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Nesting habitat suitability and breeding of Asian woollyneck (*Ciconia episcopus*) in Nepal

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Abstract

Asian woollyneck (*Ciconia episcopus*) is a large wading bird species whose conservation status has been recently downlisted, despite a lack of concrete information on its nesting ecology and breeding success. In this study, we report its breeding success and nest habitat suitability in Nepal from 39 nesting sites (2016–2020). Simal (*Bombax ceiba*) ($n=21$), followed by sal tree(*Shorea robusta*) ($n=6$), and rani-salla (*Pinus roxburghii*) ($n=4$) were the most common tree with mean height of the nesting tree, nest height, and tree diameter being 30 ± 5.8 m (± SD), 25.20 ± 5.75 m, and 1.03 ± 0.35 m, respectively. Nesting and fledging success were recorded from 31 nesting attempts at 19 of these sites, with an estimated nesting success probability of 0.81 ± 0.07 and a mean fledging success of 1.94 ± 0.25 chicks per nest. MaxEnt modelling identified a total potential suitable nesting habitat area of 9.64% (14,228 km^2) of the area in Nepal, with this located within 72 districts, mostly in the west. The modelling parameters suggest that slope, land use, and precipitation during the driest months were important determinants of nesting habitat suitability. We recommend that priority be given to conserving taller trees (especially simal) close to settlements and croplands of Nepal. Also, that future surveys should consider examining the districts highlighted by our model as being the most likely candidates for containing woollyneck nesting habitat, especially those (such as Dang District) where woollyneck nests have not been previously reported.

Keywords Asian woollyneck · Breeding success · MaxEnt modelling · Nesting · Nepal

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Introduction

Understanding the habitat needs of a species is the first step in its conservation. For birds, nesting habitat is a key element linked with population persistence (Jiménez-Franco et al. 2018), and thus, information on nesting ecology is critical for avian conservation. However, large-scale surveys aimed at identifying key nesting sites in many areas of the world are not always possible in terms of their time, personnel, and funding requirements, especially when very little is known about a species. In such situations, focused or opportunistic data collection can be used to identify local factors that can be included in predictive habitat distribution models, which in turn help ecologists or conservation practitioners identify potential new areas for future surveys. Such an approach has been effectively used for avian nesting habitat predictions in double-crested cormorants *Phalacrocorax auratus* (Sheehan et al. 2017) and red-crowned crane *Grus japonensis* (Wu et al. 2016).

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The Asian woollyneck *Ciconia episcopus* is a large wading bird species resident within Asia (BirdLife International 2020). Its conservation status has recently been downgraded to "Near-threatened" from "Vulnerable" (BirdLife International 2020) despite limited knowledge of its nesting ecology (Ghimire et al. 2021). In Nepal, this conspicuous stork is distributed throughout the lowlands and mid-hills up to an altitude of 915 m, with few occasional high altitudinal movements (Ghale and Karmacharya 2018; Inskipp et al. 2016), but little is known about its local status, distribution, and ecology (Ghimire and Pandey 2018). It has a national "Near-threatened" status in Nepal and is reported to nest in the lowlands and mid-hills along river basins (Inskipp et al. 2016). Its long-term persistence is threatened because of hunting, collection of its eggs, and nesting tree degradation; with a paucity of information on this species escalating the threats to its survival (Inskipp et al. 2016). Studies on nesting ecology and breeding of Asian woollyneck are sparse and are mostly reported from single or only a few nest site observations around its distribution range (Banerjee 2017; Kularatne and Udagedara 2017; Ghimire et al. 2020; Hasan and Ghimire 2020). Some studies have been conducted in India (Ishtiaq et al. 2004; Kittur and Sundar 2021), creating a serious gap in our knowledge on the current nesting and breeding success of this species in other part of its range (Ghimire et al. 2021). While recent attempts have been made to collate (Ghimire et al. 2021) and model the distribution of Asian woollyneck throughout its distribution range (Gula et al. 2020), there is still a severe lack of environmental suitability data for nesting in this species. Recently, Kittur and Sundar (2021) studied nesting and breeding preferences in agricultural landscape of Haryana, India. While such long-term studies are ongoing in India, Nepal still lacks clear picture of this species distribution and ecology. With this in mind, we undertake this study to begin to understand the factors influencing nest site selection in Nepal, and to use this information to inform predictive models on where future nesting surveys in Nepal should be concentrated.

Specifically we focus on identifying woollyneck nesting sites and recording information about the nesting tree and nesting success where possible. From this information, we ask the following questions: (1) what are nesting trees used by Asian woollyneck, and (2) what are the physical dimensions of those nesting trees and the height of their nest? These questions are important for understanding their nesting habitat requirements and the potential for conservation planning related to nest tree retention. We also examine: (3) what is the nesting success of woollyneck in these nests, and (4) when nests are successful, how many chicks do they fledge? These questions are important for understanding the current fecundity of the species in Nepal and the potential for population growth in areas where their nesting is protected. Finally, we use the information collected from the area around the nesting trees (based on GIS) to model predictions of suitable nesting habitat in Nepal using a presence-only modelling approach (MaxEnt; Heinanen et al. 2012) to identify the potential of new breeding areas that have not been previously surveyed for this species in Nepal (Sheehan et al. 2017). While we acknowledge the limitations of such an approach for broader species distribution modelling (Gula et al. 2020), we use this rather to help guide future survey effort for a focused assessment on the extent of their breeding distribution in Nepal.

Methods

Study area

Nepal is a landlocked country of 147516 km^2 that encompasses an extreme habitat range from hotter lowlands to the coldest snow-capped Himalayas. Thus, within a small area, Nepal harbors an unusually high diversity of plants and animals (Paudel et al. 2012). Within this area, 28.75% of the land is used for agriculture, with 83% of population dependent upon it (CBS 2011; Trading Economics 2020). There is wide variation in vegetation throughout the altitude. Subtropical regions have *Shorea robusta* dominated forest while tropical to alpine are dominated by *Pinus roxbughii*, *Pinus wallichiana*, and *Rhododendron arboretum* (Paudel et al. 2012). Asian woollyneck is distributed throughout the Nepal with higher observation in central and western Nepal (Inskipp et al. 2016; Ghimire et al. 2021). Although the woollyneck is thought to be negatively impacted by agricultural intensification, recent observations suggest a seasonal preference for croplands in Nepal (Kittur and Sundar 2020). Changes in land use have occurred in Nepal over the past few decades with modifications in agriculture, the removal of large trees, and the drainage of wetlands potentially posing significant threats to these wetland-dependant species (Inskipp et al. 2016; MoFE 2018). A major challenge in its conservation is to understand how these changes influence the habitat suitability for woollyneck.

Nesting data collection and analysis

To find nests, we first identified potential nesting areas through literature review (e.g., Inskipp et al. 2016), 50 informal interviews with bird watchers, conservationists, forest officials, and local people as it helps in detectibility of species (Martínez-Martí et al. 2016). This helped to outline 16 districts of which we purposively surveyed potential areas of four districts (in the Rupandehi District of the lowlands, and the Pyuthan, Arghakhanchi, and Dhading Districts of the mid-hills) and identified 16 nesting sites. We combined these data with opportunistic observations, i.e., information forwarded by colleagues and from the Bird Conservation Nepal database ($n = 23$). This provided us with 39 nesting sites with information about their location, and tree species where the nest was located in the tree. These nest sites were located in the mid-hills region of Nepal (29 nests from the districts of Arghakhanchi, Pyuthan, Salyan, Dhading, Jajarkot, Surkhet, Kabhrepalanchowk, Sindupalchowk, and Kaski) and in the Nepal lowlands (10 nests from the districts of Chitwan, Rupandehi, Banke, Bardia, Kailali, and Kanchanpur) (Fig. 1a). The aim of the survey was to identify as many nesting sites as possible for local conservation efforts; thus, our survey largely relied on incidental observations and their subsequent monitoring. This makes it likely we have observation bias for woollyneck closer to settlements. However, since these are the areas where changes in human activity are most likely affecting them, we do not see serious

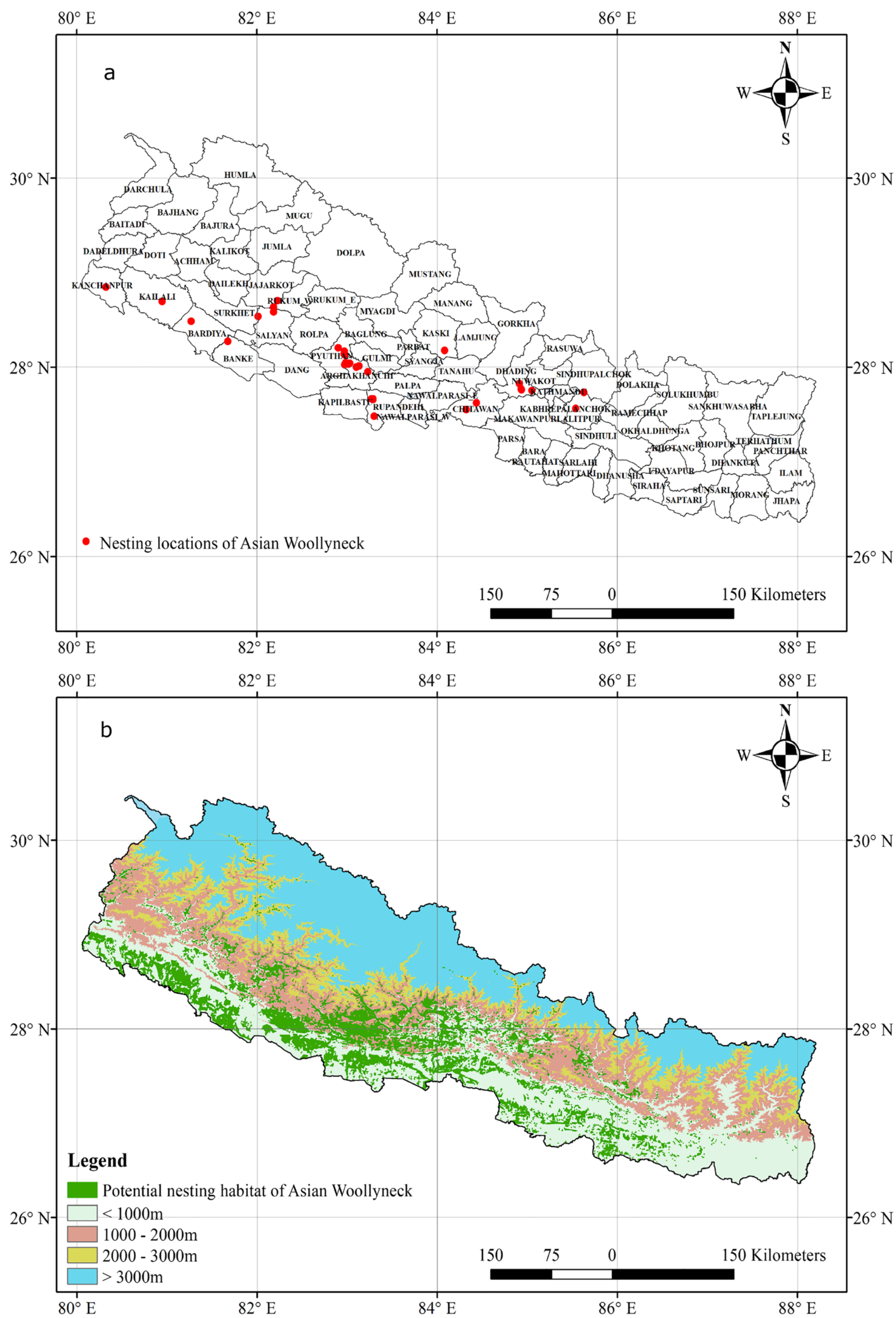

Fig. 1 **a)** Outline of the country of Nepal with the relative locations (points) of all 39 Asian woollyneck nests recorded in this study. **b)** Predictions of potential suitable nesting habitat (green) based on MaxEnt modelling of the habitat characteristics identified from the 39 nests found in the study

impact of this bias. Also, it is already known that woollyneck stork persist in human-dominated landscapes (Kittur and Sundar 2020). Regardless of these issues, this study is comprehensive in terms of number of nests monitored for woollyneck stork in Nepal. Therefore, we see that our results can be generally interpreted at least in Nepal's agricultural human-dominated landscapes.

At 29 of the 39 nesting sites, we were able to collect information about the height of the tree and height of the nest (18 trees also have diameter at breast height (DBH) measures of the nesting tree). Tree height and nest height were measured using Abney's level or tape measurement and subsequent estimation; therefore, height is presented in nearest meter, while DBH was measured using a diameter tape. For 19 of these 29 sites, we were also able to collect data on nesting and fledging success from 31 nesting attempts between 2016 and 2020. Because a number of these nesting attempts were from the same individual pairs in the same tree in different years, we used GLMMs to estimate the expected nesting success (using a logit-link binomial) and fledging success (using a log-link Poisson) by incorporating the identity of the breeding pair as a random effect into a simple "intercept-only" GLMM model to account for potential non-independent sampling. Nest is successful if at least one chick fledged from the nest while fledging sucess is number of chicks fledged from the nest. For the extended analyses where we were interested in the potential effect of region (mid-hills versus lowlands), we included a categorical explanatory variable in the model (Supplementary Material file 3). These analyses were undertaken in the package "lme4" in R (R Core Team 2019) with no overdispersion detected (overdispersion estimate range 0.8–1.1 in all models).

Modelling potential suitable habitat

We used Maximum Entropy Modelling (MaxEnt) for mapping potential suitable nesting habitat of the Asian woollyneck (Phillips and Dudik 2008) in Nepal as a means of identifying where survey effort could be focused in future studies to help identify new breeding areas that may have been previously overlooked. MaxEnt modelling is known to be effective even when few presence points are available (Wisz et al. 2008; Thibaud et al. 2014), which allowed us to make predictions despite the limited nesting data we have for this species in Nepal. Since our data source is within political boundary of Nepal, our prediction is also limited to Nepal. We acknowledge that the study would have been more comprehensive if data were available for biological borders of the species, i.e., extended to India. However, MaxEnt is also useful for small-scale prediction, for instance, it has been used to map the habitat of Egyptian vulture in Nepal (Kc et al. 2019) as well as its entire range (Panthi et al. 2021). Our data comprise from lowlands to mid-hills from far western to central Nepal where nesting of species has been known so far. Nesting records of woollyneck from east part of the Nepal are unknown (Inskipp et al. 2016). Woollyneck has been recommended as candidate species for which MaxEnt modelling could be used to understand habitat suitability (Gula et al. 2020).

Nesting presence data of Asian woollyneck was added along with 15 environmental variables (for details, see Supplementary Material file 1 Table S1) into the MaxEnt software for modelling. Our analysis included 10 replicates and selected bootstrap replicated run type recommended for handling small number of occurrence data with other default selections in logistic format to generate the map (Phillips and Dudík 2008). Model performance was assessed using area under curve (AUC) of the receiver-operating characteristic (ROC) where AUC score of 1 indicates perfect prediction whereas the values equal to 0.5 indicate random prediction (Pearce and Ferrier 2000). We used 70% occurrence data for training and 30% for testing purpose. For model evaluation, true skill statistics (TSS) were used where the value of TSS (TSS = Sensitivity + Specificity − 1) equals to 1 indicates a perfect fit and values less than 0 indicate a performance no better than random (Allouche et al. 2006). From this, we extracted the probability of occurrence of suitable nesting habitat of Asian woollyneck in Nepal and used a threshold value (0.202, see Supplementary Material file 1 Table S2) that maximized the sum of sensitivity and specificity to calculate the TSS, and thus convert the continuous probability map generated by the model into a binary presence/absence map of potential suitable nesting habitat (Liu et al. 2013). From this, we then looked at which areas have been surveyed for woollyneck relative to the model's predictions as a means of recommending where future survey effort could be focused. Ideally, we would have checked the validity of these predictions in a post-survey monitoring effort; however, because of resource limitations and travel restrictions from the COVID-19 pandemic, we were unable to do so. We hope that through this study, we provide target areas that would help to shape future studies and conservation intervention for this species.

Results

Nest location

The 39 recorded nesting sites were located across 18 districts of Nepal, which included 10 districts in the mid-hills (500–1434 m.a.s.l) and 8 lowland districts (75–250 m a.s.l) (Fig. 1a; Supplementary Material file 2 Table S1). Asian woollyneck nests were found in nine tree species (Supplementary Material file 2 Table S1) with more than half of all nests being located in simal *Bombax ceiba* (Malvaceae, $n = 21$), and other used nesting trees including sal tree *Shorea robusta* (Dipterocarpaceae, $n = 6$), rani-salla *Pinus roxburghii* (Pinaceae, $n = 4$), peepal *Ficus religiosa* (Moraceae, $n = 2$), and mango *Mangifera indica* (Anacardiaceae, $n = 2$) and one each in karam *Haldina cordifolia* (Rubiaceae), jamun *Syzygium cumini* (Myrtaceae), kadam *Mitragyna parviflora* (Rubiaceae), and utis *Alnus nepalensis* (Betulaceae). The heights of nesting trees varied from 19 to 41 m, with a mean height of 30 ± 5.8 m (± SD) and a mean DBH of 1.03 ± 0.35 m (range 0.56–2.0 m). Nests were usually located 3–6 m from the top of the tree (mean 4.5 ± 2.6 m) meaning that nests were, on average, 25.20 ± 5.75 m above ground (Supplementary Material file 1 Table S1). In the most common nesting tree (simal; $n = 21$; mean tree height = 31.93 ± 6.19 m; mean DBH = 1.14 ± 0.18 m), the nest height was, on average, 26.6 ± 4.96 m above the ground (Supplementary Material file 2 Table S1).

Nesting period and breeding success

The timing of breeding appeared to differ between the mid-hills region and the lowlands in Nepal. As per the crude information available during the survey and interviews, in the mid-hills, breeding started in December (winter season) and chicks fledged up until June (monsoon), while in the lowlands, breeding was observed from March (summer) through monsoon to November. In both areas, at least part of the nesting period coincided with the heavy monsoon period.

Nesting and fledging success were recorded from 31 nesting attempts from 19 nesting sites between 2016 and 2020. Six out of 31 nesting attempts failed (Supplementary Material file 2 Table S1), with an estimated nesting success rate of 0.81 ± 0.07 (± SE, from the GLMM modelling see Supplemenatry Material file S3). From GLMM estimates of all 31 nesting attempts, the mean fledging success was 1.94 ± 0.25 (± SE) chicks per nest, with this increasing to 2.4 per nest when only successful nests were considered; 48% of successful nests fledged 2 chicks, 28% fledged 3 chicks, and 12% each fledged 1 or 4 chicks (Supplementary Material file 2 Table S). While the raw data suggested the possibility that nesting and fledging success were higher in the mid-hills versus lowland regions, their was no clear evidence of this from the modelling (*P*-values for regional differences > 0.3, see Supplementary Material file S3).

Nesting habitat suitability

We obtained good accuracies (AUC = 0.919 + / − 0.039 and TSS = 0.733 + / − 0.102, Supplementary Material file 1 Table S2) for the MaxEnt analysis which predicted that 9.64% (14,228 km^2) of the total area in Nepal is a potential suitable nesting habitat for Asian woollyneck (Fig. 1b). The variables that were most important in determining the potential for good nesting habitat were areas of gentle slope, cropland, closer to settlements, and ~ 4 mm of precipitation during the driest month (see Suplementary Material file1 Figs. S1 and S2).

Our model predicted there is suitable nesting habitat (at least 28 km^2) in 72 districts of Nepal (out of 77) of which Dang has the highest suitable area (9.79%, 1394 km^2) followed by Kailali (7.12%, 1014 km^2) while Taplejung, Sankhuwasabha, Solukhumbu, Mustang, and Dolpa districts appear largely unsuitable for woollyneck nesting (Supplementary Material file 2 Table S2).

Discussion

To date, there have been no structured studies on nesting habitat preference of Asian woollyneck in Nepal with only two around its distribution range (both from India, Ishtiaq et al. 2004; Kittur and Sundar 2021). However, observational notes on single or multiple nest sites have increased since 2010, reflecting an increasing awareness and interest in this species. Our study is important in terms of area of coverage within a stronghold in this species' range (Ghimire et al. 2021). While this bird is known to occur at lower altitudes, a study into its nesting habitat requirements at the foothills of Himalaya (i.e., Nepal mid-hills region) has not been made. This shows that higher altitude habitats may be an important nesting habitat for this species.

Asian woollyneck have previously been found to nest on diverse tree species including fruiting trees such as *Magnifera indica*, *Syzygium cumini*, and *Mitragyna parviflora*; roadside plantation species like *Acacia nilotica*; trees on agricultural landscapes like *Dalbergia sissoo*; exortic trees like *Eucalyptus* sp.; trees with religious importance like *Ficus religiosa*; or very tall trees such as *Bombax ceiba*, *Shorea robusta*, and *Ceiba pentandra* among many others (Ishtiaq et al. 2004; Choudhary et al. 2013; Banerjee 2017; Kularatne and Udagedara 2017; Greeshma et al. 2018; Ghimire et al. 2020; Katuwal et al. 2020; Roshnath and Greeshma 2020; Kittur and Sundar 2021). Our study reports two new species used as nesting trees: *Pinus roxburghii* and *Alnus nepalensis* which are distributed in foothills of Himalayas. Asian woollyneck have also been observed nesting on rock cliffs (Rahmani and Singh 1996) or artificial structures such as cell phone towers in India and Bangladesh (Vyas and Tomar 2006; Vaghela et al. 2015; Greeshma et al. 2018; Hasan and Ghimire 2020). Such observations have not been reported from Nepal to date.

Nest heights were much higher (25.20 m) in Nepal when compared to a study in Keoladeo National Park, India (4.9 m, Ishtiaq et al. 2004). One possible explanation is that in our study, only 3 out of 39 nests were within protected areas;

thus, woollyneck nests in our study may have been placed unusually high to avoid human disturbance, or because the preserved trees in these regions are biased towards only very large ones. Based on the overwhelming number of nests in simal trees, this suggests a clear nesting use for this tree, and the preservation of such trees should be considered in local conservation efforts for this species in agricultural areas in Nepal (see also Koju et al. 2019 for evidence of the nesting value of large trees). In Haryana India, woollyneck nesting preferences was found to be non-random using *Ficus religiosa* and *F. bengalensis* much higher to their relative availability (Kittur and Sundar 2021). While we did not carry tree availability survey, anecdotal observations suggest simal trees *Bombax ceiba* is not among most abundant tree on the surveyed landscape. Without data on the characteristics of trees in the surrounding landscape, questions about nesting-tree preferences in Nepal remain for a future study.

From our observations and interviews, we found that the breeding season of Asian woollyneck varied with the geographical regions. Similar variation in the timing of breeding can be found around its distribution range: in northern India, woollyneck breed from July to September; in southern India from December to March (Ali and Ripley 1987; Del Hoyo et al. 1992; BirdLife International 2020). Another consideration in Nepal is the rice cultivation period. In mid-hills, where woollyneck nesting starts early, rice cultivation is done twice per year, with the irrigated croplands rich in invertebrates and amphibians.

Habitat quality influences breeding success (Kostrzewa 1996) and the relatively high breeding and fledging success in our study (e.g., 1.94 chicks per nest compared to 1.29 chicks for Nepal's lesser adjutant stork *Leptoptilos javanicus*, according to Karki and Thapa 2013) suggests that at least some of these birds have access to good quality habitat. But, compared to recent study in India (3.1 chicks per nests), brood size of successful nests is lower in Nepal (2.4) which depicts agricultural landscape of Haryana, India, has higher quality habitat for breeding of woollyneck (Kittur and Sundar 2021). Direct anthropogenic influences of nest sites are low within our study area, which can be attributed to conservation awareness activities conducted (Ghimire and Pandey 2018). However, two things need to be highlighted here. The first is that our measure of nesting and fledging success is likely to be biased high, because nests that fail early are less likely to be reported than those that are successful (simply because of the time available to observe the nesting birds) (Mayfield 1975). The second is that even if the high nesting success in these areas reflects good habitat, it is not certain that these critical nesting trees are protected, and may soon be lost through development or a lack of growth of new trees to replace them. Thus, there needs to be a focus on the availability of nesting trees, and their long-term viability in future habitat studies of this species.

We extended the nest observations in our study to predicting suitable nesting habitat areas of Asian woollyneck in Nepal. The total area of suitable habitat defined by the model is low and highlights the importance of conserving known breeding sites, until wider-scale surveys can be done and the factors driving population dynamics are better known. Gula et al. (2020) modelled the distribution of Asian woollyneck and found that precipitation seasonality was the most influential variable, followed by precipitation in warmest quarter, temperature seasonality, and annual precipitation. Our study found that slope, land use land cover, forest, and distance to settlement were important variables to model the suitable nesting habitat of this species. Our findings suggested that habitat with gentle slopes, cropland, proximity to settlements, and ~4 mm of precipitation during the driest month is suitable for nesting habitat. These differences are likely attributable to the differences in the types of observations (i.e., general observations versus nesting sites) and the restricted area sampled in our study. While that can be seen as a potential criticism of our study, the focus on only nesting sites in Nepal means that our results can be viewed as more appropriate for predicting local areas with suitable nesting habitat.

Gentle slopes were identified as the most important variable governing nesting suitability; however, it is possible that slope is a proxy for the presence of suitable nesting trees, since only gentle slopes tend to support food-rich habitat and the taller tree species suitable for nesting. This does not necessarily invalidate our findings, but rather opens the importance of considering geography in the selection of nesting sites by tree nesting birds. Precipitation is known to influence both distribution (Gula et al. 2020) and nesting suitability. During the driest months (i.e., November to March), woollyneck nest in the mid-hills of Nepal where birds likely require some precipitation to increase their foraging opportunities (similar to African woollyneck *Ciconia microscelis* that breed in dry seasons, Gula et al. 2020). The role of precipitation during the driest period in the lowlands is, however, more difficult to interpret especially because the nest remains unattended after fledgling of chicks (i.e., after monsoon during those driest period).

The agricultural lands of Nepal are important habitats for Asian woollyneck (Kittur and Sundar 2020). Our study found cropland as key factor in predicting nesting suitability of Asian woollyneck. One possible explanation for this is agricultural expansion and wetland shrinkage. Nepal lost 5.41% of its wetland coverage mainly due to expansion of croplands since 1990 (Li et al. 2017; MoFE 2018). Croplands are important habitat in such areas and are preferred by Asian woollyneck for nesting (Kittur and Sundar 2021). Woollyneck nests were closer to irrigation canals, further from the settlements and did not show strong preference to natural wetlands in Haryana, India (Kittur and Sundar 2021).

Our study also did not find any effect of waterbodies to nesting suitability. Surveyed sites in Nepal do not have larger irrigation canals but river-fed croplands are food-rich habitat (similar to irrigation canals in India, Kittur and Sundar 2021) which aids productivity of breeding birds. In contrast, we also found higher suitability closer to settlements. Kittur and Sundar (2021) showed lower brood size closer to settlements which reflects on our study site comparatively. Gula et al. (2020) also found a positive association of this bird with human-altered habitats that also supports our finding of nest suitability closer to the settlements. Nesting closer to settlements could be an adaptation and behavioral plasticity by the species in response in land-use change (Ghimire et al. 2021) or reflect the availability of nesting trees. Also, storks are found preferring sites closer to settlements, as they provide easy access for food resources along with reduced pressure from large predators (Schulz 1998). Many examples of woollyneck breeding in cell phone towers closer to human settlements in South Asian countries also supports this finding (Vaghela et al. 2015; Greeshma et al. 2018; Hasan and Ghimire 2020).

Interestingly, we found that the model predicted suitable nesting habitat distributed across 72 districts of Nepal, with some including larger areas and higher proportions than others (Supplementary Material file 2 Table S2). Assuming the predictions are accurate, nesting suitability for this species appears higher in the west-central part of the country followed by western part, while eastern Nepal appears to be less suitable. This coincides with the general observed distribution of this species, which is lower in the east (Ghimire et al. 2021). There have been no nesting records of this species from the eastern part of Nepal (Inskipp et al. 2016). The Dang District of western Nepal was predicted to have the highest nesting suitability. Dang is an inner terai district comprised of lower tropical to subtropical climate including two valleys, i.e., Dang and Deukhuri. However, no nests have been observed in this district, but the Asian woollyneck has been recorded in the Deukhuri valley that lies on relatively lower altitude (Inskipp et al. 2016). There have been no such studies in the Dang valley that lies mostly in the upper tropical and subtropical region. Hence, this region could be a potential stronghold habitat for the nesting of woollynecks and worthy of surveys to assess this possibility. There are also other districts with higher potentiality (Supplementary Material file 2 Table S2) which calls for research and conservation attention. Another interesting finding is nesting suitability being predicted in the Himalayan district like Manang, where occasional observation records of Asian woollyneck have been reported at 3540 m altitude (which is the highest altitude record of species in South Asia, Ghale and Karmacharya 2018). Presence of nests at 1500 m altitude may support the argument that this species makes upward movements in search of nesting habitat (Inskipp et al. 2016; BirdLife International 2020; Ghimire et al. 2021).

Our study is the most comprehensive examination of nesting in the Asian woollyneck in Nepal to date, and highlights a number of key areas that warrant urgent attention if we are to better understand its ecology and distribution in Nepal, and other parts of its distribution range. This study provides an opportunity for future studies to conduct test field surveys (especially in Himalayas and foothills) which would further validate our findings. In particular, is the species' apparent reliance on large nesting trees and their long-term persistence in these areas (see also Koju et al. 2019). Also, is whether surveys like ours can help highlight new likely distributions and nesting areas that can guide future survey and conservation efforts. Finally, is the importance of habitat suitability in the higher altitudes and the influence of climatic variables, especially precipitation. In this scenario, climate change is likely to impact the breeding success and distribution of this bird and threatening its local and region-wide persistence in some areas. We encourage similar research from other part of its distribution range to help improve upon what we have found in this study.

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Author contribution PG: conceptualization (lead), data curation (equal), funding acquisition (lead), investigation (equal), methodology (equal), project administration (lead), resources (equal), validation (equal), writing—original draft (lead). SP: data curation (equal), formal analysis (lead), methodology (lead), software (lead), visualization (equal), writing—review and editing (equal). KPB: conceptualization (equal), investigation (equal), methodology (equal), resources (equal), writing—review and editing (equal). ML: data curation (equal), formal analysis (equal), investigation (equal), methodology (equal), supervision (equal), writing—review and editing (lead). NP: conceptualization (equal), data curation (equal), investigation (equal), project administration (equal), writing—review and editing (equal). RG: conceptualization (equal), data curation (equal), investigation (equal), project administration (equal), resources (equal), writing—original draft (equal), writing—review (equal). BSB: investigation (equal), methodology (equal), project administration (equal), resources (equal), writing—review and editing (equal). SK: formal analysis (equal), methodology (equal), resources (equal), writing—review and editing (equal). LPP: project administration (equal), supervision (equal), validation (equal), writing—review and editing (equal).

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Availability of data and materials All the data used in these analyses are provided in Supplementary Material file 1 Table S1. All the data used and analysis performed are available in supplementary material along with the manuscript.

Code availability R code is available in Supplementary Material file 3.

Declarations

Conflict of interest The authors declare no competing interests.

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