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Social and ecological outcomes of tropical dry forest restoration through invasive species removal in central India

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ABSTRACT

Tropical dry forests (TDFs) support endemic biodiversity, and the livelihoods of millions of people globally. Invasive species, such as *Lantana camara,* are a predominant cause of degradation of TDFs. We examined lesser-studied vocalizing fauna and social outcomes of TDF restoration through Lantana removal, focusing on a Central Indian TDF. We quantified biodiversity using acoustics in 55 locations in restored, unrestored, and Low Lantana Density (LLD) forest sites and surveyed 656 households across villages adjacent to these forest sites. Our ecological analysis showed that in comparison to unrestored and LLD sites, restoration was not significantly associated with a different acoustic space occupancy (ASO) in higher frequencies (9–24 kHz) during night time hours, meaning restoration does not impact nocturnal vocalising or stridulating species. However, restored and LLD sites had significantly lower ASO in the day time hours, potentially due to differences in the insect community when Lantana is absent. Through the household surveys, we found that the highest number of respondents across all the three types of sites valued the cash payment they received for participating in restoration efforts. Perceptions of lower amounts of crop raiding by wild ungulates were associated by villagers with a restored site. This perception was mediated by the total number of households in a village with a restored site. Focusing restoration efforts on forests surrounding villages, restoration planners could reduce potential negative human-wildlife interactions. Combining ecological and social outcomes, we found that there are immediate positive outcomes of restoration for people. However, in the short term (three years following restoration), there was no significant biodiversity 'benefit'. Based on our results, we recommend that restoration planners (1) consult local people about their perception of forest degradation and restoration because people's perceptions can accurately mirror the condition of the forest; (2) provide a cash income for participating in restoration activities and (3) anticipate potential changes in the faunal species community in the short term when large scale invasive species removal takes place.

1. Introduction

Tropical dry forests (TDFs) are some of the most exploited forests worldwide, and occur in densely populated human-modified landscapes (Gillespie et al. 2012; Janzen 1988; Portillo-Quintero and Smith 2018). Although reduced in extent due to historic clearing, TDFs provide critical ecosystem functions, such as erosion control and water regulation (Nelson et al., 2020), and support endemic biodiversity (Gillespie et al., 2012). TDFs are also estimated to support the livelihood and subsistence needs of millions of people around the world (Schröder et al., 2021). Apredominant threat to TDFs is degradation, which results in an alteration of forest structure and diversity (Choksi, 2020; Morales-Barquero et al., 2014). The sources of degradation are numerous: unsustainable logging, overexploitation of nontimber forest products (NTFPs), overgrazing, and spread of invasive species, among others (Choksi, 2020; Dimson and Gillespie, 2020). TDFs are considered highly susceptible to invasion by plants (Mungi et al. 2021). The spread of exotic invasive species, in particular the shrub, *Lantana camara* (hereafter Lantana), is a major concern to TDFs, especially in India and Australia (Bhagwat et al., 2012).

Abbreviations: TDF, Tropical dry forest; ASO, Acoustic space occupancy; LLD, Low Lantana density; KNP, Kanha National Park; LPG, Liquified Petroleum Gas.

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Lantana's allelopathic properties and ecological resilience allow it to colonize a wide range of climate and precipitation niches, making it one of the top ten invasive plants in the world (Bhagwat et al., 2012; Mungi et al., 2020). Despite efforts using fire, mechanical, and manual labour-intensive methods to eradicate or manage Lantana and restore forests, the shrub has continued to spread aggressively in the 20th century in countries where it is considered highly invasive (Bhagwat et al. 2012). The long-term ecological impact of Lantana invasion ranges from disrupting forest succession and regeneration to increased occurrences of forest fires (Prasad, 2010). Lantana invasion can also have social impacts; for example, reduction in the availability of non-timber forest products due to overcrowding of native plants of livelihood interest (Kannan et al. 2016).

The British introduced Lantana as an ornamental shrub in India in the 1800 s and the shrub has recently become a major concern as the country works towards its forest restoration targets (Borah et al., 2018) in the United Nations' Decade of Restoration (2020–2030). In TDFs in India, research has predominantly focused on the ecological impact of Lantana invasion and subsequent restoration through Lantana removal and succession (Prasad 2012; Sharma and Raghubanshi 2007, Sundaram and Hiremath 2012). For example, studies of experimental restoration (via Lantana removal) in a southern Indian TDF showed an increase in herb and shrub species richness associated with restoration (Prasad, 2010). Studies quantifying the impact of Lantana invasion on fauna have largely focused on birds (Aravind et al. 2010, Ramaswami et al 2017). As an example, Aravind et al. (2010) found that with an increasing density of Lantana, there was a decline in bird species diversity and an increase in species evenness, indicating that some species are able to use the Lantana-dominated habitat widely (Aravind et al., 2010).

As ecological restoration has taken centre stage in the last few years, researchers and practitioners have called for (a) holistic design of restoration projects, taking into consideration people living on and using the land to be restored (Erbaugh et al., 2020; Erbaugh and Oldekop, 2018; Fleischman et al., 2022) and (b) an evaluation of the impact of restoration, which considers both social and ecological outcomes equally (Coleman et al., 2021; Pritchard, 2021). While ecological indicators of success of restoration are easier to define and are more widely accepted, social indicators are more context dependent (Le et al., 2012). For example, positive ecological outcomes could include increased tree species richness or diversity. Positive social indicators could include increased livelihood opportunities, income, or availability of food and fibre (Le et al., 2012).

In the context of Lantana invasion and TDF restoration, social outcomes of invasion and restoration are little known. One study in India found that Lantana poses a hindrance to people's forest-based livelihoods. People's perception of a change in the composition of the overstory and the reduced abundance of NTFP species due to Lantana invasion was supported by ecological evidence of such changes (Sundaram et al. 2012). At the same time, Lantana is sometimes used as supplementary firewood for cooking and heating in north India (Negi et al., 2019).. There are also important gaps in the research on ecological impacts. Few studies quantify impacts of Lantana invasion and restoration beyond bird diversity, such as changes in hydrology, soil erosion, or the richness and diversity of less studied fauna, such as insects. Understanding a variety of outcomes, intended and unintended, is crucial to inform restoration programs, so that they can achieve the multifaceted objectives of biodiversity conservation, forest regeneration and the welfare of local people.

Here, we used central India as a case study to quantify ecological and social outcomes of Lantana invasion and subsequent TDF restoration. We chose two outcomes, which address current research gaps on the impact of invasion and TDF restoration: (a) people's livelihoods and perceptions and (b) less studied fauna. We used acoustic technology to study the higher frequencies (9 to 24 kHz), which are occupied by lesser studied taxa such as insects and bats. Although acoustically derived biodiversity measures are agnostic to the species producing the vocalisations, they can rapidly provide a broad estimate of acoustic energy in the soundscape (Rappaport et al., 2022; Sueur et al., 2008) and act as a proxy for species richness and diversity (Aide et al., 2017; Dröge et al., 2021). Specifically, we ask the following questions:

(1) For local people, what are the perceived benefits and drawbacks of the presence of Lantana in forests and the subsequent restoration through the removal of Lantana?
(2) Do people in villages that have undertaken restoration perceive the ease of forest use differently to those in villages without restoration?
(3) Is there a significant difference in the soundscapes of restored, unrestored and control (Low Lantana density) sites?
(4) Is there a synergy between the social and ecological outcomes of TDF restoration?

2. Materials and methods

2.1. Study region

We carried out our research in the buffer region of Kanha National Park (KNP) in the Bicchiya subdistrict, in Mandla district of Madhya Pradesh. The region is dominated by tropical deciduous forests interspersed with meadows, which are an important habitat for charismatic species such as the Bengal tiger and are the headwaters for the River Narmada (Agarwala et al., 2016a). These forests are seasonal, with leaf fall concentrated in the summer months (Agarwala et al., 2016a). The region is also home to one of the largest populations of constitutionally recognized socio-economically disadvantaged groups (scheduled castes and scheduled tribes) including tribes, such as the *Gonds* and *Baigas*. It is estimated that over 60 % of the local population are dependent on the surrounding forest for livelihoods and subsistence, including collection of firewood, non-timber forest products (NTFP), grazing cattle, and also rely on small-scale, predominantly rain-fed, farming (Agarwala et al., 2016a; Choksi et al., 2021; DeFries et al., 2021). The study region generally receives a total annual rainfall of 1750 mm during the monsoon months (June to September) (Singh et al., 2012) and has recently experienced a weakening summer monsoon (Choksi et al., 2021). Additionally, the larger central Indian landscape has been experiencing more frequent and longer heatwaves in comparison to 1901 to 2012 (Choksi et al., 2021).

2.2. Restoration method

We studied the impact of restoration through Lantana removal by local communities in partnership with the state forest department and a local non-governmental organization, Foundation for Ecological Security (FES). Local communities used a widely implemented method of Lantana removal. In this method, Lantana was removed for three consecutive years right before the flowering season, which is in October (the plants can have two flowering seasons, the other season being the monsoon) (Negi et al. 2019) and then allowing a site to naturally regenerate. The 'cut-rootstock method' used is considered the simplest and most cost-effective Lantana removal method (Love et al., 2009). In this method, the main tap root of Lantana plant is cut below the 'coppicing zone', which is the part of the plant between stem base and rootstock (Love et al., 2009). If the Lantana plant is small a single individual can work alone to remove it. However, this method involves two to three individuals working together to remove large clumps. Once the rootstock of a Lantana plant is cut, the clump is placed upside down to avoid any regeneration when it comes in contact with soil (Love et al., 2009). 2017 was the first year of Lantana removal for all the restored sites.

2.3. Site selection

Using a propensity score based on secondary socio-economic data (total number of households in the village, total population in the village, percent literates in the village, percent scheduled tribe in the village, percent of scheduled castes in the village) and geographic factors (distance to Kanha National Park, percent forest cover in 3 km buffer; percent farm land in 3 km buffer; refer to Table S1 for the summary statistics of the matched variables), we first matched 'treatment' villages that had restored TDF sites (N = 8 villages) within their village boundaries or their surrounding forest with 'control' villages where no such restoration took place (unrestored N = 7 villages). These 'controls' - unrestored sites - had a high density of Lantana. Restored sites within forests had similar Lantana density to unrestored sites prior to restoration. Additionally, we included villages with little to no Lantana naturally occurring in their surrounding forests over the last five years as 'reference' sites (Low Lantana Density, or LLD sites, N = 4 villages). We identified LLD sites after speaking with local villagers and asking about the presence of Lantana in the last five years. Further, we visited these LLD sites multiple times to gauge the density of Lantana. We hypothesized that restored sites will eventually regenerate to resemble LLD sites. In three out of eight villages where restoration was carried out there were two or more distinct *tolas* (neighbourhoods) at least a kilometre apart. In these three villages, we established unrestored and LLD sites for comparison within the other *tola's* surrounding forests. Thus, we have a total of 16 matched villages with restored, unrestored and LLD sites within their surrounding forests.

We carried out this initial matching because the restoration was carried out opportunistically by the local villagers in their surrounding forests in collaboration with the local Forest Department and NGO, Foundation for Ecological Security (FES). We used such a sampling design and a two-step matching process because the Forest Department does not permit the collection of any data for reconnaissance purposes, and to get a research permit, we had to indicate specific locations. After a brief visual assessment of the surrounding forests of all the treatment, and potential control villages, we received the research permits to sample these forest sites. For the restored sites, the NGO FES, the Forest Department and local community members mapped the restoration sites within the forests in 2017, the year restoration was first carried out. Thus, the polygons of where restoration was carried out (N = 8; hereafter sampling sites) were readily available to us. We consulted village members about their forest use to spatially determine the other sampling sites within the unrestored (N = 8 sampling sites) and LLD (N = 4 sampling sites) forests mentioned above. We created one sampling polygon per sampling site in the surrounding forests of the matched villages where local people mentioned they frequented the forest for timber and non-timber forest product collection (unrestored, restored and LLD sampling sites N = 20; area = 58.32 ± 30.93 ha).

Within these sampling sites, to establish the exact locations to collect vegetation data and finally, deploy acoustic recorders (hereafter sampling locations), we first created an inner buffer (70 m) within each sampling site polygon. We did this to ensure that we only sample within the core of the polygon and avoid any acoustic data contamination from outside of the sites. Next, we used a random point generator in QGIS ver. 3.14 (QGIS Development Team, 2022) to create points 400 m from of each other within the core of the polygon (N random points generated = 55; when recorders were deployed the actual minimum distance between recorders was 380 m). Each of the 55 sampling locations were matched using a propensity score based on vegetation data (Section 2.6) collected at these locations and geographic and socio-economic factors from secondary data (Table S2), to ensure that the sites were statistically comparable to each other and differed only in terms of their Lantana status. We planned to retain only those sampling locations that were exact matches, and remove those locations that did not successfully match. In this study, each of the 55 sites matched successfully and thus, no sites were removed. We carried out the two matching processes using the package *matchIt* (Ho et al., 2011) in R (R Core Team, 2020). Choksi et al. (2023) provide more details on the matching of sites.

2.4. Acoustic data collection

At each sampling location (Fig. 1), we collected acoustic data for 7 to 10 days continuously at a sampling rate of 48 kHz at a medium gain (30.6 dB) using Audiomoth recorders (Hill et al., 2019). We first put the recorders in small Ziploc bags, to protected them from any potential water damage and then tied recorders to the trunks of trees at approximately 2 m above the ground. The microphone was facing the ground and thus, we can assume that the recorders captured sounds closer to the ground than in the canopy of the forest. We set our recorders to record one minute for every five minutes and used a staggered sampling design to sample during the winter season. We faced some delays in collecting all our data between the alpha and delta waves of covid-19 and thus do not have an exact overlap in terms of months of data collection in 2020 and 2021. We collected data from January to March in 2020 and December to February in 2021. Thus, for every hour we collected 12 min of acoustic data. We were only able to collect data over the winter season due to covid-19 related complete lockdown and travel restrictions during spring and summer months in 2020 and 2021. On average, we recorded 30.44 ± 8.27 h in 2020 and 42.24 ± 12.05 h in 2021 per sampling location.

2.5. Household survey data collection

In January 2022, we surveyed 50 households in 13 of the 16 villages (5 restored, 6 unrestored, and 2 LLD) with a total of 656 surveys (Complete survey instrument in Appendix 1). A village was treated as one of the three: restored, unrestored and LLD. We surveyed 13 villages and not all 16, because three out of eight villages with restored sites also had unrestored or LLD sites in their surrounding forests (refer to Section 2.3 for more details). Thus, these respondents could neither be considered as 'treatment' or 'control' groups. In each village, we sampled every other house on both sides of any lanes/ pathways within the village. Each survey lasted approximately 20 min and included questions about the socio-economic characteristics of a household, their livelihood and their perceptions of Lantana and restoration activities. Surveyors asked for verbal consent before beginning every survey, and informed the participants of their right to refrain from answering a question if they wish to. Participants were also informed of their ability to terminate the survey at any point if they wish to.

2.6. Vegetation data collection

At each sampling location, we collected vegetation data between January and April 2021. We established circular 314.2 m^2 plots (10 m radius plot). Within a 3-meter radius, we collected the data on all seedlings and saplings and the number of Lantana saplings (single stems below 1 m in height) and mature Lantana plants (>1 m in height). While we could not identify all the shrubs below the height of 1 m, we simply noted their presence within the 3-metre radius plot. Within the 10-meter radius, we collected data on the diameter at 1.35 m up from the highest point of ground at the tree's base and the height (by visual estimation) of all trees (>2 m height). Due to the constantly changing covid-19 restrictions on travel, we were unable to collect data at four sampling locations (across two restored sampling sites). Therefore, we relied on vegetation metrics collected from the closest sampling locations (approximately 400 m away) for these four missing sites.

2.7. Statistical analyses

2.7.1. Acoustic space occupancy quantification

For our response variable, we computed the acoustic space occupancy (ASO) by modifying the methods noted in (Campos-Cerqueira

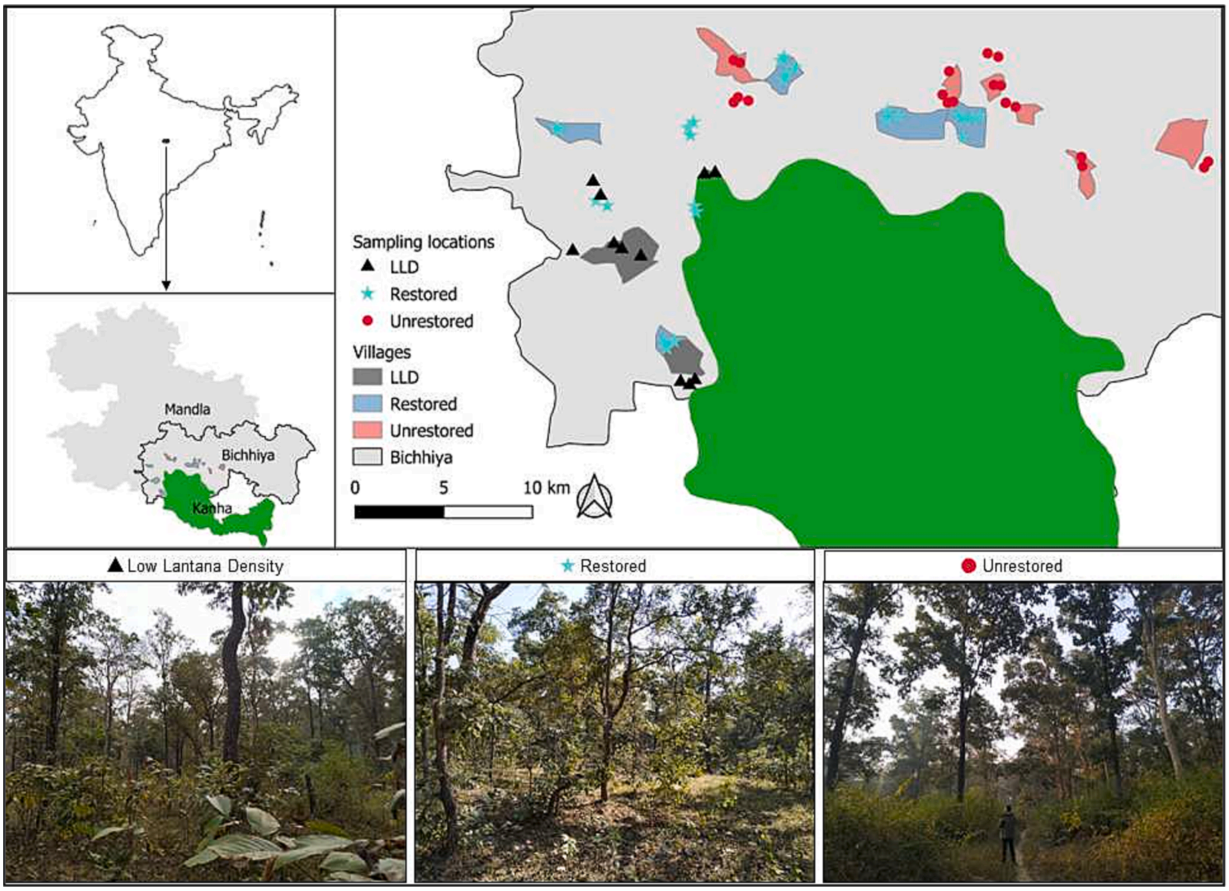

Fig. 1. Study site in Central India. Top: Map of sampling locations and villages surveyed in the buffer region of Kanha National Park (dark green). Bottom: Photos of Low Lantana Density, restored, and unrestored sites. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

et al., 2019). First, we first obtained a mean spectrum for each 1-min recording by computing a short-time Fourier transform (f = 48000, wl = 512, wn = "hanning", norm = FALSE) using the *meanspec* function (*seewave* package) in R programming environment. From this, we obtained a two-column matrix, with frequency in the first column and absolute amplitude values in the second column for 256 frequency bins. Here, the minimum absolute amplitude over all files was 0.073 and the maximum was 12104.95. We then used the *fpeaks* function in the same R package to detect the frequency peaks in the spectrums. We scaled the amplitude values resulting from the *fpeaks* to values between −1 and 1.

To distinguish biophony from background noise, we used a threshold for scaled amplitude of 0.003 (Campos-Cerqueira et al., 2019) and selected only frequency peaks above the threshold (frequency distance threshold set to zero). This selection resulted in a two-column matrix of frequency and scaled amplitude values above the scaled amplitude threshold. Thus, effectively, if there was a peak in a particular frequency/ time bin, it was considered as an acoustic niche that was 'occupied'. For our analysis, we only considered the peaks in the higher frequency range between 9 and 24 kHz. We then aggregated the peaks into 3888 bins (81 frequency × 48 time bins) with bin sizes for frequency and time set as 0.1875 kHz and 30 min respectively (i.e. each bin would consist of the 6 min recorded for every 30 min). We then calculated the ASO as the proportion of frequency bins where the scaled amplitude threshold of 0.003 was crossed for each 30-minute time bin and the total number of frequency bins (81 bins). We assumed the acoustic space occupied to represent abundance or diversity of species vocalizing in the specified higher frequency range (Burivalova et al., 2019; Gottesman et al., 2021; Zwerts et al., 2022).

2.7.2. *Statistical tests and models*

(a) Socio-economic benefits and perceptions analysis

For the household survey data analyses, we first provide descriptive statistics of perceptions related to Lantana invasion and restoration (question *i* to *iv* below).

(i) What is your perception of the Lantana density in your surrounding forest?
(ii) What use or benefit do you derive from Lantana in your surrounding forest?
(iii) What are the difficulties you face due to the presence of Lantana in your surrounding forest?
(iv) What do you perceive as the benefit of ecological restoration by way of removal of Lantana in your surrounding forest?

We used a two-tailed Z-test to determine if the differences in the proportions of responses from surveyed households with restored, unrestored, and LLD plots in their forest are significant. We used generalised linear mixed models (GLMM; R package: *lme4*) to quantify the associations between the response variable representing perceived ease of use of forest and impacts of Lantana (response variables a-d in Table 1) and the fixed and random factors in Table 1 (Fig S1 shows correlation between all variables considered in this analysis). To account for spatial variation, we included a random effect for the village in our model (N = 13). The four response variables in Table 1 are commonly accepted indicators of success of restoration (Le et al., 2012) and are relevant to this landscape. Due to collinearity (cutoff: R = 0.5; Figure S1) between the variables, % farm in 3 kms, % forest in 3 kms, size of the restoration site and distance to Kanha National Park, we only selected

Table 1
Response variable and fixed and random factors used in the on ease of forest use and perceptions models with their data sources. Refer to Table S2 for summary statistics of each variable for the treatment and control groups. A factor is fixed unless otherwise noted as 'Random variable'.

Response variables, fixed and random factors for ease of forest use and perceptions models		
Variables	**Unit**	**Data source**
Response (a): Distance covered to take cattle grazing	Kilometres covered in a day	Household survey
Response (b): Time for firewood collection	Hours in a day	Household survey
Response (c): Incidence of cattle lost to depredation in last 5 years	1 = Yes 0 = No	Household survey
Response (d): Perception of percentage of crop loss due to crop raid	1 = high crop raid 0 = low crop raid instances	Household survey
Fixed and random factors:		
Treatment variable	0 = No restoration 1 = Restoration carried out 2 = Low Lantana density	
Land owned	Acres of land owned by household	Household survey
Cows owned	Number of cows owned by household	Household survey
Buffaloes owned	Number of buffaloes owned by household	Household survey
Agriculture as primary occupation	1 = Yes 0 = No	Household survey
Firewood collection	Number of days a member of the household collects firewood in a week	Household survey
Lantana as firewood	1 = Lantana as firewood used in the household 0 = Lantana not used as firewood in household	Household survey
Interval between refills of liquified petroleum gas (LPG) cylinder	Number of months between refills of LPG cylinder.	Household survey
Random variable: Village	Factor variable of village name	

one variable for the model: % forest in 3 kms. We selected the % forest in 3 km as it is most relevant to our research questions given the high dependence on forest products in this landscape (Agarwala et al., 2016a; DeFries et al., 2021). Furthermore, to test whether the total population in the village had an impact on the perception of benefits from restoration, we also fit all GLMMs with an interaction term of total households and treatment (restored, unrestored, LLD). The fixed and random factors are described in Table 1 (summary statistics in Table S2). We present the models with the lower AIC (of models with interaction term and without interaction term) in this paper and the models with higher AIC in the Supplementary Information.

(b) Acoustic space occupancy analysis

We used a GLMM (R package: *lme4*) to quantify the effect of restoration on ASO in the frequency range 9—24 k Hz. We used the response variable and fixed and random factors listed in Table 2 (summary statistics in Table S3). We scaled and centred all the continuous variables for this model using the *scale* function in R for ease of interpretation of the association between fixed factors and the response variable. We incorporated random effects for temporal and spatial factors which could influence our results – the sampling site (N = 20) and the date of recording (N = 101 days).

2.8. Expectations

We expected that people in restored and LLD sites will report having lower Lantana densities in their surrounding forests. We hypothesized that Lantana is a significant obstacle to people's subsistence and livelihoods, mainly firewood collection and grazing. After controlling for several socio-economic and geographic factors, we expected villages

Table 2
Response variable and fixed and random factors used in the acoustic space occupancy model with their data sources. Refer to Table S3 for summary statistics of each variable for the treatment and control groups. A factor is fixed unless otherwise noted as 'Random variable'.

Response variable, fixed and random factors for acoustic space occupancy model		
Variable	**Unit**	**Data source**
Response variable: Acoustic space occupancy (ASO)	% Of frequency bins used of all frequency bins within 9 to 24 k Hz	Acoustic data
Fixed and random factors		
Tree density	Number of small, medium and large trees in a 10-metre radius plot	Vegetation survey
Large tree density	Number of large trees (>10 cm at tree base) density in 10-meter radius plot	Vegetation survey
Simpson index of plot	Simpson diversity index of all small, medium and large trees in 10-meter radius plot	Vegetation survey
% Forest cover in 3 km radius	% Forest cover in 3 km radius of sampling location	Khanwilkar et al (2021)
Total population in 3 km radius	Number of people in 3 km radius of sampling location	Govt of India census 2011
Time of day	Day (06:00 to 18:00) or Night (18:05 to 05:55)	
Year of data collection	2020 or 2021	Acoustic data
Random variable: Date of data collection	Factor variable representing the 101 days of data collection	Acoustic data
Random variable: Sampling site	Factor variable representing 20 polygons within which sampling locations for acoustic and data collection were established	

with restored and LLD sites to be associated with positive outcomes including shorter distances covered for grazing, fewer hours spent collecting firewood, fewer incidences of livestock depredation and lower perceived crop loss due to crop raids. Prior evidence from these study sites found no significant association of soundscape measures and restoration in the lower frequencies (2–8 k Hz) dominated by birds and insects (Choksi et al., 2023). However, we expected restored and LLD sites to be significantly associated with higher ASO at the higher frequencies in comparison to unrestored sites, meaning that higher number of acoustic niches are occupied in less 'disturbed' sites, because of previous studies, such as Ramesh et al. (2023), which found such evidence.

3. Results

3.1. Socio-economic benefits and perceptions analysis

(a) *For local people, what are the perceived benefits and drawbacks of the presence of Lantana in forests and the subsequent restoration through removal of Lantana?*

Fig. 2 presents the results to questions listed in Section 2.6.2a. We found two key significant differences in the three groups with respect to their perceptions of Lantana density and its uses and disadvantages. First, we found that perceptions of Lantana density accurately reflected the conditions of sites, when Lantana invasion is high. 87 % and 94 % of respondents near restored and unrestored groups perceived their surrounding forest to have high Lantana density (z = 2.500, p-value = 0.014). A significantly lower proportion of respondents (61 %) in villages near LLD sites reported high Lantana densities in their surrounding forest, compared to 93 % and 86 % (restored – LLD: z = 5.287, p-value = 0.000; unrestored - LLD: z = 7.800, p-value = 0.000) in villages near unrestored and restored sites, respectively (Fig. 2, Fig S2, Table S4a). The proportion of respondents reporting medium (restored – LLD: z = 3.078, p-value = 0.002; unrestored – LLD: z = 4.516, p-value = 0.000; Table S4a) and low Lantana densities (restored – LLD: z = 3.732, p-value = 0.000; unrestored – LLD: z = 5.150, p-value = 0.000) in villages

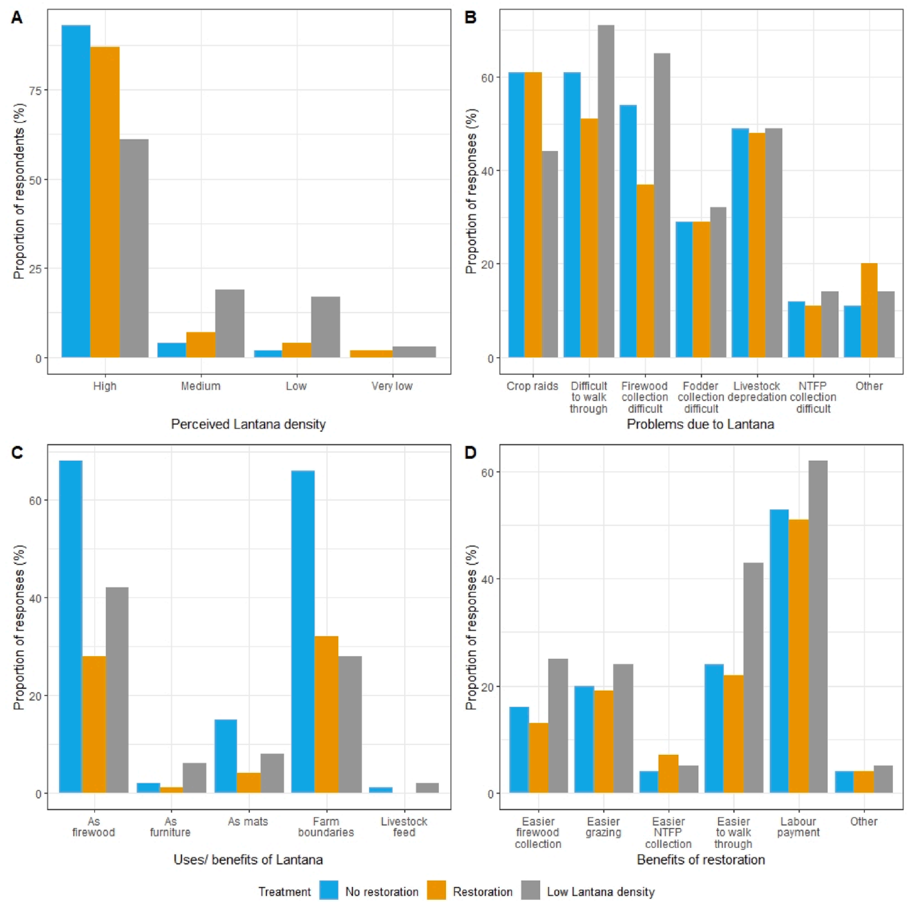

Fig. 2. Treatment group-wise responses to survey questions listed in Section 2.6.2a. Colors refer to the treatment group to which respondents belong. (A) Perceived densities of Lantana camara in the surrounding forests; (B) Uses and perceived benefits of having Lantana camara in the surrounding forests; (C) Perceived difficulties due to the presence of Lantana camara in the surrounding forests; (D) Perceived benefits of ecological restoration in the surrounding forests. Refer to Fig. S2 for the results for all the surveyed households without the treatment groups.

with LLD sites was significantly higher than in the villages with restored and unrestored sites. Second, we found that a significantly higher proportion of respondents in villages near unrestored sites used Lantana as firewood and farm boundaries than the proportion of respondents in villages near restored and LLD sites (restored – unrestored: $z = 9.286$, p-value = 0.000, unrestored – LLD: $z = 4.536$, p-value = 0.000; Table S4b).

Except for a few responses, the three treatment groups were similar in their responses to the questions about the disadvantages of Lantana in their surrounding forest and the benefits of ecological restoration through Lantana removal (Table S4c and S4d). For example, all three groups perceived Lantana to be a reason for high livestock depredation (proportion of respondents in restored = 48 %, unrestored = 49 %, LLD = 49 %; Table S4c). However, a significantly higher proportion of people in unrestored and restored listed crop raids as a difficulty due to the presence of Lantana, (restored – LLD: $z = 2.730$, p-value = 0.006; unrestored – LLD: $z = 2.893$, p-value = 0.004). Additionally, compared to villages with unrestored and LLD sites, villages with restored sites had a significantly lower proportion of people who listed '*difficulty in walking through Lantana*' as a drawback of having Lantana in their surrounding forest (restored – LLD: $z = 2.374$, p-value = 0.018; restored – unrestored: $z = 3.330$, p-value = 0.001). The objective of restoration was to increase the local community's access to timber and non-timber forest products. However, our results show that labour payment to assist in the removal of Lantana was the most commonly reported benefit of restoring their surrounding forest (proportion of respondents in villages with restored sites = 51 %, unrestored sites = 53 %, LLD sites = 62 %; Fig. 2 and Table S4d).

(b) Is there a significant difference in perceptions of ease of forest use and impacts of Lantana invasion between households living in villages that have and have not undertaken restoration?

Table 3 presents the results of the GLMMs for the response variables listed in Table 1. In model 3(A) in Table 3, we found that restoration had no significant association with the three response variables examined in Table 3 (namely, distance for grazing, time for firewood collection and cattle lost to depredation). LLD sites were associated with significantly shorter distances for grazing (Model 3(A)). Models 3(B) and 3(C) showed that restored and LLD sites had no significant association with time spent collecting firewood or on reported livestock depredation in the last five years. In model 3(D), we found that our hypothesis that restoration would be experienced differently based on the total number of households in the village held, unlike the models for the other response variables (see Table S5 a-c). We found that the perception of crop losses significantly changed depending on the whether the village had a restored forest site. (Interaction term restoration × total households in village- Table 2d; coefficient: −1.116, SD: 0.389, p-value: 0.004).

While statistically insignificant, restoration had a negative association with the distance travelled for grazing (coefficient: −0.272, SD: 0.197, p-value: 0.169). Restoration was positively associated with livestock depredation (coefficient: 0.518, SD: 0.401, p-value: 0.196) compared to unrestored sites. All our models had large standard errors, which indicate that there was large variation between households within and across villages in each treatment type.

Table 3
Estimates and standard errors (in parentheses) for models of the four socio-economic response variables (a-d) considered in this study (details in Table 1). In this table, we present the models with the lower AIC of the two types of models we fit, the first not including an interaction term and the second including an interaction term. Refer to Table S5 for the estimates and standard errors of models with the higher AIC and Fig. S3 for information on livestock owned by households. 'NA' for any fixed or random factor signifies that that particular factor was not included in the model.

Variables	(a) Distance for grazing	(b) Time for firewood collection	(c) Cattle lost to depredation	(d) Perception of crop loss
Intercept	0.925 (0.137)***	1.169 (0.935)***	−1.501 (0.305)***	0.422 (0.297)
Treatment: Restoration	−0.272 (0.197)	0.046 (0.134)	0.518 (0.401)	−0.196 (0.429)
Control: Low Lantana Density	−0.460 (0.246)#	0.098 (0.167)	0.340 (0.481)	−0.353 (0.555)
Land owned	0.062 (0.038)	−0.012 (0.021)	0.105 (0.087)	−0.075 (0.085)
Cows owned	0.062 (0.039)	NA	0.101 (0.096)	NA
Buffalos owned	0.160 (0.040)***	NA	0.118 (0.097)	NA
Household size	0.053 (0.039)	−0.029 (0.021)	0.229 (0.098)*	−0.002 (0.089)
Number of days firewood collection/ week	NA	0.140 (0.020)***	NA	NA
Use of Lantana as firewood	NA	0.111 (0.051)*	NA	NA
Interval between filling LPG	NA	0.028 (0.022)	NA	NA
Agriculture primary occupation	0.003 (0.087)	0.012 (0.047)	0.141 (0.217)	0.369 (0.197) #
% Forest in 3 km buffer	0.053 (0.100)	−0.073 (0.067)	0.269 (0.204)	0.055 (0.216)
Total households in village	−0.018 (0.064)	0.115 (0.042)**	−0.504 (0.172)	−0.075 (0.162)
Restoration × Total households	NA	NA	NA	−1.116 (0.389)**
Low Lantana density × Total households	NA	NA	NA	−0.173 (0.507)
Random variable: Village (N = 13)	0.032 (0.179)	0.017 (0.130)	0.088 (0.297)	0.127 (0.357)
N observations	652	656	637	605
Pseudo R^2	0.049	0.219	0.111	0.090
AIC	2551	2660	707	783
Distribution used	Negative Binomial	Negative Binomial	Binomial	Binomial

Significance codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '#' 0.1 '' 1.

3.2. Acoustic space occupancy (ASO) analysis

Fig. 3 shows the changes in the response variable, ASO, over a 24-hour time period. Table 4 shows the results of the GLMM for the response variable, ASO. In the day time hours (06:00 to 18:00), restored (coefficient: −0.249, SD: 0.125, p-value: 0.047) and LLD (coefficient: −0.517, SD: 0.156, p-value: 0.001) sites were significantly and negatively associated with ASO. However, during the night time hours (18:00 to 06:00) restored (coefficient: −0.121, SD: 0.147, p-value: 0.412) and LLD sites (coefficient: −0.260, SD: 0.182, p-value: 0.154) were not associated with ASO. During the day time hours, propensity score matching variables we controlled for such as total large trees had an insignificant relationship (coefficient: 0.009, SD: 0.008, p-value: 0.265) with ASO, However, it is a significant association during the night time hours (coefficient: 0.090, SD: 0.009, p-value: <0.001). The association between percent of forest cover in a 3 km radius and ASO remained unchanged during the day time (coefficient: 0.124, SD: 0.022, p-value: <0.001) and night time hours (coefficient: 0.124, SD: 0.023, p-value: <0.001). While Fig. 3 shows times when restored and LLD sites have higher ASO than unrestored sites, our GLMM models show that changes in ASO are not associated with restoration or the lack of Lantana.

4. Discussion

This study aimed to provide a holistic evaluation of a forest restoration effort in central India three years following restoration. We quantified (1) local people's perceptions of an invasive plant, *Lantana camara*, and subsequent restoration of forests through the removal of Lantana and (2) changes in soundscapes associated with restoration efforts. We found that while Lantana was considered an impediment to people's forest-based livelihoods, people also relied on it to meet their day-to day needs. Our main findings were: first, the majority of the respondents valued a cash income for participating in restoration efforts, over other forest-related benefits. Second, people reported travelling significantly shorter distances to graze their cattle in LLD sites compared to unrestored sites, which could be beneficial for vegetation regeneration. Third, people near restored sites perceived significantly lower crop loss due to crop raids by wild ungulates compared to unrestored sites, which is an important outcome for this predominantly agrarian population. Lastly, our shortly after the first restoration effort, restoration is not significantly associated with changes in the acoustic space occupancy (ASO) during night time hours. During the day time hours, however, restored and LLD sites have significantly lower ASO. In the sub-sections below, we discuss our results in detail.

4.1. Local uses of Lantana

Our results demonstrate the complexity of novel ecosystems, whereby the naturalised invasive species are generally negatively perceived but also become primary resources in the absence of alternatives (Hobbs et al., 2009). People's perception of their surrounding forest mirrors the scientific observation, as we found when we asked people about the perception of Lantana density in their surrounding forest. We found that people perceived Lantana as an impediment to forest access. Yet, we found that people in villages with unrestored sites relied significantly more on Lantana for firewood. We speculate that the higher proportion of respondents in villages with unrestored sites using Lantana to make farm boundaries, is most likely an indication of the lack of bamboo, the preferred material for farm boundaries in this landscape. Our results resemble evidence on the use of invasive plants from other parts of India. For example, in the Banni grasslands of Gujarat, woody encroachment by the invasive *Prosipos juliflora* resulted in a novel ecosystem in which the tree has significantly degraded the ecosystem important for local pastoralists, but also provides local people supplementary income through charcoal production (Nerlekar et al., 2022). Thus, if restoration is to take place at large spatial scales, it would be necessary to provide sustainable fuel and firewood alternatives to meet local people's resource needs in order to avoid negatively impacting local subsistence and livelihoods in the very short term.

4.2. Perceived benefits and drawbacks of the presence of Lantana in forests and the subsequent restoration through removal of Lantana

In all three groups, the majority of respondents perceived the greatest benefit of restoration to be a cash payment for the removal of Lantana. The intended goal of restoration, such as the ease of collecting firewood and NTFPs, were not the most frequently reported benefits of

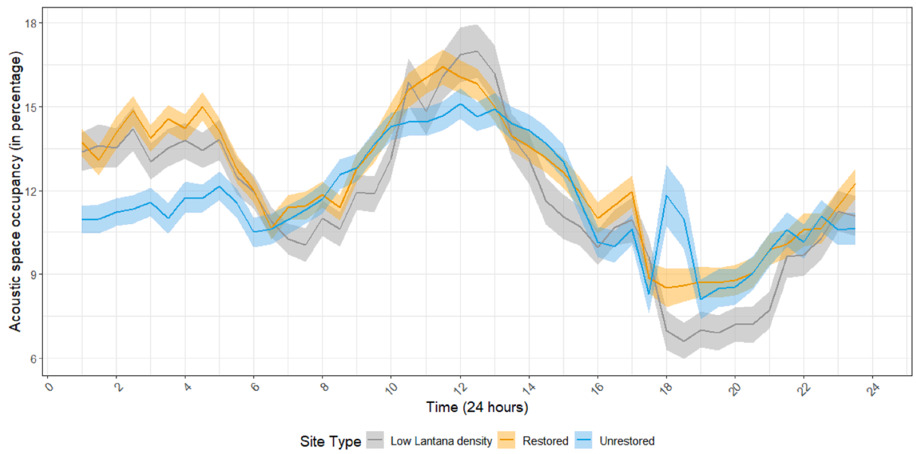

Fig. 3. Acoustic space occupancy of soundscapes between 9 and 24 k Hz over a 24-hour period. Colours represent different site types and the shaded bands represent one standard deviation around the mean represented by the solid line.

Table 4
GLMM results for the model with response variable, acoustic space occupancy (ASO).

Variables	Estimates and standard errors for: (a) Day time hours (06:00 to 18:00)	(b) Night time hours (18:00 to 06:00)
Treatment: Restoration	−0.249 (0.125) *	−0.121 (0.147)
Control: Low Lantana Density	−0.517 (0.156) ***	−0.260 (0.182)
Season (Winter 2021)	−0.004 (0.054)	−0.072 (0.070)
% Forest in 3 km buffer	0.124 (0.022) ***	0.125 (0.024) ***
Total population in 3 km buffer	0.033 (0.020)[#]	0.087 (0.020) ***
Total large trees	0.009 (0.008)	0.090 (0.009) ***
Total trees	0.074 (0.007) ***	0.040 (0.008) ***
Simpson Index for all trees	0.049 (0.006) ***	0.059 (0.007) ***
Random variable: Sampling sites (N = 20 villages)	0.059 (0.243)	0.081 (0.285)
Random variable: Date of recording (N = 101 days)	0.065 (0.256)	0.107 (0.328)
Random variable: Time (N = 48 time bins)	0.039 (0.197)	0.0345 (0.186)
N observations	13,506	11,116
Distribution used	Binomial	Binomial

Significance codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '#' 0.1 '' 1.

restoration in our study. We speculate that this could be due to two reasons: (a) the spatial scale at which restoration took place is too small for respondents to perceive such benefits, and (b) time since first restoration effort and regeneration of species of importance. Restoration was carried out in 2017, and we carried out data collection in 2020 and 2021. For example, commonly consumed or sold NTFPs include the flowers and fruits of Mahua (*Madhuca longifolia*) and Baheda (*Terminalia bellerica*), and leaves of Tendu (*Diospyrox melanoxylon*) (Agarwala et al., 2016a). In order to collect the NTFP of these species, new trees must reach a certain age and size class, which could take more than three years (the time since restoration) (Agarwala et al., 2016b). Similarly, for people to perceive the benefits of availability of firewood and timber (for construction in homes) due to regeneration of the forest, existing and new trees would have to reach a reasonable size class to be used, which can take more than three years (Agarwala et al., 2016b).

The second most commonly perceived benefit of restoration is the ease of grazing and walking through the forest, an important benefit for local people who follow traditional open grazing practices in this landscape (Agarwala et al., 2016a; DeFries et al., 2021). Specifically, of the 656 surveyed households included in this study, 56 % owned at least one cow, 23 % owned a buffalo and 76 % owned at least a single ox. Approximately 64 % of the surveyed respondents mentioned the use of forests for grazing their livestock in addition to other locations such as their fallow farms. Thus, we conclude that ease of grazing and movement in this forest is of importance to the continuation of local livelihoods.

When controlling household and village level fixed factors, LLD sites were associated with significantly lower grazing distances. We interpret this result as a positive social-ecological outcome of restoration as it reduced local people's livestock grazing footprint in the forest, which can (1) lower instances of livestock depredation by tigers (Miller et al., 2016b, 2016a) and (2) increase regeneration of tree species of livelihood interest with low resistance to trampling (Agarwala et al., 2016a, 2016b) in this landscape. With shorter grazing distances there could be lower instances of livestock depredation. In the buffer region of Kanha National Park, prior evidence indicates that the probability of livestock depredation by tigers was highest as villagers moved further away from their village and closer to denser forest, mainly found within the national park (Miller et al., 2016a). We are optimistic about this positive social outcome because LLD sites represent what restored sites could look like if Lantana does not reinvade aggressively in restored sites and people living around these restored sites could possibly experience similar benefits of travelling shorter distances for grazing.

Restoration, mediated by the total number of households in a village, was significantly negatively associated with respondents' perceived crop loss. Therefore, respondents in villages with fewer households near restored sites perceived higher crop loss than respondents in villages with more households near restored sites. It is noteworthy that people's perceptions mirror scientific observations as shown by their perception of Lantana density in these sites. Thus, their perception of crop loss due to raids by wild ungulates could be an accurate representation of the actual crop lost, even though our study did not measure the exact amount of crop lost by weight/spatial coverage. Similarly, in another TDF in southern India, local people's perception of higher instances of crop raids around high Lantana density forests was also supported by vegetation data (Sundaram et al., 2012). Further, in a recent study from the KNP found that Lantana and other invasive plant species invasions significantly reduced forage availability for herbivores, which in turn can push herbivores out of the park to raid crops in the neighbouring farms (Rastogi et al., 2023). Lastly, this is an important result because people's perceptions of crop lost to raids can negatively influence their sentiments towards the national park (*e.g.*: Haile, 2022). Thus, restoring the forests surrounding villages could help create positive sentiments towards wildlife conservation. We used percent forest cover in 3 km to account for the presence of herbivores in our GLMMs, but we recognize the limitation of this analysis in the absence of data on the abundance and movement of ungulates.

4.3. Acoustic space occupancy in restored, unrestored and Low Lantana density sites

While our analysis of people's perceptions reveals a predominantly positive picture of the restoration efforts, our ecological analysis using soundscapes is more complex. According to the Acoustic Niche hypothesis (ANH), a higher diversity (and abundance) or species vocalizing would result in higher acoustic space occupancy (ASO). We found that LLD and restored sites are associated with significantly lower ASO during the day time hours. However, during the night time hours, there were no significant differences between the three types of sites. Our results are, to an extent, consistent with prior studies from the same sites that found that the association between acoustic space use in the lower frequencies (2–8 kHz) and restoration was not significant (Choksi et al., 2023). Thus, combining previous soundscape analysis results of the lower frequencies (Choksi et al., 2023), we conclude that it could be too early to see any significant changes in the soundscapes of restored and unrestored sites.

We interpret our results to conclude that there could be a difference in the diversity and abundance diurnal species, mainly insects, vocalizing during the day. However, nocturnal species may remain unaffected by restoration. We speculate that the ASO in the higher frequencies is mainly driven by insects because of similar findings in several prior studies including Aide et al. (2017), Burivalova et al. (2022, 2019), and Ramesh et al. (2023). Instead of taking a binary view of either a positive or a negative impact of restoration on vocalizing fauna, we view this result as a possible change in the vocalizing species community in a different habitat with little to no Lantana present.

The association between percent forest cover in a 3 km radius and ASO does not change much during the day time and night time hours, which could indicate that both diurnal and nocturnal vocalizing species need similar amount of forest cover for persistence. Further, while total large trees had an insignificant association with ASO during the day time hours, this association was significant during the night time hours. We interpret this result as a potential reliance of nocturnal vocalizing species on the presence of large trees.

One study from Costa Rica found that primary forest sites, which would be expected to have higher acoustic energy, in fact had lower acoustic energy in the higher frequency range, compared to recently restored forests. The authors attributed this lack of acoustic energy at primary sites due to (a) a strong insectivorous predator community or (b) the lack of preferred vegetation for certain insects (Vega-Hidalgo et al. 2021). We speculate that these two reasons may also be why we see a significant negative association of LLD and restored sites with ASO. However, we acknowledge that without validation data on the diversity and abundance of insects using insect traps, our results must be considered with caution. Given the short time since the first restoration effort, it is necessary to repeat these acoustic measurements at several time steps in the future to understand the relationship of ASO and restoration.

4.4. Synergies between social and ecological outcomes of restoration

We find some synergy between the social and ecological outcomes of restoration. If policy-makers and practitioners were to only consider the ecological outcomes based on the soundscapes, restoration would appear to have no major significant biodiversity 'benefit' in the short term. Thus, policy-makers could argue, for example, to not invest further in such efforts. However, when we consider social outcomes alongside the ecological, we find that respondents in villages reflect a few important benefits of restoration, which could result in ecological benefits as well. Lastly, we found that local people's perceptions of the condition of their surrounding forest mirror scientific observation, reaffirming the need to include people who will be affected by well-meaning restoration efforts in the decision-making process and not rely solely on top-down and technocratic approaches (Crowley et al., 2017).

4.5. Limitations

This study has some limitations. First, propensity score matching is an alternative in the absence of the opportunity to carry out a true randomization (Luellen et al., 2005), but there could be inherent differences between the villages driving the results. We also acknowledge that it is more effective to sample the same village over time to better quantify the social and ecological outcomes instead of matching treatment and control groups. However, this was not possible as restoration had already been undertaken in some villages and not others. Second, there could be biases in our data due to the method of data collection – surveys. For example, restoration was carried out by villagers in collaboration with the local NGO and the Forest Department. The respondents' answers can be determined by what the respondent thinks a surveyor wants to hear about a restoration program and may not provide an honest response. Alternatively, the respondent may have perverse incentives to answer dishonestly if they believe that their responses may influence future restoration programs.

Another set of limitations of this study is related to the ecological analysis. Acoustic data captures only vocalizing species. Several non-vocalizing species, that are not captured in acoustic data, may be critical to the success of restoration. Thus, acoustic data does not provide a complete picture of faunal diversity. Furthermore, we used an acoustic space use analysis, which previous studies have found adequately reflect diversity of vocalising species in a location (Burivalova et al., 2021, 2019). However, our acoustic data was not validated through the laying of insect traps, for example, due to covid-19 related challenges. Similarly, due to covid-19 related travel restrictions, we could not collect acoustic data in spring or summer. We acknowledge that our results could be different if we managed to collect data in other seasons. Lastly, vegetation structure also affects sound attenuation. Sounds in the higher frequency ranges are relatively more prone to scattering in forested habitats with denser understories (Bullen and Fricke, 1982; Romer and Lewald, 1992). Therefore, we are cautious in the recommendations we can provide for restoration policy makers. When possible, we recommend the combination of human biodiversity surveys of all vocalising species in addition to the use of acoustics to determine the impact of restoration efforts on fauna. Finally, we acknowledge that a detailed analysis of vegetation regeneration following restoration could provide a more complete picture of the ecological outcomes of this effort.

5. Conclusion

Countries around the world, especially those in the tropics and subtropics, have pledged to restore degraded forests to meet carbon sequestration and biodiversity conservation goals in this UN Decade on Ecosystem Restoration. Case studies such as this one are important in assisting policy makers plan restoration efforts in a way that local people and the local ecology are benefited. The evidence we provide is applicable to numerous social-ecological systems, which grapple with balancing biodiversity conservation and local resource needs. Based on our results we recommend restoration planners should (1) consult local people about their perception of forest degradation and ways to restore degraded forests; (2) provide a cash income for participating in restoration activities; (3) provide sustainable alternatives for timber and NTFP livelihood needs before embarking on large invasive species removal projects to restore ecosystems or upscaling existing small restoration efforts; (4) recognize that social and ecological changes or 'benefits' may occur on different timelines and report these changes in an unbiased fashion; (5) anticipate potential changes in the faunal species community when large scale invasive species removal takes place in the short term.

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CRediT authorship contribution statement

Pooja Choksi: Conceptualization, Investigation, Project administration, Funding acquisition, Data curation, Formal analysis, Methodology, Writing – original draft, Writing – review & editing. **Mayuri Kotian:** Data curation, Formal analysis, Methodology, Writing – review & editing. **Zuzana Burivalova:** Methodology, Writing – review & editing. **Ruth DeFries:** Funding acquisition, Writing – review & editing.

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.

Data availability

A portion of the data and all the code related to this study can be found at https://github.com/pooja-choksi/Restoration-Benefits-Acoustics

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecolind.2023.111054.

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