Journal of Environmental Management 297 (2021) 113331

Contents lists available at ScienceDirect

Journal of Environmental Management

journal homepage: www.elsevier.com/locate/jenvman

Factors affecting the crop raiding behavior of wild rhesus macaques in Nepal: Implications for wildlife management

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A R T I C L E I N F O

Keywords:
Crop protection
Human-wildlife conflict
Human-macaque conflict
Macaca mulatta
Maize farmland

A B S T R A C T

In many areas of South Asia and Southeast Asia, macaques inhabiting agricultural landscapes are considered serious crop pests by local farmers. In Nepal, for example, the expansion of monocultures, increased forest fragmentation, the degradation of natural habitats, and changing agricultural practices have led to a significant increase in the frequency of human-macaque conflict. In order to more fully understand the set of factors that contribute to macaque crop raiding, and the set of preventive measures that can be put in place to avoid human-macaque conflict, we examined patterns of crop raiding by a group of 52 rhesus macaques (*Macaca mulatta*) in the Kavrepalanchok district, Nepal. We present data on macaque inflicted crop damage in 172 agricultural plots (each plot measuring 380 m^2) from August to October 2019. Our results indicate that farmland invasions by macaques were principally affected by crop type (maize was preferred over rice), nearness of farmland to both the forest edge and the major travel route used by the macaques, and the mitigation efforts applied by farmers to discourage crop raiding. We found that as the proportion of maize farmland in the most direct path from the macaque's main travel route to nearby crop raiding sites increased, the amount of maize damage decreased. This is likely explained by the fact that macaques traveling across several adjacent maize fields encounter multiple farmers protecting their crops. We estimated that the financial cost to individual farmer households of macaque maize and rice raiding was on average US$ 14.9 or 4.2% of their annual income from cultivating those two crops. As human-macaque conflict is one of the most critical challenges faced by wildlife managers in South Asia and Southeast Asia, studies of macaque crop raiding behavior provide an important starting point for developing effective strategies to manage human-macaque conflict while promoting both primate conservation and the economic well-being of the local community.

1. Introduction

In response to deforestation and the degradation of natural environments, human-wildlife conflict (HWC) has become one of the most prominent challenges faced by wildlife managers worldwide (Siljander et al., 2020). In Zimbabwe, for example, a recent study found that annual losses in revenue from damage to crops, property, and livestock caused by wildlife ranged from US$ 671 to US$ 998 per household, which represented 40–59% of yearly household income (Mhuriro-Mashapa et al., 2018). Disruption to local economies and to the psychological well-being and food security of farmers (Hill, 2000) is only expected to intensify, as the number of wildlife species that are forced to expand their range and search for food in human-modified landscapes increases (Galán-Acedo et al., 2019). Thus, understanding how wildlife species use anthropogenic landscapes and creating a sustainable balance between human and wildlife coexistence and HWC is critical for improving management practices for wildlife conservation (Galán-Acedo et al., 2019; Hockings et al., 2009; Patterson et al., 2018;

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https://doi.org/10.1016/j.jenvman.2021.113331
Received 10 February 2021; Received in revised form 17 July 2021; Accepted 17 July 2021
Available online 21 July 2021
0301-4797/

Thatcher et al., 2020).

Many species of nonhuman primates that inhabit anthropogenic landscapes are considered crop pests (Pebsworth and Radhakrishna, 2020). For example, studies of baboons (*Papio hamadryas*), macaques (*Macaca mulatta, M. assamensis, M. fascicularis*), vervet monkeys (*Chlorocebus pygerythrus*) and chimpanzees (*Pan troglodytes*) indicate that as their natural habitats are reduced or fragmented by human activities, wild primates living nearby orchards and agricultural fields are attracted to cultivated foods such as domesticated fruits, maize, sweet potatoes, and rice (Boug et al., 2017; Bryson-Morrison et al., 2017; Ganguly and Chauhan, 2018; Hansen et al., 2020; Hockings et al., 2009; Koirala et al., 2017; Patterson et al., 2018; Sengupta and Radhakrishna, 2018). Crop raiding, especially of calorie-dense foods, can result in increased fertility and increased primate group size leading to increased crop damage and increased HWC (Sengupta and Radhakrishna, 2018). For example, the provisioning of Japanese macaques (*M. fuscata*) was a significant factor in an almost doubling of their birth rate, increased female survivorship, and an increased rate of population growth compared to when this same population was not provisioned (Sugiyama and Ohsawa, 1982).

Factors reported to influence the frequency and intensity of nonhuman primate crop raiding include the proximity of farmland to the nearest forest edge, crop type, group size, and raider population density (Baranga et al., 2012; Hill, 2000; Lee and Priston, 2005; Mochizuki and Murakami, 2011). In offering solutions to minimize crop loss caused by primates, Priston et al. (2012) proposed that planting valuable cash crops distant to the forest edge, planting less valued crops adjacent to the forest edge, and planting deterrent crops such as chili near the forest boundary, serve as effective conservation management tools to minimize human-primate conflict. In this regard, Mochizuki and Murakami (2011) argue that a management strategy in which crops are located in open areas that are highly visible to farmers and a spatial configuration that minimizes the proximity of forest edge to farmland edge, facilitate early detection of primate invaders and reduces the amount of crop damage.

Macaques represent a highly successful and diversified radiation of 23 primate species that inhabit a broad range of island and mainland habitats in southern Europe, Asia and northern Africa (Rowe and Myers, 2016). Among primates, only humans have a more widespread geographical distribution than macaques (Thierry, 2011). In the present study we focus on crop raiding by rhesus macaques (*Macaca mulatta*). Rhesus macaques have the widest geographical distribution of all macaque species (Maestripieri, 2010), and exploit a range of forested, dry, evergreen, montane, fragmented, and urban habitats (Anand and Radhakrishna, 2020; Chalise, 2013; Uddin et al., 2020). These primates live in multimale-multifemale social groups that average 32 individuals (Fooden, 2000). Females are philopatric and form strong kin-based social bonds and alliances. Males migrate from their natal group at approximately age 5, and attempt to enter a new group to breed (Anandam et al., 2013).

In certain cultures and religions, rhesus macaques are considered 'sacred' and inhabit temples and urban centers. Across their range, rhesus macaques commonly come into conflict with the local human population as they raid crops and garbage dumps, are spatially associated with temples, are present at ecotourist sites and national parks, and have been known to enter human dwellings (Lee and Priston, 2005). Thus, they represent a challenge for wildlife managers attempting to develop management plans to protect the monkeys and avoid conflict with humans (Saraswat et al., 2015; Singh and Thakur, 2012). This is especially true in Nepal, where conflict between humans and rhesus macaques in rural areas is reported to occur on a daily basis (Air, 2015; Lee and Priston, 2005; Sharma and Acharya, 2018).

Although forest cover in Nepal has increased at an annual rate of 0.6% over the past 30 years (Tripathi et al., 2020), these 'planted' forests remain highly fragmented, and are dominated by single tree species, with low availability of wild foods for wildlife (Bhattarai, 2020; Reddy et al., 2018). In addition, the migration of households of traditional farmers into large urban centers has resulted in an increase in abandoned farmland, and a reduction in the number of farmer households and productive cropland in rural areas (Oldekop et al., 2018). These factors have intensified opportunities for HMC, as groups of wild macaques expand their range into farm fields (Bhattarai, 2020; Chalise, 2013). Rhesus macaque are now identified among the top ten crop raiding species in Nepal (CODEFUND, 2018). However, in the absence of detailed studies designed to identify the set of factors that contribute to rhesus macaque crop raiding behavior and the cost to individual farmers in lost yearly income, effective measures designed to avoid human-macaque conflict and promote macaque conservation are unlikely to be implemented.

In the current study we document the crop raiding behavior of a group of rhesus macaques whose range overlaps with a rural farming community in central Nepal. Specifically, we address the following research questions: (1) Do rhesus macaques exhibit a feeding preference and raid certain crops more commonly than other crops? Food preference is defined as disproportionate consumption relative to abundance in the habitat (Marshall and Wrangham, 2007) (2) Do preventative actions taken by farmers effectively mitigate crop damage by rhesus macaques? (3) Do factors such as the spatial proximity of farm fields to the forest edge, distance to roads/human walking trails, distance to houses, and crop type affect the amount of crop damage by rhesus macaques? (4) What is the economic cost to farmers of macaque crop raiding? And, (5) what measures can be put in place to minimize human-macaque conflict?

2. Material and methods

2.1. Study area

The study was conducted between February and September 2019 in the Panauti Municipality, Kavrepalanchok District, Nepal (85° 23′ 16.44″ to 85° 34′ 7.68″ longitude, and 27° 31′ 35.4″ to 27° 38′ 17.16″ latitude), an area of 118.1 km^2. The mean temperature during the study ranged from 11.1 °C in February to 20.8 °C in September. Annual rainfall over the past 10-year period was 1738 mm (N = 10) (Climate-Data.org, 2020). The region is dominated by needle leaved forest (47.9 km^2), broadleaved forest (40.2 km^2) and agricultural land and human settlements (29.2 km^2) (ICIMOD, 2010). The human population is 56,329 individuals, and the economy of the local community is based principally on agriculture and livestock (buffalo, cow, goats, and poultry). The main agricultural products cultivated are potatoes (*Solanum tuberosum*), Asian rice (*Oryza sativa*), maize (*Zea mays*), oranges (*Citrus unshiu*), and vegetables. Maize and rice are cultivated once per year, and during the period of our study, they were the primary crops produced. Maize is planted in April and May, and harvested before the second week of September. Rice is planted in May and June and harvested before the second week of October. The average yield of maize in the study district is 4.6 tons/ha (Timsina et al., 2016) and the average yield of rice is 3.5 tons/ha (Joshi et al., 2011). This study was conducted in wards 6, 7, 9 and 10 of the municipality (Fig. 1).

2.2. Data collection

A single group of rhesus macaques, the "OM Group" (OM refers to the name of a forest patch in the home range of the group), containing 52 individuals (11 adult females (>4 years old), six adult males (>5 years old), four subadult males (>4 < 5 years of age), one subadult female (>3 < 4 years of age), three 3-4-year-old juvenile males, eight 2-3-year-old juveniles, nine 1-2-year-old juveniles, and 10 newly born infants (0–12 months old)) inhabited our study area. The home range of our study group included forest, agriculture lands, human settlements, roads, temples, and public spaces.

This group of rhesus macaques had not been studied previously.

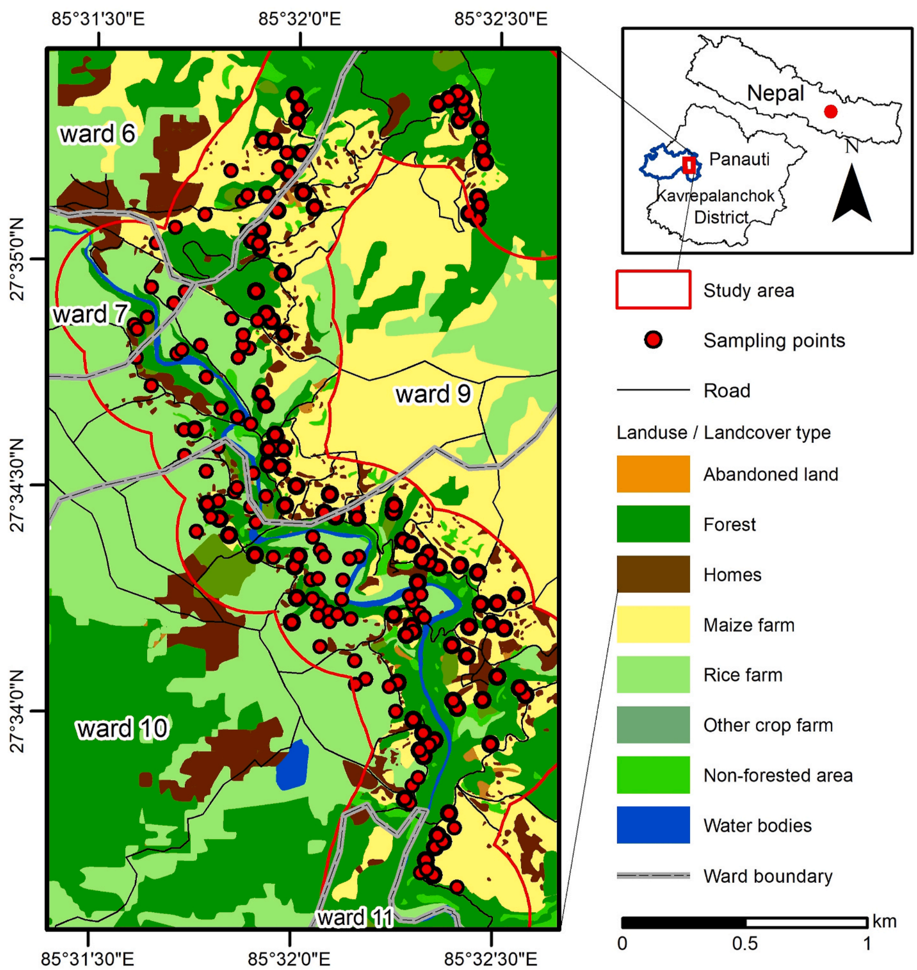

Fig. 1. Study area. The red polygon represents the "Crop Damage Sampling Area" used to estimate crop damage by the macaques. The Roshi River is indicated in blue. This river serves as the major travel route for the macaque study group. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

Therefore, before starting behavioral data collection, we conducted a preliminary survey to identify areas of forest and farmland visited by macaques and the average size of farm plots raided by macaques. This was done to more effectively monitor macaque crop damage during our main study (for additional details concerning methods and results of the preliminary survey see supplementary material, text S1). Based on the results of the preliminary survey in which the average area of farmland invaded by the macaques per crop raiding event was 381.5 m^2, and using ArcMap 10.3, we randomly selected 172 circular agricultural plots measuring 22 m in diameter (area of 380 m^2 per circular plot x 172 plots = a sampling area of 6.5 ha) within the macaques' home range. We refer to this area as the Crop Damage Sampling Area (CDSA) and used these sample plots to measure macaque crop damage. One hundred and three of these plots contained maize and 69 contained rice. Each of the sample plots was visited 1–4 time(s) from August to October 2019 after a macaque crop raiding event and prior to harvesting by local farmers. This allowed us to determine the total amount of crop damage caused by the macaques over the three-month observation period. These 172 sample plots included land belonging to 167 farmer households.

In order to estimate the weight of crop damage caused by the macaques, we collected maize ears from 60 intact maize plants and 60 rice spikelets from 60 intact rice plants. We then calculated the total weight of maize kernels and rice grains per plant and multiplied the mean weight of maize kernels/rice grains per plant by the number of damaged plants to calculate the loss in kilogram (kg) for each sample plot.

For each sample plot, we met with farm owners and asked each to describe the mitigation efforts used to protect their crops. Based on their responses, we assigned the following mitigation categories to our sample plots; (1) no guarding (2) guarding and chasing macaques occasionally (3) guarding continuously and chasing macaques away from farmland whenever the macaques were seen approaching the area.

We randomly selected 31 farmer households and interviewed each landowner to determine the total area of land cultivated in rice and maize and annual income from livestock farming. We also collected information concerning the history of human-macaque conflict (HMC) in the area, and local changes in forest cover (supplementary material, text S2).

2.3. Data analysis

We digitized the study area using Google Earth pro. We categorized patterns of land cover as forest, non-forest (grassland and abandoned land), farmland (cultivated with maize, rice, and other crops) houses, and roads. Although farmers in this region of Nepal grow crops such as tomatoes (*Solanum lycopersicum*), cauliflower (*Brassica oleracea* var. *botrytis*), and other vegetables, rice and maize accounted for over 93% of cultivated land during the study period, and therefore we limited our study to these two crops (Refer to supplementary material, text S3 & table S1 for detailed information regarding the categorization of different landscape features).

Among the three categories of farmer mitigation efforts (see above), we found that guarding and chasing macaques occasionally, did not prohibit the macaques from invading that farmer's cropland. Therefore, we merged this category with the no guarding category to create a single category called unprotected plots. We compared unprotected sample plots and protected (farmland always guarded by the farmer or his family) sample plots in our analysis. Mitigation measures used by farmers included chasing the macaques using slingshots and sticks, throwing rocks at the macaques, yelling at the macaques, and confronting the macaques prior to them reaching farm fields. Vigilant farmers and their family members guarded fields from early morning to the late afternoon every day. We used Wilcoxon signed-rank test to compare the crop damage in protected and unprotected sample plots.

To examine the set of factors that affected whether wild rhesus macaques invaded a given farm plot and the degree of damage to crops, we used a generalized linear model with a binomial distribution (logit function). Information entered into the model include distance to each sample plot from the nearest forest edge, distance from the sample plot to the macaque's major travel route, and distance to nearby roads and houses. We used crop damage (1) and no crop damage (0) as response variables and distance (in m) to the nearest forest edge, distance to homes, roads, and the mitigation efforts of the farmer as predictor variables. We also considered the distance from the macaque's major travel route to sample agricultural plots as a predictor variable.

Based on the results of the preliminary survey, we assumed that once the macaques were within sighting distance of a farm plot, group members took the most direct or straight-line route to crop raid (Supplementary material, text S1). We plotted this straight-line path using ArcMap 10.3 by constructing a central line with a 10 m buffer on either side (total width of direct path was 20 m) from the macaques' major travel route to the farm plot visited by the macaques. The size of the buffer corresponded to our estimation of macaque group spread when traveling. We refer to this as the 'most direct path'. The average length of this path was 99.1 m (SEM $\pm$ 4.82, n = 172). We then calculated the area of forest, houses, farmland with maize and farmland with rice within the most direct path based on the digitized map using the tabulate intersection tool available in ArcMap. For each direct path we calculated the area (m^2) and percentage of the area that contained houses, forest, and farmland cultivated with maize and rice.

We used a generalized linear model with a binomial distribution (logit function) to determine the influence that particular features of the landscape, situated along the most direct path of macaque travel, had on macaque crop raiding behavior. We used crop-damage (1) and no-damage (0) as response variables and the proportion (%) of forest area, house area, farmland area cultivated with maize and farmland area cultivated with rice as predictor variables. We checked the correlations of the predictors and found that none of these variables were highly correlated ($r < 0.42$). We used hierarchical partitioning in the "hier.part" package of R to determine the percentage of the independent effect contributed by each variable in the model (MacNally and Walsh, 2004). All spatial analyses were done using ArcMap 10.3. We performed all statistical analyses in R. In all analyses, probability was set at $p < 0.05$.

Finally, we calculated the market value of crop loss per plot based on the official price list of the Nepal government authorized corporation (STC, 2020) (maize US$ 0.30 and rice US$ 0.34 per kg, Exchange Rate: 1 Nepalese rupee = US$ 0.0085). The estimated economic loss to individual farmers from macaque maize and rice raiding was calculated based on (a) the area of farmland to cultivate maize and rice per household, (b) the average production (kg/ha) of maize and rice in the local area (Joshi et al., 2011; Timsina et al., 2016), and (c) the percentage of maize and rice damaged by the macaques in our sample plots.

3. Results

3.1. Crop types and crop raiding

We examined the spatial distribution of rice and maize fields to assess the degree to which macaque feeding preferences influenced crop-raiding behavior (Fig. 2). The amount of the maize crop damaged by the macaques during our 12-week evaluation period totaled 1838 kg (99.9%), whereas damage to the rice crop totaled only 1.7 kg (0.1%). Given that maize accounted for 62.1% of the total crop produced and 99.8% of the crop damaged (the macaques damaged 469.6 kg of maize and 0.6 kg of rice per ha in the sampling area), the macaques exhibited a strong preference to raid maize fields over rice fields.

3.2. Mitigation efforts and crop raiding

In the Panauti Municipality of Central Nepal, farmers protected their crops from the macaques using a variety of mitigation measures. Overall, these mitigation measures were highly successful (Fig. 3). We found that 79.6% (43 of 54) of the unprotected maize plots suffered crop damage by the macaques compared to 16.3% (8 of 49) of the protected maize plots. Overall, 92% of total maize damage occurred on unprotected plots. Over a three-month period, the average damage to unprotected maize plots was 31.3 kg (SEM $\pm$ 5.7, range 0–119.8 kg, n = 54), with total damage to unprotected plots equaling 1692.2 kg. Mean damage to protected plots was only 3 kg (SEM $\pm$ 2.4, range 0–119.3 kg, n = 49, total damage to protected plots equaled 145.8 kg). Thus, damage to unprotected maize plots was significantly greater than to protected maize plots ($W = 407.5$, $P < 0.001$). Moreover, approximately 82% of the total damage to protected maize plots involved a single plot (119.3 kg of maize damage), which was located on the boundary of a forested area and away from other maize plots. Similarly, 11.3% of the 62 unprotected rice plots (n = 7) were damaged whereas none of the 7 protected rice plots were damaged (Fig. 3). Damage to unprotected rice plots ranged from a maximum of 0.4 kg to a minimum of 0 kg (mean = 0.02 $\pm$ 0.009, n = 62, total damage = 1.7 kg).

3.3. Factors affecting crop raiding

Given that the rhesus macaques preferred maize over rice and that the damage to rice plots was extremely limited, for the remainder of our analysis we focused only on our 103 sample maize plots. We found, that nearness of a farm plot to the forest edge, nearness of a farm plot to the macaques' major travel route, and the presence of unprotected farmland were all statistically significant variables (95% confidence interval) and positively affected macaque maize crop raiding behavior (Figs. 3 and 4A–B). In contrast, distance to nearby houses and distance to roads had no direct influence on the likelihood of farmland invasion by macaques (Supplementary material, Table S2).

Our results indicate that maize plots located within 20 m (n = 69 or 67% of maize plots) of the forest edge experienced greater crop damage by macaques (59.5%, n = 41) than maize plots located >20m (n = 34) from the forest edge. In total, 89% of total maize damage (1641.1 kg) occurred in plots located <20m from the forest edge. The mean distance from the forest edge to the damaged maize sample plots was 14 m (SEM $\pm$ 1.04, range 0–32.2m; n = 51).

Given that on average the 'most direct path' taken by the macaques from their major travel route to a farm field was 100 m, we examined the proportion of invaded maize plots located within 100 m of the macaques' major travel route. We found that 62.7% of the sample maize plots (37 of 59) located within 100 m of the macaques' major travel route were invaded, resulting in a total of 1479.4 kg of crop damage (mean = 25.07 kg $\pm$ 5.4 of crop damage per sample plot, n = 59) (Fig. 5). In contrast, of the 44 maize plots located greater than 100 m from the macaques' major travel route, only 14 (31.8%) were invaded, and the total damage to these plots was 358.6 kg (mean = 8.2 kg, SEM $\pm$ 3.4, range 0–113.1 kg).

We also found that the probability of maize raiding decreased as the proportion of maize farmland located in the most direct path from the macaques' major travel route increased (Figs. 6 and 7, Supplementary material, Table S3). The proportion of maize farmland in the most direct path contributed 69.4% to the probability of reduced maize damage.

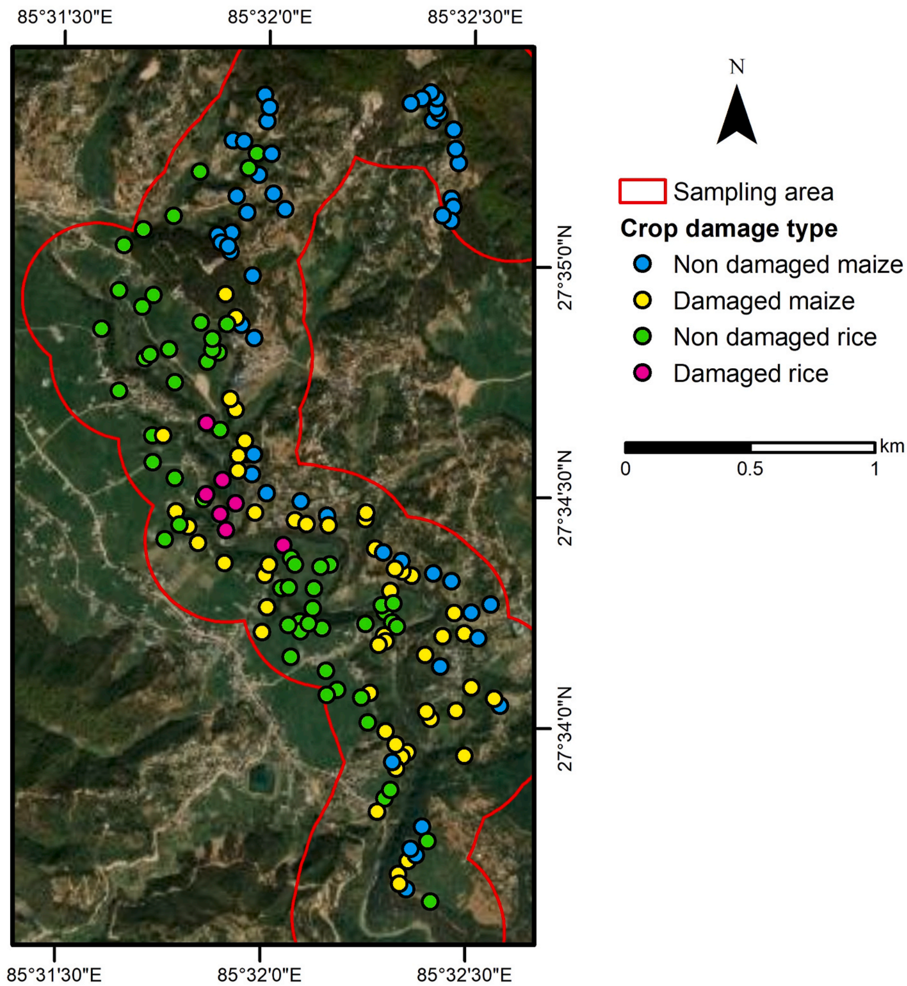

Fig. 2. Spatial distribution of sample plots and damaged and non-damaged maize and rice plots.

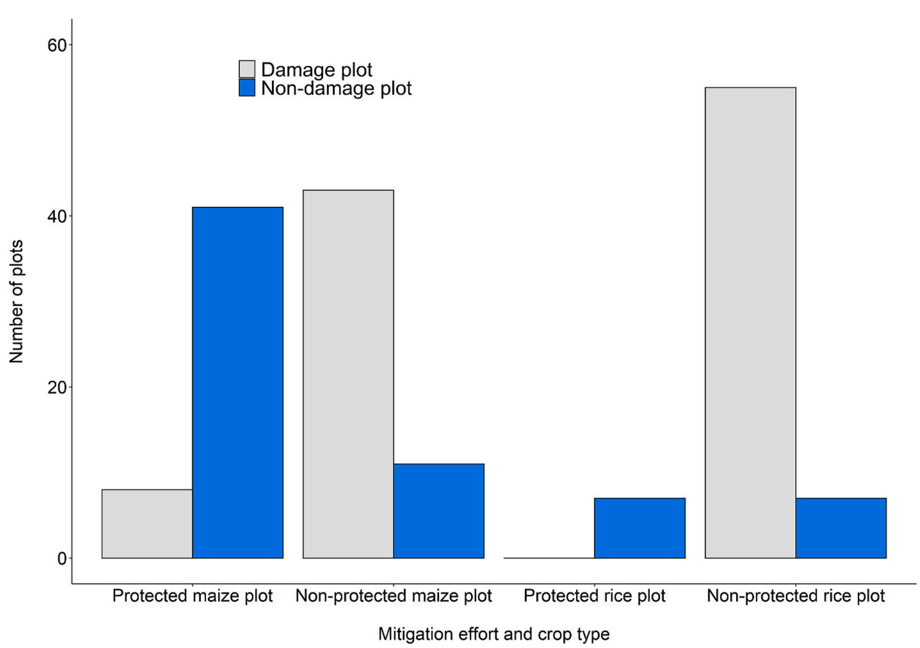

Fig. 3. Mitigation effort and damaged and non-damaged maize and rice sample plots.

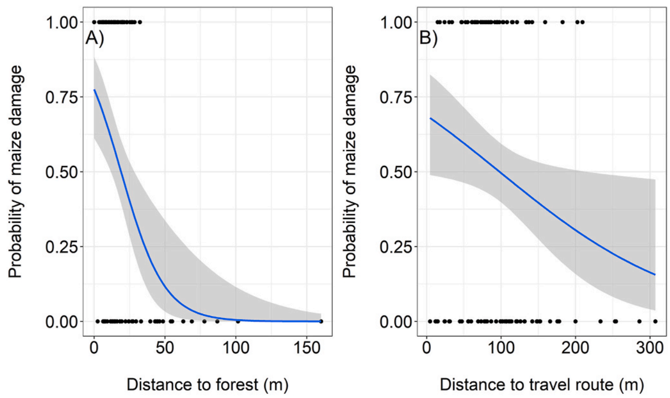

Fig. 4. Influence of distance from forest (A) and distance from the macaques major travel route (B) on maize farmland invasion by the macaques.

This is likely explained by the fact that macaques traveling across several adjacent maize fields encounter multiple farmers protecting their crops. In contrast, the area of the of houses, forest, and farmland cultivated with rice were not significant factors in whether the macaques invaded a maize farm field.

3.4. Economic cost to farmers of macaque crop raiding

The average area of maize fields per household at our field site was 0.10 ha (SEM ± 0.02, range: 0.02–0.7 ha, n = 31) and the average area of rice farmland was 0.18 ha (SEM ± 0.04, range: 0–0.8 ha, n = 31). The average annual income from farming maize and rice per household was estimated at US$ 357 (SEM ± 66.4, range: US$ 70.1–1894.3, n = 31). The average income from maize was US$ 146.9 (SEM ± 30.3, range: US$ 35–981, n = 31) and an average income from rice farming was US$ 210.6 (SEM ± 46.5, range: US$ 0–913.3, n = 31). In addition, livestock farming and the selling of milk products generated an average annual income of US$ 1237 (SEM ± 189, range: US$ 0–4037.5, n = 31) per household (Supplementary material, Table S4).

Based on market value, the total damage to rice crops caused by the macaques over the 12-week sampling period was US$ 0.6 (US$ 0.2 per ha) and the market value of maize damage totaled US$ 551.4 (US$ 140.9 per ha). On average, each farmer's household lost US$ 14.9 (SEM ± 3.1, range: US$ 3.6–99.7, n = 31) per year in response to the raiding of maize and rice crops by macaques (maize raiding caused an average of US$ 14.9, SEM ± 3.1, range: US$ 3.5–99.5, n = 31; and rice raiding caused an average of US$ 0.04, SEM ± 0.009, range: US$ 0–0.2, n = 31). This total amount of damage was 4.2% of farmer annual income from maize and rice cultivation. However, for small holder farmers, who do not cultivate rice (12.9% of sampled households, n = 4), the damage caused by the macaques was more than 10.1% of their income (Supplementary material, Table S4).

4. Discussion

In many regions of the world, especially Asia and Africa, wildlife species are increasingly forced to raid agricultural crops as either a supplemental or primary food source in response to deforestation,

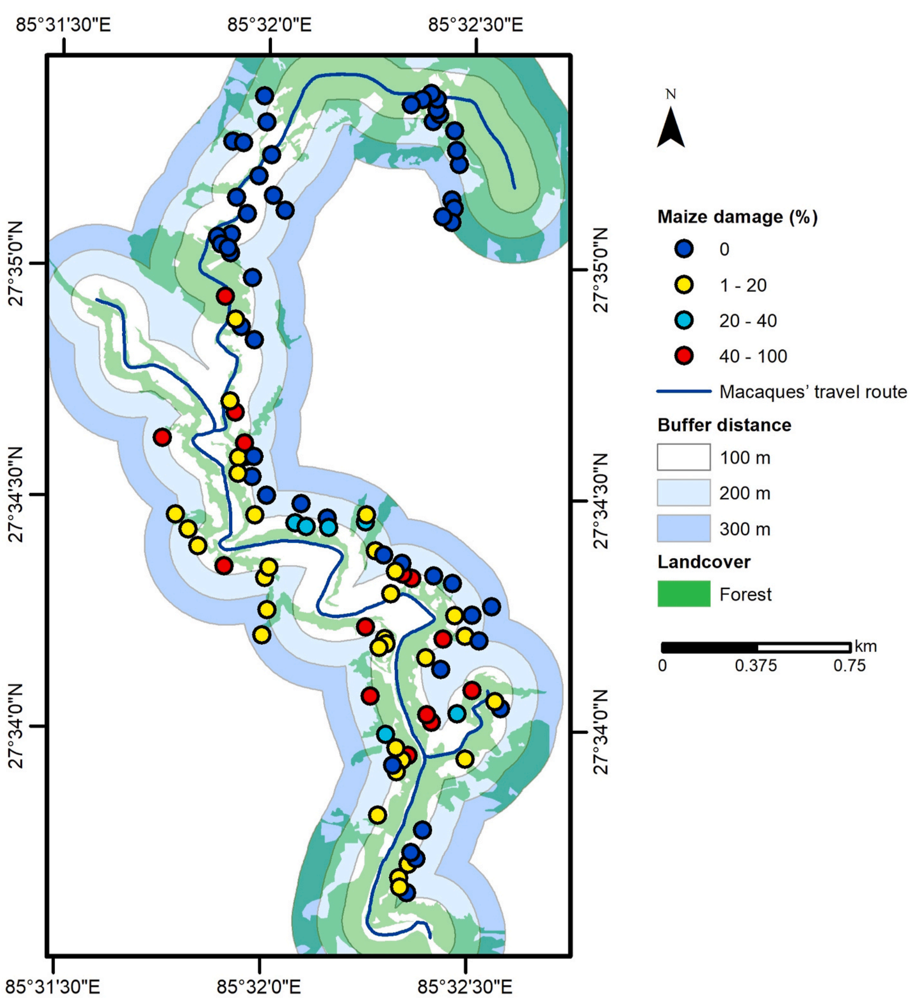

Fig. 5. Location of maize plots, percentage of maize damaged by macaques (shown in colored dots) and distance from the major travel route (shown here as a blue line). A value of 0–20% indicates that up to 20% of the total maize available in the sample plot was consumed by the macaques. A value of 20–40% indicates that 20–40% of the maize in that sample plots was consumed by the macaques, and a value of 40–100% indicates 40–100% of the maize in the sample plot was consumed by the macaques. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

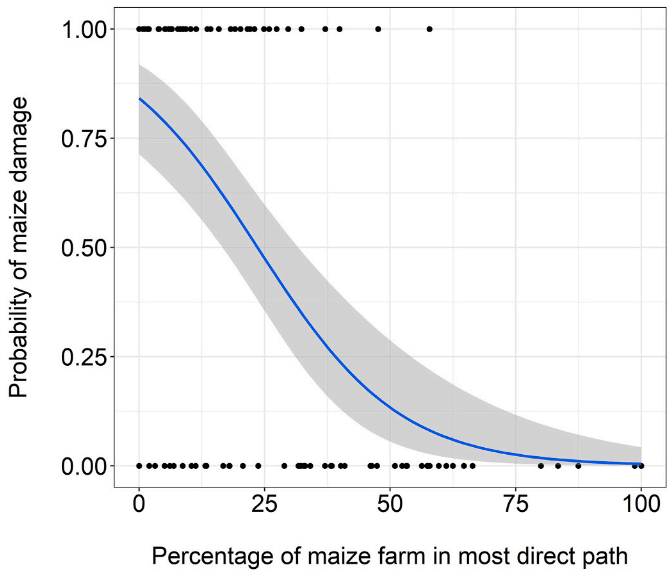

Fig. 6. Influence of the proportion of maize farmland in the most direct path taken by macaques during farmland invasions.

habitat fragmentation, and an expanding human footprint into areas previously characterized as pristine or minimally impacted by human activities (Saraswat et al., 2015; Siljander et al., 2020). For example, damage to agricultural crops by monkeys and other wildlife in Himachal Pradesh, India is estimated to result in combined annual economic losses totaling some US$ 30,133,280 (Himachal Pradesh Horticulture Department Report, 2014). Across Asia, several species of macaques are reported to cause considerable economic damage to agricultural fields and house gardens. Here, we examined patterns of HMC in a rural county in Nepal. Over the past 10 years, HMC in this region has expanded considerably and threatens both the safety of the macaques and the economic well-being of local farmers. Local residents indicated that before 2010 macaques had never invaded their farm fields. The conversion of natural habitat to planted monoculture forests, which began in the 1980s in our study region, has significantly disrupted the natural feeding ecology and ranging patterns of the rhesus macaques (SK, unpublished data) (Supplementary material, text S2).

In the present study, we quantified crop damage caused by a group of 52 wild rhesus macaques in the Kavrepalanchok District of Nepal and examined the set of factors that promote and discourage macaque crop raiding behavior. We found that the main factors affecting crop raiding in rhesus macaques were crop type, distance from the forest edge to a farm field, and the mitigation efforts of local farmers (Figs. 3 and 4A). We also found that maize fields in closer proximity to the macaques' major travel route were invaded more frequently than maize fields more

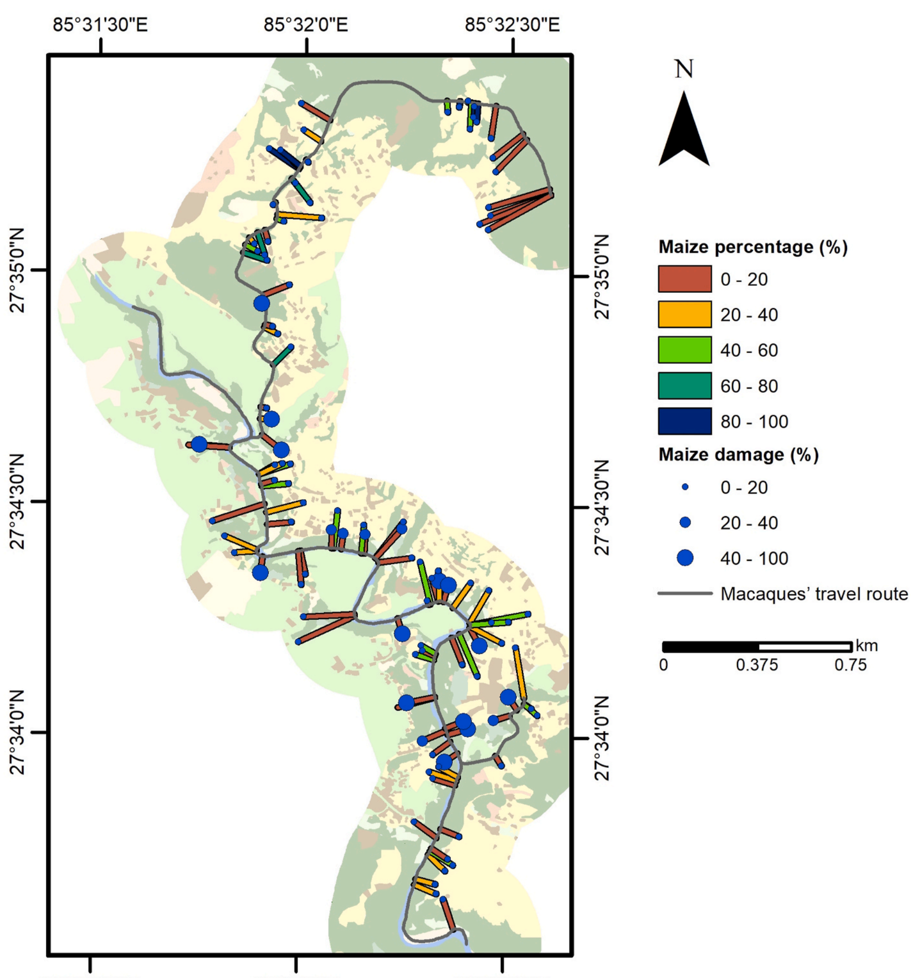

Fig. 7. Location of maize plots, percentage of maize damaged by macaque and the percentage of maize farmland in the most direct path. A value of 0–20% indicates that up to 20% of the total maize available in the sample plot was consumed by macaques. A value of 20–40% indicates that 20–40% of the maize in that sample plots was consumed by the macaques, and a value of 40–100% indicates 40–100% of the maize in the sample plot was consumed by the macaques.

distant to the macaques' major travel route (Figs. 4B and 5). However, the likelihood of maize crop raiding was negatively affected by the proportion of maize farmland located in the most direct path from the macaque's major travel route to a maize plot (Figs. 6 and 7). Although field studies of several primate species indicate that individuals are generally more attracted to larger food patches than to smaller food patches (Kalan et al., 2015), in our study area individual maize plots were relatively small (averaging of 0.10 ha), and therefore larger areas of maize farmland represent the individual properties of several farmer households, increasing the likelihood that at least one farmer or member of his family will chase the macaques from the field. We also estimated that the annual economic cost to farmers of macaques raiding maize and rice fields averaged US$ 14.9 per household. This represents 4.2% of farmer annual income from rice and maize cultivation. However, in the case of the poorest farmer households, or farmers with an annual income of less than US$ 100, economic loss from macaque crop raiding accounted for as much as 10.1% of yearly income.

Below, we present a series of low cost and low effort management practices that if implemented, could mitigate the economic costs of macaque crop raiding, and balance the needs of the macaques and the local human community. We note that in developing management policies, particular attention must be paid to smallholder farm households, whose income and food security are most at risk by increased macaque crop raiding.

Traditional methods of protecting crops throughout much of rural Asia include spending hours each day guarding agricultural plots, using stones and a slingshot to deter the monkeys, exploding firecrackers, using tin cans and drums to make loud noises, keeping guard dogs, and constructing scarecrows in the field (Air, 2015; Li and Essen, 2020; Saraswat et al., 2015). Not all methods are equally effective, and farmers complain that guarding by women and children is ineffective and costly in time and labor, and that the monkeys quickly acclimate to scarecrows (Air, 2015; Li and Essen, 2020; Saraswat et al., 2015). At our study site, farmers were observed to use all of these traditional tactics to protect their farm fields. Several farmers who were interviewed believed that confronting the macaques while they were still on their major travel route and distant to a farm field was the most effective mitigation strategy. Fully, 71% of protected plots cultivated with maize were protected from macaque crop raiding when farmers used one or more of these preemptive strategies. Similar to our findings, in Western Uganda, during half of crop raiding events by six African primate species red tailed monkeys (*Cercopithecus ascanius schmidti*), vervet monkeys (*Chlorocebus aethiops*), blue monkeys (*Cercopithecus mitis stuhlmanni*), chimpanzees (*Pan troglodytes schweinfurthii*), and black and white colobus monkeys (*Colobus guereza occidentalis*)), farmers either were absent or failed to confront the raiders; resulting in extensive crop damage. In the remaining 50% of cases the farmers actively confronted primate crop raiders and they were successful in expelling them with minimal crop damage (Wallace and Hill, 2012). A comparative study of crop damage caused by 20 species of herbivores across four sites in Asia and Africa, including elephants (*Loxodonta africana* & *Elephas maximus*), hippopotmus (*Hippopotamus amphibious*), African buffalo (*Syncerus caffer*), the greater one-horned rhino (*Rhinoceros unicornis*), and bushpigs (*Phacochoerus africanus*), in addition to vervet monkeys (*Chloropithecus pygerythrus*) and baboons (*Papio cenocephalus*), found that traditional approaches such as the use of natural barriers, shouting, chasing, drumming, and olfactory repellants were relatively ineffective in minimizing economic losses, whereas communal and coordinated guarding of fields was a more effective strategy (Gross et al., 2019).

Several different types of conservation and management measures that serve to balance the needs of both the local human population and wildlife populations have been implemented successfully. In Japan, specially designed electric fences proved effective in deterring Japanese macaques from crop raiding (Honda et al., 2011). The high cost of these fences, however, makes them impractical in most rural localities in Asia and North Africa where macaque crop-raiding is a significant problem (Priston and McLennan, 2013). A management approach that was less successful, was the creation of a nearby tourist site in Takasakiyama, Japan, in an attempt to keep the local Japanese macaque population away from farm fields. The monkeys were provisioned in the facility and this led to an increase in the macaque population from 220 to 1713 monkeys over a 22-year period. This population explosion led to an increase in crop raiding and crop damage experienced by local farmers (Knight, 2017).

Experimental studies of taste aversion, as a tool to discourage crop-raiding in olive baboons, have produced promising results (Forthman et al., 2005). However, this approach has not been replicated with wild macaques. Caution must be used to make certain that substances used to discourage crop raiding are not harmful to wildlife, passed from mother to nursing offspring, result in reduced fertility, pollute the soil, and are not harmful to the local human population (Pebsworth and Radhakrishna, 2020).

In 1997, India initiated a program of translocating rhesus macaques from areas of HMC to areas where this species had been extirpated. Over the course 15 days, 600 macaques who were members of 12 troops were trapped, transported, and released into a new location (Imam et al., 2002). None of the macaques were injured during the process, and a behavioral assessment of the macaque activity budget (i.e. time spent feeding, foraging, traveling, and resting) three-months post-release concluded that the translocated monkeys had adjusted well to the new release site. A second assessment four years later found that the local human community continued to accept and support the presence of the rhesus macaques in the area (Imam et al., 2002). However, Priston and McLennan (2013) have argued that in addition to high economic and monitoring costs associated with translocation, to be successful, the process requires finding large areas of suitable habitat that do not contain nearby farm fields and requires the consent of the local community. In addition, in many instances, translocation may just shift the monkey problem from one place to another. For example, in Uttar Pradesh, India a population of 20 translocated rhesus macaques increased to 258 monkeys during a 25 year period, resulting in the monkeys expanding their range into nearby villages (Southwick and Siddiqi, 2011). And, although Imam et al. (2002) reported that translocation was minimally disruptive to the macaques in their study, other researchers have found that translocation resulted in group disruption and increased mortality as individuals were required to locate suitable feeding, resting, and refuge sites in their new home range (Dhiman and Mohan, 2014; Southwick and Siddiqi, 2011). Therefore to be successful, wildlife conservation and management strategies must be balanced to address the specific needs, concerns, and cultural; and religious attitudes of the local human community, the local primate population, and the local ecosystem (Priston and McLennan, 2013).

4.1. Management recommendations

Based on the results of this study, we recommend five human-rhesus macaque conflict management strategies designed to promote both primate conservation and the economic well-being of this local human communities in rural Nepal. Given that the current annual loss of income from macaque crop raiding for most farmers was less than 5%, we recommend measures that we think will be locally effective and low cost in terms of time and energy to the farmers, while protecting the macaques. Some of these measures will require educational programs, financial assistance, and outreach from local or regional wildlife management and government agencies. First, it is recommended that farmers dedicate some proportion of their agricultural fields to plant cash crops that are non-preferred or avoided by the macaques. In our local area such crops could include buckwheat, mustard, ginger, turmeric, bitter gourd and taro(Air, 2015; Regmi et al., 2013). These crops should be planted within 20 m of the forest edge and within 100 m from the macaques major travel route. To strengthen this management strategy, villagers will need to establish a local market where farmers can sell their newly cultivated crops and, if necessary, can purchase crops such as maize, potatoes, and oranges for their daily consumption from farmers living more distant to wild macaque groups. For those farm fields located in the immediate vicinity of the macaque's major travel route, farmers should organize a coordinated mitigation plan with several farmers sharing the responsibility of guarding each other's fields from the macaques. We also recommend that wildlife managers work with local farmers and explain the actual loss of income from macaque crop-raiding and use local farmer input to develop effective mitigation measures to limit crop loss while not harming the macaques.

The planting of monoculture forests in rural areas of Nepal has exacerbated HMC because these monocultures fail to provide adequate food and refuges for the macaques. A program needs to be established to create small and scattered forested plots that contain wild and/or domesticated fruits and other vegetation exclusively for wildlife. These plots should be located at least 150 m from farm fields. In rural Nepal, these plants might include wild Himalayan cherry (*Prunus cerasoides*), Stony Jujube (*Zizyphus incurva*), the Fragrant bay tree (*Machilus odoratissima*), the Nepali hog plum (*Choerospondias axillaris*), White siris (*Albizia procera*), the Indian chestnut (*Castanopsis indica*), the Needlewood tree (*Schima wallichii*), Hill pepper (*Piper mullesua*), Himalayan berberis (*Berberis aristata*), Blackberry (*Rubus rugosus*), Raspberry (*Rubus ellipticus*), and the Nepalese firethorn (*Pyracantha crenulata*) (Khatiwada et al., 2020). In addition, the wildlife managers should be encouraged to work with community forest user groups to create local programs of natural forest restoration in rural areas that contain primate populations.

Given that our results indicate higher crop damage in protected plots that border forested areas compared to those located more distant to the forest, we recommend that farmers trim and debranch taller trees and clear the ground cover to create a perimeter of at least 20 m from forest edge. This would allow farmers to more easily detect and discourage macaque crop raiding. Finally, smallholder farmers should be encouraged and assisted by the local management authority to use more of their land for livestock farming (i.e. buffalo, cows, goats and poultry) rather than for agricultural production. Many farmers in our area earn more income from livestock farming than from agricultural production, and such a management strategy could increase household income and avoid losses due to crop-raiding.

In Hindu dominant countries like India and Nepal, macaques are considered as spiritual beings that have souls and are a symbol of strength and energy (Chalise, 2013; Peterson and Riley, 2017; Saraswat et al., 2015). Even in many Muslim majority areas of Indonesia, macaques are tolerated, despite their crop raiding behavior (Riley and Priston, 2010). However, these attitudes appear to be shifting as humans continue to convert natural habitats into anthropogenic landscapes and human-wildlife conflict and crop raiding intensify (Priston and McLennan, 2013; Saraswat et al., 2015). In this regard, successful mitigation measures designed to limit HMC in one area may not be effective in managing HWC in another area. Therefore, we advocate that the most successful strategies for mitigating HMC require a community-based approach that incentivizes wildlife managers to work closely with local civic leaders and farmers to develop effective solutions for that community.

5. Conclusion

Over the past 10 years, macaque crop raiding in the Kavrepalanchok District, Nepal has gone from being absent to resulting in an average loss in annual income from maize and rice farming per household of approximately 4.2%. In the absence of effective mitigation measures designed to protect farmer income and macaque safety, farmer losses are likely to increase over the next decade, resulting in actions taken by farmers to eradicate macaques from the region. Based on our analysis of HMC, we recommend that wildlife managers and the local government invest in community education programs designed to encourage farmers to protect farmland collectively, cultivate buffer crops in the vicinity of the forest edge, and to actively engage in worker paid programs designed to restore natural forests and plant fruit trees and other natural vegetation to expand suitable habitat for the macaques.

Declaration of competing interest

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

Acknowledgments

We thank Panauti Municipality, its ward offices and its management staff for providing permission to conduct this research. We also are thankful to the farmers, survey participants and the local people for their support during data collection. We thank field research assistants Devi Rai and Nabin Rawal. PAG wishes to acknowledge Chrissie, Sara, Jenni, and Dax for their support, love, and encouragement. SK is grateful to her parents, Bijay Adhikari, Bimala Guragain, Sabita Gurung, Til Prasad Pangali Sharma, Kabita Karki, Sushmita Bhandari & Sumarga Kumar Sah Tyagi for their support, encouragement and help during her research. The work was supported by the Strategic Priority Research Program of Chinese Academy of Sciences, China (XDA19050202) to LM and the CAS-TWAS President's Fellowship granted to SK. All the authors declare no conflict of interest.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2021.113331.

Credit Author Statement

Sabina Koirala: Conceptualization, Methodology, Writing-Original Draft, Investigation, Data curation, Formal analysis. Paul A. Garber: Conceptualization, Methodology, Writing-Review and Editing. Deepakrishna Somasundaram: Methodology, Formal analysis. Hem Bahadur Katuwal: Methodology, Formal analysis, Writing-Review and Editing. Baoping Ren: Resources, Writing-Original Draft. Chengming Huang: Resources, Writing-Original Draft. Ming Li: Supervision, Conceptualization, Methodology, Funding acquisition, Writing-Review and Editing.

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