Forecasting Climate-Resilient Conservation Futures for the White-bellied Heron (*Ardea insignis*) in Bhutan Based on CMIP6 Projections

2041-2060
2061-2100


@Phub Dorji

Prepared by:

DoFPS & NCHM

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Department of Forests and Park Services
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List of Abbreviations

AUC	Area Under the Curve
BC	Biological Corridor
BFL	Bhutan For Life Project
BWS	Bumdeling Wildlife Sanctuary
CMIP6	Coupled Model Intercomparison Project Phase 6
DEM	Digital Elevation Model
DoFPS	Department of Forests and Park Services
GAM	Generalized Additive Models
GLM	Generalized Linear Models
GPS	Global Positioning System
IUCN	International Union for Conservation of Nature
JDNP	Jigme Dorji National Park
JKSNR	Jigme Khesar Strict Nature Reserve
JSWNP	Jigme Singye Wangchuck National Park
Km^2	Square kilometre
NCHM	National Centre for Hydrology and Meteorology
OECMs	Other Effective Area-Based Conservation Measures
PA	Protected Area
PWS	Phibsoo Wildlife Sanctuary
RF	Random Forest
RGoB	Royal Government of Bhutan
RMNP	Royal Manas National Park
ROC	Receiver Operating Characteristic
SDM	Species Distribution Modelling
SMART	Spatial Monitoring and Reporting Tools
SSP3	Shared Socioeconomic Pathway 3
SWS	Sakteng Wildlife Sanctuary
TSS	True Skill Statistic
VIF	Variance Inflation Factor
WBH	White-bellied Heron

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Executive Summary

The White-bellied Heron (*Ardea insignis*), among the rarest birds on Earth, is currently classified as Critically Endangered as per the Red List of the International Union for Conservation of Nature, with a global population estimated at fewer than 60 individuals. Bhutan hosts the largest known population of this species, conferring upon the country a crucial responsibility for its long-term survival. While several ecological research has been conducted, impact of climate change on the distribution and habitat suitability of the White-bellied Heron at the national scale remained unexamined. The absence of studies comparing current and future habitat scenarios limits informed conservation planning and threats to the species long-term survival. This report presents the first nationwide, climate-informed habitat modelling of white-bellied heron across Bhutan, combining historical records, advanced geospatial analysis, and future climate scenarios to inform conservation priorities.

Drawing on 361 rigorously validated occurrence records collected between 2001 and 2024, the study integrates 24 environmental predictors encompassing topography, bioclimatic variables, and anthropogenic pressures. An ensemble modelling framework was employed, utilizing Generalized Linear Models (GLM), Generalized Additive Models (GAM), and Random Forest (RF) algorithms. Model performance metrics were robust, with all algorithms achieving Area Under the Curve (AUC) scores above 0.94, indicating high predictive accuracy. The strongest determinants of habitat suitability included annual precipitation, isothermality, proximity to settlements, and slope.

Under current baseline conditions, approximately 8,219 km² of Bhutan's landscape is predicted to be climatically suitable for WBH, primarily concentrated along mid-elevation river corridors. However, projections under Shared Socioeconomic Pathway 3 (SSP3)—a scenario characterized by limited international cooperation and high regional fragmentation—reveal significant spatial and temporal changes in habitat availability. By 2041–2060, suitable habitat is projected to expand to nearly 12,000 km², and by 2061–2100, up to 13,784 km². This net gain contrasts sharply with projected declines across other parts of the species' historical range, positioning Bhutan as a potential climate refuge.

Yet, these gains are not evenly distributed. The study highlights rising fragmentation and ecological instability. Districts like Dagana and Tsirang, which initially exhibit high suitability, are projected to undergo substantial declines by 2100. In contrast, Monggar and Pema Gatshel in eastern Bhutan are expected to emerge as new centres of habitat suitability, despite historically limited monitoring and protection. The persistence of unsuitable conditions in high-altitude regions such as Gasa and Haa underscores topographic and climatic constraints on range expansion.

A critical insight from this study is the emergence of pronounced protection gaps. The analysis shows that, in some districts, more than 80% of the predicted high-suitability habitat lies outside the formal protected area (PA) network. Notably, districts such as Tsirang, Paro, and Wangdue Phodrang face this scenario, emphasizing the need for conservation planning that goes beyond traditional PA boundaries. Core protected areas like Royal Manas National Park and Phibsoo Wildlife Sanctuary retain high suitability across scenarios, reaffirming their role as ecological anchors. However, others—such as Bumdeling Wildlife Sanctuary and Jigme Khesar Strict Nature Reserve—are projected to become largely unsuitable under future climate conditions.

The findings call for adaptive and anticipatory conservation strategies. The report recommends expanding Bhutan’s conservation toolkit to include Other Effective Area-Based Conservation Measures (OECMs), such as community-managed riparian buffers and seasonal no-development zones. Maintaining connectivity between southern and central corridors (Biological Corridor2–Biological Corridor4) will be essential to ensure gene flow and dispersal across fragmented landscapes. In addition, micro-zonation within protected areas and targeted restoration can help mitigate the impacts of climate-driven habitat degradation.

Wildlife tourism is highlighted as a complementary conservation mechanism, particularly in emerging refugia such as Monggar and Dagana. Structured heron-watching programs, if carefully regulated, could generate local livelihoods while fostering stewardship and public awareness. The study also underscores the importance of integrating Species Distribution Model (SDM) outputs into national land-use plans, hydropower project assessments, and climate adaptation strategies, consistent with Bhutan’s constitutional commitment to maintaining at least 60% forest cover.

In conclusion, Bhutan faces a unique conservation opportunity and responsibility to safeguard the White-bellied Heron against a backdrop of climate uncertainty. By combining predictive modelling, adaptive management, and inclusive policy frameworks, Bhutan can set an international precedent for climate-resilient conservation of critically endangered riverine species.

1. Introduction

1.1 White-bellied Heron population in the region and Bhutan

Biodiversity loss is increasing worldwide, driven largely by climate change and compounded by human-induced factors (Dirzo & Raven, 2003). Among the global avifauna, 1,469 bird species face the threat of extinction, including 222 that are classified as critically endangered (BirdLife International, 2018). The White-bellied Heron (hereafter referred as WBH) is currently classified as critically endangered under the IUCN Red List of Threatened Species under criteria C2a(i), indicating an extremely small and rapidly declining population, with the decline projected to continue in the near future. The global population is estimated at fewer than 60 individuals (Price & Goodman, 2015; BirdLife International, 2024), primarily due to alterations in its natural habitat and freshwater ecosystems. Bhutan, a small Himalayan nation whose development philosophy is deeply rooted in environmental protection and conservation, is home to the largest known population of its kind, with 29 individuals counted for the year 2025 (RSPN, 2025). Given global significance, it is imperative to conduct a comprehensive assessment of the impacts of climate and land use change on the species, through which a conservation strategy can be formulated. Historically, the WBH was confined to relatively undisturbed wetland habitats, including swamps, reed beds, and marshes across parts of eastern Nepal, the Sikkim Terai, northern Bihar (above the Ganges River), the Bhutan Duars, northern Assam, East Pakistan (now Bangladesh), the Arakan region, and northern Myanmar (Stanford & Ticehurst, 1939; Smythies, 1953; Walters, 1976; Ali & Ripley, 1987; King et al., 2001). Despite this extensive range, the species was never documented in large numbers across these areas.

1.2 Biodiversity & WBH habitats in Bhutan

Bhutan, situated in the Eastern Himalayas, is part of a global biodiversity hotspot with 69.71% forest cover (FMID, 2023) and about 52% of its land under protected areas (WWF, 2023). As of

2017, Bhutan had recorded 11,175 species (Gyeltshen & Prasad, 2022), with several new species being added over the years. Bhutan's vast altitudinal range, spanning from 97 to 7,570 meters above sea level (masl), nurtures a rich diversity of ecosystems. This high variation supports over 766 bird species, including the WBH, alongside iconic wildlife such as the Bengal Tiger, Snow Leopard, and Red Panda (Nepal, 2022; Dendup et al., 2023; Dorji et al., 2024; Dhendup & Dorji, 2018).

The WBH, one of the 106 waterbird species (Passang, 2018) found in Bhutan, is critically endangered across its range. In Bhutan, the bird is a highly protected species and is listed under Schedule I of Bhutan's Forest and Nature Conservation Act, 2023 (RGoB, 2023). The WBH specifically thrives along the river basins of mixed broad-leaved forest with altitudes ranging from 100-1500 masl, feeding along the shallow banks with medium to low riffles at 30–45 cm water depth (RSPN, 2011). The WBH prefers larger rivers during the winter and dry seasons; however, when these rivers become muddy and their banks are flooded, the birds tend to move to smaller streams and tributaries (Pradhan, 2008; Dorji, 2011; RSPN, 2011). Interestingly, more observations show that some breeding herons stay in the same general area all year, even though they move between feeding spots, occasionally flying as far as 25 kilometres along rivers, lakes, and streams (RSPN, 2011, 2015; Price and Goodman, 2015). Breeding in the WBH requires specific nest site selections and the selection process is influenced by factors such as (1) adequate food availability to support both adults and their offspring, (2) minimal risk of predation, (3) the presence and social behavior of nearby conspecifics, (4) access to suitable nesting materials, and (5) favorable climatic conditions for chick development (Collias, 1986; Hansell & Hansell, 2005; Mainwaring et al., 2014).

1.3 Problem statement

Water birds are the most impacted species due to habitat degradation and destruction, and the impact of climate change, leading to population decline (Maheswaran et al., 2021a). The comparative analysis of past and present binary ensemble models indicated that in the last century, WBH has lost ~51.98% (12,139 km^2) in its range countries, with a notable shift in north and north-eastern areas. The highest loss has been observed in India, followed by Myanmar and Bangladesh. In contrast, Bhutan tends to become more suitable with a gain of 60%, expanding the areas in the Northern regions of Bhutan (Maheswaran et al., 2021b). Compared to the neighbouring regions, this could have been attributed to better forest and riverine habitat conservation, low anthropogenic pressures, and expansion of suitable habitats due to climate change. WBH populations in Bhutan are under increasing pressure from a range of anthropogenic and ecological disturbances (RSPN, 2024). These include hydropower development, increasing land-use changes, and climatic variability that affects river flow. For instance, Bhutan’s fast-growing infrastructure sector and national ambition for hydropower-driven economic development (Nomura, 2025) have led to significant changes in riverine ecosystems. The isolated and small populations of WBH are especially vulnerable to stochastic events such as disease or flash floods, which may drive local extirpation. Further, climate change poses a significant threat to Bhutan’s biodiversity by altering habitats, shifting species distributions, and increasing the vulnerability of already endangered species. Numerous studies have explored various aspects of WBH conservation and ecological dynamics, including roosting behavior (Khandu et al., 2020a), conservation threats (Phuntshok et al., 2022), and nest habitat preferences (Acharja, 2019). Research has also examined perceived threats and conservation challenges, public knowledge and awareness, as well as attitudes toward conservation (Nima et al., 2025). Other investigations have focused on acoustic analysis methods (Dema et al., 2020), ecosystem benefits associated with WBH (Tenzin et al., 2020), and the ecological and environmental factors influencing foraging activity (Khandu et al., 2021). Additional studies have addressed nest predation (Khandu, 2022), breeding behaviors in broadleaf forests (Khandu et al., 2020b), and complex social interactions such as sexual conflict and parental infanticide (Acharja et al., 2021). Furthermore, research has linked conservation activities to foraging patterns (Khandu et al., 2020c) and identified a new critical habitat for conservation efforts (Wangdi et al., 2017).

Despite substantial research on various ecological aspects, the impact of climate change on WBH distribution and habitat suitability at the national level remains unexplored, leaving a critical gap in understanding the species' presence across the country. No studies were carried out to assess the distribution and the change in habitat suitability over time, or to compare historical and future habitat scenarios for WBH. Additionally, quantifying distribution shifts and understanding the habitat status of past, present, and future is essential for securing the long-term survival of this species.

2. Methodology

2.1 Study Area

Bhutan, a Himalayan landlocked country in South Asia with an area of 38, 394 km^2 is bounded by India towards the South, East and West, and China towards the North (27° 31 '53.11"N; 90° 26' 9.07"E). The country experiences four distinct seasons: Spring (March-May), Summer (June-September), Autumn (October-November), and Winter (December-February). Its location within the Indo-Malayan and Palaearctic realm makes it inhabitable to over 200 mammalian species, 766 bird species, 5600 plant species, 778 species of butterflies, 1940 species of moths (K. Wangdi, *pers. comm.* June, 2025), and more than 130 species of fishes (NBC, 2025). Additionally, the country's extensive protected area network encompassed by 11 Protected Areas (PA) (including Royal Botanical Park), and 9 Biological Corridors (BC) covering approximately 52% of the land area have significantly contributed to the rich assemblage of such biodiversity (WWF, 2023). The wide elevation ranges from the lowest 100 masl to as high as 7500 masl sets up a favourable condition for the establishment of different forest types. Bhutan's forest is classified into 11 different types, ranging from subtropical forest to alpine scrub forest, supporting a variety of habitat that hosts a myriad of species. The intact forest ecosystem and geographic terrain consisting mostly of steep and high mountains harbors four major river basins viz Drangmechhu, Punatsangchhu, Amochhu and Wangchhu (Alam et al., 2017). This river system is home to a wide range of water birds and aquatic animals. WBH predominantly occupies these major Himalayan River systems. However, long-term population monitoring indicates a shifting distribution, with observation of local extirpations and nesting site abandonment in several historical locations. This trend is particularly evident in the Punatshangchhu basin, where sighting frequencies upstream of the river have declined sharply over the past years (RSPN, 2025).

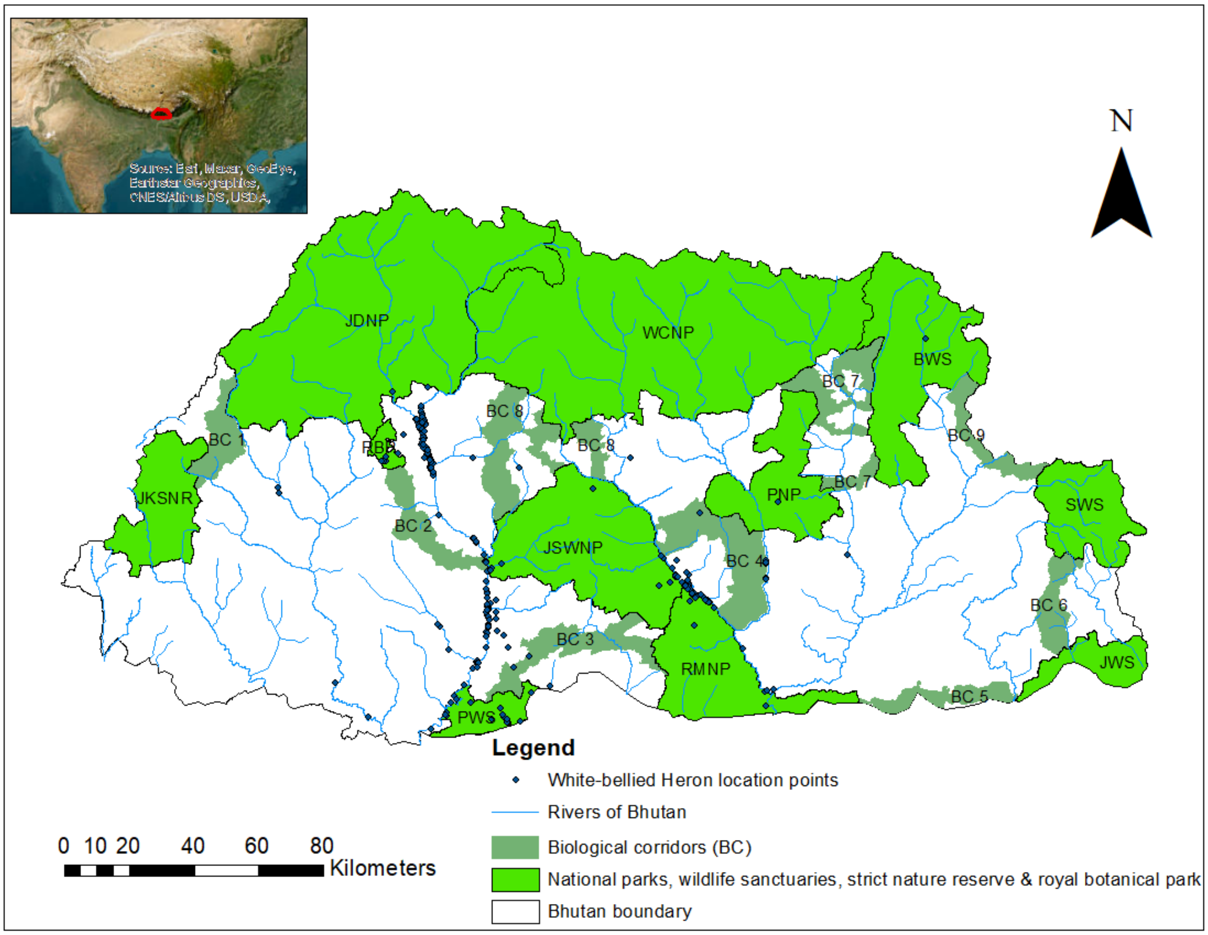

Figure 1. Spatial distribution of WBH occurrence records across Bhutan. The map illustrates the study area encompassing Bhutan, with blue dots representing documented presence locations of the WBH. River networks are highlighted in blue, providing ecological context to habitat preferences. Green polygons represent biological corridors (BC1-9) and quetzel green represents national parks (JDNP *Jigme Dorji*, WCNP *Wangchuck Centennial*, PNP *Phrumsengla*, JSWNP *Jigme Singye Wangchuck* and RMNP *Royal Manas*), wildlife sanctuaries (BWS *Bumdeling*, SWS *Sakteng*, JWS *Jomotsangkha* and PWS *Phibsoo*), strict nature reserve (JKSNR *Jigme Khesar*) and botanical park (RBP *Royal*).

2.2 Data Collection

2.2.1 Species Occurrence Data Collection

For this study, we compiled a total of 615 occurrence records of the WBH. Of these, 132 records spanning 2020–2024 were obtained from the Spatial Monitoring and Reporting Tool (SMART), while 483 records covering the period 2001–2023 were downloaded from the Global Biodiversity Information Facility (GBIF; www.gbif.org). After thorough verification and removal of duplicate entries (n = 254), we retained 361 unique occurrence points for analysis.

SMART is an advanced conservation management platform designed to support protected area and wildlife authorities in improving patrol monitoring, performance evaluation, and adaptive management strategies (FAO, 2025). Field data contributing to SMART are collected by officials from the Department of Forests and Park Services (DoFPS), with each WBH observation precisely geotagged using GPS-enabled devices and timestamped, thereby enabling high-resolution spatial analysis for conservation planning.

2.2.2 Environmental Variables

Three key environmental predictors - elevation, slope, and aspect were selected based on their ecological relevance to the occurrence of the WBH. These variables were derived from a 12.5-meter resolution Digital Elevation Model (DEM) raster provided by the Forest Monitoring and Information Division, under the DoFPS (www.dofps.gov.bt).

2.2.3 Anthropogenic Variables

To account for human influences on WBH distribution, we incorporated two anthropogenic variables: Euclidean distance to settlement and Euclidean distance to road networks. These spatial datasets were obtained from the National Land Commission Secretariat(www.nlcs.gov.bt).

2.2.4 Bioclimatic Variables

We utilized downscaled BhutanClim bioclimatic variables, comprising temperature (BIO1–BIO12) and precipitation (BIO13–BIO19), at a spatial resolution of approximately 1 km. These datasets, obtained from the National Centre for Hydrology and Meteorology (www.nchm.gov.bt), represent averaged climatic conditions for the baseline period 1996–2014.

To project potential shifts in the species distribution of the WBH, we employed future climate layers aligned with Shared Socioeconomic Pathway (SSP) scenario 3 - *Regional Rivalry: A Rocky Road*. This scenario reflects a fragmented world marked by rising nationalism, limited international cooperation, and significant challenges to both climate mitigation and adaptation (Riahi et al., 2017). Future projections correspond to two timeframes: 2041–2060 and 2061–2100, using BhutanClim bioclimatic variables at consistent spatial resolution.

2.2.5 Modelling Procedures

To model the current and future distribution of the WBH, we utilized a total of 361 presence records, supplemented with pseudo-absence points generated at a ratio of 1.5:1. This approach is commonly adopted to improve model discrimination in species distribution modelling (Barbet-Massin et al., 2012). The model building was performed in R v.4.3.3 software (R core team) and further analysis were carried out using ArcMap v.10.8.2 (ESRI, 2020).

We selected 24 environmental predictors, grouped into three categories:

- Topographic variables (elevation, slope, aspect), derived from a 12.5-meter resolution DEM.
- Anthropogenic variables (Euclidean distance to settlement and Euclidean distance to road), also available at fine spatial resolution (12.5 m).
- Bioclimatic variables (BIO1–BIO19), sourced from the BhutanClim dataset at a coarser resolution of ~1 km, representing baseline climate conditions for 1996–2014.

To ensure compatibility across layers during spatial modelling, all finer-resolution environmental and anthropogenic variables were resampled to match the course 1 km resolution of the BhutanClim climate layers. Resampling to the coarser resolution is advisable because:

  - It minimizes potential artificial precision or spatial bias during overlay and modelling (Guisan et al., 2007).
  - It ensures consistency in spatial scale, which is crucial for algorithms sensitive to resolution mismatches (Elith & Leathwick, 2009).
  - It aligns predictor variables with the scale of climate models, which are typically produced at coarser resolution (Peterson et al., 2011).

Before modelling, we applied a multicollinearity filter using a 0.70 correlation threshold, retaining predictors that were ecologically informative yet statistically independent (Dormann et al., 2013).

Species Distribution Modelling was conducted using the sdm package in R (Naimi & Araújo, 2016), leveraging an ensemble of Generalized Linear Model (GLM), Generalized Additive Model (GAM), and Random Forest (RF) algorithms. We employed bootstrapping (n = 2) to stabilize model outputs and reduce sampling bias. Model performance was assessed using the True Skill Statistic (TSS), selected over the more common AUC metric due to its robustness for presence–absence datasets (Allouche et al., 2006). Importantly, the ensemble approach combining multiple algorithms minimizes prediction error, improves robustness in spatial probability assessment, and enhances reliability in modelling efforts by combining multiple models into an individual ensemble model (Mukherjee et al., 2020; Peterson et al., 2011, Koç et al., 2024, Mohamed et al. 2023; Elith et al., 2006; Franklin, 2009), making them particularly suitable for use in a complex terrain like Bhutan.

Future projections of WBH distribution were generated using climate layers under the Shared Socioeconomic Pathway 3 (SSP3: Regional Rivalry) scenario, which characterizes a fragmented world facing significant challenges to both mitigation and adaptation (Riahi et al., 2017). Habitat suitability predictions for the WBH were made for two future periods 2041–2060 and 2061–2100 to assess potential habitat conditions in the mid and late 21st century. Final distribution maps were derived using weighted ensemble outputs combining predictions from GLM, GAM, and RF models.

2.2.5.1. District-Level Habitat Suitability Modelling

To evaluate ecological suitability for the WBH across Bhutan's districts under baseline and future climate scenarios (SSP3: 2041–2060 and 2061–2100), SDM outputs were spatially analyzed using ArcGIS. Suitability rasters classified from 0 (unsuitable) to 4 (high suitability) were processed using the following steps:

- Zonal Statistics: The Zonal Statistics as Table tool was applied using district boundaries as zones. Key indicators extracted included:
    - MEAN (average suitability)

    - MAJORITY (dominant habitat class)
    - MAX, MIN, SUM, COUNT, and VARIETY (habitat diversity)
- Temporal Comparison: Suitability data across three timeframes were compiled into a matrix to quantify shifts in district-level habitat quality.
- Transition Analysis: Changes in MEAN scores between time intervals (Baseline → 2041–2060 → 2061–2100) were calculated to assess stability, degradation, or improvement.
- Interpretation Metrics: Districts were classified into zones of high retention, emerging degradation, and persistent unsuitability using comparative indicators.

2.2.5.2. Protected Area Suitability Assessment

Habitat suitability trends within Bhutan's PAs were quantified across the same temporal sequence using spatial overlays and zonal statistics:

- Data Preparation: Suitability rasters were clipped and intersected with PA boundaries, including BCs.
- Zonal Statistics: Within each PA and subzone, metrics such as MEAN, MAJORITY, VARIETY, STD, MAX, and MIN were extracted to characterize internal habitat conditions.
- Scenario-Based Evaluation:
    - Baseline SDM identified core biodiversity strongholds (e.g., Royal Manas NP, Phibsoo WS).
    - Mid-century and end-century SSP3 scenarios revealed habitat retention (e.g., BC2–BC4) and collapse zones (e.g., JKSNR, BWS).
- Ecological Stratification: PAs were grouped by suitability performance (high resilience, moderate fragmentation, severe decline), informing conservation prioritization and corridor design.

2.2.5.3. Protection Gap and Overlay Analysis

To identify high-suitability habitat outside current PA boundaries, a protection gap analysis was conducted through spatial overlays and district-wise quantification:

- Raster Reclassification: Suitability rasters were reclassified to isolate Classes 4 (highly suitable only).
- Erase and Intersect Workflow:
    - Erase tool was used to remove areas overlapping with PAs, producing Suitable_Outside_PA polygons.
    - Intersect with district boundaries provided estimates of unprotected suitable area per district.
- Gap Index Calculation:
    - Total suitable area per district (from zonal stats) was joined with unprotected area data.
    - The Gap Index was computed using Field Calculator: **Gap Index = Suitable area *outside PA/Total Suitable Area***
    - Percent-based normalization facilitated district-level ranking.
- District Prioritization: Results were compiled into a ranked matrix identifying districts with critical gaps (e.g., Tsirang, Monggar, Dagana) versus zones with minimal suitability or coverage.

3. Results

3.1. Multicollinearity Screening

To ensure statistical robustness, predictors were evaluated using the Variance Inflation Factor (VIF). Variables with VIF < 5 were retained for modelling, resulting in the following 9 predictors:

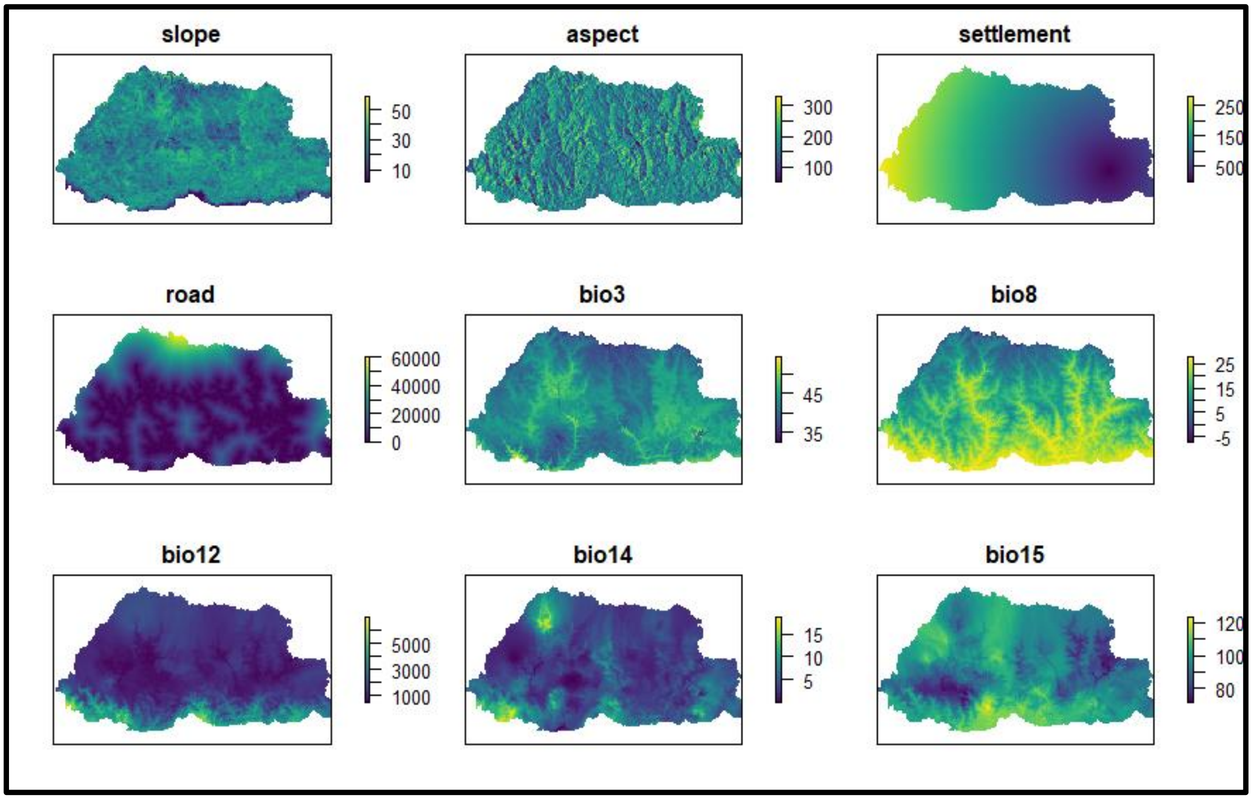

Figure 2. Spatial representation of final predictor variables retained after multicollinearity screening (VIF < 5).

Nine environmental and anthropogenic predictors—slope, aspect, settlement, road, BIO3 (Isothermality), BIO8 (Mean Temperature of Wettest Quarter), BIO12 (Annual Precipitation), BIO14 (Precipitation of Driest Month), and BIO15 (Precipitation Seasonality)—were selected for SDM of the WBH (Table 1). These predictors capture terrain complexity, human pressure gradients, and climatic variability across Bhutan, offering a robust foundation for ecological inference and model precision.

Table 1. Variance Inflation Factor (VIF) values for the final predictors selected for WBH distribution modelling.

Variable	Description	VIF
Slope	Terrain steepness derived from DEM	1.67
Aspect	Compass direction of slope surface	1.13
Settlement	Euclidean distance from human settlements	1.8
Road	Euclidean distance from road networks	1.9

BIO3	Isothermality (ratio of diurnal to annual temp range)	2.15
BIO8	Mean temperature of wettest quarter	1.98
BIO12	Annual precipitation	4.47
BIO14	Precipitation of driest month	1.77
BIO15	Precipitation seasonality (coefficient of variation)	2.82

3.2. Response Curve Analysis

The Fig. 3 presents response curves for nine key variables retained after multicollinearity screening. Each curve illustrates the model-estimated relationship between a specific environmental predictor—aspect, BIO3 (isothermality), BIO8 (mean temperature of wettest quarter), BIO12 (annual precipitation), BIO14 (precipitation of driest month), BIO15 (precipitation seasonality), slope, settlement distance, and road distance - and predicted habitat suitability for the WBH. The y-axis denotes habitat suitability (scaled from 0 to 1), while the x-axis represents the range of each variable. These curves reveal nonlinear and threshold-dependent effects that support ecological interpretation and enhance model realism.

Model-derived response curves revealed:

- Avoidance of human-modified areas, with suitability declining near settlements and roads.
- Positive associations with slope and BIO12 (annual precipitation), reinforcing WBH's affinity for moist, undisturbed riparian environments.
- Threshold effects were observed across most predictors, indicating ecological specificity in habitat selection.

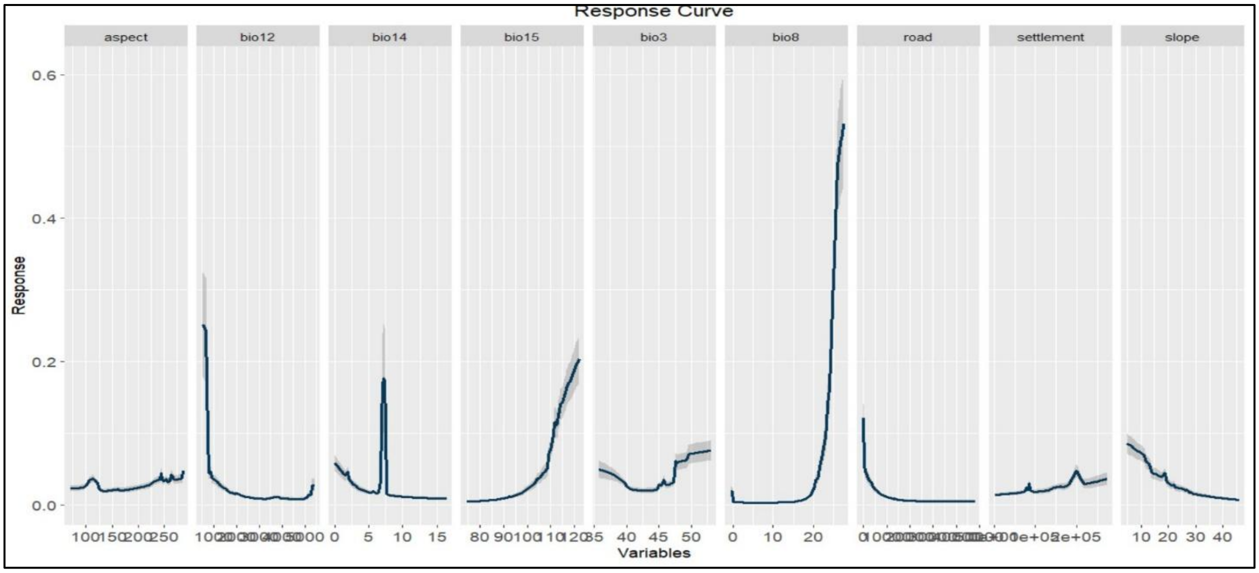

Figure 3. Response curves showing the influence of environmental predictors on WBH habitat suitability.

3.3. Model ROC and Performance Metrics

Each algorithm displayed strong classification ability based on ROC curve analysis: The Fig. 4 displays ROC curves and mean AUC scores for three classification algorithms – GLM, GAM and RF - used in modelling WBH habitat suitability. Each subplot compares model performance on training and test datasets. GLM achieved mean AUCs of 0.975 (training) and 0.981 (test), GAM produced 0.988 (training) and 0.987 (test), while RF demonstrated perfect training accuracy (1.000) and a test AUC of 0.988.

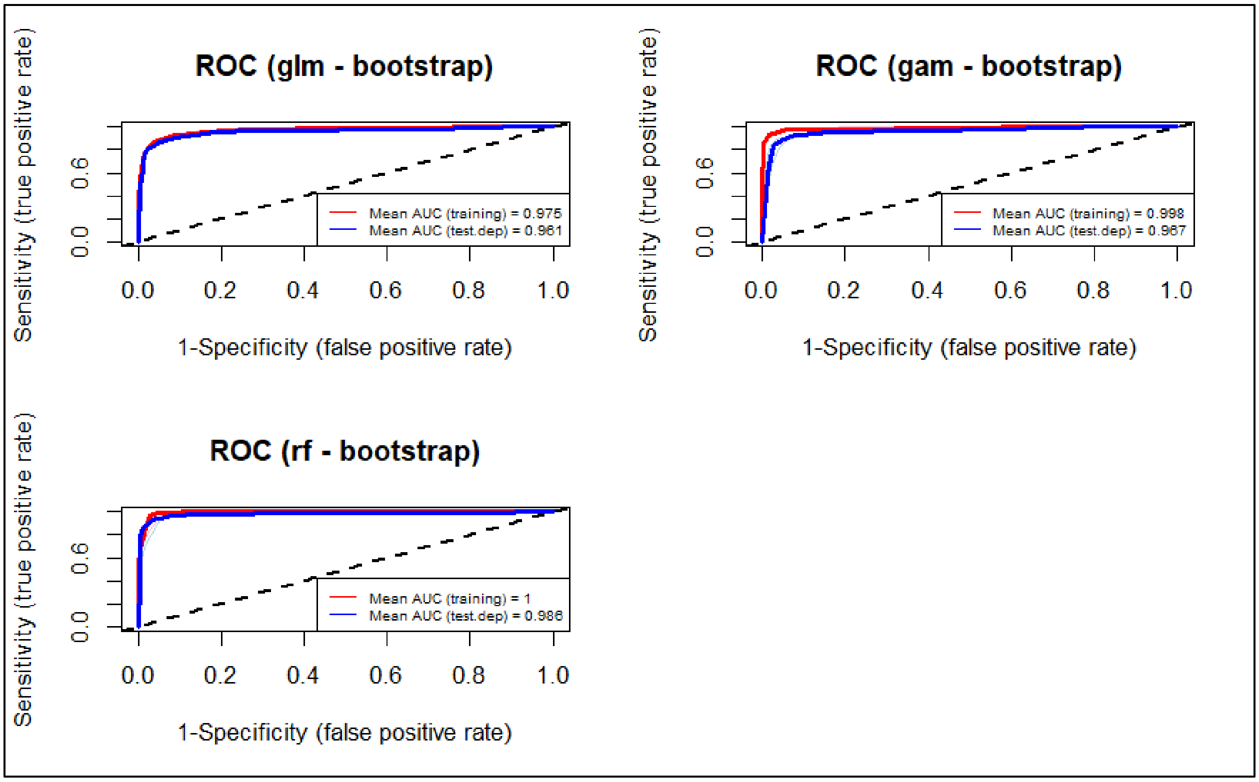

Figure 4. Receiver Operating Characteristic (ROC) curves for WBH distribution models using bootstrap replication.

All models exceeded AUC > 0.94, with RF achieving perfect training AUC. These models were integrated using a weighted ensemble, with final predictions calibrated using TSS to optimize binary habitat classification. These high AUC values confirm strong predictive capabilities across models, with RF showing superior discriminative performance (Table 2).

Table 2. Area Under Curve (AUC) values of each model selected for WBH distribution modelling.

Model	Mean AUC (Train)	Mean AUC (Test)
GLM	0.975	0.981
GAM	0.988	0.987
RF	1	0.988

3.4. Current Habitat Suitability (Baseline)

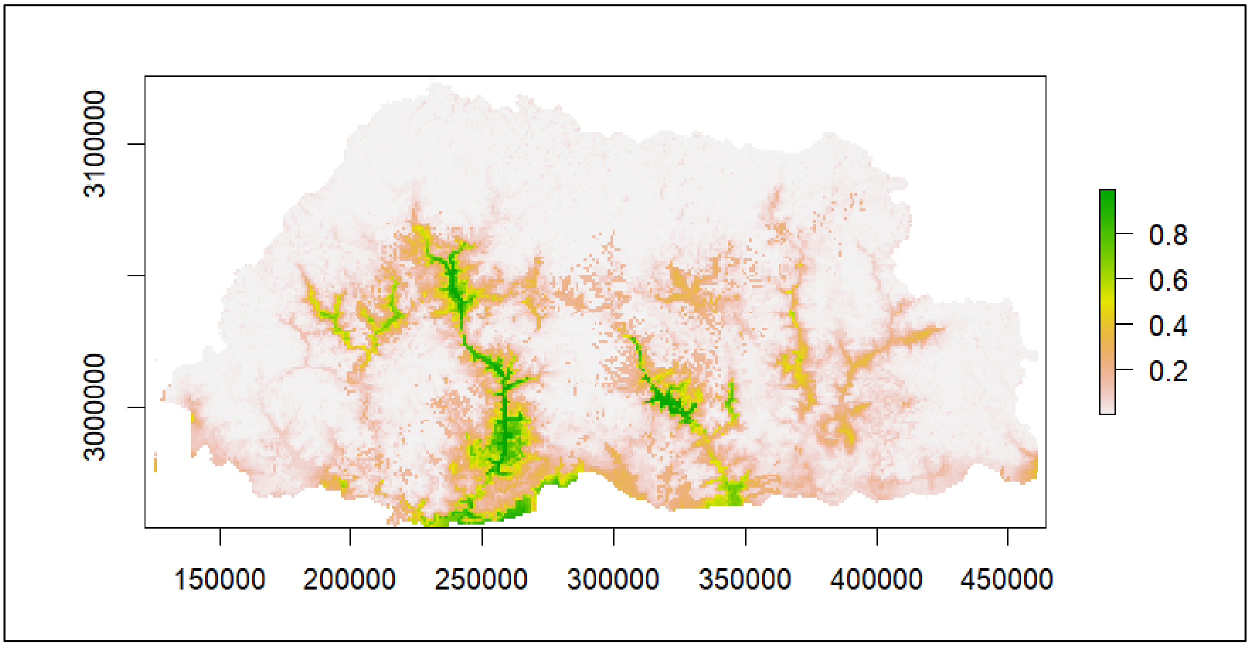

Figure 5. Predicted current habitat suitability for the WBH in Bhutan. Areas in green represent high suitability scores (≥0.8), corresponding to favorable ecological conditions, while zones in pink reflect lower suitability (≤0.2), indicating limited likelihood of species presence.

The ensemble model predicted 8,219 km² of climatically suitable habitat under current conditions (Table 3). The spatial extent and relative dominance of three suitability classes - less suitable, moderately suitable, and highly suitable - predicted by the ensemble model under baseline climate conditions. The model identifies 1,985 km² as moderately suitable habitat, with the largest share classified as less suitable (64.5%)**,** while highly suitable zones (929 km²) align with core riparian landscapes and mid-elevation regions critical for WBH conservation (Fig. 6).

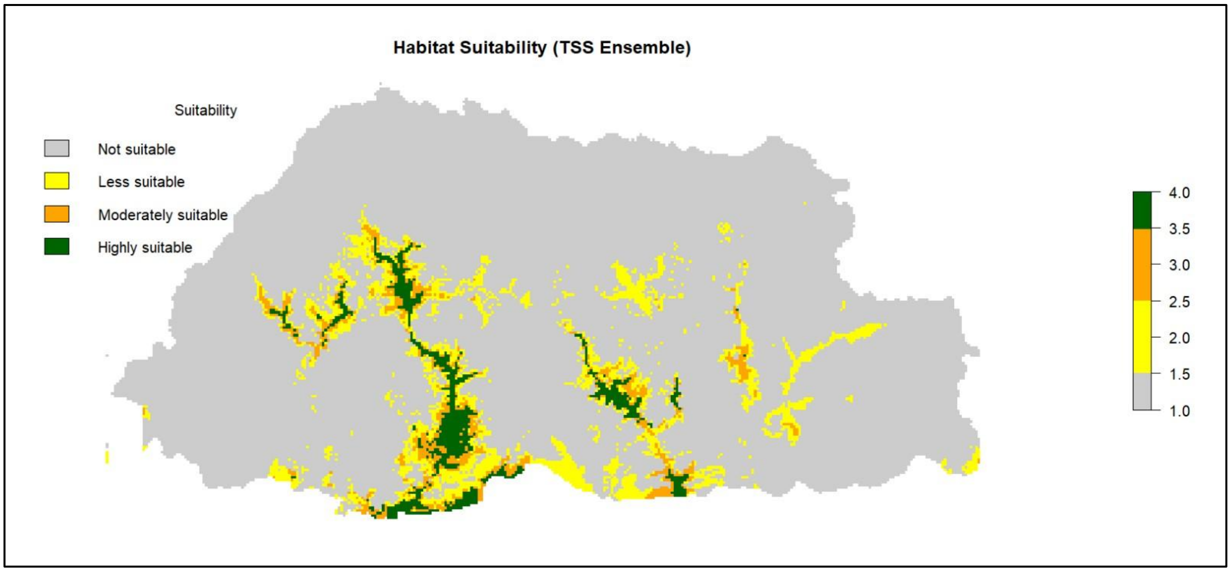

Figure 6. Predicted current habitat suitability for the WBH in Bhutan based on True Skill Statistic - optimized ensemble modelling.

Table 3. Area and proportion of habitat suitability classes under the current species distribution model for the WBH in Bhutan.

Suitability Class	**Area (km²)**	**Proportion of Suitable Habitat in the Country**
Less Suitable	5,305	14%
Moderately Suitable	1,985	5%
Highly Suitable	929	2%

3.5. Future Projection: SSP3 (2041–2060)

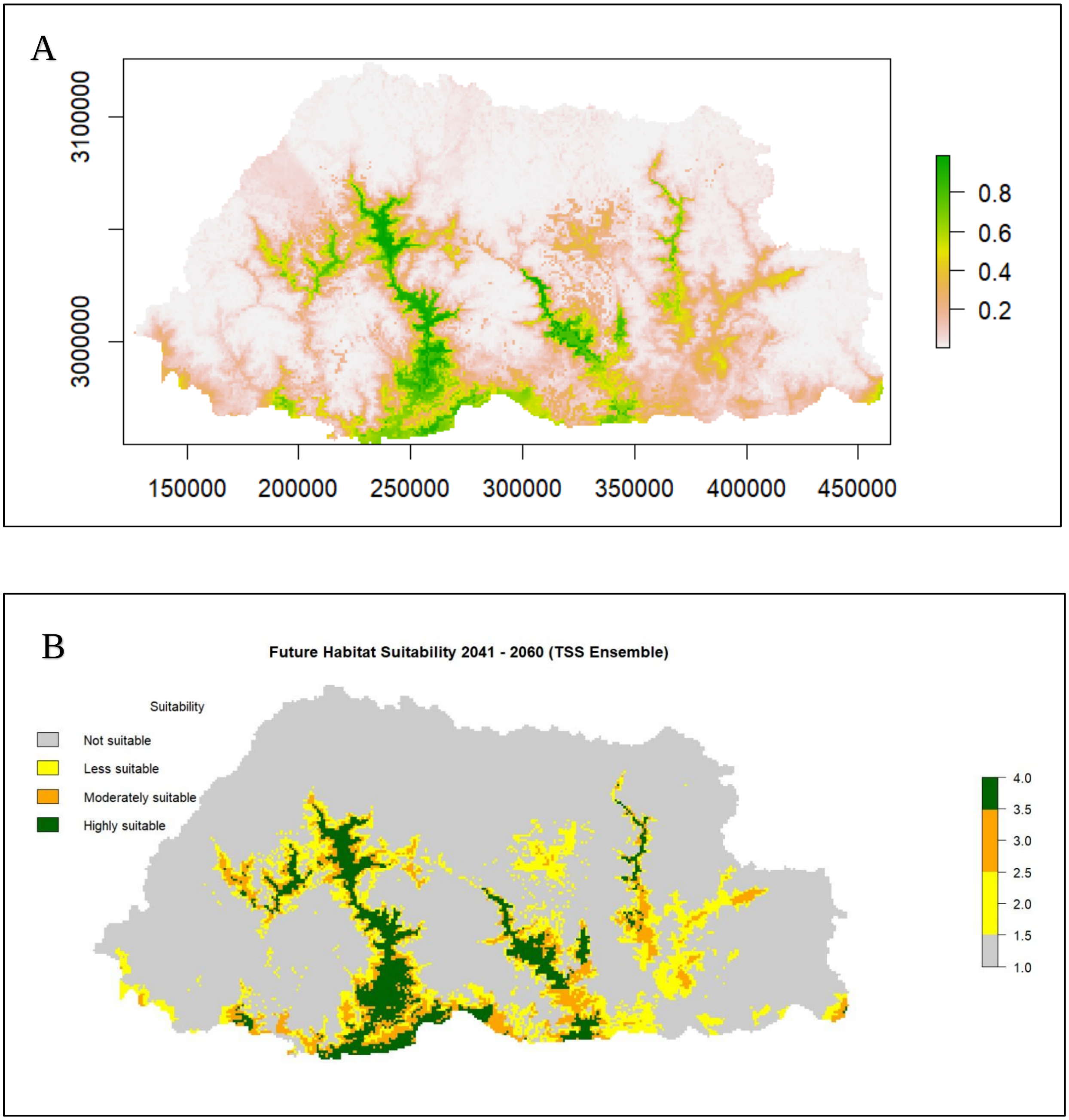

Figure 7. A & B predicted future habitat suitability for the WBH under the SSP3 scenario (2041–2060).

Total suitable habitat increases to 11,980 km² (Table 4), with a net gain of 3,761 km² in the year 2041-2060 from the baseline. However, the overall predicted habitat gains and loss is presented in Table 5.

Table 4. Predicted habitat suitability classes for the WBH under the SSP3 climate scenario (2041–2060).

Suitability Class	Area (km²)	Proportion of Suitable Habitat in the Country
Less Suitable	6,568	17%
Moderately Suitable	3,376	9%
Highly Suitable	2,036	5%

Change Analysis:

Table 5. Predicted habitat change for the WBH between current distribution and SSP3 scenario (2041–2060).

Category	Area (km²)
Habitat Gain	7,473
Habitat Loss	1,464

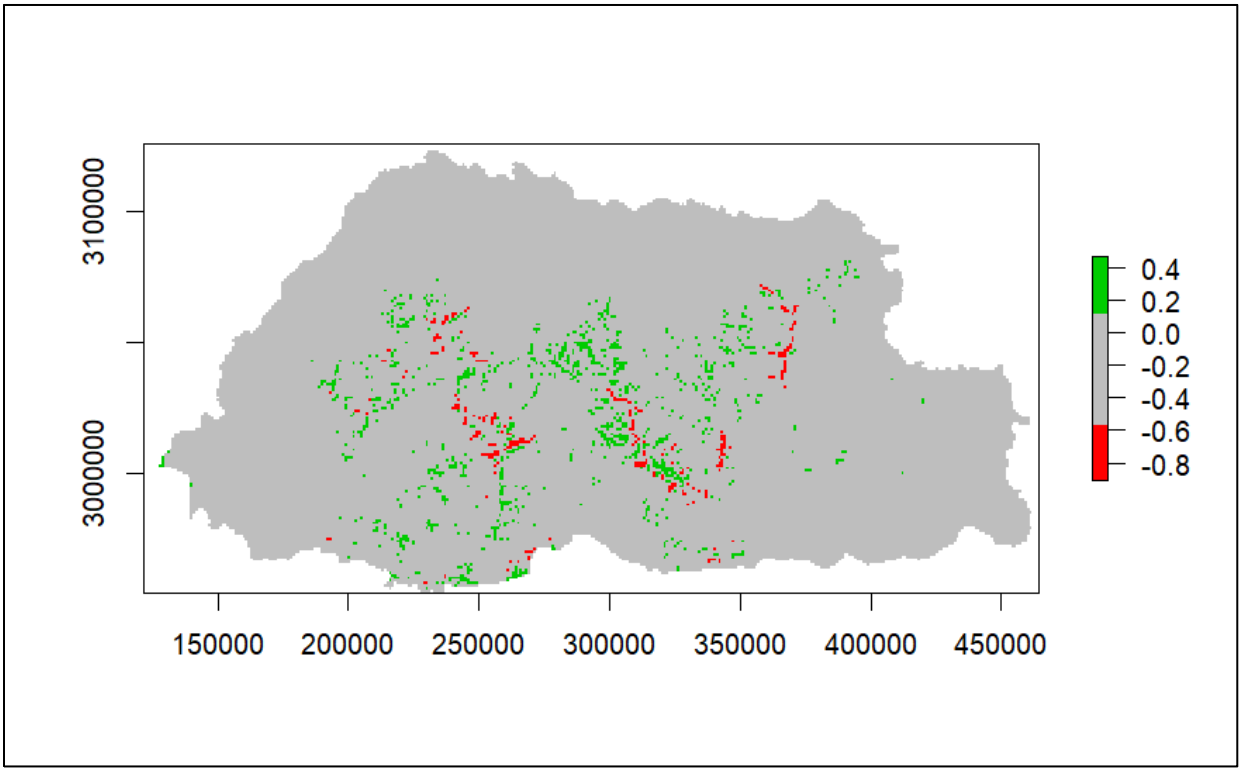

Figure 8. Predicted future habitat suitability gain and loss for the WBH under the SSP3 scenario (2041–2060).

Newly suitable zones emerge at higher elevations, while some lowland patches lose suitability.

3.6. Future Projection: SSP3 (2061–2100)

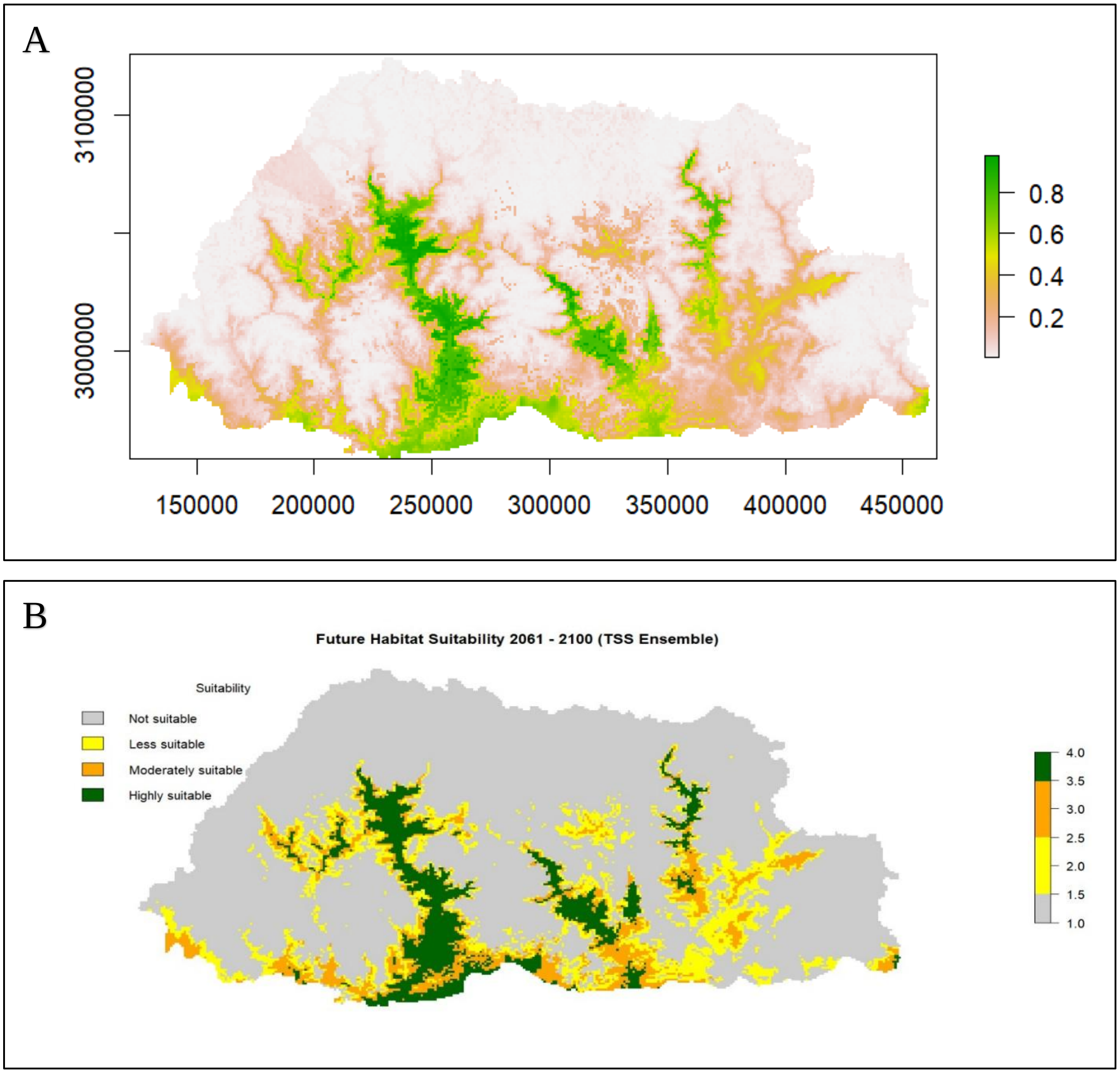

Figure 9. A & B predicted future habitat suitability for the WBH under the SSP3 climate scenario (2061–2100).

The projected suitable area slightly increases to 13,784 km² (Table 6) and reflects a net gain of 5,565 km² compared to baseline (1994-2014). Overall habitat gains and loss in the year 2061-2100 is presented in Table 7.

Table 6. Predicted habitat suitability classes for the WBH under the SSP3 climate scenario (2061–2100).

Suitability Class	**Area (km²)**	**Proportion of Suitable Habitat in the country**
Less Suitable	6,775	17%
Moderately Suitable	4,202	12%
Highly Suitable	2,807	7%

Change Analysis:

Table 7. Predicted habitat change for the WBH between current distribution and SSP3 scenario (2061–2100).

Category	**Area (km²)**
Habitat Gain	9,955
Habitat Loss	1,128

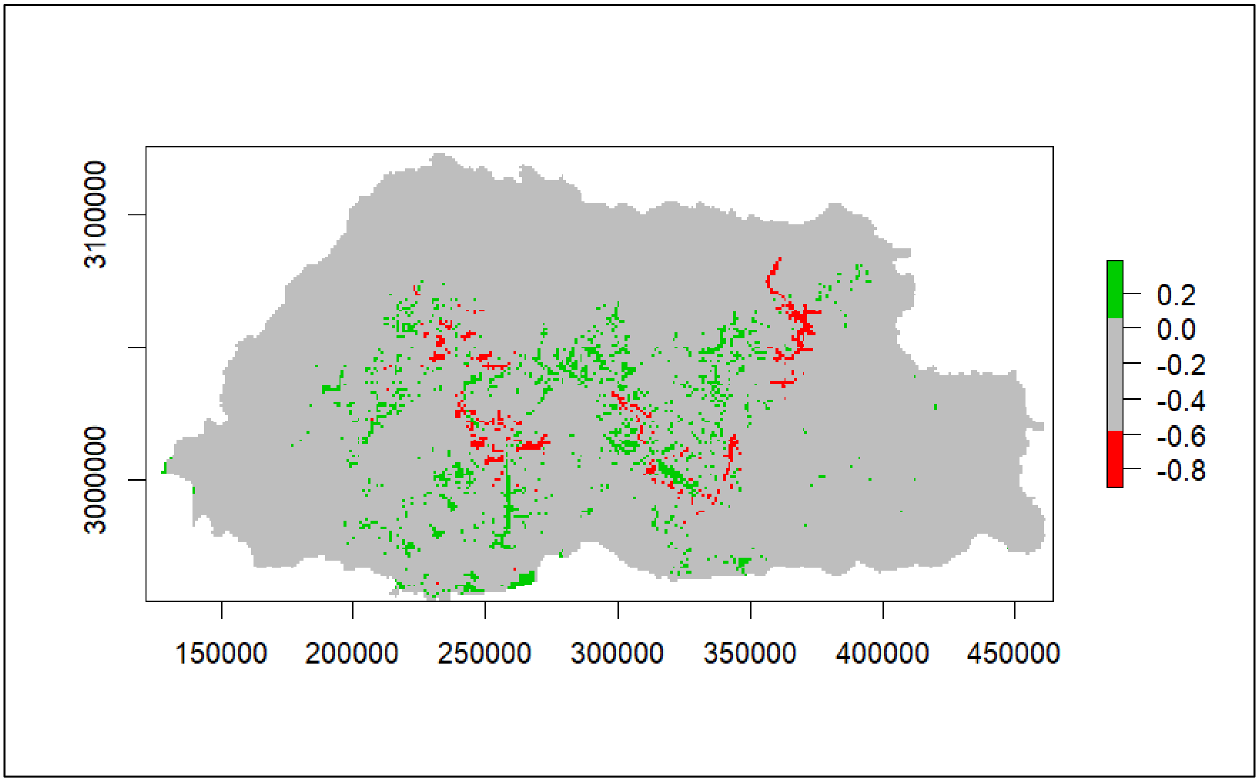

Figure 10. Predicted future habitat suitability gain and loss for the WBH under the SSP3 scenario (2061–2100).

Although gains slightly decline from mid-century, suitable habitat remains dispersed and fragmented. Conservation focus should shift toward connectivity and climate-resilient management.

3.7. District-Level Habitat Suitability Summary: Baseline Conditions

Under baseline conditions, districts such as Dagana, Tsirang, and Zhemgang demonstrate strong ecological suitability for the WBH, with MAJORITY values of 3 and MEAN scores exceeding 0.75, positioning them as key conservation priorities and potential refugia. Monggar and Pema Gatshel exhibit high habitat heterogeneity (VARIETY = 4–5), and although their MEAN scores are moderate (~0.28–0.55), the presence of highly suitable pockets (MAX = 4) suggests strong potential for targeted management. In contrast, districts like Samdrup Jongkhar and parts of Chhukha report MAJORITY values of 1 or 2 and MEAN scores below 0.3, indicating reduced habitat quality likely influenced by anthropogenic pressure or suboptimal terrain. Notably, areas with high VARIETY scores reflect ecotonal transitions and niche diversity, while districts such as

Samtse and Trashigang, despite overall low MEAN scores, show high MAX values—highlighting the presence of isolated but ecologically valuable habitat fragments deserving strategic attention.

3.8. District-Level Habitat Suitability Summary for 2041–2060 under SSP3

Under SSP3 climate projections for 2041–2060, Dagana, Pema Gatshel, and Monggar maintain high habitat suitability for the WBH, with MEAN scores exceeding 0.6 and dominant suitability classes (MAJORITY = 3 or 4), indicating strong ecological persistence despite projected pressures. Paro, Chhukha, and Bumthang exhibit moderate suitability (MEAN ~0.45–0.50), with habitat classes reaching up to MAX = 3, positioning them as transitional zones where conservation interventions may remain effective. Conversely, Gasa and Haa reflect critically low habitat suitability (MEAN = 0.02) and minimal ecological diversity (VARIETY ≤ 2), likely driven by topographic or climatic limitations (Table 8).

Table 8. Regional summary of projected habitat suitability change for the WBH across Bhutan under the SSP3 scenario for 2041–2060. The table highlights district-level trends, including high suitability retention in Dagana, sustained scores in Monggar and Pema Gatshel, early signs of ecological fragmentation in western districts, and sharp declines in northern regions such as Gasa and Haa.

Region	**Habitat Change Summary (2041–2060)**
Southern	Mixed signals: Dagana show high suitability, but neighboring districts begin to show decline
Eastern	Monggar and Pema Gatshel retains strong habitat scores, while Lhuentse and Trashigang show reduced mean values
Western	Paro and Chhukha sustain moderate suitability but with signs of ecological fragmentation
Northern	Gasa and Haa exhibit sharp declines in suitability—early warnings for future stress

3.9. District-Level Habitat Suitability Summary for 2061–2100 under SSP3

Under SSP3 projections for 2061–2100, habitat suitability across most districts shows a marked decline compared to baseline and mid-century estimates (Table 9). Previously resilient zones like Dagana exhibit steep reductions, with MEAN suitability dropping from ~1.16 to ~0.39 and MAJORITY class shifting from 4 to 1, indicating widespread degradation. Moderate retention zones such as Pema Gatshel, Monggar, and Tsirang sustain MEAN values between ~0.35 and 0.43, suggesting the presence of fragmented but viable habitat patches. In contrast, critically low suitability persists in districts like Gasa, Haa, Wangdue Phodrang, and Bumthang, where MEAN scores fall below 0.10 and MAJORITY suitability is absent, likely driven by climatic shifts, topographic constraints, or increasing anthropogenic pressures (Table 10).

Table 9. District-level trends in mean habitat suitability for the WBH across Baseline, 2041–2060, and 2061–2100 SSP3 scenarios. The table presents changes in ecological quality over time, highlighting districts with early gains followed by degradation (e.g., Dagana, Pema Gatshel), persistent decline (e.g., Gasa, Haa, Trashigang), and potential resilience (e.g., Monggar).

District	Baseline Mean	2041–2060 Mean	2061–2100 Mean	Δ* (B → 2060)	Δ (2060 → 2100)	Net Δ (Baseline → 2100)
Dagana	0.86	1.16	0.39	+0.30	−0.77	**−0.47**
Pema Gatshel	0.55	0.92	0.41	+0.37	−0.51	**−0.14**
Monggar	0.28	0.63	0.36	+0.35	−0.27	**+0.08**
Tsirang	0.73	0.71	0.43	−0.02	−0.28	**−0.30**
Paro	0.45	0.47	0.27	+0.02	−0.20	−0.18
Gasa	0.06	0.02	0.01	−0.04	−0.01	**−0.05**
Haa	0.05	0.02	0.01	−0.03	−0.01	**−0.04**
Trashigang	0.55	0.38	0.24	−0.17	−0.14	−0.31
Zhemgang	0.74	0.65	0.33	−0.09	−0.32	−0.41
Chhukha	0.50	0.46	0.26	−0.04	−0.20	−0.24

*** Changes from baseline (current till 2100)**

Table 10. Directional patterns of habitat suitability change for the WBH across Bhutan's regions under the 2061–2100 SSP3 scenario.

Region	**Trend Description (2061–2100)**	**Direction**
Southern	Loss intensifies; red zones dominate Sarpang and Samtse	⬇ Southward degradation (habitat quality drop)
Eastern	Habitat suitability retracts; Monggar and Trashigang lose resilience	➡ Eastward erosion (fragmentation intensifies)
Central	Once-strong habitat zones splinter; Dagana and Zhemgang fragment	↘ Longitudinal collapse (total loss in habitat)
Northern	Gains shift slightly upslope but remain patchy and unstable	⬆ Northward retreat (habitat shift)
Western	Paro and Chhukha undergo transition from marginal to unsuitability	⬅ Westward decline (habitat suitability deminishes)

3.10. Transition Insights

Between 2041 and 2100, modeled habitat suitability trends reveal three distinct trajectories across districts. Dagana and Pema Gatshel initially show gains in ecological quality during mid-century projections, but subsequently decline sharply—likely reflecting early conservation benefits offset by intensified SSP3 stressors. In contrast, districts such as Gasa, Haa, and Trashigang exhibit consistent deterioration throughout both periods, ending with minimal suitability and limited conservation potential. Notably, Monggar demonstrates gradual improvement over time, resulting in a net gain in habitat suitability by 2100. This trajectory positions Monggar as a potential future refugium and target for climate-resilient conservation planning (Table 11).

Table 11. Ranked transition analysis of district-level (top 5 districts) habitat suitability for the WBH under SSP3 scenario projections (Baseline to 2100). The table highlights net changes in mean suitability values (Δ Mean) and corresponding ecological trends, identifying Monggar as a resilient zone, Dagana as severely degraded, and Gasa as chronically unsuitable.

Rank	District	Net Change (Δ Mean)	Trend
🟢 1	Monggar	+0.08	Net gain (resilient)
🟡 2	Pema Gatshel	−0.14	Moderate degradation
🟠 3	Paro	−0.18	Transitional decline
🔴 4	Dagana	−0.47	Severe degradation
🔴 5	Gasa	−0.05	Chronically unsuitable

3.11. Current Habitat Suitability Within PAs (SDM Baseline Scenario)

Under baseline conditions, Royal Manas National Park and Phibsoo Wildlife Sanctuary stand out as high-performing PAs exhibiting MEAN suitability scores between 0.9 and 1.2 and dominant habitat classes (MAJORITY = 3 or 4). These sites serve as critical ecological strongholds for biodiversity conservation. In contrast, Jomotsangkha Wildlife Sanctuary demonstrates moderate habitat suitability (MEAN = 0.4–0.7) alongside high internal diversity (VARIETY = 4–5), suggesting its potential to support species persistence if adequately buffered. Meanwhile, high-altitude or rugged terrain PAs such as Wangchuck Centennial Park and Bumdeling Wildlife Sanctuary (BWS) show low suitability scores (MEAN < 0.3; MAJORITY = 1–2), likely reflecting climatic constraints or topographic barriers to habitat quality.

3.12. Projected Habitat Suitability Within PAs (2041–2060, SSP3 Scenario)

Under projected SSP3 conditions for 2061–2100, distinct habitat suitability patterns emerged across Bhutan's protected area subzones. Southern corridors—BC4, BC3, and BC2—demonstrated strong ecological resilience, with MEAN scores ranging from 0.78 to 0.95 and dominant suitability classes (MAJORITY = 3). Their internal habitat diversity (VARIETY = 4) underscores their importance as long-term refugia for the WBH.

Moderate zones such as BC5, BC7, and Jigme Singye Wangchuck National Park (JSWNP) displayed intermediate MEAN scores (~0.30–0.45) and mixed suitability classes, indicating fragmented but potentially restorable landscapes. These areas may benefit from strategic buffering or connectivity enhancement to reinforce ecological viability.

In contrast, BC6, Jigme Khesar Strict Nature Reserve (JKSNR), and Bumdeling Wildlife Sanctuary (BWS) reported severe ecological decline, with MEAN values ≤ 0.01, low maximum suitability (MAX ≤ 1), and MAJORITY classes of 0. These zones are likely unsuitable for future WBH persistence and may require alternate approaches, such as elevational rewilding or long-term restoration planning.

3.13. Projected Habitat Suitability Within PAs (2061–2100, SSP3 Scenario)

Under the SSP3 scenario for 2061–2100, protected area zones exhibited clear contrasts in habitat quality for the WBH. Southern corridors—namely BC2, BC3, and BC4—retained strong ecological integrity, with MEAN scores exceeding 1.07 and high habitat suitability classes persisting. These areas remain critical strongholds for biodiversity under intensifying climate pressures.

Moderate-performing zones such as BC5, BC7, and JSWNP showed viable habitat conditions, but with evident spatial fragmentation (STD > 1.0). These regions may benefit from targeted micro-zonation and internal restoration planning.

Conversely, BC6, BWS, JKSNR, and Jigme Dorji National Park (JDNP) displayed severe habitat decline, with MEAN values as low as 0.001–0.11 and suitability capped at Class 1. Their poor resilience under SSP3 suggests a need for alternative conservation strategies, such as elevational rewilding or assisted migration planning.

3.14. Consolidated Habitat Suitability Findings in Districts and PAs (Baseline → 2041–2060 → 2061–2100 SSP3)

Eastern districts, particularly Monggar and Pema Gatshel, consistently retain areas of suitable WBH habitat that lie outside Bhutan's protected area network across all modeled timeframes.

These districts are strong candidates for recognition as Other Effective Area-Based Conservation Measures (OECMs).

Mid-elevation regions adjoining BC3 and BC4 corridors demonstrate ecological resilience throughout baseline and future SSP3 scenarios, suggesting their critical role in climate-adaptive conservation strategies.

In contrast, northern zones such as JKSNR and BWS are projected to become ecologically unsuitable for WBH by the end of the century, indicating a need for alternative conservation planning in these high-altitude areas (Table 12).

Table 12. Projected habitat suitability trends and conservation implications for Bhutan's protected areas across Baseline, 2041–2060, and 2061–2100 SSP3 climate scenarios. The table summarizes mean suitability values, directional trends, and strategic recommendations for each PA, highlighting areas of persistence (e.g., BC2–BC4), moderate fragmentation (e.g., JSWNP), and future unsuitability (e.g., JKSNR, BWS).

Protected Area	Baseline MEAN	2041–2060 MEAN	2061–2100 MEAN	Suitability Trend	Implication
BC4 (East-Central Corridor)	High (~0.90)	Very High (~1.10)	Retained (~1.07)	⬆ Moderate gain → stable	Climate-resilient refugia candidate
JSWNP (Central Belt)	Moderate (~0.45)	Moderate (~0.40)	Slight decline (~0.55)	↔ Stable to fragmented	Needs internal restoration zones
JKSNR (Western Belt)	Low (~0.10)	Minimal (~0.01)	Unsuitable (~0.001)	⬇ Habitat collapse	Long-term unsuitability under SSP3
BWS (Eastern Belt)	Low (~0.15)	Near-zero (~0.01)	~0.001	⬇ Severe degradation	May require elevation shift strategies
BC2–BC3	Moderate (~0.65)	High (~0.95)	High (~1.10)	⬆ Improvement → resilience	Crucial for corridor protection

Protected Area	Baseline MEAN	2041–2060 MEAN	2061–2100 MEAN	Suitability Trend	Implication
JDNP (North-Western Belt)	Moderate (~0.50)	Decline (~0.30)	Low (~0.15)	⬇ Progressive loss	Buffering needed

3.15. Protection Gap Analysis

3.15.1. District-Level Distribution of Suitable WBH Habitat Outside Protected Areas (2041-2060, 2061–2100)

Across most districts, only a very small proportion of suitable WBH habitat falls outside protected areas, typically ranging from 0.0% to 1.5%, with slight increases in fragmentation projected by 2061–2100. Districts like Lhuentse, Monggar, Paro, and Wangdue Phodrang consistently show moderate gaps (~0.7–0.9%) throughout both future periods, indicating the presence of minor buffer zones or transitional fragments that may require further protection. Trongsa exhibits a more pronounced rise in unprotected habitat—from 0.3% to 1.5%—signaling potential fragmentation pressure in central Bhutan that could benefit from ecological corridor planning. Meanwhile, districts such as Gasa, Haa, Pema Gatshel, Samtse, Trashigang, and Tashi Yangtse report no suitable WBH habitat outside protected areas (Table 13).

Table 13. District-wise distribution of high-suitability WBH habitat (Classes 3–4) located outside formal protected areas under SSP3 scenarios for 2041–2060 and 2061–2100. The table summarizes total suitable habitat per district, absolute area of unprotected habitat, and protection gap percentage. Values support prioritization for conservation interventions and spatial planning.

Dzongkhags	Suitable Area 2041-2060	Suitable Area Out of PAs (2041-2060)	Gap for 2041-2060 (%)	Suitable Area 2061-2100	Suitable Area Out of PAs (2061-2100)	Gap for 2061-2100 (%)
Bumthang	0.0	0.0	0.0	0.0	0.0	0.0
Chhukha	28.0	23.7	84.8	14.0	12.3	88.0
Dagana	362.0	299.5	82.7	420.0	348.4	83.0

Gasa	1.0	0.0	0.0	8.0	0.0	0.0
Haa	0.0	0.0	0.0	0.0	0.0	0.0
Lhuentse	64.0	53.6	83.8	179.0	116.6	65.2
Monggar	14.0	6.1	43.6	44.0	37.4	84.9
Paro	16.0	12.5	78.4	26.0	20.9	80.5
Pema Gatshel	0.0	0.0	0.0	1.0	0.0	0.0
Punakha	211.0	184.9	87.6	350.0	290.3	83.0
Samdrup Jongkhar	0.0	0.0	0.0	5.0	0.1	1.4
Samtse	0.0	0.0	0.0	0.0	0.0	0.0
Sarpang	205.0	103.8	50.6	260.0	124.0	47.7
Thimphu	102.0	100.4	98.4	78.0	75.0	96.2
Trashigang	0.0	0.0	0.0	0.0	0.0	0.0
Trongsa	75.0	25.7	34.2	125.0	41.4	33.2
Tsirang	254.0	232.7	91.6	324.0	294.6	90.9
Wangdue Phodrang	329.0	261.9	79.6	509.0	381.7	75.0
Tashi Yangtse	0.0	0.0	0.0	0.0	0.0	0.0
Zhemgang	367.0	162.4	44.2	457.0	210.3	46.0

4. Discussion

The results of this study provide the most comprehensive climate-informed distribution modelling for the White-bellied Heron (*Ardea insignis*) in Bhutan to date, with significant implications for conservation planning in the Eastern Himalayas. Ensemble projections across SSP3 scenarios present compelling evidence that, while Bhutan currently serves as a critical refugium, future climate trajectories are likely to reshape habitat distributions—fragmenting current strongholds and introducing novel, often unprotected, high-suitability zones. These findings underscore the urgent need for adaptive, anticipatory conservation strategies rooted in spatially explicit data and long-term ecological forecasting.

4.1. Climate-Driven Range Expansion and Retraction

Contrary to negative trends observed in other range countries such as India, Myanmar, and Bangladesh (Maheswaran et al., 2021b), Bhutan demonstrates a significant net habitat gain for WBH across all projected timeframes. Climatically suitable areas expand from 8,219 km² under baseline conditions to 11,980 km² by 2041–2060, and further to 13,784 km² by 2100. This trajectory indicates that Bhutan's mid-elevation ecosystems, particularly riparian zones buffered by intact forest cover, may become increasingly vital for global WBH conservation—echoing broader range-shift patterns in Himalayan taxa under thermal stress (Telwala et al., 2013).

However, expansion is neither linear nor universally beneficial. Notably, high-suitability areas begin to emerge in previously low/unreported WBH presences districts such as Monggar, Pema Gatshel, and Lhuentse, many of which lie outside the existing PA network. These new zones mirror range shifts observed in other montane bird species, where climate change drives habitat redistribution beyond current conservation boundaries (Hole et al., 2009). This emerging mismatch between climate-adjusted habitat distributions and formal conservation coverage demands recalibration of Bhutan's spatial planning.

4.2. Fragmentation and Ecological Instability

Despite aggregate habitat gains, model outputs suggest an increase in spatial fragmentation. Districts such as Dagana and Tsirang, which demonstrate strong suitability in mid-century projections, undergo steep declines by 2100. Northern zones, including Gasa and Haa, remain persistently unsuitable across all scenarios, likely constrained by topography, altitude, and climatic variability.

This fragmentation reduces carrying capacity and amplifies risks for isolated WBH populations—already vulnerable due to low reproductive rates and susceptibility to stochastic events like flooding or disease outbreaks (Price & Goodman, 2015). The emergence of high-suitability patches surrounded by suboptimal landscapes reflects increasing ecological isolation, a trend consistent with climate-induced fragmentation documented among river-dependent species (Domisch et al., 2013). Moreover, protected areas such as JSWNP and BC5–BC7 show moderate

MEAN suitability but high internal variability (STD > 1), emphasizing the need for micro-zonation and habitat restoration to preserve internal connectivity.

4.3. Protected Area Efficacy and Coverage Gaps

One of the most striking results is the mismatch between projected WBH habitat and Bhutan’s existing conservation network. While core PAs like Royal Manas National Park and Phibsoo Wildlife Sanctuary continue to act as ecological anchors, emerging high-suitability zones in districts such as Monggar, Trongsa, and Dagana fall outside PA boundaries.

The gap analysis reveals that districts like Tsirang, Paro, and Wangdue Phodrang may have over 80% of their future WBH habitat outside formal conservation areas. These spatial gaps highlight the need to move beyond a static PA model toward a more dynamic, climate-responsive network.

A promising pathway lies in the integration of Other Effective Area-Based Conservation Measures (OECMs). Recognized under the Convention on Biological Diversity’s post-2020 global framework, OECMs encompass community-managed forests, sacred sites, riparian buffer zones, and seasonal no-development zones that deliver long-term biodiversity outcomes (IUCN-WCPA, 2019). Districts like Monggar and Pema Gatshel, consistently retaining suitable habitat outside the PA system, are strong candidates for OECM designation. This approach allows Bhutan to formalize informal stewardship practices while enhancing ecological coverage.

4.4. Conservation Planning in a Fragmented Future

The study's findings offer actionable guidance for Bhutan’s conservation planning. Protected corridors such as BC2, BC3, and BC4 demonstrate high habitat retention across all timeframes, positioning them as potential climate-resilient refugia and critical dispersal routes. Maintaining and enhancing landscape connectivity between these corridors—especially across elevational gradients—should become central to WBH conservation policy.

Conversely, northern parks such as BWS and JKSNR projected to become chronically unsuitable, may require adaptive rewilding strategies, habitat compensation schemes, or repurposing for other compatible conservation objectives. Moderate-performing zones like JSWNP and BC7, though spatially fragmented, can benefit from targeted internal management interventions—e.g., riparian reforestation, or seasonal visitor zoning.

Importantly, districts containing small but high-quality habitat pockets—evidenced by high MAX scores amidst declining MEAN values—may serve as ecological stepping stones or satellite habitats. These areas warrant protection through either PA expansion or OECM recognition to ensure spatial continuity.

4.5. Wildlife Tourism as a Conservation Ally

In addition to conventional protection mechanisms, wildlife tourism offers a promising yet underutilized tool for WBH conservation in Bhutan. Heron-watching activities, designed for non-breeding seasons and developed in coordination with communities and park authorities, could support low-impact ecotourism while fostering public awareness and local stewardship.

Bhutan's success in nature-based tourism—e.g., snow leopard treks, red panda watch in Jigme Dorji National Park—provides a viable model (Dendup et al., 2021). By establishing observation platforms, interpretive trails, and seasonal guidelines, future WBH tourism initiatives could serve both conservation and livelihoods, especially in emerging refugia districts like Dagana, Monggar, and Pema Gatshel. However, careful zoning and impact monitoring will be crucial to prevent disturbance or over-commercialization of sensitive sites.

4.6. Policy and Research Implications

The projected range shifts under SSP3 carry deep policy relevance. Bhutan’s constitutional commitment to maintaining ≥60% forest cover (RGoB, 2008) provides a stable foundation for integrating SDM outputs into national land-use plans, Environmental Impact Assessments (EIAs), and energy infrastructure development. Given the documented impacts of hydropower on WBH habitat—e.g., Punatsangchhu basin degradation—strategies to reconcile energy goals with biodiversity priorities are vital (Phuntshok et al., 2022).

On the research front, this study fills a longstanding gap by offering the first nationwide, ensemble-modeled WBH habitat forecast using robust predictors and multitemporal SSP3 projections. Future efforts should focus on validating these predictions through field surveys in eastern and central Bhutan, where model-identified zones have been historically under-sampled. Moreover, incorporating variables like river hydrology, prey availability, and seasonal habitat dynamics can further refine species distribution models for climate-vulnerable taxa.

4.7. Conclusion

Bhutan’s projected expansion of climatically suitable WBH habitat represents a rare conservation opportunity amidst widespread species decline. However, spatial fragmentation, protection gaps, and ecological volatility underscore the need for multifaceted conservation strategies. By integrating climate-resilient corridor planning, OECM recognition, regulated wildlife tourism, and fine-scale ecological management, Bhutan can set a global example of adaptive conservation grounded in cultural values and scientific foresight.

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