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Are Galliformes of the High Himalayas Well Protected? Identifying Conservation Priority Areas Using an Assemblage-Level Approach

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ABSTRACT

Understanding the distribution patterns of less charismatic species that co-occur with a charismatic umbrella species is critical for ecosystem protection. However, conservation efforts often overlook non-charismatic taxa, especially the distributions of multiple co-occurring species. Here, we use an assemblage-level approach to identify key conservation areas for a functionally important and abundant group of Galliformes occurring at high elevations in the Indian Himalayas. We address three main questions: (1) What factors influence Galliformes species distribution patterns? (2) Where are the specific regions of high species richness and high endemism in these landscapes? and (3) To what extent do these regions overlap with the current network of protected areas? We conducted extensive camera-trapping surveys covering 26,000 km^2 of high-altitude habitat. We found that vegetation cover and temperature seasonality were the most important predictors of Galliformes species distributions. Regions of high Galliformes species richness and endemism had low overlap with the protected area network (12.5% and 8.8%, respectively). We also found that the transition zone between the Greater and Trans-Himalaya is particularly important for conserving the Phasianidae assemblage inhabiting snow leopard landscapes. Our study has global significance as we bring attention to the value of assessing assemblage-level patterns for functionally significant taxa that occur largely outside the protected area networks designed primarily for umbrella species conservation.

1 | Introduction

Understanding the factors influencing species distributions is crucial for effective conservation management. There is growing interest in assessing the impacts of climate change and land-use change on species distributions, not only at local scales but also across broader regional landscapes (Araújo and New 2007; Forester et al. 2013). To manage large landscapes, conservationists frequently apply the umbrella species concept, aiming to protect multiple focal species that share the same habitat (Roberge and Angelstam 2004). However, the ecological benefits of this approach—particularly its effects on the population viability of co-occurring species—are rarely assessed empirically (Caro 2003; Curveira-Santos et al. 2021).

Summary

Conservation efforts often focus on charismatic animals, such as large carnivores, while many other species that play important ecological roles receive little attention. In this study, we focus on a group of ground-dwelling birds (Galliformes) that are common and ecologically important in the high-altitude regions of the Indian Himalayas but are often overlooked in conservation planning centered on snow leopards. Using large-scale camera-trap surveys across 26,000 km^2, we examined which environmental factors influence where these bird species occur, identified areas with high species diversity and unique species, and assessed how well these areas are covered by existing protected areas. We found that vegetation cover and seasonal temperature changes strongly influence the distribution of these birds. Importantly, most areas with high species diversity and unique bird species fall outside the current protected area network in our study area. We also show that the transition zone between the Greater and Trans-Himalaya is particularly important for conserving these birds, many of which live in landscapes managed primarily for snow leopard conservation. Our findings highlight the need to look beyond single flagship species and consider groups of co-occurring, functionally important species to better protect mountain ecosystems.

- **Practitioner Points**
  - Most areas with high Galliformes diversity and endemism lie outside existing protected areas, indicating important conservation gaps.
  - The Greater and Trans-Himalayan transition zone supports key bird assemblages and should be explicitly incorporated into landscape-level conservation planning.
  - Incorporating assemblage-level data for functionally important but non-charismatic taxa can strengthen conservation outcomes in flagship-species landscapes.

Improving the management of extensive landscapes that span multiple species' ranges requires a deeper understanding of the distribution patterns of less-studied, non-charismatic species that play critical roles in maintaining ecosystem function, such as seed dispersal, pollination, and pest control (Sekercioglu 2006; Curveira-Santos et al. 2021). For example, frugivorous birds that share habitats with large mammals, such as elephants or tigers, help regenerate forests by dispersing seeds over large distances (Whelan et al. 2008). Ground-feeding birds belonging to the family Phasianidae, which includes pheasants and partridges, form a crucial prey base for many predatory birds and mammals (Ramesh et al. 1999).

The high mountains of the Indian Himalayas are home to the charismatic snow leopard (*Panthera uncia*), an umbrella species for the conservation of these unique landscapes (Alexander et al. 2016). Over the past two decades, conservation action in the Indian Himalayan region has largely focused on snow leopard protection. India's snow leopard conservation efforts include the Global Snow Leopard and Ecosystem Protection Program (GSLEP), which promotes transboundary cooperation, and SECURE Himalaya, which emphasizes habitat protection and community-based conservation. Conservation in the Himalayas has also focused on snow leopards through government-led initiatives, such as Project Snow Leopard, launched in 2009 by the Ministry of Environment and Forests. Since its inception, Project Snow Leopard has worked to integrate snow leopard conservation into broader landscape-level planning, with an emphasis on collaboration with local communities (SPAI). In addition, state-level initiatives and protected areas—such as Hemis National Park and Kibber Wildlife Sanctuary—play a vital role in safeguarding snow leopard habitats (Sharma and Singh 2020).

Snow leopard landscapes are also home to a diverse assemblage of ground-dwelling birds belonging to the order Galliformes, which co-occur with the snow leopards but have received relatively little attention despite being functionally important. Galliformes play a key role in seed dispersal in the high Himalayas (Brooks et al. 2019). For example, recent work has demonstrated the role of the chukar partridge in dispersing pistachio seeds—an economically important forest product (Essa et al. 2021). Unsurprisingly, hunting of Galliformes for meat and habitat loss due to land conversion for agriculture and aquaculture are among the predominant threats to Galliformes in the Himalayas (Gupta et al. 2022). Previous studies on the distribution patterns of Galliformes indicate that many highly threatened species are endemic to the Himalayas (Singh and Banyal 2013; Thakur et al. 2021) and that existing protected area networks are perhaps inadequate for their conservation (Dunn 2015; Dunn et al. 2016). Additionally, little is known about the ecological drivers influencing the distributions of high-altitude Phasianidae species. Therefore, there is a pressing need to examine species distribution patterns and develop a mechanistic understanding of the Galliformes species assemblage.

Protected Areas (PAs) have been shown to contribute substantially to bird conservation, especially in threatened terrestrial ecosystems (Cazalis et al. 2020; but see Rayner et al. 2014). However, Ghosh-Harihar et al. (2019) found that 28%–33% of bird species in India do not overlap with PAs established for tiger conservation, another of India's flagship species. Although protected areas have been designated in high-elevation regions of the Himalayas, detailed assessments of their effectiveness for bird conservation remain limited (Ghosh-Harihar et al. 2019). Previous work has examined PA coverage for Galliformes only at very coarse spatial scales (Dunn et al. 2016). Moreover, previous work is lacking in information on the daily activity patterns of Galliformes, which could be valuable for informing conservation actions. Conservation planning increasingly requires approaches that aim to preserve species, populations, and ecosystems both within and beyond PAs. However, many studies rely on single-species distribution maps or occurrence records to assess overlap with PAs (Ghosh-Harihar et al. 2019; Moradi et al. 2019), making it difficult to discern broader, community-level patterns. While single-species studies are essential for addressing extinction risk, multi-species approaches offer greater potential for evaluating whether umbrella-based conservation strategies deliver wider biodiversity benefits.

Recent advances in species distribution modeling enable researchers to use multi-species approaches that examine assemblage-level properties and generate spatially explicit maps of high species richness and composition (Guisan and Rahbek 2011; D'Amen et al. 2015; Zurell et al. 2020). For example, a recent study investigated assemblage-level properties by creating spatially explicit community richness and composition maps for butterflies and grasshoppers (D'Amen et al. 2015), and subsequent studies have since tested the accuracy of assemblage-level modeling approaches (Zurell et al. 2020). This assemblage-centric approach provides an immense opportunity to assess the coverage of existing protected areas and creates a single framework under which to design conservation interventions for functionally important taxa that have so far only received species-specific attention for conservation.

In this study, we take an assemblage approach to examine the distribution patterns of Phasianidae species inhabiting high-elevation regions of the Indian Himalayas, with a particular focus on snow leopard habitats in Himachal Pradesh (Suryawanshi et al. 2021). Research on Galliformes has historically been concentrated in Western Europe and Southeast Asia (Boakes et al. 2010), and our study seeks to help address this geographical bias. Specifically, we ask: (1) What are the ecological drivers of Galliformes species distribution in high-elevation Himalayan landscapes? (2) Are there regions of high species richness and high endemism in these landscapes? And (3) To what extent do these regions overlap with the current protected area network? We conducted extensive camera-trapping surveys to build species distribution maps and community-level indices for our study area, and we also describe daily activity patterns of Galliformes based on camera-trap data. Our study highlights the conservation value of Galliformes in an understudied region and underscores the need to extend conservation planning beyond existing PAs.

2 | Methods

2.1 | Study Site

The study was conducted in the Indian state of Himachal Pradesh between 2016 and 2019 (30°22′–33°12′ N and 75°47′–79°04′ E). This work formed part of a large-scale effort to assess populations of snow leopards and their prey (Suryawanshi et al. 2021). The study area encompassed approximately 26,000 km^2 of high-elevation habitat (Figure 1), defined here as areas above 2000 m asl. Large-scale camera trapping was conducted across potential snow leopard habitat using a stratified sampling approach from 2016 to 2019.

The region is characterized by open temperate grassland ecosystems, dominated by grasses in drier areas and herbs and shrubs in wetter ones. In wetter parts of the Greater Himalaya, dominant plant genera include *Geranium, Ephedra, Polygonum, Podophyllum, Rhododendron, Lonicera* (honeysuckle), *Potentilla*, and grasses, such as *Stipa* and *Leymus* (Singh and Singh 1987). The drier Trans-Himalaya region is dominated by grasslands interspersed with thorny shrubs and small herbs, with *Stipa* sp., *Leymus* sp., *Elymas* sp., *Carex* sp., *Caragana* sp., *Lonicera* sp., and *Potentilla* sp. as the most common genera (Singh and Singh 1987). The ecological heterogeneity and variation in vegetation structure across this extensive area support a diverse avifauna (Kala 2000).

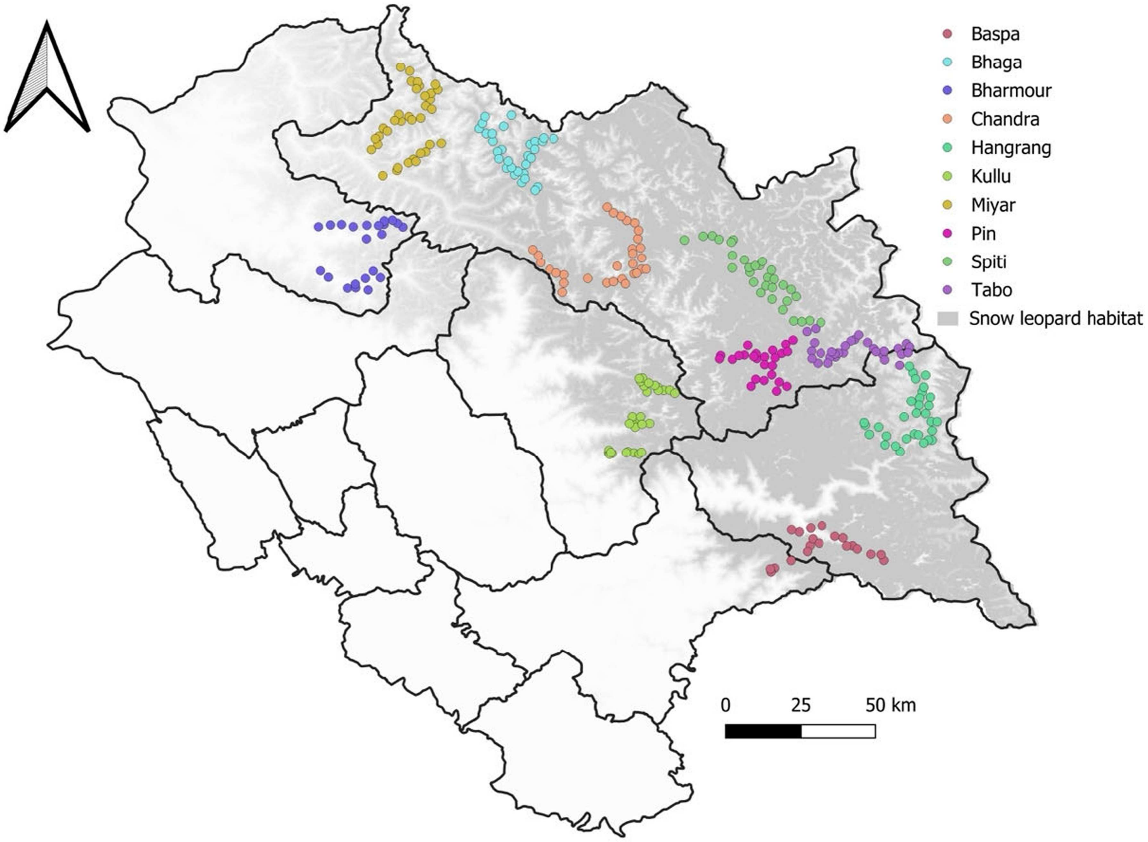

FIGURE 1 | Location of the study sites and camera-trapping survey locations across the high-elevation region of Himachal Pradesh, India.

2.2 | Species Occurrences and Environmental Predictors

To record species occurrences, we conducted camera trapping surveys at 10 sites. At each site, the area was gridded into 4 × 4 km cells, and 21 to 36 cameras were installed depending on site size. Typically, each site covered approximately 500 km^2 (see Suryawanshi et al. 2021 for details), with camera traps spaced approximately 4 km apart. Since the home range sizes of most of our study species are unknown, we relied on the average home range sizes of related pheasants (0.021–0.527 km^2) to rule out non-independent samples (Chiatante and Meriggi 2022). We installed traps at 284 locations for a minimum duration of 54 days (Table 1). Our study employed a stratified sampling approach in which all habitat types were sampled representatively. This stratified approach enabled us to sample the heterogeneity in habitat variables, which is important for niche-based modeling of multiple species. Survey sites were selected to represent gradients of snow leopard occupancy and from habitats where occupancy surveys had not been conducted previously. For recording detections of Galliformes, four sites (Spiti, Tabo, Hangrang, and Pin) were selected from the areas with high snow leopard occupancy, and three sites (Chandra, Miyar, and Bhaga) were selected from low occupancy areas. The elevation from these two strata ranged from 3000 to 5000 m asl. The third stratum included snow leopard habitat with unknown occupancy and included three sites (Kullu, Baspa, and Bharmour). The elevation ranged from 2000 to 4500 m asl in this stratum.

All Galliformes images were tagged using digiKam image management software (https://www.digikam.org/). Presence–absence data were generated for each species using the *camtrapR* package (Niedballa et al. 2016) in R. Although non-detections in camera trap studies do not represent true absences because of imperfect detectability, they can be treated as absence points in a presence–absence framework when derived from thorough sampling (Cushman et al. 2024; Faure et al. 2024; Jamali et al. 2024). Importantly, these observed non-detections differ from pseudo-absences generated from background datapoints in species distribution models.

The spatial extent of the camera-trapping design allowed us to capture broad-scale heterogeneity in habitat variables across snow leopard habitats. To model species distributions, we selected environmental predictors related to climate, topography, and vegetation that are known to influence bird distributions. Vegetation cover (Patterson and Best 1996), temperature (La Sorte and Jetz 2010), precipitation (Baker et al. 2012), and land cover (Skowno and Bond 2003) are well-established drivers of avian distribution patterns.

Annual bioclimatic variables were obtained from the Worldclim database at a spatial resolution of 30 arc-seconds (~ 1 km^2) (Fick and Hijmans 2017). Land cover data were derived from the Globcover Global Land Cover Map dataset (ESA 2010 and UC Louvain), which was retrieved using the Google Earth Engine platform. Vegetation cover was retrieved from the USGS Landsat 8 Collection 1 Tier 1 TOA Reflectance dataset by calculating the NDVI (Normalized Difference Vegetation Index) using the Google Earth Engine. Elevation data were downloaded from the Shuttle Radar Topography Mission (SRTM) digital elevation model in the Google Earth Engine and used to calculate a terrain ruggedness index. To reduce multicollinearity, we performed pairwise correlation tests and retained only variables with correlation coefficients < 0.8 (Evans 1996). The final set of predictors included temperature seasonality, precipitation seasonality, NDVI, land cover, and terrain ruggedness index. All environmental predictors used in the models are described in Table 2.

2.3 | Ensemble Models

We modeled species-environment relationships using an ensemble modeling approach to explain and predict Galliformes species distributions. Ensemble modeling combines predictions from multiple models rather than choosing a single modeling method, and has been shown to improve prediction performance (Thuiller 2003; Araújo and New 2007; Valavi et al. 2023). Because our data set included both presence and absence data, we incorporated true absences into model fitting; inclusion of absence data has been shown to improve model accuracy (Václavík and Meentemeyer 2009, helpfiles of rspatial.org). We used the *ssdm* package in R (Schmitt et al. 2017) to build ensemble models based on four algorithms: generalized linear models (GLM), general additive models (GAM), classification tree analysis (CTA), and support vector machines (SVM). The performance of species distribution models (SDMs) was assessed using the area under the curve (AUC) in a receiver operating characteristic (ROC) plot.

TABLE 1 | Camera-trapping effort across 10 survey sites in Himachal Pradesh.

Site	Estimated area (km^2)	Sampling year	No. of cameras deployed	Sampling duration (days)	Total trapping effort (days)
Bhaga	480	2018	30	60	1800
Bharmour	352	2019	21	89	1869
Chandra	496	2018	31	62	1922
Kullu	480	2019	30	128	3840
Miyar	576	2018	36	61	2196
Pin	370	2016	25	54	1350
Baspa	320	2019	20	76	1520
Tabo	464	2017	29	61	1769
Hangrang	484	2017	31	60	1860
Spiti	760	2017	31	60	1860

TABLE 2 | Environmental variables used in species distribution models and their relative variable importance for the three modeled species. Variable importance was estimated by permuting each predictor and comparing the Pearson correlation between the original and permuted predictions. Higher values indicate greater influence. Scores are expressed as percentages.

Predictor	Source	Ensemble model results		
		Alectoris chukar	*Lophophorus impejanus*	*Tetraogallus himalayensis*
Precipitation seasonality	https://www.worldclim.org/data/bioclim.html	9.84	8.58	18.66
NDVI	https://developers.google.com/earth-engine/datasets/catalog/LANDSAT_LC08_C01_T1_TOA	49.10	53.23	9.46
Temperature seasonality	https://www.worldclim.org/data/bioclim.html	18.31	4.79	35.47
Landcover	http://due.esrin.esa.int/page_globcover.php	8.22	17.25	15.21
Terrain ruggedness index	https://www.usgs.gov/centers/eros/science/usgs-eros-archive-digital-elevation-shuttle-radar-topography-mission-srtm-1	14.54	16.15	21.29

For model evaluation, we used the area under the receiver operating characteristic curve (AUC) values. An AUC value of 1.0 indicates perfect discrimination ability, whereas a value of 0.5 or less indicates a performance no better than random. Although Lobo et al. (2008) criticized the AUC approach for model evaluation in a presence-only data framework (Lobo et al. 2008), our model explicitly included absences rather than background locations (or pseudoabsences), and, as such, we used the AUC approach for model evaluation, which is the standard approach under such circumstances.

To assess the predictors of Galliformes distributions, we compared variable importance for the three focal species (*Alectoris chukar*, *Lophophorus impejanus*, and *Tetraogallus himalayensis*). Variable importance was calculated using model simplification and Pearson correlation coefficients (SSDM help files; Schmitt et al. 2017; Thuiller et al. 2019). In this method, correlation coefficients were computed between predictions from the full model and from models in which each environmental variable is permuted in turn. The *ssdm* package implements a randomization technique to assess the importance of each variable (Schmitt et al. 2017). The process involves calculating the Pearson correlation between the standard predictions (fitted values) and predictions obtained by randomly permuting the variable of interest (Thuiller et al. 2019). A high correlation, indicating minimal difference between two sets of predictions, suggests that the permuted variable has little influence on the model. This procedure was repeated multiple times, and the average correlation values across all iterations were used to rank predictor importance for each selected model. This method is independent of the modeling algorithm, allowing for direct comparisons across different model types.

2.4 | Assemblage-Level Properties and Protected Area Network

We used SDM predictions to map species richness and endemism patterns and assess their overlap with the coverage of Himachal Pradesh's protected area network. We used stacking procedures that incorporated probabilistic species-occurrence maps to generate a species richness map for the study region. Stacked SDMs generally outperform JSDMs (joint species distribution models) for species assemblage predictions (Zurell et al. 2020). However, stacked SDMs could be biased toward overprediction of low species richness and underprediction of high species richness (Zurell et al. 2020). The *ssdm* package in R uses a stacking algorithm based on probabilistic occurrence maps following the approach of Calabrese et al. (2014), in which per-cell species occurrence probabilities are summed to produce species richness estimates (Calabrese et al. 2014).

Endemism was quantified using the weighted endemism index (WEI; Crisp et al. 2001; Raes et al. 2009). For a given cell c, WEI was determined as the sum of the inverse geographic range sizes ($r_{i,c}$) of all n_c species occurring in that cell. This method avoids the use of arbitrary thresholds, such as region size or range size, for defining endemic species and instead employs a continuous weighting approach, assigning greater importance to species with smaller ranges and progressively lower weights to more widespread species. To compare the coverage of the protected area network over regions of high species richness, we overlaid maps of species richness and weighted endemism maps

Alectoris chukar *Lophophorus impejanus* *Tetraogallus himalayensis*

Lerwa lerwa *Pucrasia macrolopha* *Catreus wallichii*

FIGURE 2 | Camera-trap images of the six different Phasianidae species detected in the study area. *Alectoris chukar* was detected on 304 occasions, *Lophophorus impejanus* on 243, *Tetraogallus himalayensis* on 112, *Lerwa lerwa* on 20, *Pucrasia macrolopha* on 19, and *Catreus wallichii* once.

with the protected area map of Himachal Pradesh and quantified the degree of spatial overlap. Similarly, we created an endemism map for the study region.

2.5 | Galliformes Daily Activity Patterns

To examine the daily activity patterns of Galliformes species, we visualised histograms of detection times using the *camtrapR* package in R (Niedballa et al. 2016). To ensure temporal independence among detections, we used the *camtrapR* package to filter out images recorded within the same hour so that only one capture event per species per hour was retained.

3 | Results

3.1 | Galliformes Species Distribution in the Indian Himalayas

We recorded 596 detections of six Phasianidae species over 19,986 camera-trap nights (Table 1 and Figure 2). Three of the six species that were detected had more than 20 independent location detections and were therefore included in ensemble modeling: chukar partridge (*Alectoris chukar*), Himalayan monal (*Lophophorus impejanus*), and Himalayan snowcock (*Tetraogallus himalayensis*). Chukar partridge and Himalayan monal were the most frequently detected species, followed by Himalayan snowcock. Chukar partridge had the widest distribution, being detected at all 10 camera-trapping sites, with 304 total detections and 83 independent location detections. Himalayan monal had 243 total detections but was recorded at only three of the 10 sites, with 30 independent location detections. We recorded 112 detections (32 independent location detections) of Himalayan snowcock, 20 detections (seven independent location detections) of snow partridge (*Lerwa lerwa*), 19 detections (eight independent location detections) of koklass pheasant (*Pucrasia macrolopha*), and one detection of cheer pheasant (*Catreus wallichii*) (Figure 3). Owing to low sample sizes, we could not model the distribution of the latter three species.

To identify predictors of Galliformes species distributions in this region, we compared variable importance for the three species: *Alectoris chukar*, *Lophophorus impejanus*, and *Tetraogallus himalayensis*. For *A. chukar* and *L. impejanus*, NDVI was the most important variable explaining species distribution patterns. For *T. himalayensis*, however, temperature seasonality explained the most variation (Table 2). Ensemble model evaluation showed good performance across all four models for all three species (Table 3). For example, for *L. impejanus*, AUC values were high for all the models: 0.96 (GAM), 0.96 (SVM), 0.95 (CTA), and 0.85 (GLM). Similarly high values were obtained for the other species, except for the GLM models for *A. chukar* (AUC = 0.69) and *T. himalayensis* (AUC = 0.55; See Table 3 for model evaluation results).

3.2 | Species Richness, Endemism, and Protected Area Network

We mapped Galliformes species richness across the state and overlaid this map with the PA network to assess the extent of coverage of areas with higher species richness (Figure 4). Only 12.5% of areas with a species diversity index greater than one intersected with polygons represented by PAs. We also generated a map of weighted endemism and overlaid it with the PA network. Only 8.8% of highly endemic regions (weighted endemism index > 0.8) intersected with PA polygons.

3.3 | Galliformes Species Activity Patterns

All five species for which activity patterns could be assessed were primarily diurnal (Figure 5). *T. himalayensis* showed two activity peaks: a dominant peak between 06:00 and 08:00 h and a secondary peak between 15:00 and 17:00 h. *A. chukar* showed activity throughout the day (06:00–18:00 h) without a clear

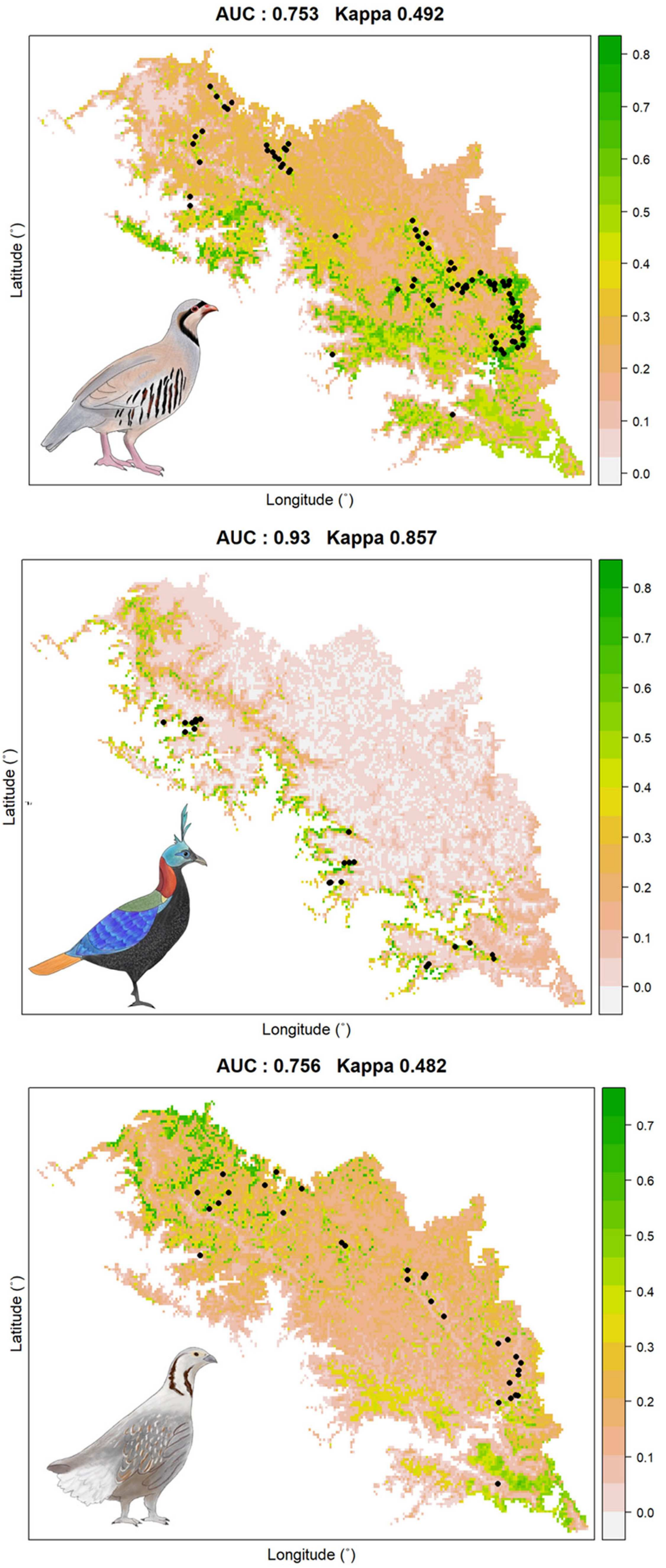

FIGURE 3 | Predicted probability of occurrence maps for three Phasianidae species based on ensemble species distribution models: (a) *Alectoris chukar*, (b) *Lophophorus impejanus*, and (c) *Tetraogallus himalayensis*. Species with < 20 detections were excluded from modeling. Bird illustrations created by Adithi S. Rao.

TABLE 3 | Area under the curve (AUC) values for ensemble species distribution models derived using multiple modeling algorithms.

Species	GLM	GAM	SVM	CTA
Alectoris chukar	0.69	0.75	0.84	0.73
Lophophorus impejanus	0.85	0.96	0.96	0.95
Tetraogallus himalayensis	0.55	0.82	0.81	0.85

peak. *L. impejanus* showed two activity peaks: one between 06:00 and 08:00 h and another between 18:00 and 20:00 h. *L. lerwa* and *P. macrolopha* showed a single pronounced activity peak between 05:00 and 06:00 h. Activity patterns for the cheer pheasant, *Catreus wallichii*, could not be calculated because only one detection was recorded.

4 | Discussion

Our study adopts an assemblage-level approach to examine and explain the distribution patterns of Phasianidae species inhabiting the high-altitude regions of the Indian state of Himachal Pradesh. Using extensive camera-trap surveys, we modeled species distributions and generated spatially explicit maps of species richness. We found that Galliformes distributions vary among species and are largely governed by vegetation cover and temperature seasonality in this region.

Himalayan Phasianidae species exhibit unique and largely non-overlapping distribution patterns. Vegetation cover was the most important predictor for both *A. chukar* and *L. impejanus*, particularly for the latter, with both species showing higher probabilities of occurrence in areas corresponding with higher NDVI values. This finding is consistent with previous studies demonstrating the importance of vegetation cover for pheasant distributions in the Himalayan mountains (Ramesh et al. 1999; Thakur et al. 2021). In contrast, the distribution of *T. himalayensis* was primarily restricted to higher-elevation regions of the Greater and Trans-Himalaya and was more strongly influenced by temperature seasonality than by vegetation cover. *A. chukar* exhibited a relatively broad distribution compared with the more restricted distributions of *L. impejanus* and *L. lerwa*. In addition, we also quantified the daily activity patterns of these five Galliformes species and found them to be predominantly diurnal. All species showed an activity peak at around 6:00 h, suggesting a temporal overlap in their activity patterns.

Large parts of the Indian Himalayas are recognized as biodiversity hotspots for Galliformes (Cai et al. 2018; Thakur et al. 2021) and for birds in general (see Acharya et al. 2024). Himachal Pradesh contains an area of approximately 26,000 km^2 with an elevation greater than 2000 m, hosting species with widespread distribution across various habitats and landscapes, as well as species uniquely confined to certain regions in the higher mountains of the Himalayas. (Cai et al. 2018). To assess large-scale distribution patterns, we developed a spatially explicit species richness map to identify zones of high species richness that could be of high conservation importance. We found that the current PA network overlaps with only 12.5% of the areas with high Galliformes species richness, encompassing both widespread and range-restricted species. Our results indicate that areas falling within Hangrang, Tabo, Bharmour, and Kullu—located in the transition zone between the Greater and Trans-Himalaya—are particularly important for the protection of the Phasianidae assemblage occurring within snow leopard habitats. These transition zones support relatively high diversity of Phasianidae species, and this finding could help in identifying further areas of conservation importance.

Past studies have shown that PAs in the Eastern Himalayas are insufficient both in terms of area and conservation measures for Phasianidae species, especially under projected range shifts driven by future climate change (Chhetri et al. 2021). To operationalize the conservation of this unique assemblage, there is an urgent need to engage local communities and raise awareness about the importance conserving areas outside formal PAs (Andrade and Rhodes 2012). Future conservation programs need to focus on mitigating the key threats to Galliformes, including through awareness programs aimed at controlling populations of free-ranging dogs and reducing hunting pressure. Our study further highlights that the limited overlap between current PA coverage and zones of high Galliformes richness and endemism represents a significant conservation gap that needs to be addressed. Currently, around 22% of the land in our study area is under legal protection, either in the form of wildlife sanctuaries or national parks. However, our results indicate the need to establish community conservation reserves in areas of high endemism. A recent example is the declaration of a conservation reserve in the Tsarup Chu region in the Lahaul and Spiti district within the snow leopard habitat. The establishment of this reserve represents an important milestone, as its management committee included local panchayat leaders, setting a valuable precedent for community involvement in conservation across snow leopard landscapes.

Evidence suggests that hunting remains a serious threat to pheasant species in these regions. Kaul et al. (2004) conducted a study in the Indian Western Himalaya examining the hunting practices targeting large mammals and pheasants. The primary motivation for hunting was to supplement dietary protein, although some species were also hunted for commercial purposes, including the sale of meat and animal parts. Notably, several threatened species, such as the western tragopan (*Tragopan melanocephalus*) and Himalayan monal (*Lophophorus impejanus*), were hunted in the majority of villages where they occurred (Kaul et al. 2004). Raising awareness of the functional importance of the Galliformes species group, together with participatory, community-based conservation interventions, could help reduce these pressures.

A caveat of our study is that only three of the six detected species were included in our analyses due to limited sample sizes. Koklass pheasant (*Pucrasia macrolopha*), cheer pheasant (*Catreus wallichii*), and snow partridge (*Lerwa lerwa*) were excluded from the stacked model owing to insufficient detections. Nevertheless, all eight koklass pheasant detections occurred within the transition zone that we proposed as a conservation priority (three in Bharmour, one in Kullu, and four in Hangrang). Similarly, of the seven independent location detections of snow partridge, six occurred within the proposed priority region (four in Bharmour and two in Hangrang).

Another limitation associated with our distribution models is that we did not explicitly model imperfect detection. Although

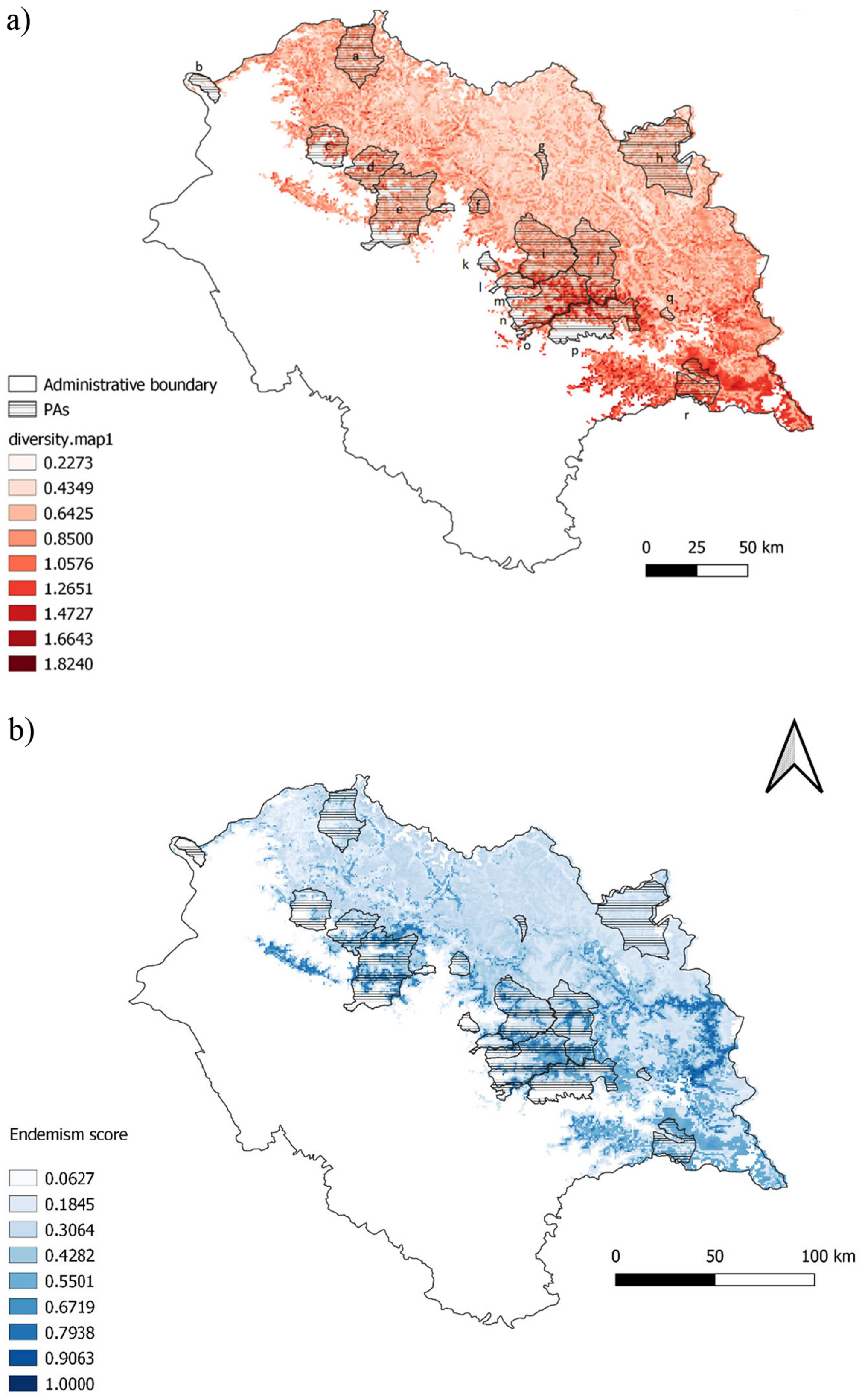

FIGURE 4 | (a) Species richness map generated using stacking of predicted occurrence probabilities for the three modeled species. The local species richness map was created by summing habitat suitability probabilities across species. (b) Endemism map based on the weighted endemism index (WEI), calculated by weighing each species by the inverse of its geographic range size. Shaded regions in both panels represent protected areas (PAs) in Himachal Pradesh. Protected area abbreciations: a = Sechu Tuan Nala WLS; b = Gamgul Siahbehi WLS; c = Tundah WLS; d = Kugti WLS; e = Dhauladhar WLS; f = Inderkila NP; g = Chandratal WLS; h = Kibber WLS; i = Khirganga NP; j = Pin Valley NP; k = Kanawar WLS; l = Great Himalayan NP; m = Sainj WLS; n = Great Himalayan NP; o = Tirthan WLS; p = Rupi Bhaba WLS; q = Lippa Asrang WLS; r = Raksham Chitkul WLS.

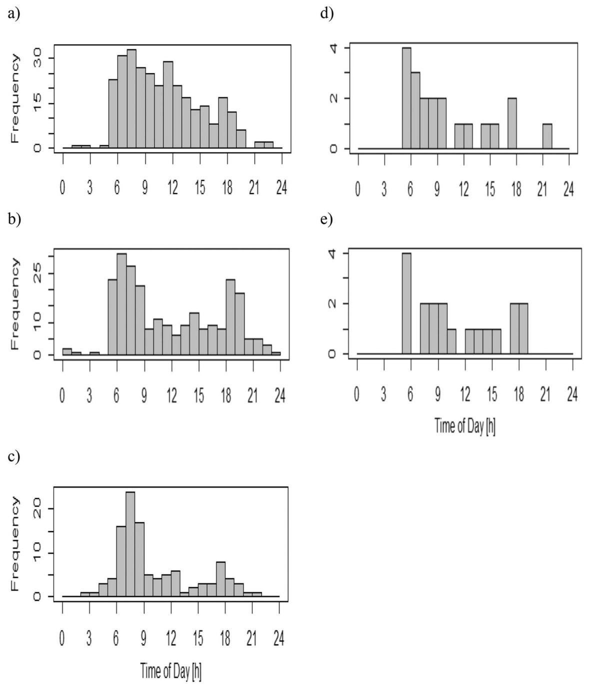

FIGURE 5 | Daily activity patterns of five Phasianidae species detected in the study area: (a) *Alectoris chukar*, (b) *Lophophorus impejanus*, (c) *Tetraogallus himalayensis*, (d) *Lerwa lerwa*, and (e) *Pucrasia macrolopha*.

we placed camera traps at each site for at least 54 days, we cannot assume a perfect detection probability. Future studies incorporating detection probability would improve the accuracy of species distribution estimates. Finally, surveys at nine of the ten sites were conducted in summer (May–August), while one site was surveyed from summer through autumn (May–October). Since our sampling duration was largely restricted to the summer months, we may have failed to detect winter distributions of altitudinal migrants, highlighting an important area for future research to obtain a more complete understanding of seasonal distribution patterns.

Our study shows the need for a quantitative assessment of the distributions of species using a multi-species approach at a landscape scale. An alternative assemblage-level approach, the spatially explicit species assemblage modeling (SESAM) framework, has been proposed to correct for overprediction biases associated with stacking binary SDMs (Guisan and Rahbek 2011). However, SESAM can be unreliable when species richness predictions are biased toward low- or high-richness sites (Calabrese et al. 2014). Recent studies show that ensemble SDMs outperform JSDMs (joint species distribution models), and that probabilistic stacking yields more accurate assemblage and richness predictions than binary stacking methods (Zurell et al. 2020). Accordingly, our use of benchmarked ensemble modeling approaches provides reliable predictions for this region. Few studies have attempted to assess the coverage of PA networks using spatially explicit species richness maps (but see Moradi et al. 2019), yet such maps are critical for identifying habitat corridors in Himalayan landscapes where climate change is causing widespread habitat loss.

Advances in species distribution modeling have enabled researchers to use robust ensemble approaches that are less susceptible to bias (Thuiller 2003; Zurell et al. 2020). While single-species studies remain essential (Ashoori et al. 2018), conservation approaches that evaluate the impact on complex communities at the landscape scale are increasingly necessary in the context of rapid environmental change in the Himalayas. Global populations of Himalayan monal, cheer pheasant, snow partridge, and koklass pheasant are declining (BirdLife International 2022). The recently released State of India's Birds report documents sharp declines in cheer pheasant populations (SoIB 2020), while trends for other species could not be investigated due to data deficiency. Previous research has demonstrated that fluctuations in bird population sizes directly impact the ecosystem services they provide, including seed dispersal by frugivorous birds, nitrogen translocation, and pest regulation by insectivorous birds. To ensure the proper functioning of ecosystems, the abundance and spatial distribution of these species must remain unaffected by negative influences (Gaston et al. 2018). Conservation efforts must therefore be expanded to maintain ecosystem functionality at multiple levels, encompassing broader spatial scales and a diverse range of species. This study demonstrates the utility of a multi-species, assemblage-level approach for identifying areas of high conservation significance. The priority areas identified for Galliformes in this study represent promising targets for future conservation planning, research initiatives, and citizen science engagement.

Author Contributions

M.S. and K.S. conceived the idea, design, experiment (supervised research, formulated question or hypothesis). A.S.R., J.P., M.K., and A.B. performed the experiments (collected data, conducted the research). M.S. and A.S.R. wrote the paper (or substantially edited the paper). M.K., A.B., and K.S. developed or designed methods. M.S. analyzed the data.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

We are happy to share the raw data for the analyses and results reported in this manuscript upon reasonable request.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section.
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