Investigating the roles of fire and cattle grazing on vegetation, invasives, and their implications on Bengal Florican (*Houbaropsis bengalensis*) breeding habitat use

by

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Under the supervision of

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May 2025

DECLARATION

I hereby declare that the work conducted under the thesis entitled **"Investigating the roles of fire and cattle grazing on vegetation, invasives, and their implications on Bengal Florican (*Houbaropsis bengalensis*) breeding habitat use"**, is a record of original and independent research work done by me and subsequently submitted for the award of the degree of **Master's in Wildlife Science** at the **Academy of Scientific and Innovative Research**. This research work has been carried out under the guidance and supervision of **Dr. Anukul Nath, Scientist-C** and co-supervision of **Dr. Sutirtha Dutta, Scientist-E** of Wildlife Institute of India, Dehradun. The work has not formed the basis for the award of any other degree, diploma, or any other qualification. I also declare that the thesis embodies my own work, analysis, observation, understanding and the particulars given in it are true to the best of my knowledge.

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CERTIFICATE

This is to certify that the thesis by **Aadya Thammaiah** entitled "**Investigating the roles of fire and cattle grazing on vegetation, invasives, and their implications on Bengal Florican (*Houbaropsis bengalensis*) breeding habitat use**" is an original and independent research work submitted to the Academy of Scientific and Innovative Research, for the award of the degree of Master's in Wildlife Science.

Aadya Thammaiah has put one semester of research work embodied in this thesis under my guidance and supervision. The work presented in this thesis has not been submitted to any other University or Institute for the award of any degree, diploma or distinction.

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It is certified that the M.Sc. Dissertation titled "**Investigating the roles of fire and cattle grazing on vegetation, invasives, and their implications on Bengal Florican (Houbaropsis bengalensis) breeding habitat use"** submitted by **Aadya Thammaiah** has been examined by us for plagiarism check as per UGC (Promotion of Academic Integrity and Prevention of Plagiarism in Higher Educational Institutions) Regulations. The following inferences are drawn from this check:

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List of Abbreviations

BF Bengal Florican
LM Linear Model
GLM Generalised Linear Model
LDA Linear Discriminant Analysis
CLR Conditional Logistic Regression
AIC Akaike Information Criterion

Executive Summary

1. Grasslands, though ecologically important, are often overlooked in conservation. These ecosystems are shaped by land-use practices such as fire and grazing, which can help maintain open habitats when appropriately applied. Mismanagement, however, can promote invasive species, threatening native biodiversity. The Bengal Florican (*Houbaropsis bengalensis*), a critically endangered grassland specialist, highlights the need for targeted conservation in such systems. This study assessed the combined effects of fire and grazing on grassland plant communities, including invasive plants, and Bengal Florican breeding habitat selection in Manas National Park.

2. For the vegetation survey, I selected study sites along gradients of fire frequency (based on 23 years of FIRMS data) and grazing intensity (using distance from human settlements as a proxy). At each site, I used circular plots to sample vegetation and assess species composition. To examine drivers of plant and invasive species abundance, I applied linear models (LMs), incorporating key covariates such as distance to forests, roads, and climate moisture index (CMI). I then used Indicator Species Analysis (ISA) to identify species associated with different fire-grazing regimes. I also performed a Linear Discriminant Analysis (LDA) to assess how well vegetation communities and structure could distinguish between different fire conditions. For Bengal Florican habitat assessment, I quantified vegetation structure visually and insect abundance using sweep netting in display and paired control sites. I used Binomial Generalised

Linear Models (GLMs) and Conditional Logistic Regression modelling to evaluate habitat selection by the species.

3. Tree and sapling densities peaked under intermediate fire, whereas shrubs and herbs had the highest density in low fire regimes. Saplings, shrub as well as grass cover peaked in low grazing regimes, but herb cover was highest in low grazing conditions. Among invasives, *Leea asiatica* and *Chromolaena odorata* were more frequent in intermediate fire, while *Mikania micrantha* and *Ageratum conyzoides* thrived under low fire. Grazing showed significant effects only on *Mikania micrantha*. ISA identified native species such as *Dillenia pentagyna* as indicators of low grazing and *Cymbopogon flexuosus* for medium and high fire regimes, among others. Bengal Florican selected sites with higher insect abundance, shorter vegetation (25–50 cm), with low (outside the PA) and high fire frequency (within the PA).

4. My results showed that plant communities showed species-specific responses to fire and grazing conditions. Bengal Florican habitat-use reflected a preference for open, short grasslands with high insect abundance. In conclusion, my study found that effective conservation requires tailored fire and grazing strategies that sustain open structure and control invasives, especially for the conservation of species such as the Bengal Florican.

1. INTRODUCTION

Grasslands are some of the most neglected and under-studied ecosystems, often overshadowed by forests in conservation efforts, despite being biodiversity hotspots with high conservation value (Thakur et al. 2024). As a result, very few grassland species receive conservation attention. Typically, a single flagship species like the one-horned rhinoceros dominates conservation strategies in riverine/wet grasslands of north India. Smaller, less charismatic species, such as the Bengal Florican (*Houbaropsis bengalensis*), receive far less focus, even though they represent a threatened ecological community and play an important role in maintaining ecosystem integrity. The presence of the Bengal Florican is closely linked to grassland health as it has a very specific niche that makes it a grassland-obligate (Baral et al. 2003), yet it is often overlooked in grassland policies. This singular focus on larger, charismatic species overlooks key grassland dynamics and threats to other threatened species, excluding them from conservation policies and management practices.

The wet grasslands of India have declined in expanse dramatically over the last century, largely due to agricultural conversion of riverine grasslands and damming / training of river courses. Such wet grasslands are shaped by land-uses like cattle grazing and management practices like fire that strongly influence habitat characteristics. Optimal use of these practices become vital, especially with declining grassland extent and increasing human pressures on what remains (Briske 2017). Controlled burning and grazing can restrict woody encroachment in grasslands receiving relatively higher rainfall (Sankaran et al. 2005) and maintain them as open grasslands, but improper management can cause degradation (Briske

2017). Fire, while used to prevent woody encroachment and control invasive plants, may have the opposite effect if not managed properly (Knapp et al. 1998; Banerjee et al. 2023). Although fire controls vegetation, it can also create opportunities for invasive species to spread, altering the ecosystem and disrupting the habitat requirements of Bengal Florican for breeding (Mahood et al. 2019). There are significant knowledge gaps regarding the effects of fire management practices on the structure of India's wet grasslands that need to be investigated for effective conservation policies. In Manas National Park, the last stronghold of the Bengal florican in India (Nath and Dutta pers. obs.), one such gap involves understanding how fire and grazing affect the spread of invasive plants, especially in Bengal Florican breeding habitats (Mahood et al. 2019). Since grasslands offer a chance to assess fire as a management tool and understand how varying fire frequencies impact ecosystem function, it is crucial to study these dynamics in the context of different species (Knapp et al. 1998).

In India, the decline of alluvial grasslands is closely related to the decline of the Bengal Florican population as well. Due to their specialization on grasslands, with a decline in wet grasslands, an increase in agricultural expansion, and change in vegetation composition, the species faces imminent extinction risk (Brahma 2013). These risks to the Bengal Florican also include increase in fire frequency, invasive species and change in vegetation composition with increase in human interference, and also happen to be areas that have not been studied extensively in the Indian context (cite).

Wet grasslands of India have a long history of fire management. They are also grazed by livestock. Both of these agents can favour some vegetation (species and forms) over others, in turn affecting the distribution and fitness of grassland-obligate species that are very poorly understood. The impact of fire on invasive species can vary significantly, especially when it comes to native woody species in grasslands. In the Western Ghats of India, fire-induced mortality in plants was highest in *Cytisus scoparius* (scotch broom) and lowest in *Ulex europaeus* (gorse), with fire promoting the regeneration of gorse and *Acacia mearnsii* (black wattle) seedlings (Sriramamurthy et al. 2020). This indicates that fire can differentially affect invasive species, potentially aiding the management of some while exacerbating the spread of others. This makes it all the more important to study, as changes in frequency and intensity, coupled with different causal mechanisms such as grazing by ungulates and cattle, moisture level, soil nutrients etc., can have an impact on the grassland dynamics (Rinella et al. 2009). Consequently, this can negatively affect the already declining habitats for species like the Bengal Florican, highlighting the critical need to understand grassland dynamics in the context of such species.

Even though fire is used as a grassland management tool around the world, the response of different fire frequencies remains understudied, especially in the context of invasive species, vis-à-vis grazing. Fire in different intensities and frequencies has a different effect on different species, which makes it essential to understand the use of fire as a grassland management tool in specific contexts. This context includes local grassland decline, as well as in the context of specific species that are highly dependent on these same habitats.

An important part of habitat management is the use of bioindicators to inform policies. When it comes to grasslands, birds could be a good indicator of grassland health, especially species like the Bengal florican; they are grassland obligates that are sensitive to change, both ecological and anthropogenic (Brahma 2013). This makes understanding the health and management of a grassland ecosystem using the perspective of a species like the Bengal florican important.

My study aims to fill these gaps by exploring how fire and grazing affect grasslands, with a focus on their implications on Bengal Florican habitats, using the following objectives:

1. **Objective 1:** To understand the effects of fire and grazing on vegetation composition and invasive plants in Bengal Florican breeding habitats

    a. What is the composition and abundance of different vegetation (trees, saplings, shrubs, grasses and herbs) in different conditions of fire and grazing?

    b. What is the abundance of different invasive (*Ageratum conyzoides, Chromolaena odorata and Mikania micrantha*) plants, woody (e.g., *Bombax ceiba, Leea asiatica*) encroachers in different conditions of fire and grazing?

Hypothesis 1:

Fire is used as a management tool in grasslands for various purposes, mainly being the prevention of woody encroachment by changing the composition of the soil that makes it unconducive for woody plants to grow beyond a particular stage (Briske 2017). It is effectively used across the world as a tool to maintain grasslands, including in India (Bezbarua et al. 2024). In Manas National Park, fire is used to prevent the encroachment of woody species as well as to maintain a fresh flush of grasses for the ungulate population in the park (Bezbarua et al. 2024). However, there is no established protocol for the frequency of burning regimes, and Manas has experienced over two decades of socio-political unrest, during which fire and grazing remained largely uncontrolled (Nath et al. 2023). Hence, some areas experience frequent fire while others do not; therefore, even though fire can be an effective tool to prevent woody encroachment, fires that are too frequent may cause degradation of the habitat by depletion of the soil nutrients and moisture that allows other non-woody invasives to grow (Briske 2017; Banerjee et al. 2023). Hence it is hypothesized that invasive plants and woody encroachment in Bengal Florican habitats will be influenced by a combination of fire frequency and cattle grazing. Consequently, it can be predicted that invasive plants will be more abundant in areas that experience high cattle grazing, whereas the abundance of woody species will be greater in areas that experience less or too frequent fires.

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2. **Objective 2:** To understand habitat selection of Bengal Florican for breeding

    a. What are the habitat requirements for Bengal Florican males to select a display site/territory?
    b. What fire and grazing conditions are highly selected by the Bengal Florican males for display?

Hypothesis 2:

Based on a-priori knowledge from a different landscape (Cambodia), Bengal florican prefers burned grasslands without tall scrub for courtship display of males and females tend to select unburned areas for all activities, though they may be still found within the areas used by males (Gray et al. 2009). Therefore, it is predicted that relatively short-height grasslands (grass assemblage dominated by *Imperata cylindrica*) with less woody cover will be selected by the breeding males. Further, the moisture content is known to influence grassland vegetation community and structure that can also influence site selection by breeding males (Gray et al. 2009). We also expect that insect diversity and abundance will be higher in breeding sites (male display sites) compared to other available grassland patches in the study site, as males require a high-energy and protein diet for display activities which can be strenuous, and females may be within the territory of the males for mating (extrapolating from the breeding ecology of Lesser Floricans) (Ram et al 2023), even though they might raise their chicks in other areas (Gray et al 2009).

2. METHODS

2.1 Study area:

The study was undertaken in Manas National Park (850 sq. km), Assam. It is located in two main districts, Chirang and Baksa under the Bodoland Territorial Council (Thakur et al. 2024). Manas National Park has the second largest contiguous grasslands in the North-eastern part of India, with semi-evergreen alluvial grasslands covering around 43% of its total area (Nath et al. 2023). There is a paucity of information on the fire management practices that take place here, and understanding the grasslands better that takes into account the requirements of various species, instead of just one or two will help put in place better management policies. In the current scenario, there is no set protocol when it comes to fire engagement of grasslands, with extensive and uncontrolled burning that takes place between late January and February, until the start of March (Naryan 1992). This also happens to overlap with the breeding season of the Bengal Florican, making it all the more important to understand how fire can affect the population, directly as well as indirectly (Naryan 1992). Manas National Park also holds the highest population of Bengal Florican in India with 50 males and 17 females estimated as of 2021 (Thakur et al. 2024), and the population structure might be affected with the increase in anthropogenic activities in and around the park, especially the regular burning of its habitat, grasslands, that takes place. Manas also happens to be well-studied and documented in many other aspects, including management and land-use changes, making it an ideal place to study the historical aspects of the Bengal Florican habitat and the management of the latter.

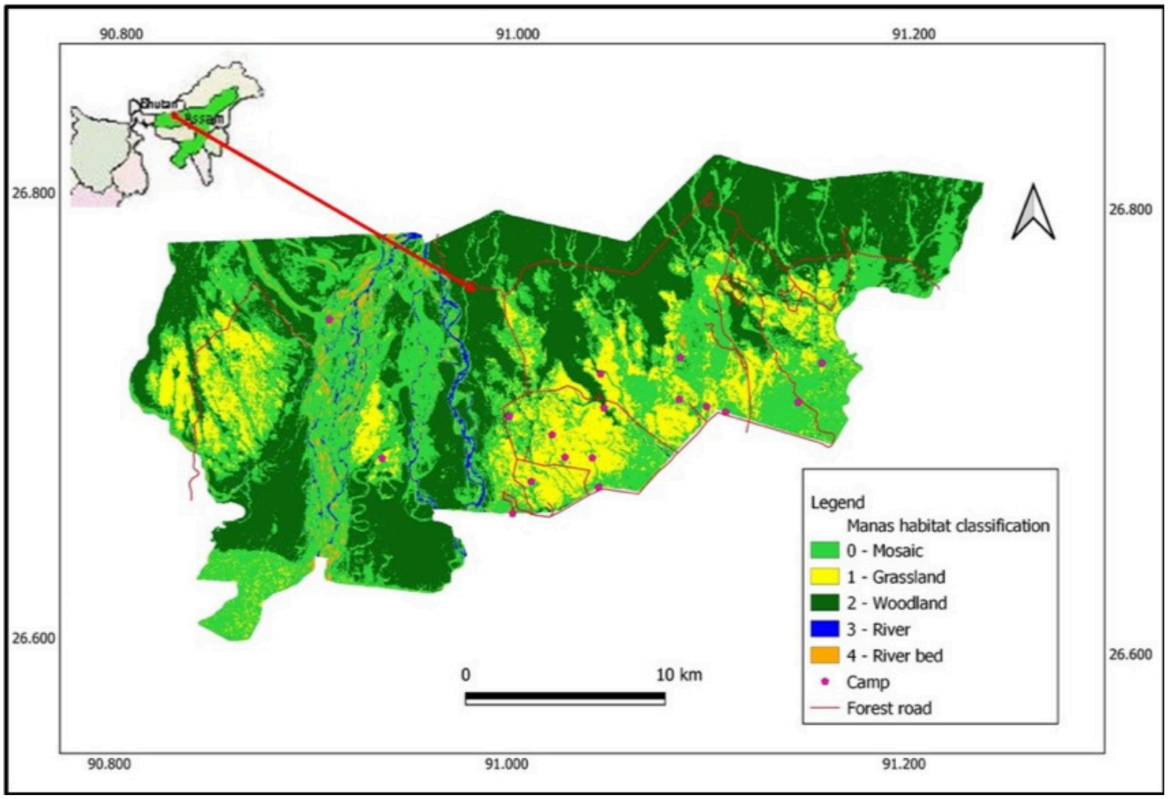

Fig. 1. A map of Manas National map along with the habitat types (Thakur et al., 2024)

2.2 Field methods:

For Objective 1, the abundance and composition of the trees, saplings, shrubs, grasses, herbs and invasive plants were quantified. For Objective 2, the habitat characteristics (insect abundance and composition, *Leea asiatica* abundance (woody invasive plant), and vegetation structure of the male-Bengal Florican display territories and a similar number of unused areas were quantified.

Objective 1:

2.2.1 Abundance and Composition of Plants and Invasives

Vegetation surveys were conducted across grassland sites categorized by fire frequency (low, medium, high) and cattle grazing intensity (low, medium, high), resulting in 9 condition combinations. Sites were selected using remote-sensed fire data from Fire Information for Resource Management System (FIRMS) which is a NASA database and proximity to human settlements (as a proxy for grazing). A grid of 500 x 500 m was overlaid in the park, and the fire frequency was calculated as the number of fire occurrences over ~22 years of data (from January 2002 to November 2024) per grid. It was then categorised as low if the number of fire occurrences were less than 3, medium if they were equal to or between 3 and 7 and high if they were equal to or more than 7. Grazing was considered high 1 km away from human settlements, medium up to 4.5 km, and low beyond that. This was categorised based on the the attempt to include the effects of historical grazing in the park during the insurgency that started in the 1980s and ended in the 2000s (Nath et al. 2019). These categories were made in order to allow for a systematic capture of the variance in different fire frequencies as well as grazing intensities over the years as well as across the landscape.

A 500 × 500 m grid was laid using ArcGIS, and ~10 grids per condition were sampled to ensure spatial spread. Within each grid, vegetation was sampled at multiple points using a nested design appropriate to plant type (Krebs 1999)(Table 1).

Environmental covariates such as Distance from Road, Distance to Forest and Climate Moisture Index were extracted via ArcGIS for modelling vegetation density.

Table 1: Field Methods for Objective 1 – Quantifying Plant and Invasive Abundance and Composition

Component	**Method Description**
Site Selection	Sites categorized by fire frequency (low, medium, high) using FIRMS data, and grazing pressure based on distance to human settlements (high, medium, low).
Grid Setup	500 × 500 m grids overlaid using ArcGIS. Grids selected (9 different conditions, ~10 per condition, 4 circular vegetation plots per grid) to ensure spatial coverage and interspersion
Sampling Units	Vegetation surveys conducted with replicates ≥100 m apart and ≥100 m from roads.
Sampling Design	Random sampling within grids using nested circular plots: 1 m radius for grasses/herbs, 3 m radius for saplings, shrubs and invasives and 10 m radius for trees
Variable Measurement	

Grass & Herb Cover	Estimated visually as percentage cover, including bare ground
Tree, Sapling & Shrub Abundance	Counted as individuals per plot
Invasive Plants Quantification	- Density of *Bombax ceiba* and *Leea asiatica* (woody invasives)- % Cover of *Chromolaena odorata*, *Ageratum conyzoides*, and *Mikania micrantha* (herbaceous invasives).
Remote Sensing Covariates	Distance from Road, Distance to Forest and Climate Moisture Index (CMI) extracted in ArcGIS and ENVIREM database for analysis.

Objective 2:

2.2.2 Bengal Florican Habitat Use and Characteristics

Habitat selection by Bengal Florican was assessed by comparing vegetation and insect characteristics between used (male-display) sites and unused/available sites. For 25 individuals,four sampling points per territory were sampled for micro-scale. An equal number of randomly chosen available sites beyond 600 m from display sites were also sampled. The characteristics that were noted down included vegetation structure, insect abundance and richness as well as Leea asiatica density (Table 2). Environmental covariates such as Distance from Road, Distance to Forest and Climate Moisture Index were also extracted via ArcGIS to help determine the macro and micro scale habitat selection of the species.

Table 2: Field Methods for Objective 2 – Bengal Florican Habitat Characteristics (Used vs Unused Plots)

Component	**Method Description**
Used Sites	25 Bengal Florican territories sampled. 4 points per territory (display site, 50 m, 100 m, 200 m in 3 different directions).
Unused / Available Sites	25 randomly selected sites, all beyond a 600 m buffer from known display territories, sampled using the same spatial design.
Variable measurement	
Insect Abundance & Composition	Sampled using square sweep nets (0.5 × 0.5 m mouth, 1.5 m trailing net)(Spafford et al. 2013); swift circular sweeps; insects identified to Order level and released.
Vegetation Structure	Visually estimated proportional cover over 10m within height classes: <25 cm, 25–50 cm, 50–100 cm, 100–200 cm, >200 cm.
***Leea asiatica* Density**	Counted using a 3 m radius circular plot.
Remote Sensing Covariates	Distance from Road, Distance to Forest, and Climate Moisture Index (CMI) extracted via ArcGIS and ENVIREM database for inclusion in multiscale habitat selection models.

2.3 Analytical methods

All analysis of data was performed using R, utilising several different packages as and when required.

Objective 1:

2.3.1 Abundance and Composition of Plants and Invasives

To understand how fire and grazing, individually and in combination, could affect the abundance and composition of tree, sapling, shrub, grass, herb and invasive species, linear models were fitted to explain the variation in density of plants and invasives. The density of plants and invasives were log transformed (response variables) and their responses to fire (low, medium and high) and grazing frequency (low, medium and high), along with other remotely sensed predictors, including distance to forest, Climate Moisture Index (CMI), Precipitation, elevation, distance to water and distance to road, were examined using linear models. These predictor variables were tested for multicollinearity and only the most ecologically meaningful variable among the correlated ones was included in the modeling routine. I used separate full models to test hypotheses on factors influencing, tree density, sapling density, shrub density, grass cover, herb cover, variation of density of woody invasives, *Bombax ceiba* and *Leea asiatica*, as well as variation in percentage cover of *Ageratum conyzoides, Chromolaena odorata* and *Mikania micrantha.* Estimated Marginal Means (EMMs) were then used to visualize if fire and/or grazing influences the above response variables. The results were then plotted using ggplot2 in R.

Subsequently, in order to understand the possible difference in vegetation characteristics among different fire and grazing conditions, a Linear Discriminant Analysis (LDA) was performed. Performing an LDA allows for a reduction in the dimensions of the data, while also simultaneously accounting for grouping of data by maximising the ratio of the variance that exists between and within the groups. The results were then plotted using *ggplot2*.

Lastly, an Indicator Species Analysis (ISA) using the “indicspecies” package was performed for each of the tree, sapling, shrub, herb, grass and invasive species separately to ascertain whether any of the fire or grazing or combination of conditions were represented by particular species of plants or invasives (McCune and Grace, 2002). The results with moderate and strong associations were then reported.

Objective 2:

2.3.2 Bengal Florican Habitat Selection

The aim of Objective 2 was to understand breeding habitat selection of Bengal Florican, explore any role that invasive plants, in particular, *Leea asiatica* may have in this selection, and ascertain how fire and/or grazing influence the selection of breeding territories. This was done at two scales; micro and macro. At the micro scale, resource selection functions were developed by comparing habitat characteristics in breeding territories with that in surrounding available sites in a matched design, using conditional logistic regression (binomial Generalised Linear Model), The predictor variables included a) insect abundance (expected to positively influence habitat selection), b) proportion of tall vegetation > 200 cm (expected to negatively influence habitat selection), c) principal components (variables that are a combination of variables of the data that reduce dimension) extracted from the proportional cover of < 100 cm vegetation in various height categories (PC1 and PC2– the two axes that explain 60% of the variation in the data), d) structural diversity of vegetation based on Shannon index, e) Leea density, and f) fire and g) grazing levels for each point. I built a full model with the above predictors and candidate subset models with alternate combinations of these variables, thereafter selecting the least AIC model for inference. The effect of significant variables in habitat selection was visualised using the Estimated Marginal Means (*emmeans*) against different covariate values

To understand resource selection at the macro-scale, I used remotely sensed variables including tall or short vegetation, distance to forest, distance to human settlement (proxy for grazing), fire frequency over the past 23 years, Climate Moisture Index (CMI), Precipitation, elevation, and distance to road. I extracted these variables from Bengal Florican territories (used sites) and from a set of randomly generated 100 points across grasslands (unused sites). I compared habitat characteristics between used and unused sites using General Linear Model of binomial family. Predictor variables were checked for multicollinearity using correlation analysis and only the most ecological meaningful ones were used in the GLM (Kerbs 1999).

3. RESULTS

Objective 1: *Response of vegetation structure to fire, grazing and associated covariates*

A total of 346 plots were sampled in 90 grids of the nine different conditions (Fig. 2). The total number species that were detected (including uniquely unidentified vegetation) are as follows:- tree (38 species), sapling (121 spp.), shrubs (89 spp.), herbs (158 spp.), and grasses (34 spp.).

The most abundant trees were *Dillenia pentagyna*, *Lagerstroemia parviflora* and *Bombax ceiba*. *Grewia* sp. and *Glochidion* sp. were the most abundant sapling species. In shrubs, *Desmodium heterocarpon* was the most abundant. Among herbs, *Diplazium esculentum* was the most abundant. *Saccharum narenga* and *Arundinella* sp. were the most abundant grasses. Among invasive plants, *Leea asiatica* and *Mikania micrantha* were the most abundant.

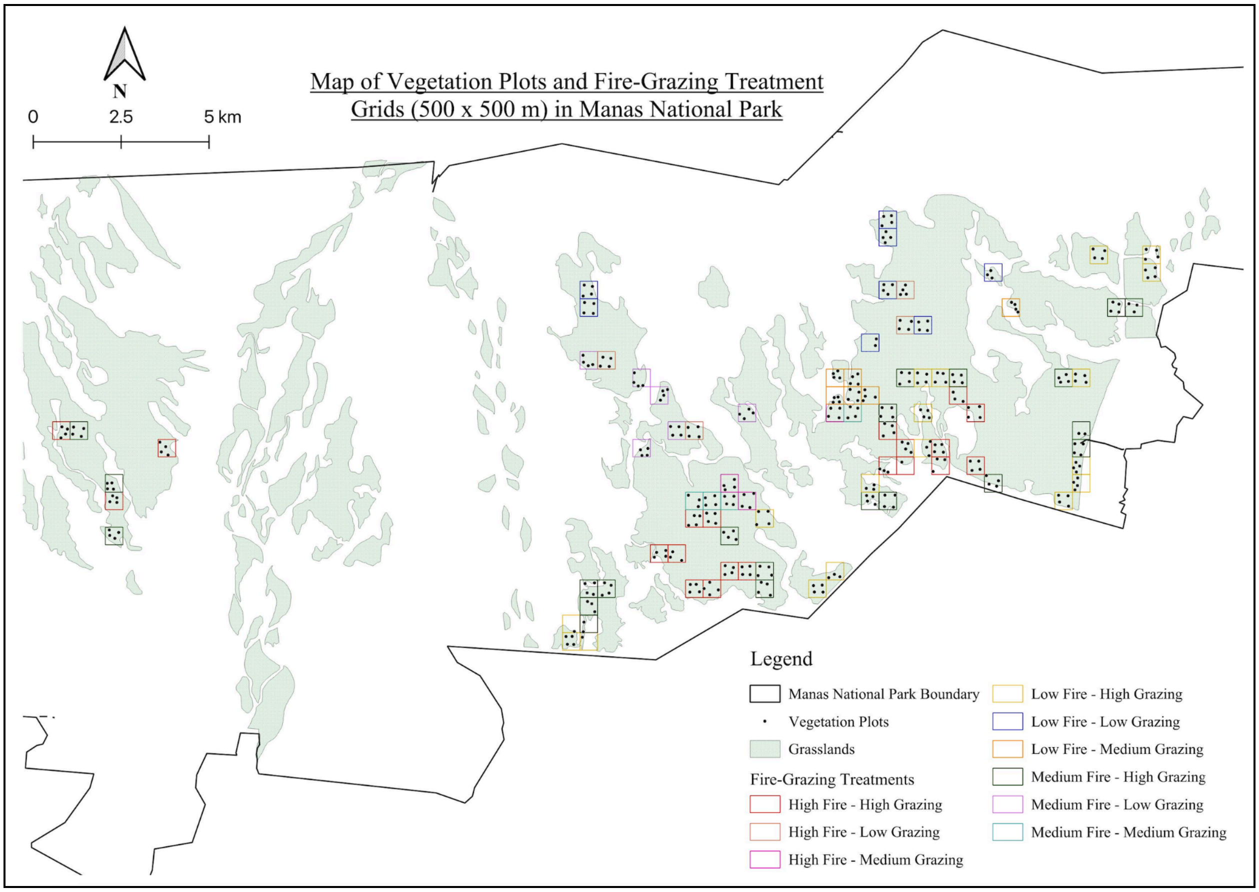

Fig 2. A map of the vegetation plots and fire-grazing condition grids (500 x 500 m) sampled in Manas National Park (2025)

Exploratory patterns of vegetation variables (density of trees, saplings, shrubs, herbs and grasses against their potential drivers (fire frequency, Climate Moisture Index (CMI) and distance to forest are presented in Figure 3.

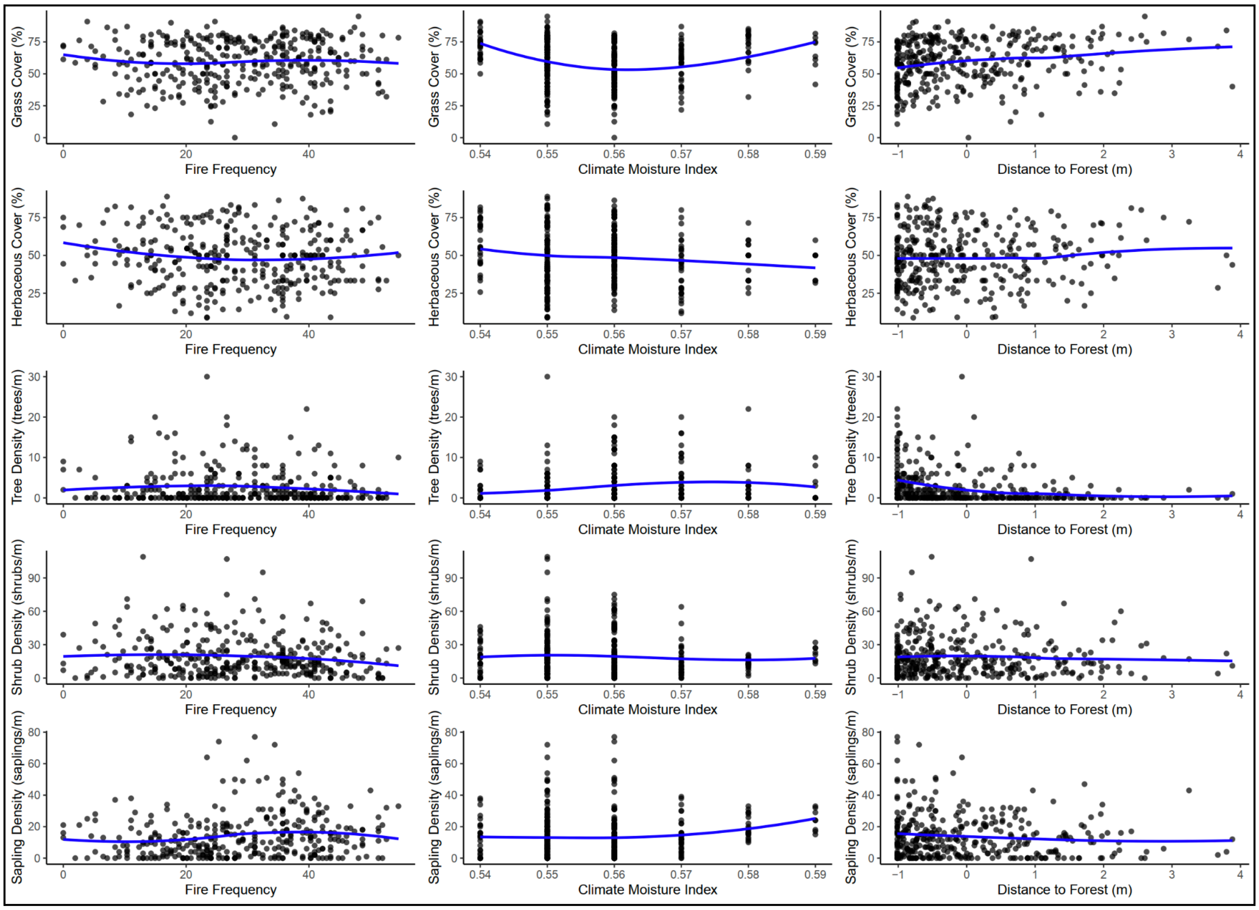

Fig 3. Panel of graphs depicting the exploratory patterns of vegetation variables (percentage cover of grass and herbs and density of trees, saplings and shrubs) against their potential drivers (fire frequency, Climate Moisture Index (CMI) and distance to forest (log transformed)).

3.1 Factors affecting vegetation structure

Among the potential drivers of vegetation structure, Climate Moisture Index (CMI), precipitation (Bio_12), Distance from human settlement (Dist_human) and Digital Elevation Model (DEM) were strongly correlated (>0.5, Table 3), of which, CMI was considered more ecologically meaningful (Gray et al. 2009) and retained in the full models.

Table 3: Correlation table between covariates used for LM

	df	**CMI**	**Bio_12**	**DEM**	**dist_human**	**dist_water**	**fire**	**road_dist**
df	1.00	-0.05	-0.02	0.02	-0.08	0.08	0.26	-0.07
CMI	-0.05	1.00	0.89	0.85	0.87	0.31	0.21	0.14
Bio_12	-0.02	0.89	1.00	0.98	0.78	0.27	0.26	0.14
DEM	0.02	0.85	0.98	1.00	0.74	0.26	0.24	0.16
dist_human	-0.08	0.87	0.78	0.74	1.00	0.34	0.06	0.11
dist_water	0.08	0.31	0.27	0.26	0.34	1.00	0.23	-0.13
fire	0.26	0.21	0.26	0.24	0.06	0.23	1.00	-0.17
road_dist	-0.07	0.14	0.14	0.16	0.11	-0.13	-0.17	1.00

The full model (GLM) included fire levels, grazing levels, CMI, distance to forest and distance to road. We examined the effects of these factors on tree density, sapling density, shrub density, herb cover and grass cover.

Model results showed that grazing and fire regimes have differential effects across vegetation strata. Medium fire frequency favoured tree and herb cover, while low fire favoured shrub density and herb cover and negatively impacted sapling density. Sapling density and grass cover were low under medium grazing intensity, whereas shrub density decreased but herb cover increased under low grazing. Interactive effects of fire and grazing, especially combinations of low fire and low grazing had a negative effect on herb cover. Other ecogeographical variables also played a crucial role in shaping the vegetation structure. Tree and sapling density decreased with distance from forest edges. The Climatic Moisture Index (CMI) had a weak positive effect on saplings and shrubs but negatively affected herbs (Table 4)

Linear Discriminant Analysis showed that low and high fire areas could be distinguished based on vegetation characteristics with 50.8% accuracy, but had considerable overlap with the intermediate fire frequency plots (Figure 4). Vegetation structure varied by fire intensity: medium fire supported the highest tree and sapling density, and herb cover, while low fire areas showed the highest density of shrubs and *Mikania micrantha*; high fire was associated with increasing grass cover and taller vegetation. Overall, fire intensity influenced both species composition and vertical vegetation structure, with medium fire supporting the most diverse and structurally complex habitats. Bare ground cover was highest under low fire. Lower vegetation layers (0–25 cm and 25–50 cm) had highest cover under low fire, while mid and upper layers (50–100 cm, 100–200 cm, and >200 cm) were highest under high fire.

Estimated Marginal Means plots showed that tree and sapling densities peaked under medium fire, while shrub densities and herb cover were highest in low fire, though herb trends were influenced by fire–grazing interactions. They also depicted saplings and grasses had highest densities under high grazing, while herbs peaked in low grazing. (Figs. 5-12)

Table 4: Effects (β estimate and SE) of potential variables (from the global models of each) on plant density in Bengal Florican habitat of Manas Tiger Reserve (2025)

	Tree Density	**Sapling Density**	**Shrub Density**	**Herb Cover**	**Grass Cover**
(Intercept)	0.52*** (0.11)	2.54*** (0.15)	2.58 (0.14) ***	35.95*** (3.48)	63.98*** (2.17)
Medium grazing	0.15 (0.11)	-0.34 * (0.15)	-0.01 (0.15)	7.96 . (4.67)	-7.61 *** (2.28)
Low grazing	0.24 (0.16)	-0.13 (0.22)	-0.52 * (0.21)	19.38 *** (5.82)	-1.97 (3.26)
Medium fire	0.25 * (0.11)	0.05 (0.15)	0.01 (0.15)	11.04 * (4.80)	-0.74 (2.29)

Low fire	0.14 (0.12)	-0.71 *** (0.16)	0.34 * (0.15)	12.51 ** (4.52)	-3.36 (2.34)
Medium fire X Medium graze	-	-	-	-9.328	-
Medium fire X Low graze	-	-	-	-18.46**	-
Low fire X Medium graze	-	-	-	-8.189	-
Low fire X Low graze	-	-	-	-21.06**	-
Distance to Forest	-0.282 ***(0.0472)	-0.156 *(0.065)	-0.0104 (0.0625)	0.959 (1.158)	3.729*** (0.956)
CMI	0.105 (0.067)	0.185* (0.092)	0.164 . (0.089)	-4.451** (1.694)	-0.991 (1.358)
Distance to Road	0.029 (0.046)	0.027 (0.062)	0.0193 (0.0604)	0.236 (1.145)	2.325** (0.924)
Adjusted R^2	0.1621	0.1123	0.02458	0.0241	0.0821
F-stat	10.54 on 7 and 338 DF	7.233 on 7 and 338 DF	2.242 on 7 and 338 DF	1.774 on 11 and 334 DF	5.408 on 7 and 338 DF

Legend: *** : p < 0.001 (Highly significant), ** : p < 0.01, * : p < 0.05, (no star) : p > 0.05 (Not significant)

Table 5: Group means of different vegetation densities and cover in different fire levels

Fire Level	**Tree Density**	**Shrub Density**	**Sapling Density**	**Grass Cover**	**Herb Cover**
Low	3.19	24.94	9.71	55.76	46.78
Medium	3.79	15.28	19.66	61.14	51.07
High	1.68	18.33	15.44	61.48	47.21

Table 6: Group means of invasive plants' densities and cover in different fire levels

Fire Level	***Leea Asiatica* density**	***Bombax Ceiba* density**	***Chromolaena Odorata* cover**	***Ageratum Conyzoides* cover**	***Mikania Micrantha* cover**
Low	6.59	0.78	8.49	8.37	23.07
Medium	17.21	1.45	12.68	7.26	16.22
High	12.39	0.99	7.53	3.98	7.13

Table 7: Group means of different vegetation species richness in different fire levels

Fire Level	Tree	Sapling	Shrub	Herbs	Grasses
Low	1.40	2.84	3.43	5.47	4.78
Medium	1.46	4.05	3.20	3.96	4.80
High	0.79	3.49	3.20	3.64	4.83

Table 8: Group means of different vegetation structure percentage cover in different fire levels

Fire Level	Bare Ground	0–25 cm	25–50 cm	50–100 cm	100–200 cm	>200 cm
Low	15.00	12.17	12.83	20.18	24.76	14.46
Medium	12.20	9.70	11.28	17.26	29.88	19.05
High	13.13	7.96	8.79	16.25	34.50	18.81

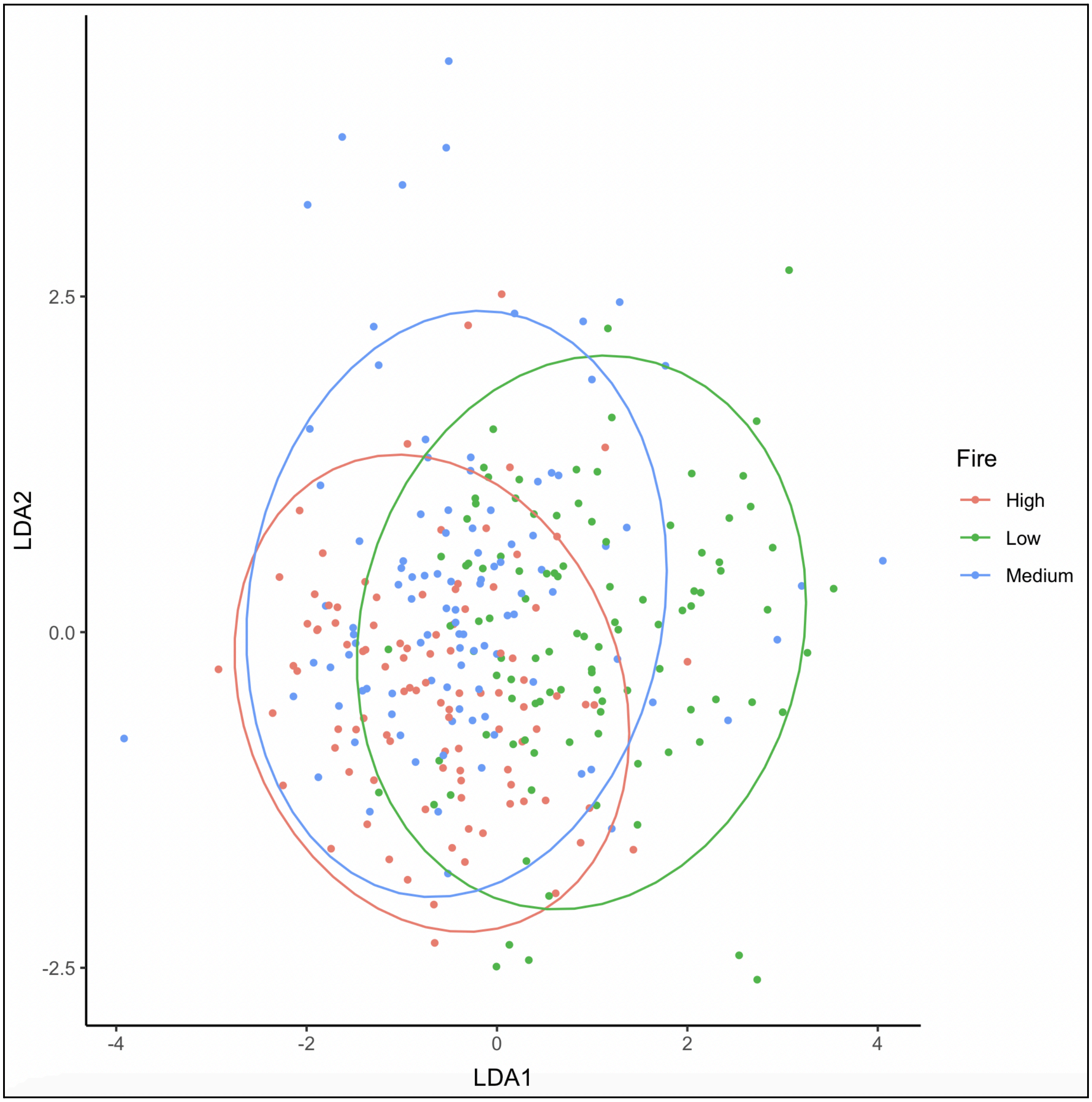

Fig 4. Linear Discriminant Analysis (LDA) plot showing separation of grassland sites under different fire regimes (High, Medium, Low) based on habitat variables. Ellipses represent 95% confidence intervals for each fire condition group, indicating partial overlap and suggesting moderate differentiation in habitat

structure influenced by fire intensity.

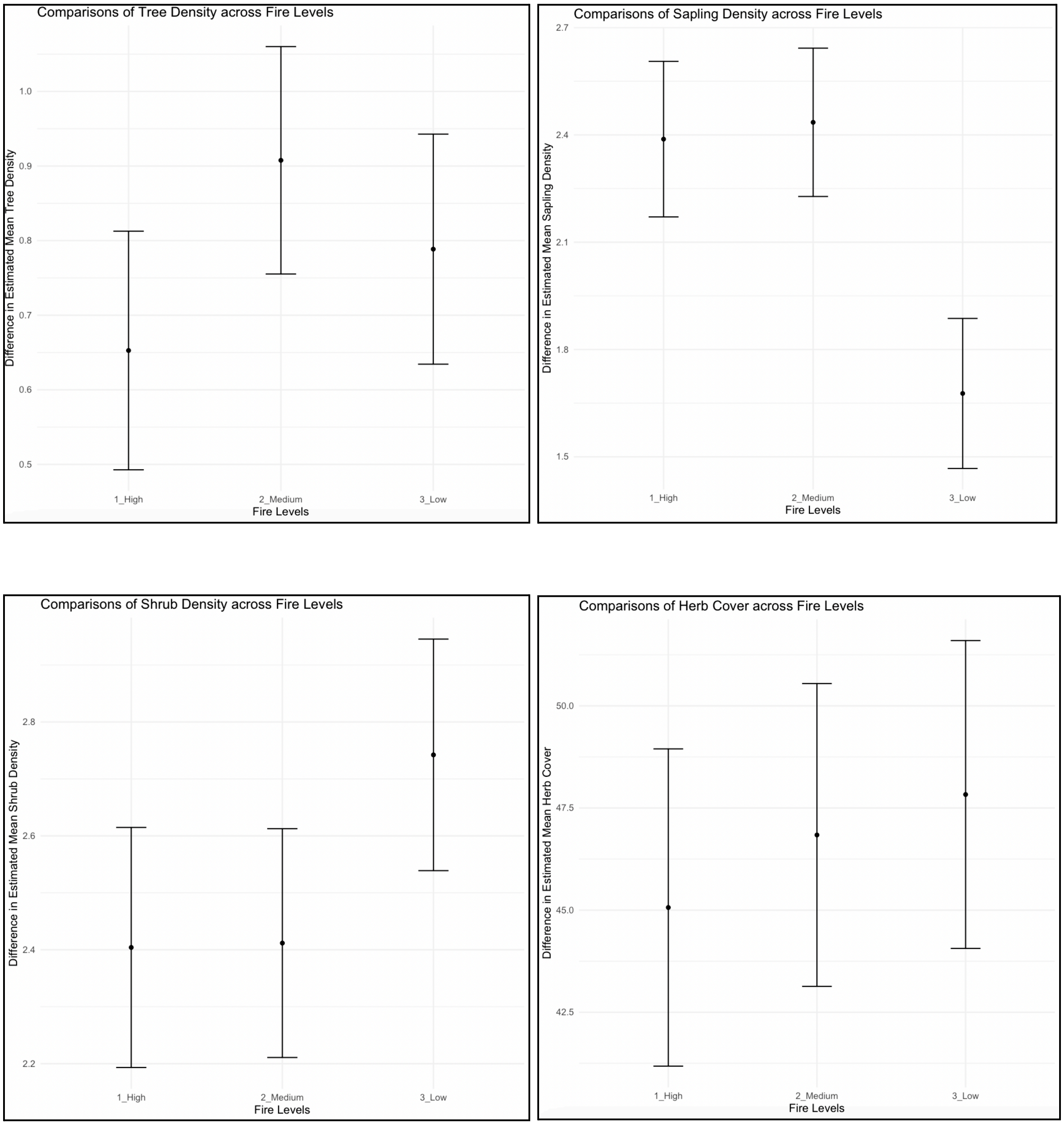

Fig 5,6,7,8: Estimated differences in vegetation structure (tree, sapling and shrub density, and herb cover) across fire regimes (High, Medium, Low) with SEs.

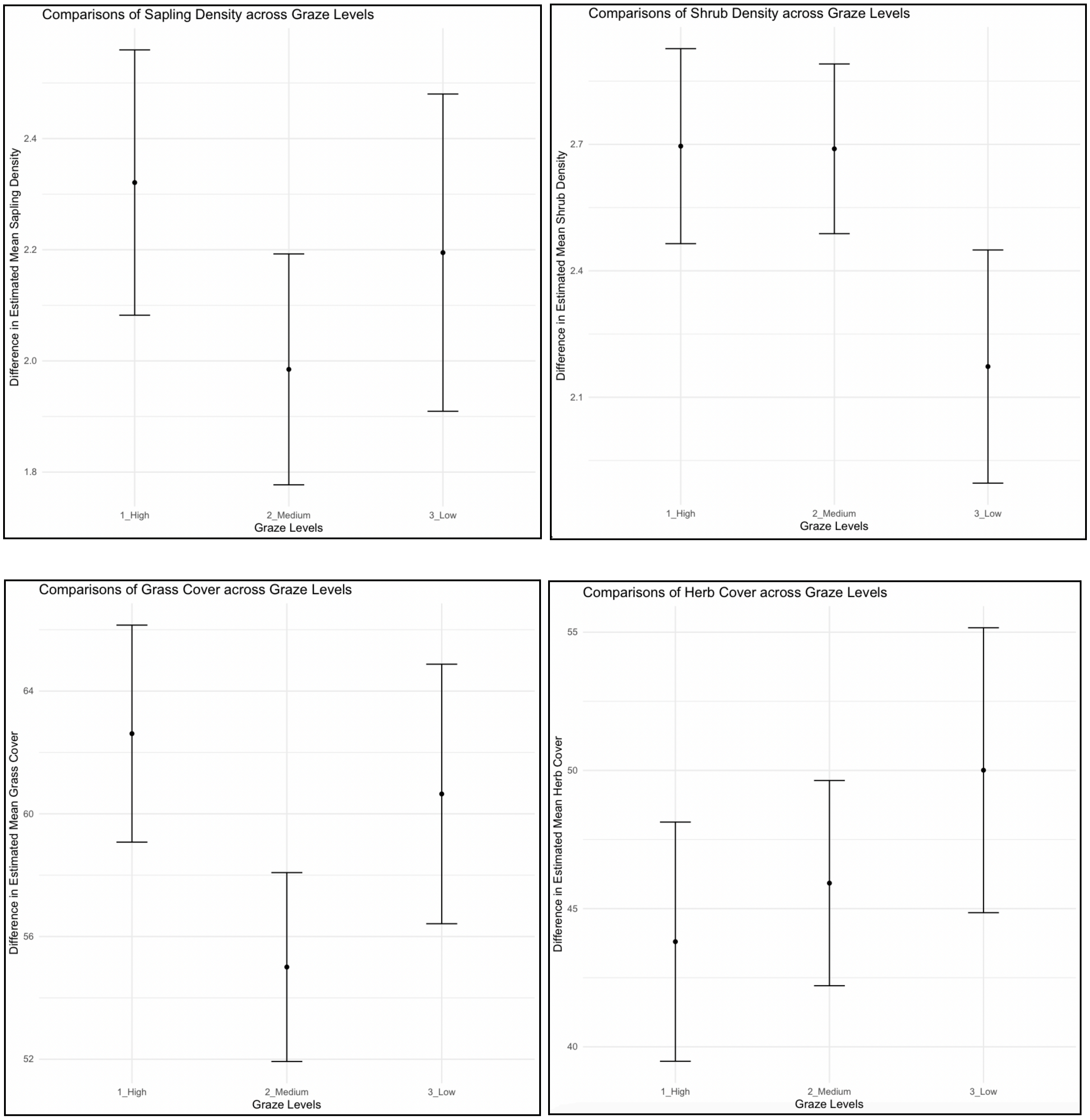

Fig 9, 10, 11, 12: Estimated differences in vegetation structure (tree, sapling and shrub density, and herb cover) across grazing regimes (High, Medium, Low) with SEs.

3.2 Factors affecting invasive plants

Invasive and native species showed varied responses to fire, grazing, and environmental factors. *Ageratum conyzoides* increased under low fire but declined with forest distance and CMI. *Chromolaena odorata* responded positively to medium fire and declined with forest distance. *Mikania micrantha* was more abundant under both fire levels and low grazing but declined with increasing distance from forest and CMI. *Bombax ceiba* declined with higher CMI, while Leea asiatica decreased under low fire and with distance from roads.

Estimated Marginal Means plots revealed among invasives, *Ageratum*, *Mikania*, and *Leea* were most abundant in low fire plots, while *Chromolaena* peaked in medium fire. Grazing significantly influenced only *Mikania*, which showed highest density under low grazing (Figs. 13-17).

Table 9: Effects (β estimate and SE) of potential variables on invasive plant density in Bengal Florican habitat of Manas Tiger Reserve (2025)

Predictors	***Ageratum conyzoides* density**	***Chromolaena odorata* density**	***Mikania micrantha* density**	***Bombax ceiba* density**	***Leea asiatica* density**
(Intercept)	11.51 (4.69)*	10.81 (5.39)*	22.94 (5.95)***	-6.43 (2.51)*	-0.61 (5.99)
Medium grazing	0.07 (0.16)	-0.11 (0.18)	0.25 (0.20)	0.16 (0.08).	0.36 (0.20).
Low grazing	0.16 (0.23)	0.014 (0.258)	0.949 (0.285)***	-0.211 (0.120).	-0.353 (0.287)
Medium fire	0.246 (0.158)	0.553 (0.181)**	0.563 (0.200)**	0.096 (0.084)	0.121 (0.201)
Low fire	0.421 (0.162)**	0.041 (0.186)	0.836 (0.205)***	-0.120 (0.086)	-0.662 (0.207)**
Distance to Forest	-0.355 (0.066)***	-0.339 (0.076)***	-0.451*** (0.084)	-0.034 (0.035)	-0.134 (0.084)
CMI	-0.197 (0.093)*	-0.177 (0.107).	-0.428 (0.118)***	0.137 (0.049)**	0.053 (0.119)
Distance to road	-0.092 (0.064)	-0.123 (0.073).	0.034 (0.081)	-0.039 (0.034)	-0.376 (0.082)***

Adjusted R^2	0.1328	0.1082	0.1979	0.05529	0.1248
F-stat	8.546 on 7 and 338 DF	6.98 on 7 and 338 DF	13.16 on 7 and 338 DF	3.884 on 7 and 338 DF	8.028 on 7 and 338 DF

Legend: *** : p < 0.001 (Highly significant), ** : p < 0.01, * : p < 0.05, (no star) : p > 0.05 (Not significant)

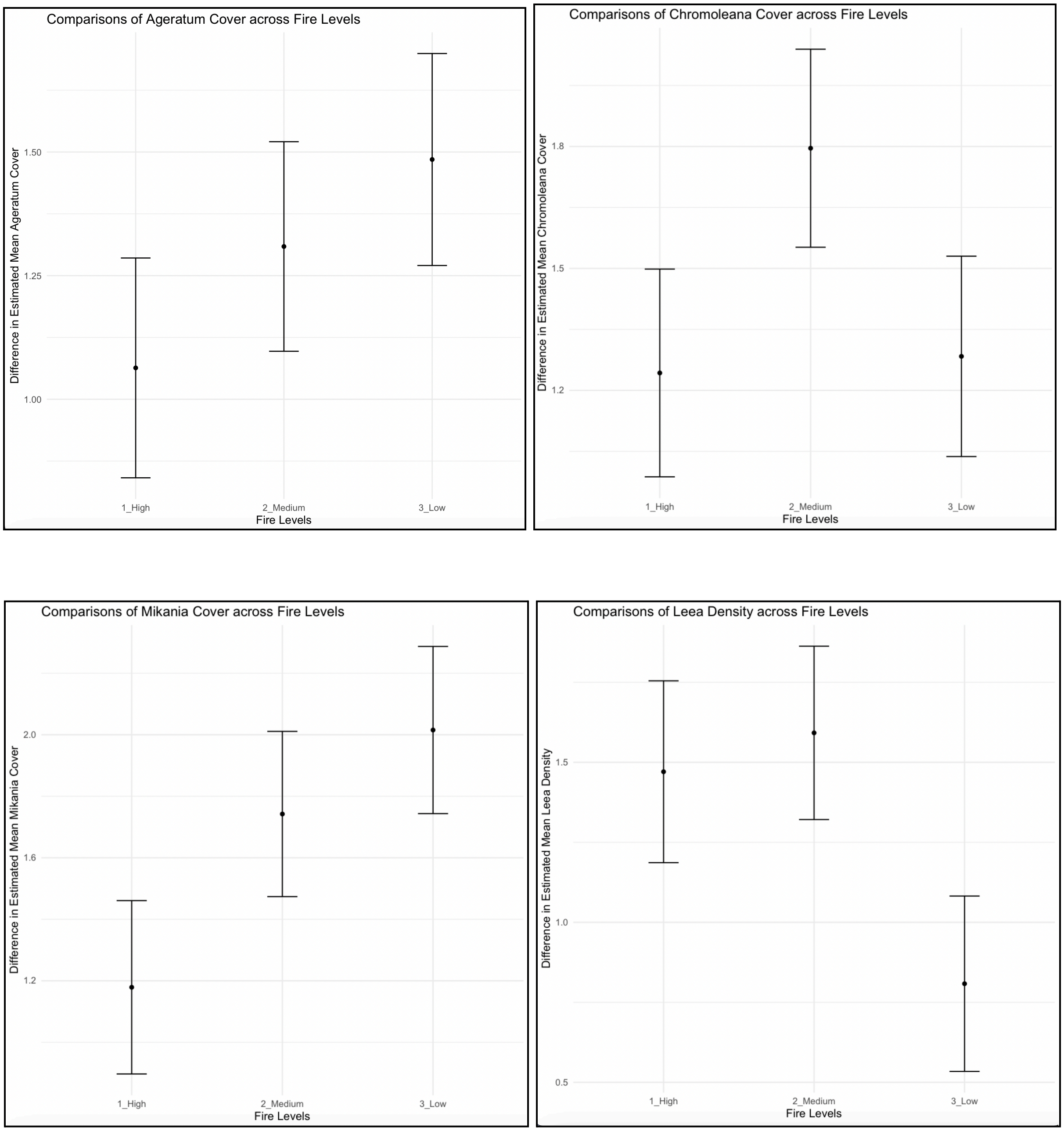

Fig 13,14,15,16: Estimated differences in invasive species cover (*Ageratum, Chromolaena, and Mikania*) across fire regimes (High, Medium, Low) with SEs.

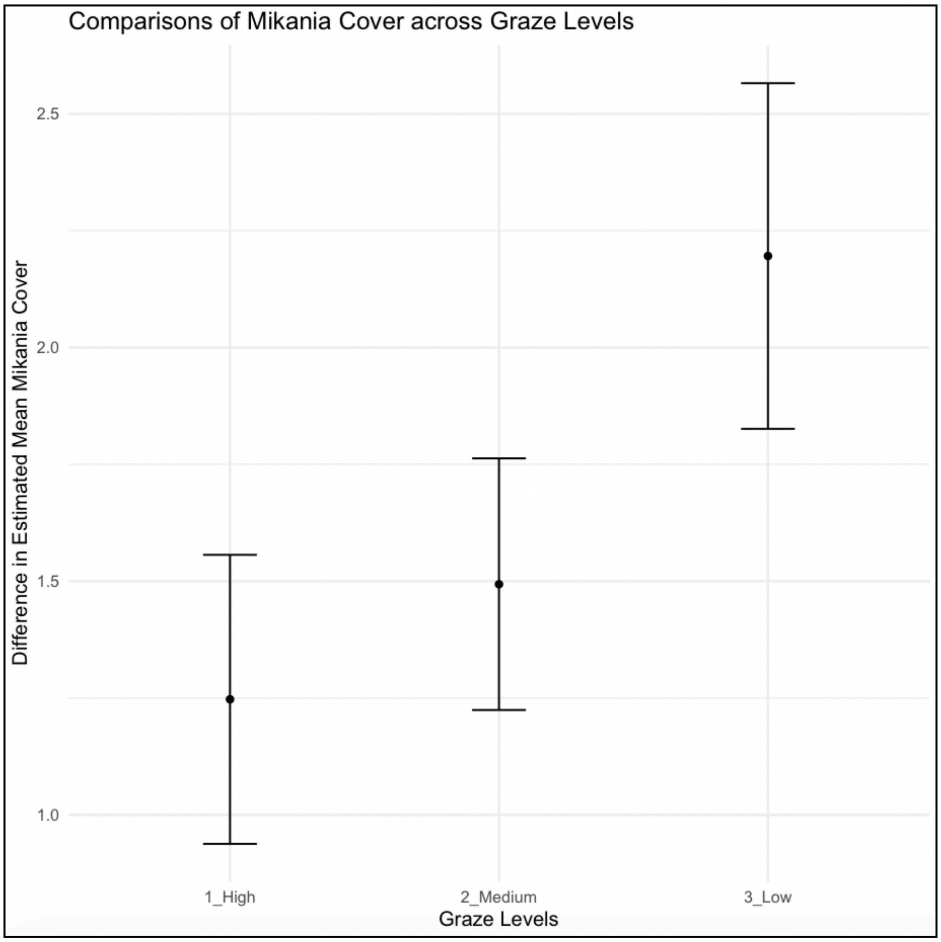

Fig 17: Estimated differences in invasive species cover (*Mikania*) across grazing regimes (High, Medium, Low) with SEs.

3.3 Indicator Species Analysis

Indicator Species Analysis across 346 vegetation plots covering three fire and three grazing levels as well as the nine fire-grazing condition combinations identified specific species associations between the fire and grazing regimes. Among these, only those having Indicator Values (IndVal) ≥ 0.4 were considered. In the trees, *Dillenia pentagyna* and *Lagerstroemia parviflora* were indicative of low grazing, while *Glochidion* sp. was weakly associated with high fire-high grazing conditions. Saplings such as *Grewia* sp. and *Syzygium operculatum* were linked to high and medium fire, respectively, whereas *Dillenia pentagyna* and *Bischofia javanica* were associated with moderate fire-grazing and low fire-low grazing combinations. Shrubs like *Plectranthus ternifolius*, *Olax nana*, and *Clerodendron serratum* were associated with high to medium fire plots. Among herbs, *Spilanthes* sp. and *Oxalis corniculata* showed weak to moderate associations with low and high fire levels, respectively, and *Lygodium flexuosum* linked to low grazing and high fire-low grazing combinations. Grass indicators included *Ophiuros exaltatus* and *Eragrostis* sp., which were moderately associated with medium to high fire regimes. *Cymbopogon flexuosus* exhibited a weak to moderate association under high and medium fire regimes and across varying grazing intensities. These results highlight distinct indicator species across vegetation strata, providing insights into the ecological responses of plant communities to varying fire and grazing pressures in grassland systems of Manas.

The legend for the below tables is as follows:

IndVal Range	Strength	Colour
0.37-0.45	Weak-Moderate	
0.45-0.6	Moderate	
>0.60	Strong	

G - Grazing; F - Fire; L - Low; M - Medium; H - High

Table 10: Indicator species analysis showing the association strength of tree, sapling, shrub, herb and grass species across combined fire and grazing regimes.

Category	**Species**	GL	GM	GH	FL	FM	FH	FL GL	FL GM	FL GH	FM GL	FM GM	FM GH	FH GL	FH GM	FH GH
Trees	*Dillenia pentagyna*															
	Lagerstroemia parviflora															
	Glochidion sp.															

Saplings	*Bischofia javanica*															
	Grewia sp.															
	Syzygium operculatum															
	Dillenia pentagyna															
Shrubs	*Plectranthus ternifolius*															
	Olax nana															
	Clerodendron serratum															
Herbs	*Spilanthes sp.*															
	Oxalis sp.															
	Lygodium flexuosum															
	Paederia foetida															

Grasses	*Ophiuros exaltatus*															
	Cymbopogon flexuosus															
	Eragrostis sp.															

Objective 2

3.4 Habitat selection of Bengal Florican

Macro- and micro-scale analyses of Bengal Florican breeding habitat selection revealed that site preference is influenced by a combination of environmental, ecological, and anthropogenic factors. At the macro-scale, Generalized Linear Models (binomial) using remotely sensed data found that breeding habitat selection was negatively influenced by tall grass cover (more than 60% percentage cover) and CMI, while higher fire frequency and greater distance from roads positively influenced selection (Table 11 and 12).

At the micro-scale, descriptive analysis across 203 plots (101 used, 102 unused) (Fig 18) showed that insect abundance and short vegetation cover were significantly higher in used sites (9.33±0.46 and 0.938±0.011 respectively) in comparison to unused sites (6.65±0.37 and 0.847±0.019, respectively) (Fig.

19). Generalized Linear Models (conditional logistic regression) to compare alternate hypotheses/candidate models explaining third order breeding habitat selection of Bengal Florican based on ground data collected in matched use/availability design found maximum support for the model with additive effects of a) percentage cover of tall (>2 m height) vegetation, b) vegetation PC2, which was positively associated with 25-50 cm sward height, c) insect abundances, and d) fire levels (Table 13). Model results showed that habitat selection was negatively influenced by tall vegetation, and was positively influenced by vegetation PC2 (25-50 cm vegetation), insect abundance, and high fire frequency (Table 14). An *emmeans* performed on the results to visualize the selection of different fire conditions showed that estimated mean for BF selection was highest in high fire conditions (0.72 ± 0.07), followed by low (0.46 ±0.06) and medium (0.35 ±0.08) fire conditions (Fig 20). Other variables such as the prevalence of invasive Leea asiatica showed no effect on habitat selection.

Further analysis using conditional logistic regression models revealed that within the park (115 plots), the probability of Florican territory selection was highest in high fire areas (0.225), but outside the park (Kokilabari Seed farm, Agrang and Betbari–88 plots), low fire areas had the highest selection probability (0.231) (Fig. 21)

These results showed that male-florican prefer structurally open habitats with moderate grass (25-50cm) height, high insect availability, frequent fire, and less tall vegetation.

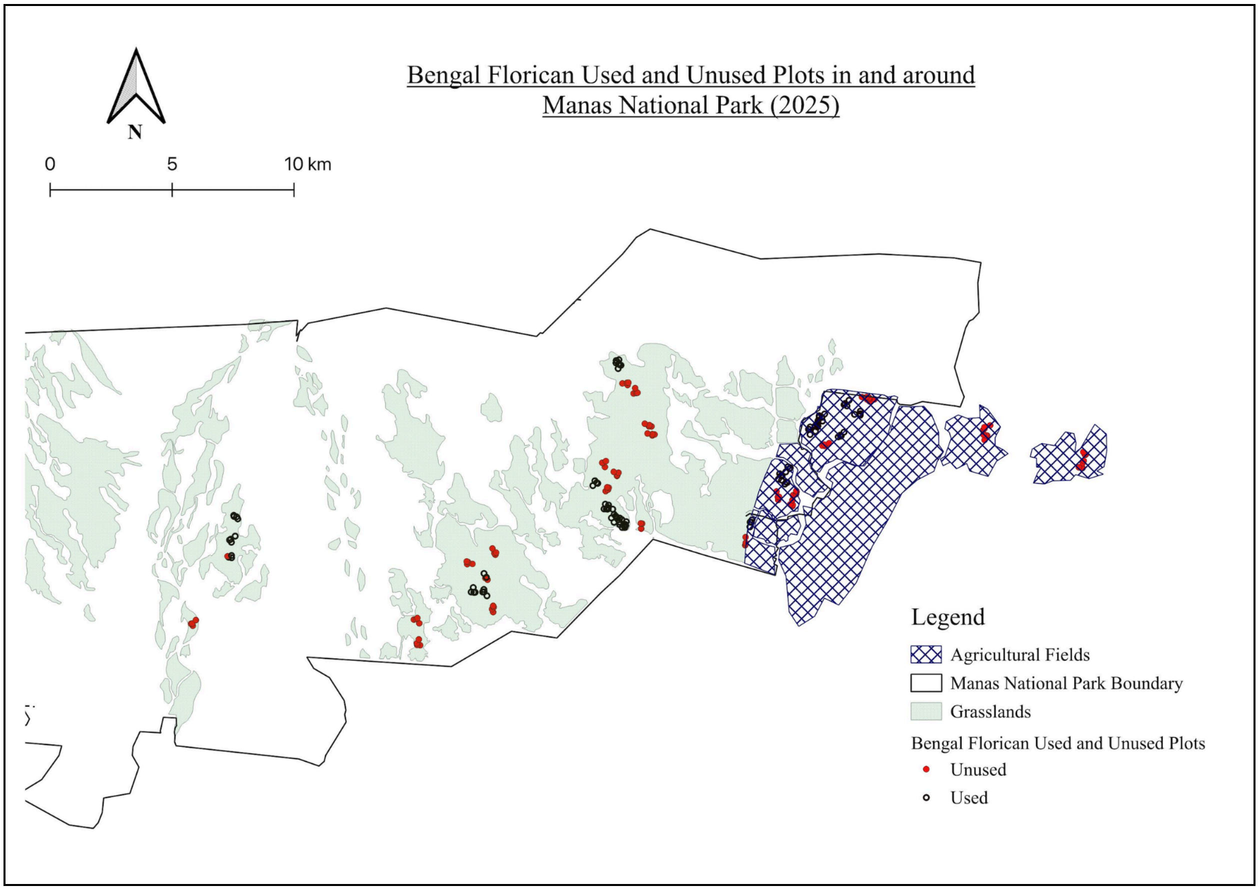

Fig 18. Map of Bengal Florican Used and Unused plots that were sampled in and around Manas National park (2025)

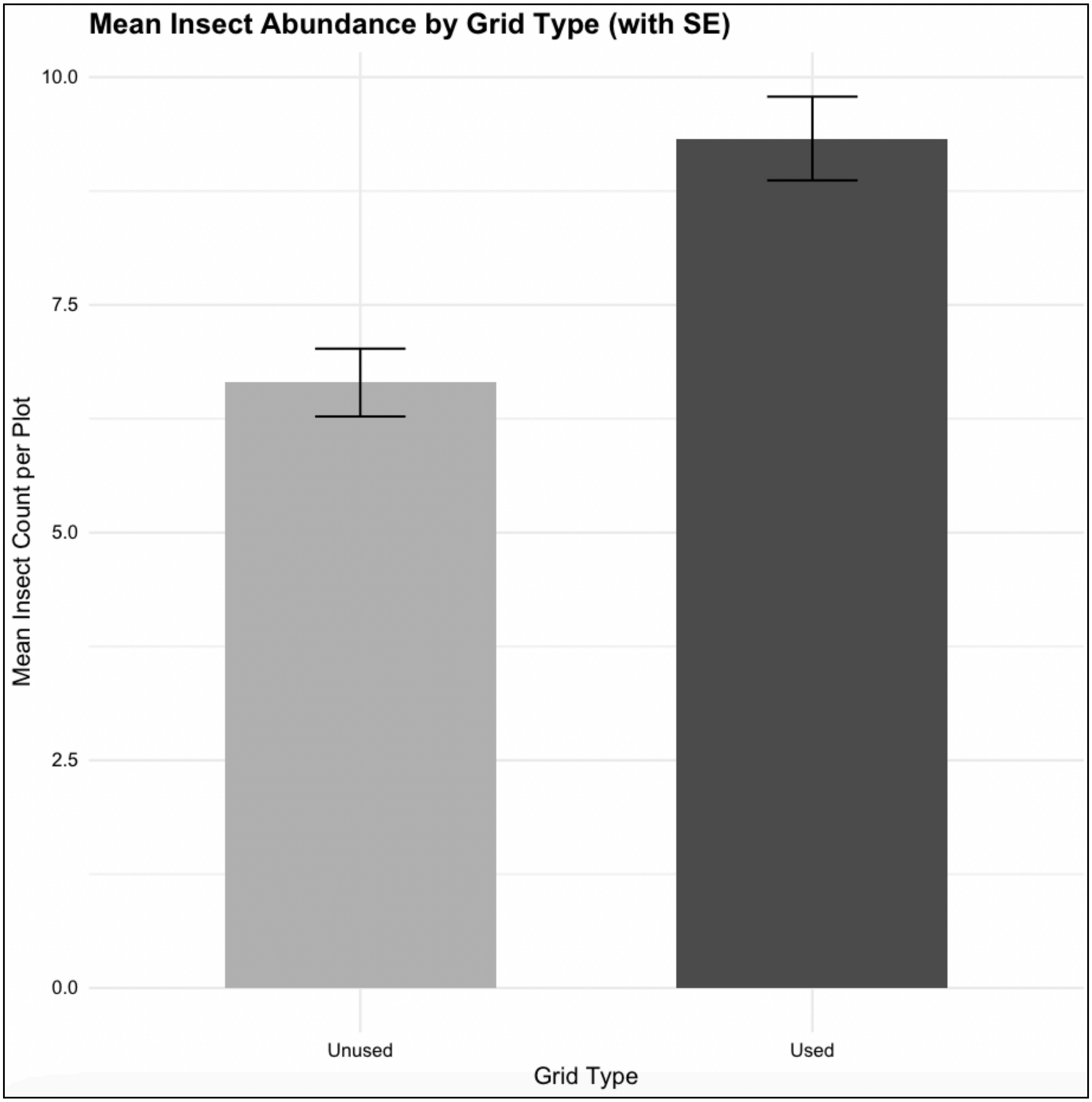

Figure 19: Mean insect abundance (± SE) per plot across grid types

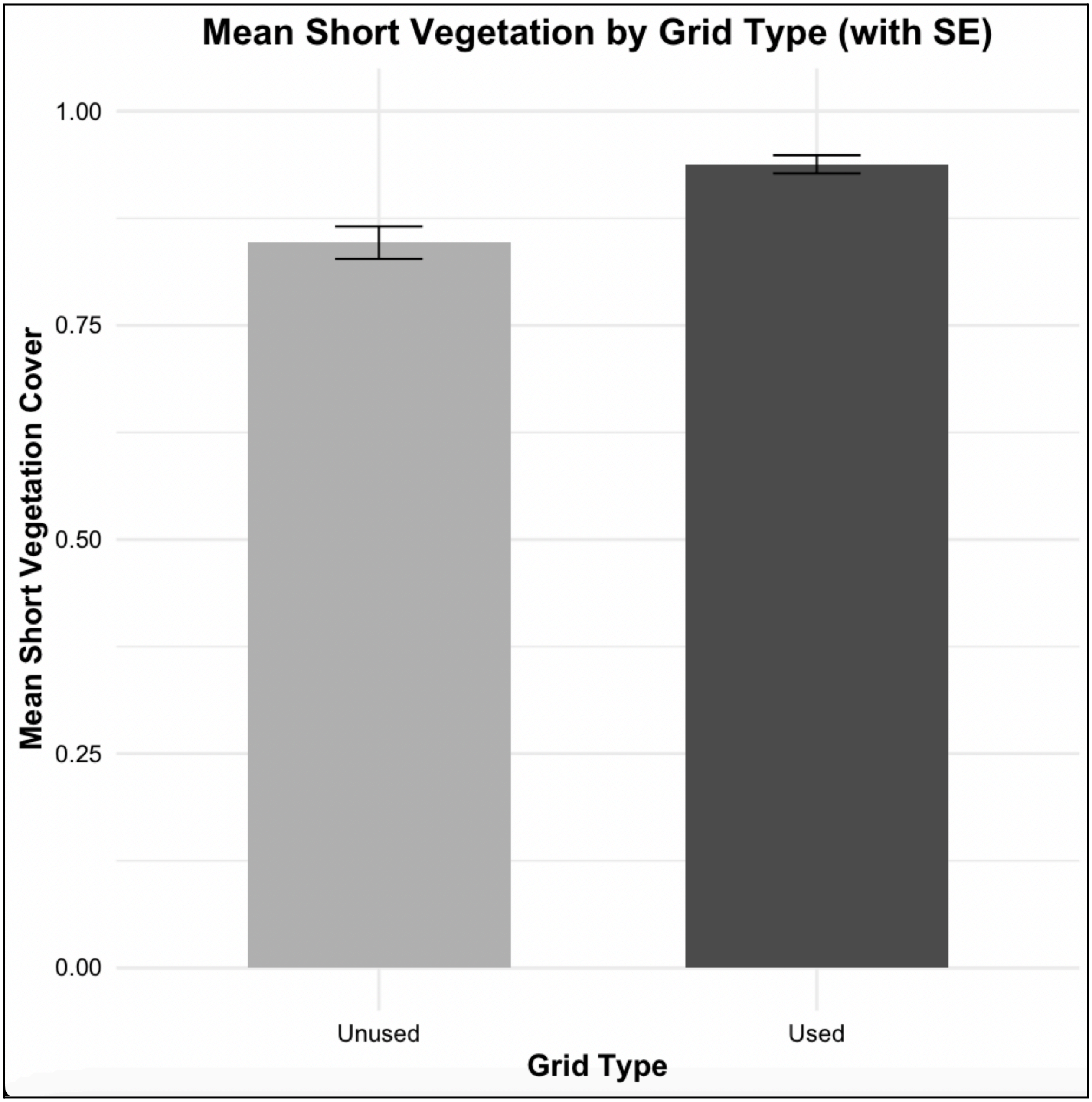

Figure 20: Mean short vegetation cover (± SE) in unused versus used grid types.

Table 11: Comparison of model statistics explaining breeding habitat selection of Bengal Florican based on remotely sensed data in Manas Tiger Reserve during 2025.

Model Formula	df	logLik	AICc	delta	weight
bf ~ grass + CMI + fire + dis_road	**5**	**-127.341**	**264.9**	**0.00**	**0.554**
bf ~ grass + CMI + fire + dis_road + dis_water (Global model)	6	-127.316	266.9	2.03	0.201
bf ~ grass + CMI + fire	4	-131.564	271.3	6.38	0.023
bf ~ grass	2	-134.177	272.4	7.51	0.013
bf ~ grass + CMI + fire + dis_water	5	-131.516	273.2	8.35	0.009
bf ~ CMI	2	-171.872	347.8	82.90	0.000
bf ~ fire + I(fire^2)	3	-184.817	375.7	110.83	0.000
bf ~ dis_water	2	-187.943	379.9	115.04	0.000
bf ~ 1 (NULL model)	1	-189.984	382.0	117.09	0.000

bf ~ dis_road	2	-189.873	383.8	118.90	0.000
bf ~ fire	2	-189.907	383.9	118.97	0.000

Table 12: Effects (coefficients from the least AIC model) of remotely sensed variables on breeding habitat selection of Bengal Florican in Manas Tiger Reserve (2025)

Predictor	**Estimate**	**Std. Error**	**z value**
(Intercept)	0.247	0.198	1.249
Tall grass	-3.099	0.444	-6.979
CMI	-0.665	0.251	-2.645
Fire	0.518	0.188	2.753
Distance to Road	0.547	0.189	2.888

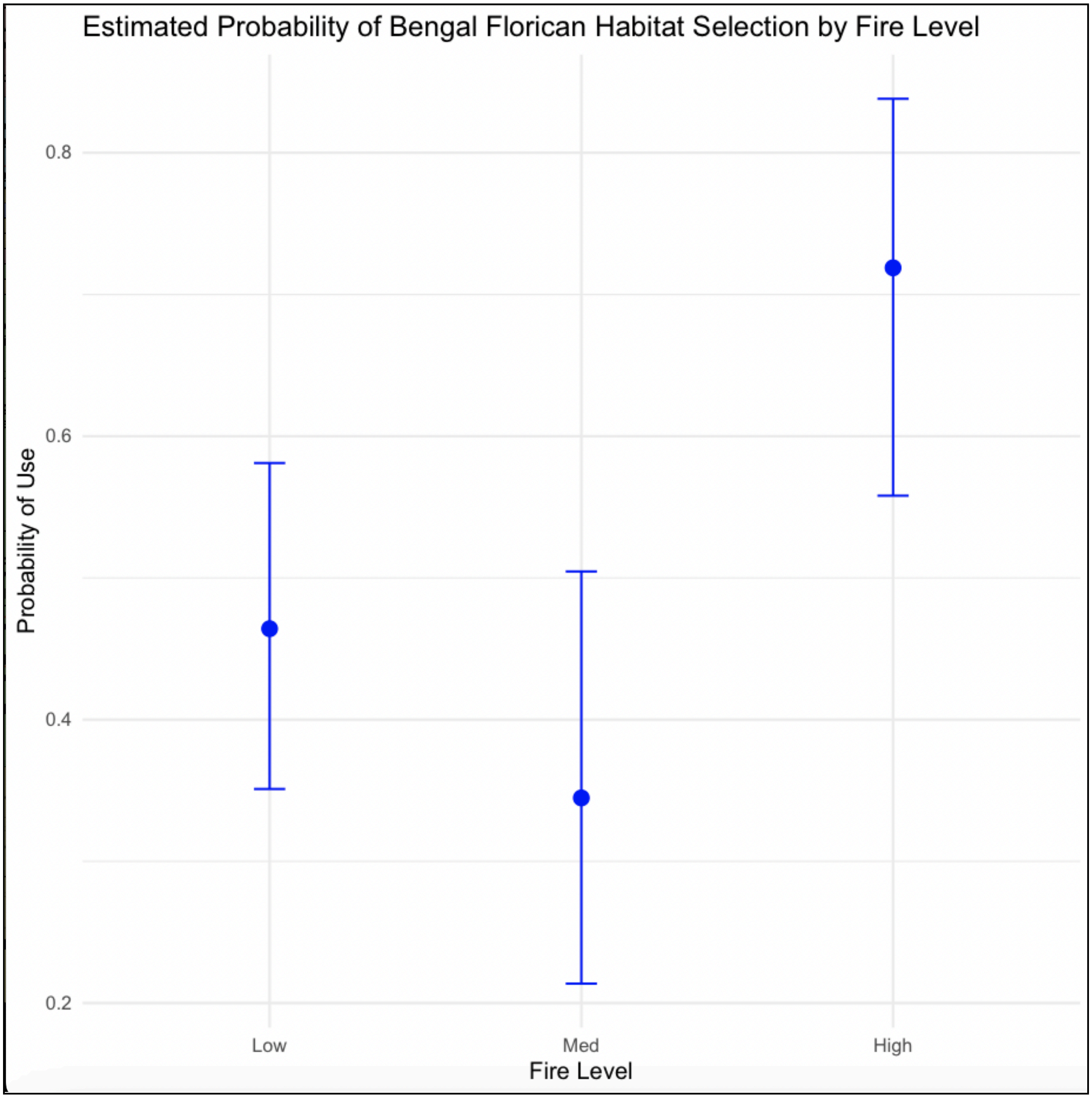

Fig 21: Estimated probabilities of Bengal Florican habitat selection across three fire levels (Low, Medium, High), based on GLM marginal means ± SE

Table 13: Comparison of model statistics explaining breeding habitat selection of Bengal Florican based on field data in Manas Tiger Reserve during 2025.

Formula	df	logLik	AICc	Δ (delta)	Weight
y ~ tall + pc2 + vegstrdiv + insect_no + fire + grz	**9**	**-108.828**	**236.6**	**0.00**	**0.391**
y ~ tall + pc2 + insect_no + fire	6	-112.490	237.4	0.82	0.259
y ~ tall + pc2 + vegstrdiv + insect_no + leaa + fire	8	-111.027	238.8	2.21	0.130
y ~ tall + vegstrdiv + pc1 + pc2 + insect_no + leaa + fire + grz (Global model)	11	-107.714	238.8	2.22	0.129
y ~ tall + pc2 + vegstrdiv + insect_no + fire	7	-112.455	239.5	2.90	0.092
y ~ tall + pc1 + pc2 + vegstrdiv	5	-122.266	254.8	18.25	0.000
y ~ tall + pc2	3	-124.470	255.1	18.47	0.000
y ~ tall + pc2 + vegstrdiv	4	-124.095	256.4	19.80	0.000
y ~ fire + grz	5	-127.405	265.1	28.53	0.000

y ~ insect_no	2	-130.795	265.6	29.06	0.000
y ~ tall	2	-131.694	267.4	30.86	0.000
y ~ insect_no + leaa	3	-130.702	267.5	30.94	0.000
y ~ fire	3	-132.727	271.6	34.99	0.000
y ~ 1 (NULL model)	1	-140.706	283.4	46.84	0.000

Table 14: Summary of the best GLM estimates predicting y to understand the effect that various variables have on the selection of breeding habitat by male Bengal Florican on a micro scale.

Predictor	**Estimate**	**Std. Error**	**z value**
(Intercept)	0.36	0.52	0.7
tall	-4.06	1.38	-2.95
pc2	0.39	0.17	2.31
insect_no	0.13	0.04	3
fireLow	-1.08	0.45	-2.4
fireMed	-1.58	0.49	-3.25

4. DISCUSSION

Fire and grazing shaped vegetation across grassland plots, with medium fire promoting higher tree and sapling density, and greater herb cover, as well as taller vegetation, hence supporting structurally complex habitats. In contrast, low fire increased shrub cover and bare ground, while grazing effects varied, with low grazing enhancing herb cover but reducing shrubs. These patterns were further influenced by proximity to forests and environmental gradients, highlighting the interactive role of fire, grazing, and landscape context in determining vegetation structure.

These shifts in habitat structure directly influenced Bengal Florican habitat selection. Floricans preferred open grasslands maintained by frequent fire, with abundant insects and short vegetation cover, while avoiding sites with tall vegetation and wetter conditions. Within protected areas, selection peaked in high fire zones, whereas outside, low fire areas were more frequently used. Together, the results underscore the importance of various practices like burning in maintaining the vegetation structure and resource conditions critical for Bengal Florican breeding habitat.

4.1 Effect of fire and grazing on plant composition and invasives

From a conservation management perspective, it is crucial to determine which fire frequency or cattle grazing intensity is most conducive to maintaining ecological balance, particularly in ecosystems such as grasslands where disturbances are both natural as well as anthropogenically induced and necessary.

4.1.1 Effect of fire and grazing on invasives

The results of the study showed varying effects of fire and grazing regimes on different invasive plants that were studied; Low grazing intensity, particularly in the northernmost parts of the grassland, appears to favour the spread of *Mikania*. These areas tend to be more moist, creating optimal conditions for *Mikania* to establish and proliferate; but with relation to its fire condition preferences, it seems to thrive in areas which are drier. (Nath et al. 2019). In contrast, *Chromolaena* showed the highest density under high grazing pressure. This pattern may be attributed to the physical impact of grazing, which compacts and hardens the soil surface. Such conditions can suppress native vegetation and disturb the ground layer, creating ecological niches that *Chromolaena* can exploit more effectively than other invasive species ((Joshi et al. 2006, Nath et al. 2019,). Other invasive species did not show any preferential response to particular grazing levels. Regarding fire regimes, both *Mikania* and *Chromolaena* seemed to be favoured by medium fire frequency, with the former also thriving in low fire regime, although the possible reasons for this are less understood. Limited evidence suggests that high levels of fire could be detrimental to *Chromoleana* (Williams et al. 2004), but a more robust look into the effect that different fire intensities have on the spread of invasive species like *Chromoleana* is required. In a dynamic system such as grasslands, it becomes important to look at the combined effects of different factors; as such, only fire and grazing levels may not realistically explain the effects on plant and invasive communities.

Leea asiatica is a woody encroacher that seems to be fire resistant, as its density is correlated with the fire frequency. The evidence also indicates a tendency to flourish near roads, potentially linked to its seed dispersal mechanism involving mammals (Suárez-Esteban et al. 2013). Whereas, *Bombax* shows higher density in areas with higher moisture level, though evidence suggests that they can flourish in both dry as well as moist conditions (Hossain et al. 2025).

It is important to note that coupled with the fact that invasive species occur more frequently near forest edges and contribute to succession, invasives have spread significantly throughout the park (Nath et al. 2019) and pinpointing whether one or two factors have a significant effect on it becomes complex with only one season's data.

An indicator species analysis showed that no invasive plant indicated any particular fire or grazing condition, which is in line with the data from previous years showing an indiscriminate spread of invasives across fire and grazing regimes throughout the park. This finding mirrors broader observations across the park, where invasives show an indiscriminate spread across condition types, likely influenced by edge effects and landscape connectivity (Vila et al. 2011, Wilkerson et al. 2013).

The complexity of these interactions makes the importance of regular monitoring of invasives important, especially near forest edges and roads. Although fire may play a role in the control of invasives, more long term studies that are invasive species specific are required to fully understand the interactions. It can be helpful if invasive removal interventions start from grasslands that are adjacent to forest patches as they are most susceptible to invasive-induced succession.

4.1.2 Effect of fire and grazing on trees, saplings, shrubs, herbs and grasses

Vegetation tends to have different needs and requirements at different stages of their growth and development, as well as different kinds of vegetation will have varied preferences of environmental and habitat characteristics (Spasojevic et al. 2014). My results showed that vegetation responses to fire and grazing also varied by growth form and life stage.

Tree density is the highest in areas that have an intermediate level of fires suggesting that a certain level of fire can promote tree establishment and persistence, maybe by reduced competition (Donaldson et al. 2022). Intuitively, tree density decreases with an increase in distance from forest edges in line with seed dispersal and increased regeneration rates near forest sources (Miao et al. 2018). Grazing had no significant effect on trees implying a resilience to grazing.

My data indicates that fire frequency favours saplings and suppresses shrubs, revealing differential response and/or competition between these layers, although this may vary with species of shrubs and saplings (Duncan et al. 2003, Baraza et al. 2006). The sapling layer was dominated by xyz species that are fire resistant. Interestingly, distance from forest patches has a negative effect on saplings but no effect on shrubs, potentially indicating that other factors like fire and moisture have stronger effects on shrub density than proximity to the forest.

Herb cover was favoured in areas with low grazing, medium and low fire conditions individually, but combinations of conditions of low and medium fire and grazing had a negative effect on herb cover which can be tied to successional strategies. Herbs are ruderals that prefer to establish themselves in areas that have low competition (Menges et al. 1983), but are influenced by complex synergistic effects of fire as well as grazing that are worth exploring in the context of moisture and light as a factor as well.

Grass cover was highest in mediumly grazed areas, suggesting that an intermediate amount of disturbance can facilitate an increase in abundance of grasses (Fensham et al. 1999), as grasses are most susceptible to herbivory as well as trampling. Fire had no significant effect on grass cover, which could depict resilience against different fire frequencies over the years as well as efficient post-fire recovery. Another interesting effect that was observed was the increase in grass cover with an increase in distance to forest, which could indicate the need for openness (Lyons‐Galante et al. 2017).

When it comes to understanding how different fire and grazing conditions affect the overall densities of plant communities in an area, taking into account the complex interplay of several variables becomes important to be able to grapple with ever-changing grassland dynamics. Using an LDA to do so allows for a reduction in the dimensions of the data, allowing for a better understanding of the forces at play to ultimately allow better grassland management policies that are more inclusive. The LDA that was performed on the plant community structure shows that there is a difference in the low, medium and high fire structures, especially between low and high fires. This shows that fire does have an influence on the vegetation, but not so distinctly as to create independent clusters.

4.1.3 Effect of fire and grazing on specific species of vegetation

Considering that an ISA allows for the detection of species that are not only abundant but also have a fidelity to certain conditions, making these species good indicators of a particular ecological condition. It also allows for a more specific, community level clarification of the responses to the conditions and other variables.

Tree species like *Dillenia pentagyna* were significantly associated with low grazing conditions, showing a particularly strong association, regardless of the fire regimes. This implies that *Dillenia pentagyn*a potentially has a greater competitive advantage in areas with lower grazing pressure, which may possibly allow for greater regeneration or less browsing damage, though not much is known about this. *Glochidion* sp. is another woody species that has a moderate association with conditions that have both high fire and grazing, suggesting that it is a hardy species that is resilient and can outcompete other plants in the face of harsh competition (Chheang et. al 2021).

Exploring the different saplings that act as indicators can provide an interesting insight into regeneration ecology of woody plants in grasslands; Species like *Dillenia pentagyna* in the sapling stage seem to persist best under moderate combinations of both fire and grazing, suggesting a balanced disturbance regime supports its regeneration, in comparison to its adult counterpart. This could be due to the high carbon and nitrogen content of *Dillenia pentagyna* leaves, which can be a trait that is adaptation to herbivory pressure (Cera et al. 2022, Arunachalum et al. 2002) This may also be because of the difference in requirements of saplings and trees; moderate fire may allow for the creation of establishment gaps, while low-to-moderate grazing could reduce competition from other saplings (LaMalfa et al. 2021). Certain species like *Grewia sapida* show a strong affinity to conditions that have medium and high fires, as well as moderate grazing that can be explained by its "fire-loving" nature. Different species of *Grewia* are fire-adapted colonizers that have a high resilience to fire and are not perturbed by moderate disturbances like grazing (Tews and Jeltsch 2004).

The ISA on shrubs showed *Plectranthus ternifolius, Olax nana* and *Clerodendron serratum* all had moderate associations to areas that had medium to high fire frequency, indicating that they are all resilient when it comes to fire-based disturbances. *Clerodendron serratum* also emerges as an indicator species under low grazing conditions, implying that although it can persist through fire, it may be sensitive to grazing, likely due to the latter limiting its regeneration capacity, though the specific reasons are not clear.

Herbaceous plants tend to be ruderal and stress-resistant, and one of the first colonizers during succession, and hence tend to prefer more open areas to grow (Grime 1977). Herbs like Spilanthes sp. act as moderate indicators for low fire conditions, and are unperturbed by grazing pressures which indicates that it may be sensitive to frequent fires but grazing does not act as a key limiting factor, although not much information is available about this aspect. *Oxalis* sp., on the other hand, acts as a moderate indicator for intermediate and high fire regimes, indicating that they likely colonise the area quickly and may have high stress tolerance that allows them to do so (Rashid et al. 2020). Other species like *Lygodium sp.* show a moderate association with low grazing regimes, as well as moderate and high fire conditions, which could imply that a low grazing pressure coupled with a moderate amount of fire disturbances over the years, allows the species to establish and spread, particularly in moist or semi-shaded microhabitats which are generally their preferred habitats. They also occur frequently among trees and shrubs in disturbed environments that is in line with their frequency in conditions with intermediate to high fire frequency conditions (Wang et al. 2022).

When it comes to grasses as indicators for different fire and grazing regimes, grasses like *Ophiuros exaltatus* and *Cymbopogon flexuosus* show a moderate association with intermediate and high fire regimes. Although generally the former is not considered a fire-resistant species, the presence of it in these fire regimes could suggest an increased adaptation to regular fire cycles that needs to be further researched. Similarly, for *Cymbopogon flexuosus,* the association with medium and high fire frequency conditions is most likely due to the fire-tolerant nature of the grasses (Soman et al. 2023).

Ultimately, while the roles of fire and grazing in shaping plant communities become increasingly clear, especially for native species, their impact on invasives remains complex and context-dependent. For robust habitat management and conservation, it is important and recommended that prioritizing multi-season and multi-factor analyses must be carried out to fully capture the interplay between disturbances and vegetation dynamics.

4.2 Habitat selection of Bengal Florican for breeding

It is crucial to understand which fire frequency best supports ecosystem function while minimizing adverse outcomes. This holds especially true in grasslands that host critically endangered species such as the Bengal Florican. Determining an optimal fire regime is not straightforward, as my findings reveal that fire and grazing exert a limited but ecologically meaningful and often species-specific effects on different components of the vegetation community. These effects, in turn, can influence the habitat suitability for species like the Bengal Florican, which rely on specific grassland conditions for breeding.

The results from studying the habitat characteristics of the Bengal florican to understand its selection of territories for breeding display provided several different insights that can ultimately help in prescribing more inclusive management practices. A simple analysis of the mean insect abundance between used and unused plots of the Bengal Florican display territories showed that the mean number of insects was almost

40% more in the Bengal Floricans territories. Insects are important to quantify when it comes to understanding habitat selection by the Bengal Floricans because they can be considered a proxy for food resource abundance during the breeding season. This is because the insects constitute a critical food resource for many grassland birds, especially during nesting and chick-rearing, where protein requirements are elevated (Wilson et al. 1999, McCracken et al. 2004, Goebel et al. 2024). Therefore, areas with higher insect density likely provide superior foraging opportunities and may enhance reproductive success and chick survival, influencing habitat selection (Wilson et al. 1999, Mwansat et al. 2015). However, one of the limitations of the study was the inability to obtain data on the insect communities beyond order level classification. Family or genus level identification would have provided a much more in-depth outlook on how insect composition may play a role in habitat selection. Therefore, from these results, it can be considered a significant aspect of habitat selection by the Bengal Floricans that is worth exploring in more detail to further the understanding of the ecology of the species. This, in turn, will enable the management of other potential habitats in a way that supports both the conservation of the species and the maintenance of grassland habitat diversity.

The habitat selection was analyzed on a micro as well as a macro scale, and this is significant as the former is important to prescribe specific strategies when it comes to conservation and management practices on the local scale, while the latter can help in building prediction maps to identify and highlight areas of conservation importance for the species. The results of micro scale analysis (GLM and CLR) both fundamentally perform find the probability of selection of a habitat, but differ in the grouping of sites; the latter allows for a more in-depth look at the selection of territories in particular sites while the former provides a more general outlook. Including both in my study allows for a more robust perspective and hence interpretation to ultimately allow for realistic conservation and management strategies.

My study found that areas with tall vegetation structures were strongly selected against, and a preference for vegetation structures between 25-50 cm was determined, both aligning with the well-known preference of Bengal Floricans, for more open grasslands, which may facilitate an increased mate visibility and probability of being seen by a potential female during display (Munjpara et al. 2013, Dutta et al.). As expected, insect abundance also had a positive effect. CMI seems to have a negative effect on site selection, which implies that the BFs prefer drier grasslands; this could be the case as historically they are known to thrive in *Imperata cylindrica* dominated grasslands that are comparatively drier grasses (Narayan 1990, Li et al. 2020).

To understand the effects of fire, it's essential to consider how fire may influence the other covariates and underlying ecological processes; fire plays a major role in maintaining the open structure of grasslands and stimulating new plant growth, which in turn supports higher insect abundance (Silva et al. 2020, Da Silva et al. 2021, Gordijn et al. 2021). BFs seem to select high fire conditions most and low fire conditions comparatively less inside the park, but select low fire conditions outside; this has interesting implications when it comes to fire management. One of the reasons that they select low fire conditions outside the park, which are mainly encroached parts of the park converted into agricultural fields, may be because burning outside the park is infrequent, and has historically been infrequent. The main driving force to select these areas might be the short vegetation structure, the openness of the fields as well as an abundance of insects throughout the breeding season (Wolff et al. 2001, Bretragnolle et al. 2011, Dutta et al. 2018). There could be other factors at play, such as increased visibility by the structures present in these fields (Wolff et al. 2001); for example, in Kokilabari where the maximum number of male Floricans were spotted, an interesting field observation was made where the bunds or slightly elevated boundaries separating an agricultural field from another were being frequently used by some displaying males for standing display; except these displays did not involve much walking, but only standing stationary in one place and looking around at a slow but steady pace, most likely on a bund, with puffed up breast feathers, slightly spread wings to show-off the white patch, and cocking and fanning of the tail feathers. This would continue for a varying amount of time, ranging from 20 minutes up to an hour. Although the walking display and standing display without the cocking and fanning of the tail feathers was observed for brief periods of time inside the park, this particular kind of display was only observed in this agricultural field that had bunds to facilitate it. Another observation from these agricultural fields was that the Bengal Florican territories were mainly in areas that had *Persicaria hydropiper* (in Kokilabari) or *Xanthium strumarium* patches (Agrang and Betbari), both of which are short vegetation whose height does not exceed one metre.

Invasive plants, like *Leea asiatica*, showed no significance in the habitat selection by the BFs, which could suggest that stronger forces that are at play in a dynamic grassland ecosystems have a greater role to play when it comes to habitat selection by them. When it comes to plant composition, having baseline information about different grassland vegetation is a step towards understanding the habitats of different grassland species that are not megaherbivores, including birds like the Bengal Florican. Knowing the different ways plant composition and communities may change under different practices also helps understand how different management practices can affect grasslands and to what extent, ultimately contributing to a greater understanding of the species that reside there.

In conclusion, fire and grazing have a variety of influences on grasslands and are important factors that need to be considered for robust grassland management plans. Continued monitoring of invasive species is essential, especially near forest edges and roads is essential to curb the spread, as fire does not seem to have much of an effect in doing so. From my study, structural heterogeneity, maintained through appropriate fire cycles, emerges as the most crucial management target, especially for grassland obligates like the Bengal Florican. Understanding Bengal Florican habitat selection at the micro scale enables more targeted habitat management tailored to the species' specific ecological needs. On the other hand, examining selection at the macro scale supports broader landscape-level predictions of suitable habitats, aiding in the identification of key areas for conservation. Recognizing how anthropogenic practices such as fire management and cattle grazing shape vegetation composition and structure is essential, as these changes can have cascading effects on the biodiversity grasslands support. These ecosystems and their components serve as vital habitats for several important species that are often overlooked in conservation and management policies and practices. A more integrated understanding of these interlinked factors is crucial for designing inclusive and resilient conservation policies as conserving rapidly dwindling habitats such as grasslands is the need of the hour.

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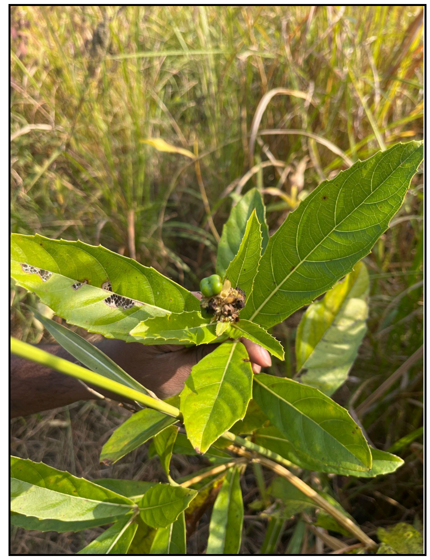
6. Appendix

6.1 Select vegetation from Manas National Park

Ageratum conyzoides and Arundinella sp.





Arundinella sp., Bischoffia javanica & Clerodendron serratum



Cymbopogon flexuosum, Dillenia pentagyna & Diplazium esculentum

Eragrostis sp. & Glochidion sp.

Grewia sp., Lagestroemia parviflora & Leea asiatica

Lygodium sp. & Mikania micrantha

Ophurios sp., Oxalis sp. & Persicaria hydropiper

Plectranthus ternifolius, Spilanthes sp. & Syzygium operculatum

Xanthium strumarium

6.2 Select individuals of Bengal Florican from Manas National Park, 2025.

Male Bengal Florican in breeding display plumage (Picture taken by Richard Sangma and Saurav Das)

Standing display by male Bengal Florican (Picture taken by Richard Sangma and Saurav Das