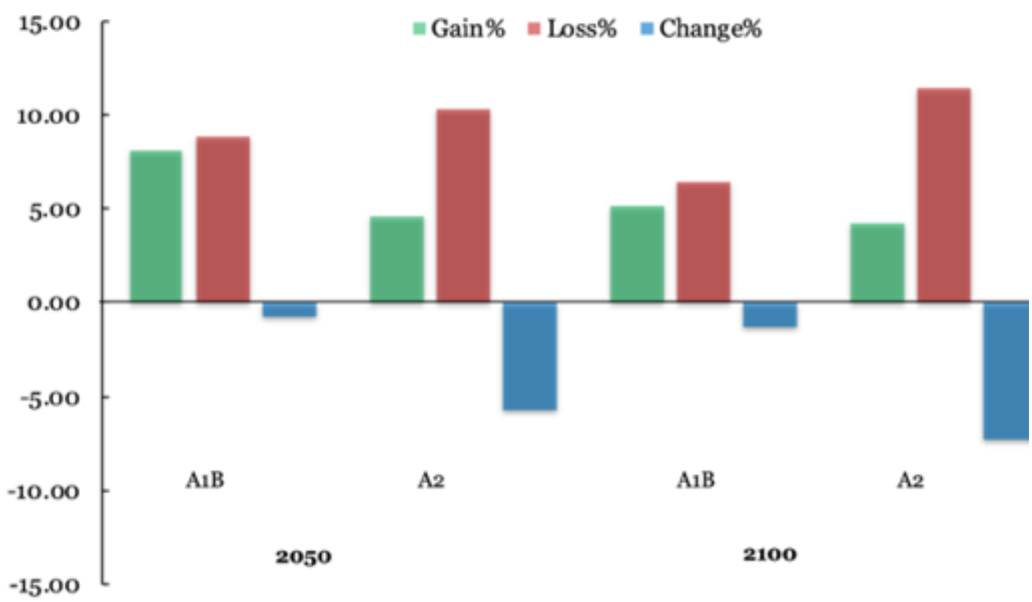
	Kanchanpur	Kailali	Bardia	Surkhet	Dang	Kapilbastu	Nawalpur	Chitwan	Makwanpur	Parsa	Bara	Rautahat	Sarlahi	Saptari	Sunsari	Jhapa
Low	122	2	231	2	11	18	65	183	23	142	167	27	89	34	12	1
Medium	52	0	172	0	0	11	54	192	26	79	62	0	58	18	2	0
High	2	0	67	0	0	0	88	529	37	24	3	0	5	0	0	0
Total	176	2	470	2	11	29	207	904	86	245	232	27	152	52	14	1

Figure B8. Percentage change in habitat suitability for greater one-horned rhinoceros in Nepal predicted by the ensemble model in different climate and land use change scenarios. a. Climate change only and b. Land use change only. SSP1-2.6 and SSP5-8.5 are two different climate change scenarios that anticipate a mean warming of 2°C and 5.5°C by 2100, respectively. A1B scenario – Moderate increase in land use across all resources and A2 scenario – High emphasis on development with adverse impact on the environment.

a.



b.



Appendix C: Checklist for key informant interviews

A. Introduction

1. Introduction of the researcher
2. Description of the research project and its objectives
3. Consent of the participants using participant information sheet and consent form

B. Respondent

1. Name:
2. Age Group: **a.** 18-30 years **b.** 31-40 years **c.** 41 -50 **d.** >50 years
3. Sex: **a.** Male **b.** Female
4. Affiliation: **a.** Government **b.** I/NGO **c.** Community Organization **d.** Others
5. Experience in Biodiversity Conservation: **a.** < 5 years **b.** 5-15 years **c.** > 15 years

C. Checklist

1. Do you know any studies conducted for greater one-horned rhinoceros in the context of climate change? **a.** Yes **b.** No

2. If yes, please list

3. Do you think greater one-horned rhinoceros is vulnerable to climate change? **a.** Yes **b.** No

4. If yes, what could be the extent of climate change vulnerability to greater one-horned rhinoceros in Nepal? **a.** Extremely vulnerable (0.81–1) **b.** Highly vulnerable (0.61–0.80) **c.** Moderately vulnerable (0.41–0.60) **d.** Vulnerable (0.21–0.40) **e.** Least vulnerable (0–0.20)

5. In your opinion, what are the key vulnerability factors that needs to be considered for securing the long-term future of greater one-horned rhinoceros in Nepal in the context of climate change?

6. Please complete and rank the proposed indicators developed for greater one-horned rhinoceros in Nepal.

Rank	Sensitivity	Rank	Exposure
	IUCN red list status		Degree of exposure to increased temperature
	Geographic range		Degree of exposure to precipitation change
	Population size		Drought
	Temperature tolerance		Flood
	Environmental clues for reproduction		Uncontrolled fire
	Food habit of the species		
	Abundance of food resource		
	Freshwater requirements	**Rank**	**Adaptive capacity**
	Habitat requirements		Dispersal ability
	Susceptibility to diseases		Dispersal opportunity
	Invasive species		Generation time
	Poaching		Reproductive rate
	Human-wildlife conflict		Genetic diversity

7. Are there any ongoing conservation activities that are likely to serve as adaptation measures for rhinoceros in Nepal in the context of climate change? **a.** Yes **b.** No

8. If yes, please list

9. What further research needs to be conducted for greater one-horned rhinoceros in relation to the impacts of climate change?

Appendix D: Additional publication during the doctoral research period

Chet Bahadur Oli, Saroj Panthi, Naresh Subedi, Gagan Ale, **Ganesh Pant,** Gopal Khanal and Suman Bhattarai (2018). "Dry season diet composition of four-horned antelope Tetracerus quadricornis in tropical dry deciduous forests, Nepal". PeerJ 6: e5102. https://doi.org/10.7717/peerj.5102 (Q1; Impact Factor 2.984, SNIP 1.895, H Index 70, 69^{th} percentile).

Dry season diet composition of four-horned antelope *Tetracerus quadricornis* in tropical dry deciduous forests, Nepal

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ABSTRACT

It is essential to assess the feeding strategies of threatened species during resource-scarce seasons to understand their dietary niche breadth and inform appropriate habitat management measures. In this study, we examined the diet composition of four-horned antelope (FHA) *Tetracerus* and *quadricornis*, one of the least studied ungulate species, in Banke National Park, Nepal. A total of 53 fresh pellet groups were collected between December 2015 and January 2016 and analyzed using micro-histological fecal analysis technique. First, we prepared 133 micro-histological photographs of different parts of 64 reference plant species. Then we compared 1,590 fragments of 53 fecal samples with photographs of reference plants to assess the percentage of occurrence of different plant species in FHA diet. A total of 30 plant species belonging to 18 different families were identified in fecal samples. Chi-square goodness of fit tests showed that FHA appeared not to feed all plant uniformly. Out of 1,520 identified fragments in fecal samples, 1,300 were browse species and 220 were grass species. Browse represented 85.5% of the identified plant fragments, suggesting that FHA might be adopting a browser strategy at least during winter when grasses are low in abundance and their nutritive quality is poor. Tree species had the highest contribution in the diet (46.55%) followed by shrubs (24.52%). The family Gramineae was consumed in the highest proportion (27.68%) followed by Euphorbiaceae (11.95%). Overall, our results suggest that FHA has the feeding plasticity to adapt to resource fluctuation. Based on the findings of this study, we recommend that dicot plant species—particularly fruit trees and shrubs, which are the major source of nutrients for FHA during resource-lean, dry season—be conserved and natural regeneration of these taxa be promoted.

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Additional Information and Declarations can be found on page 11

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Keywords Banke National Park, Dry season, Feeding ecology, Four-horned antelope, Micro-histological technique

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INTRODUCTION

Knowledge of the diet composition of endangered wildlife species is very important to understand foraging ecology and to devise conservation management actions for their long-term persistence (*Belovsky, 1997*; *Ahrestani et al., 2016*). Such knowledge is particularly important for ungulates in seasonal environments (*Parker, Barboza & Gillingham, 2009*) where resource availability is pulsed in summer and scarcity is particularly acute during the arid winter season (*Styles & Skinner, 1997*; *Ahrestani, Heitkönig & Prins, 2012*). This seasonal flux in quality and quantity of resource availability (e.g., forage) often has nutritional costs for ungulates (*Parker, Barboza & Gillingham, 2009*). For example, reduced availability of preferred forage has been found to alter the composition of graminoid and browse in the diet, negatively influencing the maintenance of body mass of American elk *Cervus elaphus* during winter (*Christianson & Creel, 2009*). In the Mediterranean region, hares *Lepus europaeus* were found to eat herbs (preferred food) in the wet season but increase their diet breadth in the dry season by consuming herbs, fruits, and grains (*Sokos, Andreadis & Papageorgiou, 2015*). In the Indian trans-Himalaya, a medium-sized ungulate grazer, the blue sheep bharal, (*Pseudois nayaur)* was found to have a mixed diet (mainly browse) during resource-limited winter seasons due to reduced availability of graminoids, resulting from competition with domestic livestock (*Mishra et al., 2004*; *Suryawanshi, Bhatnagar & Mishra, 2010*). Change in diet balance affects reproduction, growth, and survival of animal influencing life history parameters such as body mass of adult females which correlates with vital rates like birth mass, growth rates and survival of young (*Pekins, Smith & Mautz, 1998*). Understanding the diet composition of a species during resource-lean season is therefore critical to understand diet plasticity and inform forage management measures.

The four-horned antelope (FHA) *Tetracerus quadricornis* is a medium-sized, solitary ungulate (adult shoulder height 55–65 cm, weight 18–21 kg) endemic to the Indian sub-continent (*Leslie & Sharma, 2009*). It is widely but patchily distributed with fragmented populations in dry deciduous forests from the Himalayan foothills in Nepal to the Gangetic floodplains and the Peninsular mainland in India (*Rahmani, 2001*; *IUCN SSC Antelope Specialist Group, 2017*). Estimates suggest that fewer than 10,000 FHA remain in the wild (*IUCN SSC Antelope Specialist Group, 2017*). However, the population of FHA is suspected to have declined throughout its range, mainly due to habitat loss and fragmentation (*Sharma, Rahmani & Chundawat, 2009*). Although presently it is classified under the 'Vulnerable' category, the assessment of the IUCN Red List of threatened species states that "no subpopulation is estimated to contain more than 1000 mature individuals and it is possible that it is already close to reaching the Endangered category" (*IUCN SSC Antelope Specialist Group, 2017*). In Nepal, FHA is reported to occur in dry deciduous hill sal *Shorea robusta* and mixed Shorea-Terminalia forests in four protected areas of Nepal: Bardia National Park (*Pokharel, 2010*; *Kunwar et al., 2016*), Chitwan National Park (*Pokharel, Ludwig & Storch, 2015*), Parsa National Park and Banke National Park (*DNPWC, 2017b*). Its distribution is restricted to open canopy dry deciduous mixed forests, characterized by short grassland patches, sparse understory and undulating terrain (*Krishna et al., 2009*;

Sharma, Rahmani & Chundawat, 2009; Baskaran et al., 2011). It has been found to be sympatric with barking deer *Muntiacus muntjak* in the monsoon season in Nepal (Pokharel et al., 2015). Nepal's National Parks and Wildlife Conservation Act, 1973 has listed this species under the protected species list, prohibiting hunting (GoN, 1973).

To date, studies on wild populations of FHA have been focused on its distribution (Krishna, Krishnaswamy & Kumar, 2008; Sharma et al., 2013; Pokharel, Ludwig & Storch, 2015) and habitat ecology (Sharma, Rahmani & Chundawat, 2009; Baskaran et al., 2011) with few studies on its feeding ecology (Sharma, Rahmani & Chundawat, 2009; Baskaran et al., 2011; Pokharel et al., 2015; Kunwar et al., 2016). Although these previous studies have been useful in improving our understanding of the natural history, ecology and behavior of the species, we still know little about the responses of the species to changes in habitat components, interspecific interaction with other sympatric species, habitat requirements and population abundance. Since it continues to lose its habitat to agricultural development, livestock grazing, fire, and encroachment by invasive species like Banmara (*Lantana camara)* (Krishna et al., 2009), information on diet composition is particularly important for conservation management interventions. Previous studies showed that FHA predominantly consumes a browse-dominated diet, especially with highly nutritious plant parts such as fruits, flowers and fresh leaves (Baskaran et al., 2011; Pokharel et al., 2015; Kunwar et al., 2016). In summer, when the availability of grass is high, FHA has been found to increase its diet breadth and consume grass species as well as the forb species *Ageratum conyzoides* (Kunwar et al., 2016). *Cynodon dactylon* and *Acacia nilotica* were identified as the main winter dietary species of FHA in Madhya Pradesh, India (Sharma, Rahmani & Chundawat, 2009). The browse to grass ratio was high in the dry winter season and low in the wet monsoon season in the diet of FHA in Bardia, Nepal (Kunwar et al., 2016).

While previous studies on food habits of FHA have provided important insights into its seasonal pattern of feeding revealing its generalized feeding strategy, more in-depth and rigorous studies are needed to confirm if the findings of these species are applicable to all habitat conditions. Most of the previous studies had a small sample size (e.g., 20 pellet samples for dry winter season feeding analysis; (Kunwar et al., 2016)) making it difficult to draw any broad generalization of their diet patterns. Studies with sufficient sample size are needed not only to understand the variability present in the diet but also to ensure the validity of broader inferences. It has been documented that an ungulate species may be forced to consume different food species in different sites due to difference in food density and composition as well as the density of other co-occurring species, habitat, predation risk, monsoon seasonality and competition with sympatric species including livestock (Fritz, Garine-Wichatitsky & Letessier, 1996; Wilsey, 1996; Valeix et al., 2009). Site-specific studies on diet composition can thus be very useful not only in informing site-specific habitat management and species conservation measures but also in improving our understanding of the species feeding ecology in diverse habitat types and developing a general theory. Banke National Park, which lies in the foothills of the Siwalik mountain range, has diverse habitat types from pure *Shorea robusta* forests to mixed dry deciduous Shorea-Terminalia-Albizzia forests. Before it was established as a national park in 2010, it was managed as a production-forest to produce timber and fuel wood. Livestock grazing and human use of the landscape for the collection of fodder and non-timber forests products was also common under previous management regime. The density of other sympatric ungulates (e.g., barking deer, spotted deer *Axis axis*) and the density of potential predators is less in comparison to other national parks where FHA occurs (e.g., Bardia National Park). These peculiarities offer a unique opportunity to assess if food habits of FHA in this national park are consistent with findings from other protected areas.

In this study, we examined the dietary composition of FHA in Banke National Park, Nepal, which is the first of its kind in this park. We specifically examined whether FHA consumes all potential forage plant species equally when the availability of such species is low. We hypothesized that if FHA is a selective browser, it would include a high proportion of browse in its diet. We also predicted that if this animal has a more flexible generalized grazer- browser mixed feeding strategy, it would continue to consume grasses despite their low quality in dry season while balancing the composition of dicots, which retain their nutritive quality during winter. The findings are useful for the government of Nepal and conservation stakeholders for planning forage and habitat management measures.

MATERIALS AND METHODS

Study area

This work was conducted with research permission (1082-2072-9-2) from Department of National Parks and Wildlife Conservation for research in Banke National Park (N27°58′13′ to N28°21′26″ latitude; and E81°39′29″ to E82°12′19″ longitude). This park extends along the Churia foothills of the western part of the Terai Arc Landscape of Nepal (Fig. 1). Established in 2010 as an effort to conserve the tropical deciduous ecosystem and to double the tiger *Panthera tigris* population in Nepal, it covers an area of 550 km^2 in its core zone and 343 km^2 in its buffer zone (DNPWC, 2017a). The park connects the Bardia National Park in the west and Suhelwa Wildlife Sanctuary of India through the forests in the southern part, with its buffer zone. Its elevation ranges between 153 to 1,247 m above the mean sea level. Mean maximum temperature is around 40 °C in summer but drops to very low during winter. Seasons are of four types, monsoon (Jun–Sep; the wet season with abundant rainfall), autumn (Oct–Nov), dry winter (Dec–Feb) and spring (Mar–May). The park contains eight ecosystem types: *Shorea robusta* forest, deciduous riverine forest, savannas and grasslands, mixed hardwood forest, floodplains, Bhabar and foothills of Chure range (DNPWC, 2017a).

Data collection

Field surveys were conducted between December 2015 and January 2016 to collect the pellets of FHA and vegetation samples. Before going to the field for data collection, 22 key informant interviews were conducted with local people and park staff to identify the potential habitats of FHA. Based on information obtained from the key informant interview, we identified FHA hotspots and randomly laid transects of 500 m long and 20 m width on a map. Transect surveys are widely used method to collect fecal samples of ungulates (Pokharel et al., 2015; Kunwar et al., 2016). The survey team, which included the first author, three field assistants and an expert from National Trust for Nature

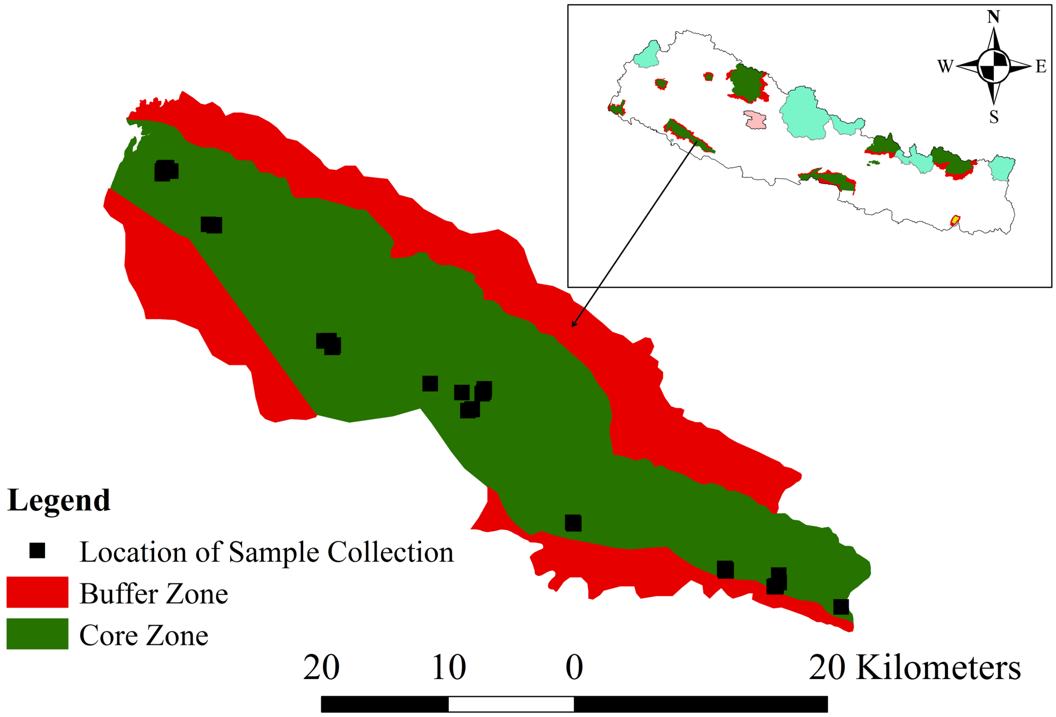

Figure 1 Map of the study area, Banke National Park, showing the core and buffer zones and the locations of sample collection. The inset shows the location of Banke National Park within Nepal. Colored areas on the inset map indicate other protected areas (source of shape file: *UNEP-WCMC & IUCN, 2017*).
Full-size DOI: 10.7717/peerj.5102/fig-1

Conservation - Bardia Conservation Program walked along the 40 transects to collect the pellets samples. Wherever we recorded pellets, we established a plot of 10 m × 10 m around the pellet and collected the fecal samples and sample of all species of vegetation within these plots for lab analysis. This is a recommended and widely used plot size for the study of dietary patterns of wild animals (*Schemnitz, 1980*; *Panthi, 2011*; *Panthi et al., 2012*; *Aryal et al., 2015a*). Leaves, twigs, fruits, and barks of all plants were collected.

The pellets of FHA were identified checking the shape, size, and texture of pellets following *Pokharel (2010)* who has confirmed size and shape details of FHA pellets by installing camera traps in the suspected middens of FHA in Bardia National Park (see Fig. S1). These FHA pellets were available as a reference for the verification of the pellets at Bardia National Park. These reference pellets and the assistance of a trained wildlife technician (Mr. Binti Ram Tharu) from NTNC-BCP helped to minimize misidentification of pellets during the field survey. In drier habitat, the pellets can decay very rapidly, and further laboratory analysis can be difficult (*Jung & Kukka, 2016*) so fresh pellets, not more than seven days old, were identified based on texture and moisture content. We randomly sub-sampled 25 % each sample group for further analysis. These samples were air dried for five days in the field to remove moisture and prevent fungal growth. The collected plant samples were preserved in the herbarium and stored in the well ventilated dry room of the Banke National Park Office, Overy Banke and sent to Central Department of Botany, Tribhuvan University, Kathmandu for further verification.

Micro-histological analysis

Micro-histological fecal analysis technique was used to determine plant composition of FHA fecal matter (*Sparks & Malechek, 1968*; *Holechek & Gross, 1982*). This method is widely used as a diet analysis tool to investigate the dietary composition of ungulates (*Shrestha, Koirala & Wegge, 2005*; *Nagarkoti & Thapa, 2007*; *Aryal et al., 2015b*; *Jung, Stotyn & Czetwertynski, 2015*; *Wangchuk, Wegge & Sangay, 2016*). This method involves microscopic recognition of indigestible plant fragments of plant groups and preparation of reference and fecal slides and their interpretation. Samples of plant parts were dried in the oven at 60 °C in the laboratory and ground separately into powder using an electric blender. The powder of each sample was sieved using a 212 mesh.

The micro-histological slides of reference plants, as well as fecal sample slides, were prepared using the methods of *Norbury (1988)*. In this method, reference samples or fecal samples were placed in Petri dishes and bleached with 50 ml of 4% sodium hypochlorite for 6–24 h at room temperature to remove mesophyll tissue and to render the epidermis identifiable. The bleached contents were then rinsed well in a sieve, and then the rinsed fragments were stained with a few drops of a gentian violet solution (1 g/100 ml water) for 10 s and again well rinsed. The stained fragments were mounted on standard microscope slides in a DPX Mountant medium and covered with a cover slip (*Norbury, 1988*). Both reference slides and fecal pellet slides were observed immediately after preparation at magnification 400× with a digital microscope, and each fragment was auto-photographed using Bel Photonics (*Norbury, 1988*; *Panthi et al., 2015*). A diet analysis expert (Mr. Binod Shrestha) trained the first and fourth authors to identify the plant fragments. A total of 133 micro-histological photographs of different features of 64 plant species were prepared for the reference library. For each sample, 30 non-overlapping and distinguishable fragments were observed by moving the slides from left to right in the microscope. Specific histological features such as cell wall structure, shape and size of cells, trichomes; and shape and size of stomata were identified as key features to match the features of fecal plant fragments with reference plant (*Panthi, 2011*; *Aryal et al., 2012*).

Data analysis

The plant fragments identified from the micro-histological analysis of the pellet samples were assigned into one of the following four levels of classification with different categories under each classification: (1) growth form: (i) grasses, (ii) forbs, (iii) shrubs, (iv) climbers (vine plants) and (v) trees; (2) class: (i) monocots and (ii) dicots; (3) family; and (4) species. The idea behind this classification was to assess the relative contribution of different categories of plant taxa under each classification to the diet of FHA. We added the total number of fragments of each species and rounded to the nearest 5 fragments.

Diet composition was expressed as the percentage occurrence of plant species (*Cavallini & Lovari, 1991*).

$$\text{Percentage Occurence} = \frac{\text{Number of fragments of a species or other category}}{\text{Total number of plant fragments identified}} \times 100$$

we performed the goodness of fit chi-square test to identify whether FHA ate all plants uniformly. Our research hypothesis was that FHA would not eat all plants species, family, growth form (grass, forb, climber, shrub, and tree) and class (monocot and dicot) uniformly. We also hypothesized that FHA would be a browser during winter. All tests were performed using Microsoft Excel and R software version 3.4.1 (*R Core Team, 2013*).

RESULTS

A total of 1,590 plant fragments from 53 pellet samples were analyzed through micro-histological technique. Out of the total plant fragments, (4.4%) were unidentified, and these were excluded from statistical analysis. A total of 30 species belonging to 18 different families were identified in the pellets of FHA. Out of 30 species, the FHA diet included 14 tree species, eight shrubs, two forbs, five grasses, and one climber (Table 1). The dicot shrub species *Phyllanthus emblica* had the highest percentage occurrence in FHA diet (6.92%) whereas the dicot shrub *Clerodendrum viscosum* had the lowest percent occurrence (0.94%). FHA appeared not to feed all plant species uniformly ($\chi^2 = 312.56$, $df = 29$, $p < 0.001$) at the species level. Similarly, at the family level, FHA did not consume all plant families uniformly ($\chi^2 = 1982.41$, $df = 17$, $p < 0.001$). The family Gramineae which consists of 9 species contributed 27.68% of the diet whereas Verbenaceae contributed only 0.94% of the diet (Table 1). At the growth form level, FHA did not consume all growth forms (grass, forb, climber, shrub, and tree) uniformly ($\chi^2 = 1001.71$, $df = 4$, $p < 0.001$). In general, trees constituted a large proportion of diet contributing 46.55%, followed by shrubs (24.52%,), grasses (13.84%,), forbs (8.18%) and climber (2.52%) (Table 1).

Similarly, FHA did not use plants equally at the class (monocotyledonous and dicotyledonous) level ($\chi^2 = 229.01$, $df = 1$, $p < 0.001$). A total of 66.36% of FHA's diet was composed of dicotyledonous plants, and 29.25% of FHA's diet was monocotyledonous. The study identified 1,300 fragments of browse (forbs, climbers, shrubs, and trees) and 220 fragments of grass in FHA's diet. The ratio of browse to grass was found to be 85.53%: 14.47%, showing a strong affinity towards browse plant species in the dry season.

DISCUSSION

Assessment of the dietary choices of a species during low resource availability period is critical to understand its foraging plasticity and inform subsequent habitat and forage management measures. In this study, we examined the winter season food habit of FHA, a sparsely distributed yet threatened species native to Nepal and India (*IUCN SSC Antelope Specialist Group, 2017*), based on micro-histological analysis of the collected fecal pellet samples. We hypothesized that if FHA is a selective browser during winter, it should show evidence of selectively foraging on browse in its diet.

Our result shows that dicots had a significantly higher percentage of occurrences in FHA pellets than monocots (suggesting that FHA might be adopting a browser strategy at least during winter when graminoids and grass species are low in abundance). Plant species differ in protein and fiber contents which influences animals' food choice (*Klaus-Hügi et al., 1999*). Smaller antelopes have smaller stomach compared to larger ruminants but

Table 1 **Percentage compositions of various plant categories identified in pellets of FHA.**

Family	Species	Class	Growth form	Percent occurrence
Gramineae	*Hemarthria compressa*	Monocot	Forb	6.29
	Imperata cylindrica	Monocot	Grass	4.09
	Eulaliopsis binata	Monocot	Grass	3.14
	Bambusa vulgare	Monocot	Tree	2.83
	Thysanolaena maxima	Monocot	Shrub	2.83
	Themeda triandra	Monocot	Grass	2.52
	Heteropogon contortus	Monocot	Grass	2.2
	Cynodon dactylon	Monocot	Forb	1.89
	Digitaria spp.	Monocot	Grass	1.89
Gramineae total				27.68
Compositae	*Terminalia alata*	Dicot	Tree	4.4
	Terminalia chebula	Dicot	Tree	2.52
	Terminalia belerica	Dicot	Tree	1.57
Compositae total				8.49
Euphorbiaceae	*Phyllanthus emblica*	Dicot	Shrub	6.92
	Mallotus philippensis	Dicot	Tree	5.03
Euphorbiaceae total				11.95
Leguminoseae	*Acacia catechu*	Dicot	Tree	4.72
	Bauhinia vahlii	Dicot	Climber	2.52
Leguminoseae total				7.24
Rubiceae	*Xeromphis spinosa*	Dicot	Tree	5.97
Rhamnaceae	*Zizyphus mauritiana*	Dicot	Tree	4.4
Oleaceae	*Nyctanthes arbortristis*	Dicot	Shrub	3.77
Apocynaceae	*Carissa spinarum*	Dicot	Shrub	3.46
Dipteriocarpaceae	*Shorea robusta*	Dicot	Tree	3.46
Lythraceae	*Woodfordia fruiticosa*	Dicot	Shrub	2.83
Anacardiaceae	*Buchanania lanzans*	Dicot	Tree	2.52
Myrtaceae	*Eugenia* spp.	Dicot	Tree	2.52
Sapindaceae	*Schleichera oleosa*	Dicot	Tree	2.52
Rutaceae	*Aegle marmelos*	Dicot	Tree	2.2
Tilaceae	*Grewia* spp.	Dicot	Shrub	2.2
Myrsinaceae	*Myrsine semiserrata*	Dicot	Tree	1.89
Liliaceae	*Asparagus phillipensis*	Monocot	Shrub	1.57
Verbenaceae	*Clerodendrum viscosum*	Dicot	Shrub	0.94
Unidentified				4.4
Identified total				95.6
Dicot total				66.36
Monocot total				29.25
Tree total				46.55
Shrub total				24.52
Grass total				13.84
Forb total				8.18
Total				100

have high metabolic requirements. This prohibits them from feeding large quantities of coarse grass species that are high in fiber and low in protein (*Owen-Smith, 1992*). In dry deciduous tropical forests, graminoids lose their palatability and nutritive quality during the dry season in comparison to wet season (*Sukumar, 1989*; *Baskaran, 1998*). This could probably explain why monocots were not eaten as much as dicots. *Berwick (1974)* and *Sharma, Rahmani & Chundawat (2009)* concluded that FHA is a selective feeder. The food selectivity by FHA may result from nutritional requirements; they need to decrease fiber intake, and maximize protein intake in order to increase digestibility.

Our results support the hypothesis that FHA adopts a browser strategy during winter, but we cannot rule out the possibility that FHA is a mixed feeder with substantial feeding plasticity to balance nutritional requirements. The presence of grasses in 14.3% of plant fragments suggests that grasses also have a substantial contribution to FHA diet. Our results of higher contribution of browse are consistent with the findings of *Kunwar et al. (2016)* who reported that browse constituted nearly two-thirds (66.95%) of the overall diet while grass species occurred only 13.68% (the rest, 19.77% remained unidentified). A study from India has, however, shown that FHA had more or less equal proportion of grass and browse in FHA diet in the winter season (14 grass, five herbs, four trees and one shrub) (*Baskaran et al., 2011*). This discrepancy in findings could be due to differences in study location, sample size and the high proportion of unidentified plants in their analysis. *Baskaran et al. (2011)* had 48% of the plant remains in their FHA fecal samples which could not be identified whereas in our study we have only 4.40% of the plant fragments that remained unidentified.

Our results showed plant species differ significantly in their contribution to FHA diet (Table 1). The shrub *Phyllanthus emblica* of the family Euphorbiaceae occurred most frequently (6.92%) in FHA diet. In their study in Bardia National Park, *Kunwar et al. (2016)* identified *Berlaria cristata* as the shrub species with the highest frequency of occurrence (5.33% of total fragments identified) in FHA diet in the winter season. The cafeteria experiments of *Berwick (1974)* in Gir forest ecosystem, India, and *Sharma, Rahmani & Chundawat (2009)* in Van Vihar National Park cum Zoo in Bhopal, India, showed that *Zizyphus mauritiana* contributed most to the diet of captive FHAs in winter. Our study also revealed a moderate contribution (4.40%) of *Zizyphus mauritiana*. Although *Zizyphus mauritiana* is highly palatable, its thorns inhibit its consumption in the natural habitats (*Berwick, 1974*). The FHAs in the Banke National Park do not appear to use many plants of the climber growth form as indicted relatively low percentage of occurrence in fecal samples.

FHA distribution is determined by the tree species richness in India (*Sharma, Rahmani & Chundawat, 2009*). In our study, tree species constituted a substantial proportion of FHA diet. On the whole, trees contributed the highest proportion (46.54%) of diets of FHA followed by shrubs (24.53%), grasses (13.84%), forbs (8.18%) and climbers (2.52%). But *Baskaran et al. (2011)* showed in tropical forests of southern India during the dry season that grasses were the major constituent of FHA diet (28.6%) followed by trees (8.0%), shrubs (5.6%) and herbs (6.7%). Our findings of the higher proportion of browse in FHA's diet supports the results of the feeding observations made on this species in Bardia National

Park, Nepal (*Kunwar et al., 2016*) and captive antelopes in India (*Solanki & Naik, 1998*). Our results also show the high proportion of the Gramineae family in the diet of this species similar to the findings of *Kunwar et al. (2016)*. Although *Baskaran et al. (2011)* assert that FHA is the generalist in feeding strategy, our study showed that it consumes more browse plant species than grasses in the winter season. According to *Hofmann (1989)*, concentrate feeders choose a high quality diet and show a remarkable degree of forage selectivity. Some herbivores such as elephants graze in the monsoon season and browse in the winter season (*Pradhan et al., 2008*). Our results show that FHAs in Banke National Park may have the plasticity to behave as concentrate feeders, consuming different proportions of various plant species and growth form.

During the monsoon season grass availability is high so the ungulates behave more like pure grazers because they can find palatable grasses everywhere, but they behave more like browsers in winter, a season of resource scarcity (*Pradhan et al., 2008*). Consistent with that finding, we found the FHA to act as a browser in resource scarce seasons. Browse was the major contributor to FHA's diet in all seasons, but the proportion of trees in the diet was high in the winter season and low in summer and monsoon season (*Kunwar et al., 2016*). Similarly, we found a high browse to grass ratio in winter season.

The micro-histological analysis method which we used for our study, includes multiple successive sampling from the individuals, pellets and epidermis fragments. Sample size, therefore, could affect the estimates of species diversity in the diet (*Katona & Altbäcker, 2002*). In our study, we randomly read 30 plant fragments per slide per pellet from 53 independent pellet groups for determining FHA diet which we hope provides a reasonable sample size. Of the total plant fragments, only 4.40% diet remained unidentified in this study. This percentage was 48% in *Baskaran et al. (2011)*. *In-vitro* digestibility also greatly influenced the results of micro-histological analysis particularly in the estimation of grass and forb content (*Vavra & Holechek, 1980*). FHA eats fruits, flowers and fresh leaves (*Berwick, 1974*; *Baskaran et al., 2011*) which are highly digestible. Thus, this percentage of unidentified plants in the diet could be due to high mastication and efficient digestion by the animal. We collected pellets and plants samples from only one protected area during a single season. More rigorous and detailed information could be obtained from multi-season and multi-site study.

Overall, our results suggest that FHA has the feeding plasticity to adapt to resource fluctuations. Future studies on nutrient content analysis of different diet plant species and causes of changes in diet composition across seasons would be particularly useful for habitat conservation and management. Based on the findings of this study, we recommend that dicots, particularly fruit trees and shrubs, which are the major source of nutrients for FHA especially during winter, be conserved and natural regeneration be promoted.

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ADDITIONAL INFORMATION AND DECLARATIONS

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Competing Interests

The authors declare that there are no competing interests.

Author Contributions

- Chet Bahadur Oli conceived and designed the experiments, performed the experiments, analyzed the data, contributed reagents/materials/analysis tools, prepared figures and/or tables, authored or reviewed drafts of the paper, approved the final draft.
- Saroj Panthi analyzed the data, contributed reagents/materials/analysis tools, prepared figures and/or tables, authored or reviewed drafts of the paper, approved the final draft.
- Naresh Subedi and Ganesh Pant authored or reviewed drafts of the paper, approved the final draft.
- Gagan Ale performed the experiments, authored or reviewed drafts of the paper, approved the final draft.
- Gopal Khanal contributed reagents/materials/analysis tools, authored or reviewed drafts of the paper, approved the final draft.
- Suman Bhattarai conceived and designed the experiments, performed the experiments, authored or reviewed drafts of the paper, approved the final draft.

Field Study Permissions

The following information was supplied relating to field study approvals (i.e., approving body and any reference numbers):

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Data Availability

The following information was supplied regarding data availability:

The raw data are provided in the Supplemental Files.

Supplemental Information

Supplemental information for this article can be found online at http://dx.doi.org/10.7717/peerj.5102#supplemental-information.

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Appendix E: Media coverage of the research findings

Appendix E1: News feature published in The Guardian
https://www.theguardian.com/environment/2022/jan/24/wildlife-experts-plan-future-rhino-nepal-aoe

The age of extinction
Conservation

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About this content

Neelima Vallangi

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Leading the charge: wildlife experts plan for future of Nepal's rhinos

One-horned species was nearly extinct before poaching was curbed. Now the climate crisis could pose a greater threat

The one-horned rhinoceros in Nepal's Chitwan national park. Photograph: Sergi Reboredo/Alamy

Ganesh Pant worries about the future. While he delights in the stunning conservation accomplishment that has seen the numbers of greater one-horned rhinos in Nepal jump from 100 in 1965 to 752 in 2021, he wants to be sure that success will continue.

Before the 1950s, as many as 1,000 rhinos roamed the grasslands and forests of Nepal. But by 1965, rampant hunting, poaching and changes in land use had brought the species close to extinction in the country. Then, the national park was established in 1973 and thanks to concerted conservation efforts, the rhino population began to bounce back.

Today, Chitwan national park has the second-largest concentration of one-horned rhinos after India's Kaziranga national park, with the two parks accounting for 70% of the species' global population. Besides playing a key role in the ecosystem, Chitwan's rhinos help attract huge numbers of tourists each year, contributing considerably to the country's economy. In 2019, there were 185,000 foreign visitors to the park.

Greater one-horned rhinos at Chitwan national park. More than 100 of the species died of natural or unknown causes between 2016 and 2020. Photograph: Hemis/Alamy

But the greater one-horned rhino is still classified as vulnerable by the International Union for Conservation of Nature (IUCN), and a new threat has emerged. While there were only about five confirmed deaths due to poaching between 2016 and 2020, more than 100 rhinos were reported to have died of natural or unknown causes. "Poaching used to be the reason for rhino mortality. But in recent years, the government has done an excellent job in protecting rhinoceroses from poaching," says Pant, a conservation officer working for the Department of National Parks and Wildlife Conservation in Nepal.

> **We are talking about adaptation because mitigation might take a long time ... it's not under our control**
> **Ganesh Pant, conservation officer**

"At this point, we cannot say that [these deaths are] only due to the impacts of climate change," says Pant, who is studying for a PhD with the University of Southern Queensland, Australia. But he believes that the climate crisis could be one of the underlying causes. Pant and a team of researchers developed a set of 21 indicators to assess the vulnerability of the rhinos in Nepal to climate change. They concluded that they were "moderately vulnerable" to the impacts of global warming, primarily due to the likelihood of invasive species and extreme flooding in prime rhino habitat, along with habitat fragmentation, droughts and forest fires.

"I've tried to look at the likely shift in the habitat of the rhinoceros in Nepal in the next 50 years in different climate change scenarios," he says. "And to find out what would be the adaptation measures - to enhance the resilience of the rhinoceros in the context of likely impacts of climate change."

A one-horned rhinoceros grazing at Chitwan. They require enough flooding to maintain their grassland habitat. Photograph: imageBroker/Alamy

Rhinos are a highly adaptive species, hence their categorisation as moderately vulnerable. "That means it's not at risk of immediate extinction due to climate change, but we have to consider it at the moment if we are to sustain the population for the long run," says Pant.

Wendy Foden, a conservation biologist, agrees: "We are currently experiencing the fastest rate of climatic change in 65m years. If conservation planning efforts are to remain relevant and strategic, they must include the best available science on anticipated future impacts."

Recent studies have shown several species of animals are already feeling the impact and are responding by shifting their habitats and even growing appendages or larger beaks, legs and ears to better regulate their body temperature in some cases. However, predicting the effects of the climate crisis on biodiversity is a challenge, in part because of the lack of long-term observational data.

Q&A

How are the climate and biodiversity crises linked?

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"It would be very unwise to plan species conservation actions before thoroughly assessing what can go wrong for that species, the mechanisms of potential impacts, how sensitive it is to these, and whether it is likely to be able to adapt of its own accord," says Foden, who chairs the IUCN Species Survival Commission's climate change specialist group, and led the development of IUCN guidelines for assessing species vulnerability to climate change.

"These provide the foundations from which to build solid conservation plans. So in most cases, climate change vulnerability analysis is imperative for species conservation planning."

A greater one-horned rhino in Janakauli community forest, a buffer zone bordering Chitwan. Working more closely with the local community, as well as increased security, has helped rescue Nepal's rhinos from poachers. Photograph: Gemunu Amarasinghe/AP

Pant's research looked at the one-horned rhino's climate crisis vulnerability according to sensitivity, exposure and adaptive capacity. Sensitivity is how strongly a species is likely to be affected by climate change; exposure is the extent to which their physical environment will change; and adaptive capacity is their ability to overcome the negative impacts of climate change.

While the one-horned rhinos fared well in the climate change vulnerability analysis, the changing climate is already threatening the rhino population in Chitwan national park. The species is dependent on a certain level of annual flooding to maintain its habitat.

But over the last few years, extreme flooding has affected the park several times, sweeping rhinos downstream into India and bringing debris and rubbish from upstream. Drought is also occurring more often, leading to fewer of the ponds that rhinos wallow in to regulate their temperature. Invasive species such as the bitter vine (*Mikania micrantha),* and *Chromolaena odorata,* a flowering shrub also known as Siam weed, are spreading at an alarming pace, encroaching into the grasslands that are the rhinos' prime habitat. Global heating is expected to exacerbate extreme flooding and prolonged droughts, as well as the rapid growth of invasive species in the future.

More frequent and longer droughts are likely as climate change intensifies. This will cause problems for rhinos, which need ponds to wallow in to help regulate their temperature. Photograph: Galyna Andrushko/Alamy

According to Naresh Subedi, conservation programme manager at Nepal's National Trust for Nature Conservation, better population and habitat management are crucial in the fight against the climate crisis. "Currently, our rhino population increment rate is 5%, for example. If we maintain 8% rhino population increment annually, then even if we lose 3% of the rhino population by the annual flood or climate-induced incident, they still will be in a good position."

Pant agrees, noting that while floods are only seasonal, maintaining a suitable habitat all year is vital to sustain a healthy population. Another recent study by his team found that more than a third of rhinoceros habitat in Nepal could become unsuitable within 50 years due to mostly to climactic changes, but also land use changes.

Rising tide: why the crocodile-like gharial is returning to India's rivers

Read more

Pant has proposed seven adaptation measures to secure the one-horned rhino's future that include: maintaining the ponds rhinos need for wallowing; managing the impacts of floods; creating "refugia"; and actively managing habitats to provide a mosaic of grasslands and wetlands.

"We are talking about adaptation because mitigation might take a long time and also depends on several factors," says Pant. "It's not under our control, so the only thing we can do is safeguard the rhinoceros under these extreme conditions. That's our priority at the moment."

Find more age of extinction coverage here, and follow biodiversity reporters Phoebe Weston and Patrick Greenfield on Twitter for all the latest news and features

Appendix E2: News article published in OnlineKhabar National Daily Newspaper, Kathmandu, Nepal

https://english.onlinekhabar.com/climate-change-impact-on-nepal-wildlife.html

onlinekhabar EN

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Climate change impact on Nepal's wildlife is already visible. It's high time stakeholders made efforts to stop this

Bhuwan Singh Bist and Nishan KC
July 29, 2021

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Spotted deer in the Suklaphanta National Park. Photo: Wikipedia Commons

Nepal is ranked the world's fourth most vulnerable country to climate change impacts. The Department of Hydrology and Meteorology (DOHM) in 2017 studied Nepal's climatic trends from 1971 to 2014 and found that the country's average annual maximum temperature climbed by 0.056 degrees celsius. Climate change's negative impacts can be distinct in a variety of sectors across the country, particularly in the wildlife sector. With a wide altitudinal range from 60 to nearly 8849 m, coupled with heterogeneous climatic and topographic conditions, Nepal is considered a global wildlife hotspot, with 1.1 per cent of the world's known fauna. More than 23 per cent of the land area has been declared as a protected area in Nepal.

Climate change has popped up as a top threat to wildlife in recent decades across the globe. The current global climate shift has already begun to affect wildlife assemblages and ecosystem dynamics, and Nepal's wildlife is no exception. Climate-induced events have impacted Nepal's wildlife both within and outside the protected areas. The principal impacts of climate change on Nepal's wildlife include: shifting in spatial distribution and suitable habitats of species along the altitudinal gradients; reduction in population size of species due to illicit trade and poaching; increased forest fire, floods, wildlife diseases and invasive species; and shrinkage of habitat and local extinction. Although all wild species, from small to large, are vulnerable to climate change in Nepal, few research works have been documented to establish the impact of climate change on wildlife such as on one-horned rhinoceros, Asian elephant, Himalayan musk deer, blue sheep, Bengal tiger, snow leopard, common leopard and bats.

Examining documented scientific research

File: A one-horned rhinoceros in Chitwan National Park

A study report published in 2020 by Ganesh Pant and his team revealed that the one-horned rhinoceros populations in Nepal are moderately vulnerable to the possible impacts of climate change and they may be impacted indirectly as a result of extreme weather events such as floods and droughts, food shortages caused by the spread of invasive plant species, and anthropogenic pressures such as hunting, poaching, human-wildlife conflict, and pollution. Similarly, a study published in 2021 by SanjanThapa's team on the distribution impacts of five species (greater short-nosed fruit bat, great Himalayan leaf-nosed bat, intermediate horseshoe bat, Leschenault's rousette, greater false vampire) in the Himalayas under climate change found that the potential distribution range for greater false vampire and greater short-nosed fruit bat is expected to expand by an average of 30% and 15%, respectively while that for, Leschenault's rousette, intermediate horseshoe bat and the great Himalayan leaf-nosed bat are expected to dwindle by an average of more than 18%, 15% and 4%, respectively.

The potential habitat of snow leopard and blue sheep will be reduced with future climate change, according to a study published in 2016 by Achyut Aryal and his team on the future distribution and impacts on snow leopard and blue sheep under climate change. The predicted distribution of snow leopard will be reduced by 14.57% in 2030 and by 21.57% in 2050 after including the predicted distribution of blue sheep. A study published in 2012 by Jessica L Forrest's research team on the vulnerability of snow leopards to climate change revealed that the substantial reduction of the alpine zone will result in a decrease in the current snow leopard habitat in Nepal by up to 40% under high emission scenarios.

In the same way, Sandro Lovari and his colleagues published a research report in 2013, focusing on the food habits and competition of two big cats–the snow leopard and the common leopard–under climate change and found that the impacts of climate change have been skyrocketing in Nepal's mountains, resulting in an increase in common leopard habitat while the habitat of the snow leopard will be significantly reduced. In 2018, Rajapandian Kanagaraj and his research team published a study report on Asian elephant range shift in Nepal and India as a result of climate change, finding that 41.8% of the current 256,518 km^2 of habitat will be strayed by the end of the century due to climate-induced effects and anthropogenic pressures. Ganga Ram Regmi and his team published a study report on Assamese monkeys in 2018 that revealed the future distribution of their habitat was heavily influenced by climate parameters such as precipitation, annual temperature, and seasons. Pramod Lamsal and his team published a study in 2018 on the effects of climate change on musk deer habitat distribution, which found that by 2070, 29.47% of suitable habitat for musk deer will be reduced.

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Climate change as a threat

File

Aside from the studies mentioned above, there is ongoing evidence to indicate the impacts of climate change on Nepali wildlife, particularly in the Terai plains. Prolonged droughts, changes in rainfall patterns, and greater floods are all consequences of climate change, which have a direct impact on wildlife habitat and their distribution patterns. Few among many examples include the drowning of one of the last remaining populations of blackbuck (40 out of 281) in 2015 from Krishnasaar Conservation Area. Similarly, Chitwan National Park, which is the stronghold and provides refuges to the second largest population of one-horned rhinoceros in the world, is affected by the adverse effect of climate change along with many flagship species to lesser-studied small mammals due to the flash floods in Rapti and Narayani rivers. Wild mammals, particularly swamp deer, spotted deer, wild water buffalo, one-horned rhino, and blackbuck, have been killed or displaced on a regular basis because of heavy floods across the Terai protected area.

The Bengal tiger was observed at 3,165 metres in Ilam and 2,500 metres in Dadeldhura districts in 2020 as wildlife experts speculate one of many reasons may possibly be the impacts of climatic change. As a result of habitat fragmentation and the effects of climate change, the human-wildlife conflict has been on the rise in recent years. Wild mammals such as Asian elephants, common leopards, Bengal tigers, one-horned rhinoceros, bears, and wild boars are the common species involved in human fatalities and injuries.

Krishna Prasad Acharya's team examined the trend of wildlife attack records in Nepal from 2010 to 2014 and found that the majority of frequent leopard attacks on humans happened outside protected areas, primarily around human settlements, during April, the driest month of the year. This has really put challenges on park managers, concerned stakeholders including the government who have been working for decades to recover multiple species before they are only remembered in the pictures. Nepal has been achieving historic success in recovering multiple species whether it is one-horned rhinoceros or Bengal tiger or blackbuck or other species. It is also equally important to maintain such success, in the long run. However, factors like climate change have been the most pressing threat that could definitely stop the successful history of wildlife conservation in the world putting an end to decades of struggle in species conservation and ecosystem restoration.

The way forward

File: Shivapuri National Park

Forests play an integral role in minimising the negative impact of climate change by regulating the carbon cycle, balancing the ecosystem, promoting healthy wildlife habitats, and providing essential goods and services for sustainable growth and livelihood. Research works have revealed that the world's forests stored about twice as much carbon dioxide as they emitted between 2001 and 2019. So, to safeguard the wildlife habitat and minimise the impact of climate change on them, the foremost step is to oppose actions that lead to deforestation or forest degradation throughout Nepal. Rigorous field-based research should be carried out to identify the potential habitats of threatened species and enhance the habitat management practices like controlling invasive species, managing suitable vegetation, constructing fences, wildlife corridors, artificial ponds and water holes in appropriate areas.

A robust and species-specific study on the effects of climate change can aid in the prediction of future habitat and distribution of species, allowing for timely management measures and interventions. Climate change mitigation and adaptation strategies include minimising the human footprints on the environment and promoting electrical vehicles, solar energy, improved cooking stoves, and banning plastic production should be adopted at both local and national levels throughout the country. Human activities determine the future of wildlife, so we should lessen activities that contribute to global climate change and create a win-win situation for both humans and wildlife. We are not far enough to lose wildlife like a pygmy hog and Indian chevrotain if the factors that cause climate change are not stopped. It is now the right time for the government of Nepal to think, act, implement and monitor on recovering the species and restore ecosystem making sound, effective and robust climate policy specific on the species at a landscape level.

Bhuwan Singh Bist is an MSc Wildlife Management and Biodiversity Conservation student at the School of Forestry and Natural Resource Management and Nishan KC is a BSc Forestry final year student at the Institute of Forestry, Pokhara Campus, Nepal.

Bhuwan Singh Bist and Nishan KC
Thursday July 29, 2021, 9:16 am

Appendix E3: News published in highlife, a local newspaper, Queensland, Australia

https://highlifemagazine.net/ganesh-pant-nepalese-rhinos/

highlife downs living

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GANESH PANT NEPALESE RHINOS

Published on October 10, 2021 | **in** Students/Education

After coming close to extinction, Nepal's greater one-horned rhinoceros numbers are on the rise, but a new challenge looms. University of Southern Queensland PhD student Ganesh Pant is delving into the potential impacts of climate change on the endangered species, with their limited habitat expected to dwindle.

"The impacts of climate change on this rhino species isn't well studied, so I wanted to build on it," he said. "Alongside other stakeholders and experts, we developed indicators to measure the animals' vulnerability. My findings show that the Nepalese rhinos are likely to be moderately impacted by the effects of climate change."

While 752 rhinos currently inhabit the grasslands and riverine forests of Southern Nepal, a third of this habitat could be unsuitable in the next 50 years. "We're expecting a change in the quality of their environment, with parts of the wetlands predicted to dry up. Climate change also poses other threats, such as fires, floods, invasive plant species and woody thickening in rhinoceros habitats. Right now, only 1.7 per cent of Nepal is a liveable environment for these rhinoceroses – so it's important we use this information to try and mitigate the future impacts."

Pant's research has also pinpointed new areas in Nepal which could be inhabited by rhinos in the future. "Some of these are outside protected areas," he said. "An international airport has been proposed for one of these spaces, part of which is likely to be suitable habitat for rhinoceroses in the future. This study provides a basis for discussion with the government on using an alternative site. It's important we protect the rhinos, not only do they bring in tourism for the local communities, they also form an essential part of the ecosystem."

University of Southern Queensland Professor Tek Maraseni is the principal supervisor of the PhD research project. "Although Nepal only occupies 0.03 per cent of the world, it is in the top 25 countries for biodiversity," he said. "The findings of this research will help the Nepalese Government and protected area managers to make informed decisions and place the right resources in the right places. There are two recommendations that are very specific; they must continue current conservation and anti-poaching activities, and start to plan the translocation of some rhinoceroses to other suitable pockets of land."

The University of Southern Queensland is set to introduce new Wildlife Management courses next year, and Pant recommended a career in conservation. "It's a great job – working to maintain the Earth and make it a better place to live," he said. "And facing the uncertainties of climate change, the more people educated in this area, the better."

Readers also enjoyed our story about USQ Study on 2020 Lockdown

Appendix E4: Research highlights in the University of Southern Queensland (USQ) Media

https://www.usq.edu.au/news/2021/10/climate-change-impact-on-nepal-rhinos

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Want to help preserve and protect our natural world? Learn the key skills with one of the University's hands-on courses in **Wildlife Management**.

Cover photo credit: Sagar Giri

University of Southern Queensland PhD student Ganesh Pant (left) and University of Southern Queensland Professor Tek Maraseni.