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भारतीय वन्यजीव संस्थान
Wildlife Institute of India

Ecological impacts of major invasive alien plants on native flora in Rajaji Tiger Reserve, Uttarakhand

A report submitted to:

DST-Science and Engineering
Research Board,
Govt. of India, New Delhi

PROJECT REPORT

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DST No: CRG/2019/001077

Principle Investigator

Dr. Amit Kumar

Co-Investigators

Dr. Navendu Page
Prof. Qamar Qureshi

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ABBREVIATIONS USED

A/F	- Abundance /Frequency
AUC	- Area Under the Curve
Ca	- Calcium
CAMPA	- Compensatory Afforestation Fund Management and Planning Authority
CCA	- Canonical Correspondence Analysis
EC	- Electrical conductivity
ISMP	- Invasive Species Management Plan
K	- Potassium
LI	- Lantana Invaded
N	- Nitrogen
Na	- Sodium
NBAP	- National Biodiversity Action Plan
NTCA	- National Tiger Conservation Authority
OC	- Organic carbon
OM	- Organic matter
P	- Phosphorus
RTR	- Rajaji Tiger Reserve
TSS	- True Skill Statistic
UI	- Uninvaded

EXECUTIVE SUMMARY

Invasive alien plants pose severe ecological threats, significantly impacting biodiversity, ecosystem processes, and human well-being. Despite several research and conservation efforts, species such as *Lantana camara, Parthenium hysterophorus, Ageratina adenophora,* to name a few, continue to spread aggressively, outcompeting native vegetation and disrupting ecological balance. This is particularly evident in biodiversity-rich regions such as India, where diverse habitats from the Western Ghats to Himalayan landscape face increased vulnerability to such invasions. This current study focuses on the Rajaji Tiger Reserve (RTR) in Uttarakhand, within the Shivalik hills, to investigate the invasion patterns and ecological impacts of a major invasive plant species.

Located in the Shivalik hills, the Rajaji Tiger Reserve spans 820 km² within the Gangetic Plains biogeographic zone. The rugged terrain ranges from 250-1100m in elevation, featuring a moist to dry sub-tropical climate. RTR's diverse vegetation includes Northern Tropical Moist Deciduous Forests and Northern Tropical Dry Deciduous Forests, comprising Sal Forest, Mixed Forest, Riverine Forest, Scrubland, Grassland, and Sub-tropical Pine Forest. In order to assess the extent of the plant invasion and its ecological ramifications, a multi-faceted methodology was employed. Field surveys, remote sensing, and GIS mapping were utilized to map the distribution and density of major invasive species across different forest ranges namely Chillawali, Beribara, Dhaulkhand, Haridwar, Ramgarh, Motichur and Kansrao of western Rajaji. A total of 127 plots, each measuring 10x10 meters, were randomly selected using a 2-km grid system and sampled for vegetation from 2021 to 2023. This investigation focused on the distribution of *Lantana camara*, *Ageratina adenophora*, and *Parthenium hysterophorus*, with data analyzed using the MaxEnt algorithm to predict species distribution and identify high-risk areas. Additionally, to assess the ecological impacts of invasive alien plant species on native flora, 64 sites comprising of 32 invaded and 32 uninvaded plots across different forest ranges were monitored for two years (2021-2023). Data collection included vegetation cover, habitat parameters, and soil physiochemical properties to understand the influence of invasive species on native plant communities, with a specific focus on areas heavily invaded by *Lantana camara*.

Based on the field observations, the study revealed the presence of 12 common invasive and alien species, including *Lantana camara*, *Parthenium hysterophorus*, and *Ageratum conyzoides*, with varying densities across the area. Notably, *Lantana camara* exhibited a density of 5268.08 stems/ha, while *Parthenium hysterophorus* had 1257.44 individuals/ha, *Ageratum conyzoides* had 1148.93 individuals/ha, and *Senna tora* had 468.08 individuals/ha. The Non-metric Multidimensional Scaling analysis unveiled similarities in species composition among the Chillawali, Beribara, Haridwar, and Dhaulkhand ranges, indicating a shared ecological context. Furthermore, the clustering of most invasive species in one coordination as per Canonical Correspondence Analysis suggested a potential invasional meltdown, where non-native species mutually facilitate each other's establishment or exacerbate their impact on native species.

Distinct range-wise distribution patterns were observed, with *Ageratina adenophora* covering 19.2 km^2 in Chillawali, *Lantana camara* dominating 23.5 km^2 in Haridwar, and *Parthenium hysterophorus* prevailing over 28.5 km^2 in Dholkhand. Based on soil sampling in consecutive years (2021-2023), *Lantana*-invaded (LI) sites exhibited higher pH levels (6.66±0.29) compared to uninvaded (UI) sites (6.45±0.60). Additionally, LI areas showed lower organic matter (1.91±0.93%) and phosphorus content (1.106±0.57 ppm) compared to UI sites (2.209±2.09% and 2.23±2.01 ppm, respectively), but higher sodium (37.57±11.81 kg/ha) and nitrogen content (0.09±0.013%) compared to UI sites (36.63±9.54 kg/ha and 0.1±0.05%, respectively).

The findings suggest that *Lantana* invasion can alter soil nutrient composition, potentially impacting soil quality and productivity in the long run. The study also identified significant differences in soil pH, organic carbon (OC), and phosphorus levels between *Lantana*-invaded and uninvaded sites. The t-tests revealed substantial disparities in pH (t-value = -1.92477, p = 0.031894), OC (t-value = 4.81448, p = 0.00002), and phosphorus (t-value = 2.60029, p =

0.007159) levels, highlighting the ecological implications of *Lantana* invasion on soil parameters. Furthermore, Pearson correlation and t-tests indicated positive correlations between sodium (Na) and potassium (K) levels in LI sites with electrical conductivity (EC), OC, and organic matter (OM), while phosphorus exhibited positive correlations with OC and OM but a negative correlation with soil pH. In UI sites, nitrogen (N), phosphorus (P), and potassium (K) showed a positive relationship with each other. Interestingly, a notable correlation between canopy cover and soil pH was observed in both invaded and uninvaded sites, indicating an inverse relationship influenced by the presence of *Lantana*. This suggests that *Lantana* invasion may lead to reduced canopy cover and lower soil pH, potentially affecting other plant species and overall ecosystem health. Overall, these findings underscore the complex interactions between invasive species, soil properties, and native plant communities in the western Rajaji, emphasizing the need for effective management strategies to mitigate the ecological impacts of invasion.

While past management practices of the reserve have shown localised success in controlling invasive species, their scalability and long-term effectiveness remain limited. Inconsistent funding, time bound interventions such as manual removal and the resilient nature of invasive species have hindered the efficacy of these practices. Nonetheless, significant efforts have been made to eradicate *Lantana* infestation in the reserve, highlighting the potential for effective management with sustained efforts. Therefore, in response to the persistent challenge of invasive species, a comprehensive 'Invasive Species Management Plan' is proposed for RTR. This strategic framework emphasizes targeted eradication efforts, the establishment of native plant nurseries, strategic transplantation and seed broadcasting, topographical removal of invasive plants, manual uprooting with minimal soil disturbance, comprehensive 5-year planning, timely operation and funding, rigorous monitoring and scientific documentation. These components, integrated into a holistic management approach, aim to enhance the resilience of RTR against invasive species and support the restoration of native ecosystems.

The following key recommendations have emerged after this study:

- Develop forest range specific and invasive species-specific management plan for three to five years to complete removal and eco-restoration of the targeted sites.
- Mapping the forest range with invasive species infestation in order to identify invasion hotspots and a comprehensive understanding of their distribution across the range.
- Holistic and time-phased approach: Removal of invasive species in the 1st year followed by monitoring for at least three to five years.
- Timing of removal: Ensure removal of invasive species prior to flowering or fruit setting.
- Control burning of slashes and supplementary planting with grasses such as *Cynodon dactylon, Chrysopogon* spp., *Apluda mutica, Vetiveria zizanoides, Heteropogon contortus, Bothriochloa* spp., *Sporobolus* spp., *Sorghum helepense, Dichanthium annulatum, Setaria* spp., *Paspalidium flavidum* and *Neyraudia arundinacea* and subsequent monitoring for three to five years.
- Strengthen the ecological restoration activities involving enrichment of invaded areas with native plant species, emphasizing leguminous plants such as *Atylosia, Phaseolus,* and *Cajanus* to enhance nutritional value.

1. INTRODUCTION

The invasive problem is not merely a local issue but a global concern that has garnered the attention of scientists and researchers worldwide (Smith-Ramesh, 2017). Numerous studies have underscored the severity of the threat posed by invasive alien plant species to ecosystems across the globe (Jones et al., 2020). For instance, research by Simberloff et al., (2013) highlighted invasive species as the primary driver of biodiversity loss on islands, emphasizing the urgent need for effective conservation management. Despite concerted efforts, the invasive threat persists, with certain species proving particularly challenging to control (Veitch and Clout, 2002). One such example is *Lantana camara*, a notorious invader known for its aggressive colonization and detrimental effects on native ecosystems (Kannan et al., 2013). These species represent a formidable ecological challenge globally, as researchers and scientists endeavor to comprehend the extent and impacts of these invaders on native ecosystems (Mungi et al., 2018; Lamsal et al., 2018; Rai and Singh, 2020). Studies from around the world underscore the severity of the threat posed by major invasive plants, with research highlighting their detrimental effects on biodiversity, ecosystem processes, and human well-being (Schelhas et al., 2021).

Despite the growing body of research, the invasive problem persists, with certain species proving particularly tenacious in their spread and impact (Langmaier and Lapin, 2020). In India, renowned for its rich biodiversity and ecological significance, the invasion of alien plant species poses a significant threat to native ecosystems (Pathak et al., 2019). Despite extensive research on the topic, challenges persist with invasive species such as *Lantana camara* continuing to wreak havoc on native flora and fauna (ICFRE, 2020). The diverse array of habitats, from the lush forests of the Western Ghats to the arid landscapes of Rajasthan, are increasingly vulnerable to the encroachment of invasive species (INABP, 2019).

The Himalayan belt, encompassing the fragile ecosystems of the Shivalik hills, is particularly vulnerable to invasive species due to its unique biodiversity and active vegetation import (Dogra et al., 2009). The introduction of non-native species alters soil composition (Perkins and Nowak), disrupts species interactions (Seebens et al., 2018), and poses a serious threat to native biodiversity (Sagoff, 2005). Numerous studies have documented the deleterious effects of invasive plants on India's biodiversity, with *Lantana camara* emerging as a prominent example (Bhagwat et al., 2012). The prevalence of invasive species, especially exemplified by the persistence of *Lantana camara*, underscores the urgent need for comprehensive research and management strategies (Gupta, 2018). Despite concerted efforts to control its spread, other species such as *Ageratina adenophora* and *Ageratum conyzoides* continue to proliferate, outcompeting native vegetation and altering ecosystem dynamics (Rai and Singh, 2020). The intricate web of ecological relationships in this biodiversity hotspot is increasingly susceptible to disruption, underscoring the urgency of addressing the invasive problem. Against this backdrop, this study seeks to investigate the invasion patterns and ecological impacts of a major invasive plant species in the Rajaji Tiger Reserve (RTR) in Uttarakhand, India.

1.1 Project objectives

(i) To study the invasion patterns of alien plants in RTR.

(ii) To assess the ecological impacts of invasive alien plant species on native flora.

(iii) To suggest ecological restoration measures.

(iv) To assess the efficacy of various management practices in controlling the invasion of alien species.

Lantana camara invasion on the hill slopes of Rajaji.

2. STUDY AREA

The Rajaji Tiger Reserve (RTR; 29°51′ N to 30°15′ N, 077°52′ E to 078°22′ E) fall within the Gangetic Plains biogeographic zone and upper Gangetic plains province (Rodgers et al, 2002) of Uttarakhand state which cover an area of 820 km^2. The entire terrain is rugged and highly undulating with altitude ranges from 250-1100m above msl. The climate is moist to dry sub-tropical with an annual rainfall of 2200mm. According to Champion & Seth (1968), Sub-tropical Shiwalik Sal and Northern Tropical Dry Deciduous Forests are the broad forest types in RTR.

2.1 Vegetation of Rajaji Tiger Reserve

Based on the physiognomy and floristic composition, the vegetation of RTR has been classified broadly under the Northern Tropical Moist Deciduous Forests and grouped into six forest types such as Sal Forest, Mixed Forest, Riverine Forest, Scrubland, Grassland (savannah), Sub-tropical Pine Forest (Champion and Seth 1968). Classified under the Tropical Moist Deciduous and Tropical Dry Deciduous Forests, the forest ecosystems of the reserve are quite varied and diverse in terms of flora and fauna. The major plant associations in the reserve include *Shorea robusta*, *Mallotus philippensis* and *Haldina cordifolia* community: *Shorea robusta*, *Terminalia bellirica* and *Bridelia retusa* community; *Dalbergia sissoo*, *Senegalia catechu* community; *Syzygium cumini*, *Phoebe* sp. and *Drypetes* sp. community.

2.2 Intensive Study Area: Western Rajaji

The present study was conducted in the western part of RTR, encompassing 07 forest ranges namely Chillawali, Dhaulkhand, Beribara, Haridwar, Ramgarh, Kansrau, and Motichur (**Figure 1**). This area is characterized by a diverse array of forest types, including dense Sal Forests, mixed forests, riverine vegetation, and old plantations of *Tectona grandis* (Teak) and *Eucalyptus tereticornis* (Safeda). The varied terrain and vegetation types in these ranges create a rich mosaic of habitats, supporting a wide variety of flora and fauna. These forest ranges are not only crucial for the survival of many species but also play a significant role in maintaining ecological balance and biodiversity. The unique physical features and vegetation types of each forest range provide varied habitats for wildlife (**Table 1**). This knowledge is essential for formulating effective management strategies and conservation plans.

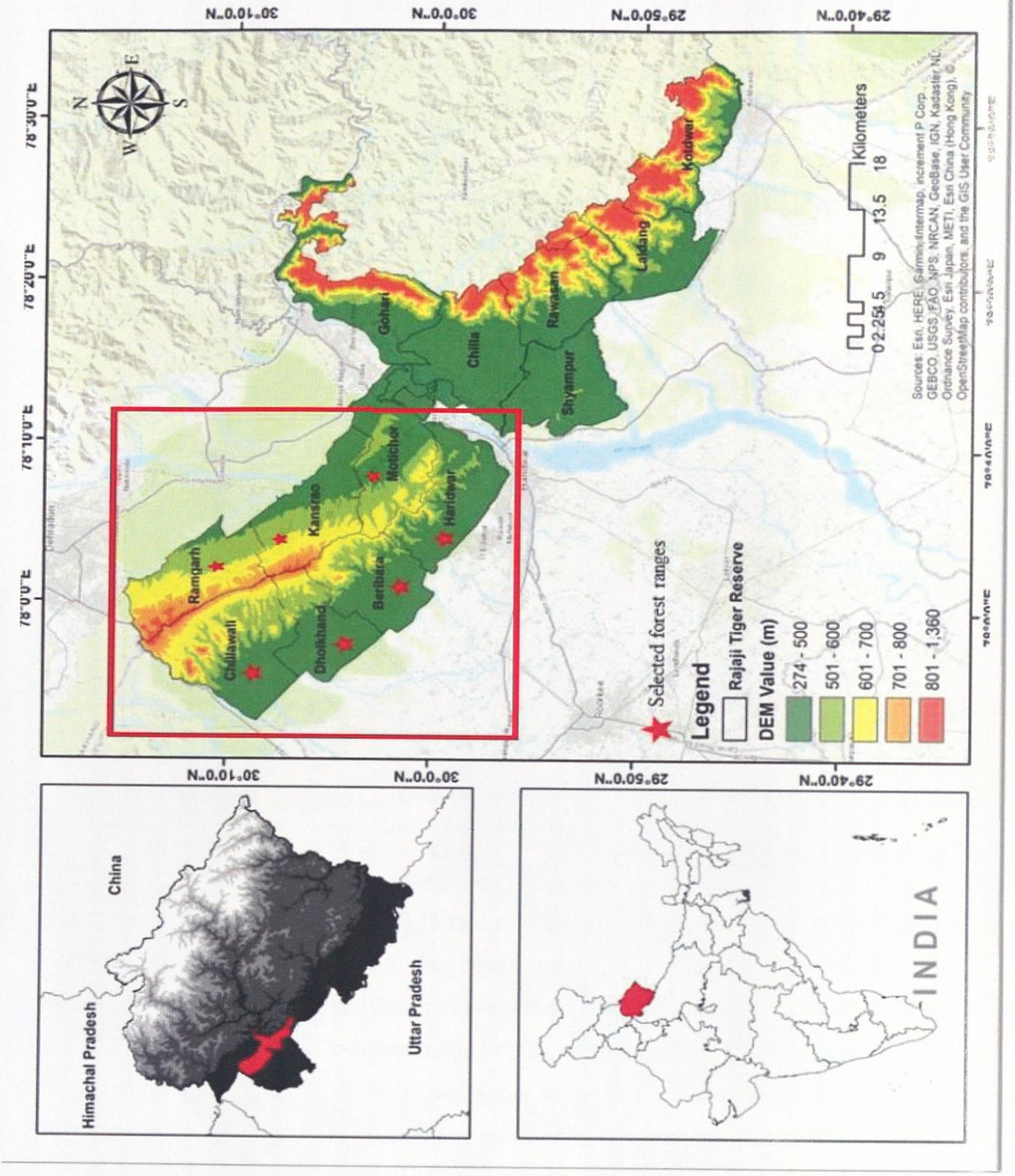
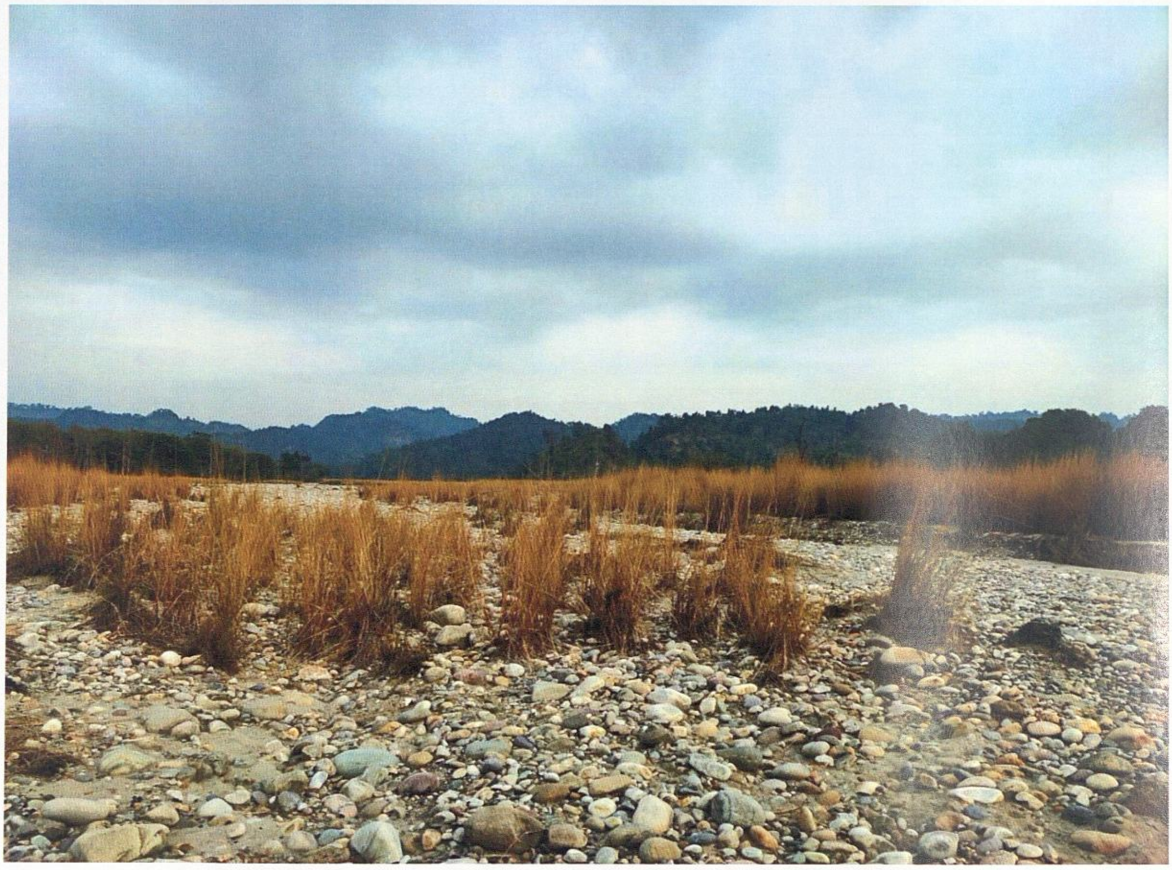


Figure 1: Map showing selected sites in Rajaji Tiger Reserve, Uttarakhand.

Table 1. Details of the area and physical features of selected forest ranges in the Western Rajaji, Uttarakhand.

S. No.	Forest Range	Geographical area (km^2)	Physical features
1	Chillawali	115.31	Characterized by relatively steeper and unstable habitat, tall and exposed cliffs covered with tufts of grass, mixed forest, riverine forest & old plantations of Teak and *Eucalyptus*. High anthropogenic pressure.
2	Dholkhand	59.951	Characterized by steeper and stable habitats; tall and exposed cliffs covered with tufts of grass, Sal Forest, mixed forest, riverine tracts & old plantations of Teak. Relatively less anthropogenic pressure.
3	Beribara	73.046	Characterized by steeper and stable habitats; tall and exposed cliffs covered with tufts of grass, *Anogeissus* forest, mixed forest, riverine forest dominated by one or more species of *Zizyphus* and *Saccharum*. Relatively less anthropogenic pressure.
4	Haridwar	85.255	Characterized by steeper and unstable habitats; tall and exposed cliffs, mixed forest, riverine forest dominated by *Zizyphus* spp. High anthropogenic pressure.
5	Kansrau	79.327	It boasts diverse vegetation, including Sal and Teak, across uneven terrain ranging from 360m to 860m elevation, creating a lush green landscape.
6	Motichur	80.422	Characterized by moist deciduous forest dominated by Sal trees, the range is delineated by the Ganga, marking its eastern border. Vital corridors facilitate elephant migration between Motichur and Chilla ranges, crucial for their seasonal needs.
7	Ramgarh	77.03	Characterized by moist deciduous forest, very dense forest dominated with Sal trees.



Top: Grassland habitat in Eastern Rajaji. **Bottom:** Riverine habitat in Western Rajaji.

Top: A glimpse of the landscape enroute to the Goral ridge, Dhaulkhand range. **Bottom:** Dense Sal forest in Ramgarh range.

3. METHODOLOGY

3.1 Site and Species Selection

In order to understand the invasion patterns of invasive alien plant species, the forest ranges, namely Chillawali, Dhaulkhand, Beribara, Haridwar, Ramgarh, Kansrau and Motichur located in the western part of Rajaji Tiger Reserve (RTR) in Uttarakhand were studied. Whereas, to assess the ecological impacts of invasive alien plant species on native flora, four forest ranges namely, Chillawali, Dholkhand, Beribara, and Ranipur (Haridwar) in western RTR were selected (**Figure 2**). Based on reconnaissance and extensive field surveys in selected forest ranges of western RTR, common and dominant invasive alien plant species were observed and enlisted in detail. Considering the dominance of *Lantana camara* across different forest ranges in RTR, *Lantana camara* was studied using vegetation sampling in invaded and uninvaded areas.

3.2 Study Design

3.2.1 Study the invasion patterns of alien plants

The primary objective of the study was to study the invasion patterns of a major invasive within the western Rajaji. Based on a grid-based 2km system, plots were randomly selected in the seven forest ranges. To comprehensively understand the invasion patterns, a total of 127 plots were sampled for vegetation from 2021 to 2023. Each plot, covering an area of 10x10m, included individual count of herbs, shrubs, and trees and information of habitat characteristics was also observed (**Figure 2**). In order to understand the range wise species composition across different forest ranges, Non-metric Multidimensional Scaling analysis was conducted on species information obtained through vegetation sampling. Canonical Correspondence Analysis (CCA) was carried out to understand distribution of invasive species and native vegetation. Further, invasion pattern across different forest ranges was analysed using ratio of abundance (A) and frequency (F), wherein an A/F ratio below 0.025 signifies regular distribution, values between 0.025 and 0.05 suggest a random distribution and ratios exceeding 0.05 indicate a contagious distribution (Cottam and Curtis, 1956).

Figure 2: Top & Bottom - Vegetation sampling carried out in Dhaulkhand range.

In this study, employing the same grid-based technique, we investigated the distribution of invasive species across different ranges of the western Rajaji. A balanced ecological resolution and logistical feasibility were achieved by adopting a 2-km grid size (**Figure 3**). Based on the grid, three major invasive alien plant species (*Lantana camara*, *Ageratina adenophora*, and *Parthenium hysterophorus*) were identified for inclusion in this study. Field surveys systematically recorded the presence and abundance of invasive species within each grid cell. The collected data underwent analysis using the MaxEnt algorithm, integrating environmental variables to predict species distribution. This approach is crucial for conservation efforts as it identifies high-risk areas, informing effective management strategies. The careful selection of a 2-km grid size was a pivotal decision, considering ecological and logistical factors. This choice mitigates the risk of oversampling and ensures accuracy in capturing the broader distribution pattern.

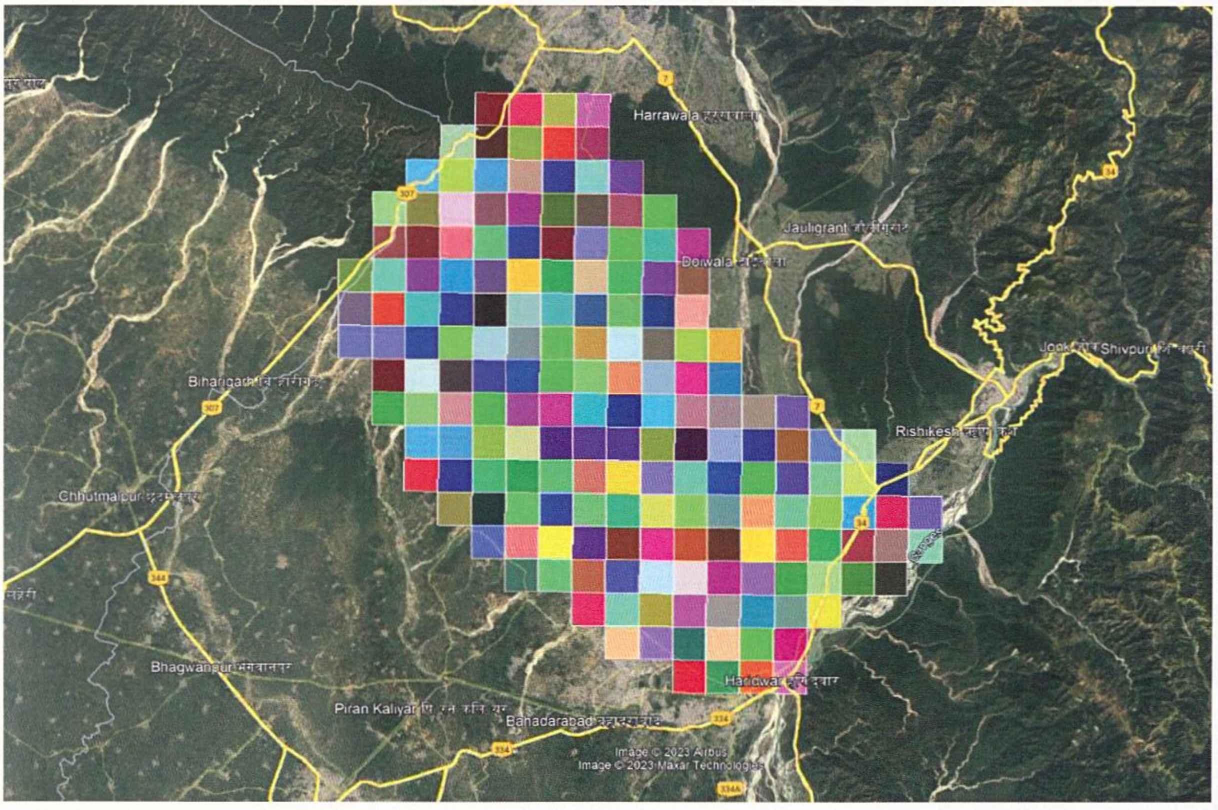


Figure 3: Grid-based technique used in the present study.

A comprehensive dataset comprising 200 occurrence records for three distinct species such as *Lantana camara, Ageratina adenophora,* and *Parthenium hysterophorus* was meticulously assembled through a combination of field surveys, online database searches, and literature references. *Lantana camara* accounted for 100 occurrence records, while *Ageratina adenophora* and *Parthenium hysterophorus* contributed 60 and 40 occurrence records, respectively. Utilizing a handheld Garmin GPS-based system, field surveys were conducted between January 2022 and July 2022, resulting in 186 georeferenced occurrence points. Additionally, 12 occurrence records were extracted from published literature. To address potential spatial sampling bias, a spatial thinning technique, specifically the spThin package in R (Hijmans et al., 2011), was applied. This procedure led to the judicious selection of 76 geo-referenced points, forming the foundation for constructing robust species distribution models. Nineteen bioclimatic variables with a spatial resolution of 1 km were obtained from worldclim datasets. An initial test for multicollinearity was conducted, and ecologically meaningful variables were retained for species distribution modeling. Variable correlations stronger than $|r| > 0.7$, guided the selection process. The resulting species distribution models provide essential insights for effective invasive species management in Western Rajaji (**Figure 4**).

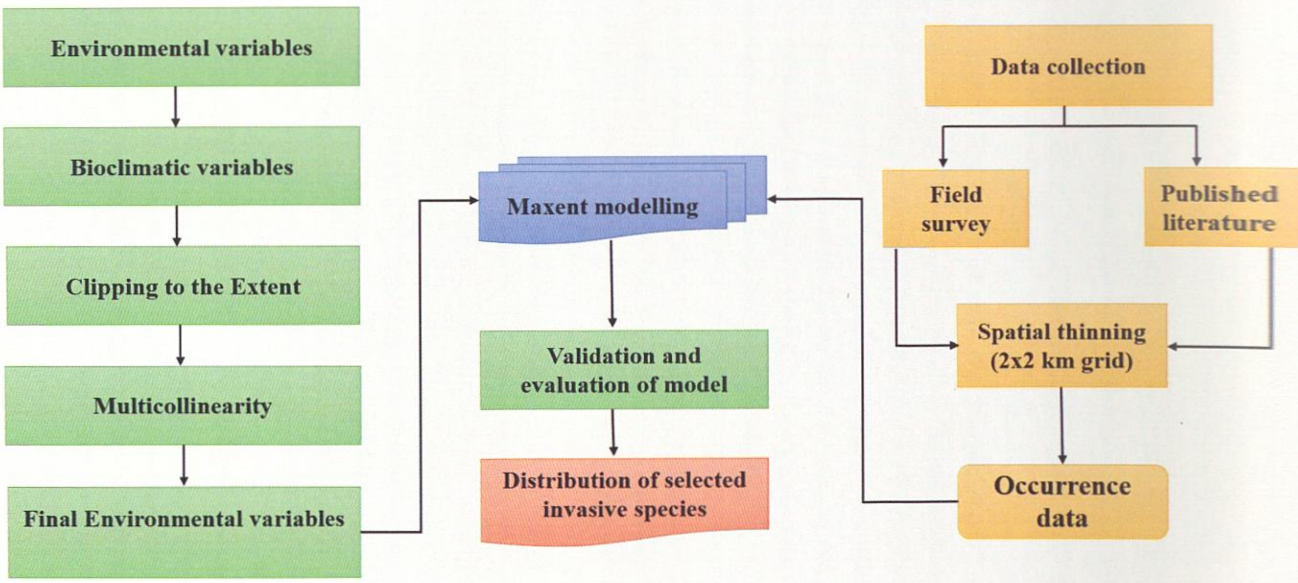


Figure 4: Methodology adopted for understanding the spatial distribution of selected invasive species.

3.2.2 Assess the ecological impacts of invasive alien plant species on native flora

3.2.2.1 Vegetation sampling

In order to understand the impact of invasive alien plant species on native flora, a total of 64 sites, comprising 32 invaded (LI) sites and 32 uninvaded (UI) sites were selected across various habitat types (**Figure 5**). The investigation specifically targeted invaded plots characterized by a gradient of invasion with over 50% cover of *Lantana camara*, and uninvaded plots without any invasion. Within each studied plot, the cover and abundance of invasive plant species were meticulously assessed at an optimal scale of one hectare, representing diverse habitat types in the westernmost ranges. Stratified random sampling with quadrat plots (10x10m) for trees shrubs and herbs was employed during field data collection. Recorded data included crucial habitat parameters such as elevation, geographic coordinates, slope, aspect, plant habit, habitat characteristics, herbaceous cover, canopy cover, and the total number of species present. Individual measurements of *Lantana camara*, including its height, were also documented to provide a comprehensive understanding of the invasive plant's influence on the native plant community.

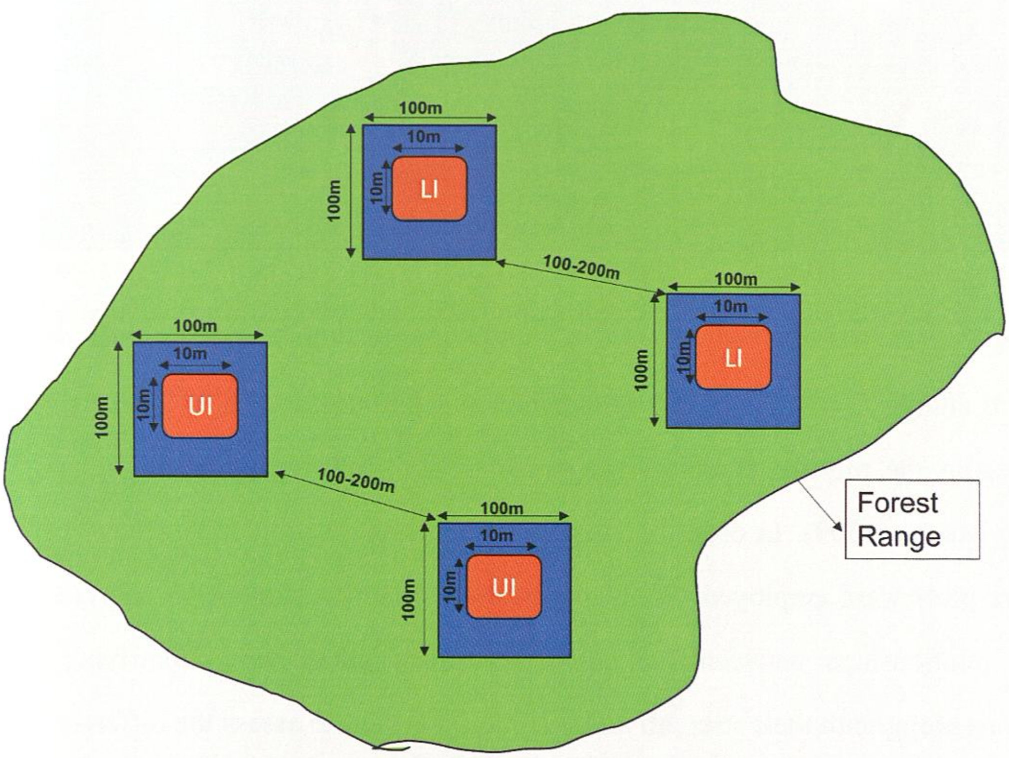


Figure 5: Design adopted for studying *Lantana* invaded (LI) and uninvaded (UI) sites.

3.2.2.2 Soil Sampling and Laboratory Analysis

Soil sampling was conducted in both invaded and uninvaded plots across the westernmost forest ranges during 2021-2023. Samples were collected before the monsoon to prevent nutrient leaching. A core sampler was used at 10cm and 30cm depths, creating composite samples from five locations per plot. These samples were stored in airtight polyethylene bags. Laboratory analysis included assessing physiochemical properties of the soil, such as pH, EC, OC, OM, N, P, K, Ca, and Na, using standard methods (**Figure 6**). The study aimed to understand the relationship between native and invasive plant assemblages with abiotic parameters, comparing seasonal variations in native flora density with invasive plant density, edaphic characteristics, and other ecologically significant predictors in invaded and uninvaded plots.

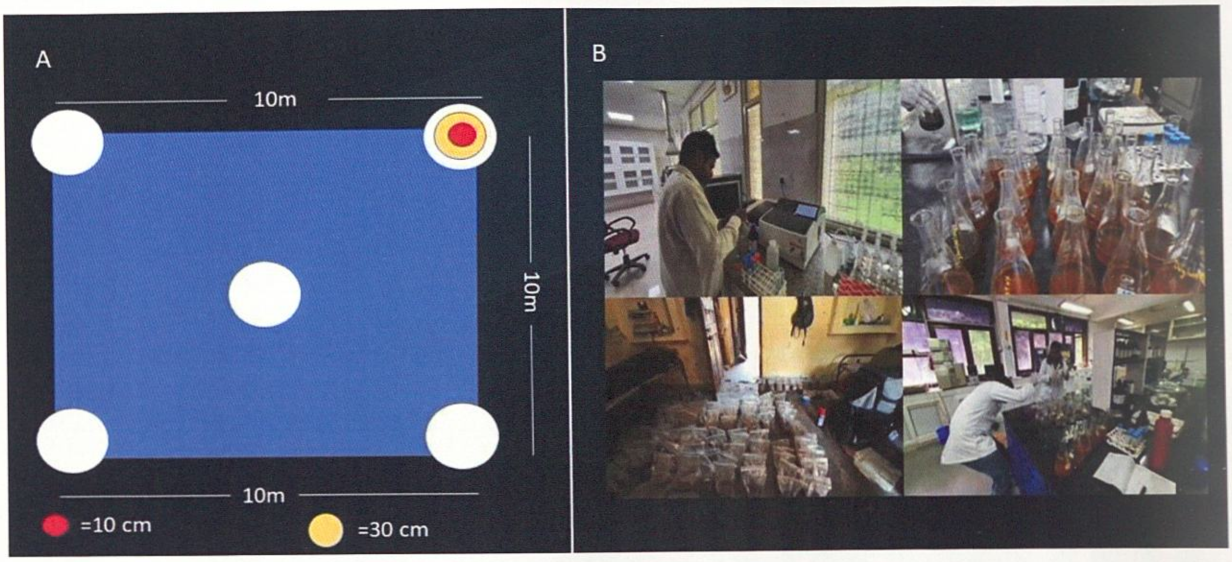


Figure 6: Sample plot for the soil collection (left) and soil laboratory analysis (right).

In order to analyse the information, we conducted a rigorous statistical analysis of a dataset encompassing the physico-chemical properties of soil and vegetation in LI and UI plots following Manly (2009). In order to visually compare these properties across different plot types, box plots were employed. We also performed Pearson correlation analysis to explore potential relationships between the physico-chemical parameters, identifying significant associations along with their strength and direction. Further, to assess the differences between LI and UI plots, we utilized a T-test, specifically the paired t-test, to compare the means of paired observations from both plot types. These analyses were facilitated by the "corrplot" (Wei and Simko, 2021) and "ggplot2" (Wickham, 2016) libraries in R Studio (R Core Team, 2021). The comprehensive statistical approach provided valuable insights into the interplay between soil properties and vegetation in the context of the *Lantana* invasion (Manly, 2009).

3.2.3 Management history: Current and past management practices

In order to understand the management history of RTR especially Western Rajaji, an in-depth examination of historical and current management practices was carried out. Working Plan by Pandey (2010) and Raiselly (2022) were consulted to trace the evolution of management strategies and conservation initiatives over time. Further, the detailed information gathered on the invasive species management including removal and monitoring of invasive species was obtained from *Lantana* उन्मूलन (eradication) register maintained at each forest range of the reserve. Existing literature in the form of regional studies such as Das et al., (1996), Rishi, (2009), Kimothi et al., (2010), Rishi, (2010), Kumar and Subudhi (2013), Kaushik, (2014), Ramaswami et al., (2014), Chandane and Vashishtha, (2015), Ravi, (2016), Upadhyay et al., (2019), Mondal et al., (2021), Mondal, (2023), Yadav et al., (2023). Furthermore, field consultations with forest staff from various forest ranges within the reserve provided firsthand insights into current and past management practices along with challenges faced in the invasive species management. Informal conversations with the *Van Gujjars*, a local indigenous community, offered valuable perspectives on how different management practices help both the community and the forest ecosystem. Thus, systematically integrating and analyzing data from these diverse sources including individual discussions, management history of Rajaji Tiger Reserve's, highlighting key practices, challenges, and outcomes over the years was studied.

4. RESULTS AND DISCUSSION

4.1 Invasion patterns of invasive alien plant species

Based on the field observations, the current study envisages 12 common invasive and alien species, namely *Lantana camara, Parthenium hysterophorus, Ageratum conyzoides, Ageratina adenophora, Mesosphaerum suaveolens, Senna tora, Senna occidentalis, Bidens pilosa, Xanthium strumarium, Fernandoa adenophylla, Imperata cylindrica* and *Broussonetia papyrifera* in Western Rajaji.

Based on the 127 quadrat plots (10×10m) laid during the years 2021 and 2022 across different forest ranges namely Chillawali, Beribara, Dhaulkhand, Haridwar, Ramgarh, Motichur and Kansrao of western Rajaji, the present study reports *Lantana camara, Parthenium hysterophorus, Ageratum conyzoides* and *Senna tora* as the most dominant invasive species. The density of *Lantana camara* was recorded 5268.08 stems/ha (1756.02 individual/ha), while *Parthenium hysterophorus* had 1257.44 individuals/ha, *Ageratum conyzoides* had 1148.93 individuals/ha and *Senna tora* had 468.08 individuals/ha. The high density of these invasive species indicates that these species have been spreading rapidly and have dominated in the area. Based on the field observations, it was observed that *Lantana camara, Parthenium hysterophorus, Ageratum conyzoides* and *Senna tora* have effectively established and spread across different forest ranges in western Rajaji. *Ageratina adenophora* that generally prefers moist habitats and shaded areas was observed dominating in moist deciduous forests in Ramgarh, Motichur and Kansrao forest ranges. *Parthenium hysterophorus* was extensively spread in open areas along the roadside in Haridwar and Beribada forest ranges. *Xanthium strumarium* was relatively abundant in disturbed areas along human habitations and roadside areas. The other co-dominant invasive species in western Rajaji include *Mesosphaerum suaveolens, Senna occidentalis,Sida cordifolia* and *Bidens pilosa.* Notably, the native species such as *Sida cordifolia*have extensively invaded along roadside areas and open areas where the fire-strip was cleared of its vegetation by the park management, whereas *Justicia adhatoda* and *Pogostemon benghalensis* preferred closed canopy areas from dry to moist deciduous forests.

4.1.1 Range wise species composition

In order to understand the range wise species composition across different forest ranges, Non-metric Multidimensional Scaling analysis was conducted on species information obtained through vegetation sampling from Chillawali, Beribada, Dhaulkhand, Haridwar, Motichur, Kansrao forest ranges. The results reveal distinct patterns in species composition (**Figure 7**), providing valuable insights into the ecological dynamics of the area. The analysis indicates that Chillawali, Beribara, Haridwar, and Dhaulkhand ranges exhibit similar species composition, suggesting a shared ecological context among these areas. Characterized by Tropical dry deciduous forest with abundance of distinct species such as *Anogeissus latifolia, Lannea coromandelica, Terminalia bellirica, Bombax ceiba, Senegalia catechu, Albizia lebbeck, Mitragyna parvifolia, Phyllanthus emblica, Aegle marmelos, Naringi crenulata* and *Cordia* spp. towards southern slopes and open riverine tracts comprising of species such as *Saccharum* spp, *Vetiveria zizanoides, Setaria* spp., has contributed in evenness of vegetation in these ranges. The observed similarities in species composition among Chillawali, Beribara, Haridwar, and Dhaulkhand ranges may signify common ecological factors influencing plant distribution and community structure. This shared pattern in terms of vegetation could be attributed to similar site factors and environmental conditions, disturbance regimes, and grazing history due to *Van Gujjars* in these areas. On the other hand, Kansrao and Motichur ranges demonstrate a degree of similarity in species composition, with Motichur displaying subtle differences. Characterized by Tropical moist to dry deciduous forests towards the northern side, these ranges have comparatively dense forests and close canopy cover due to high moisture regime and site factors. Understanding these differences is crucial for targeted conservation efforts, especially invasive species management, holistically.

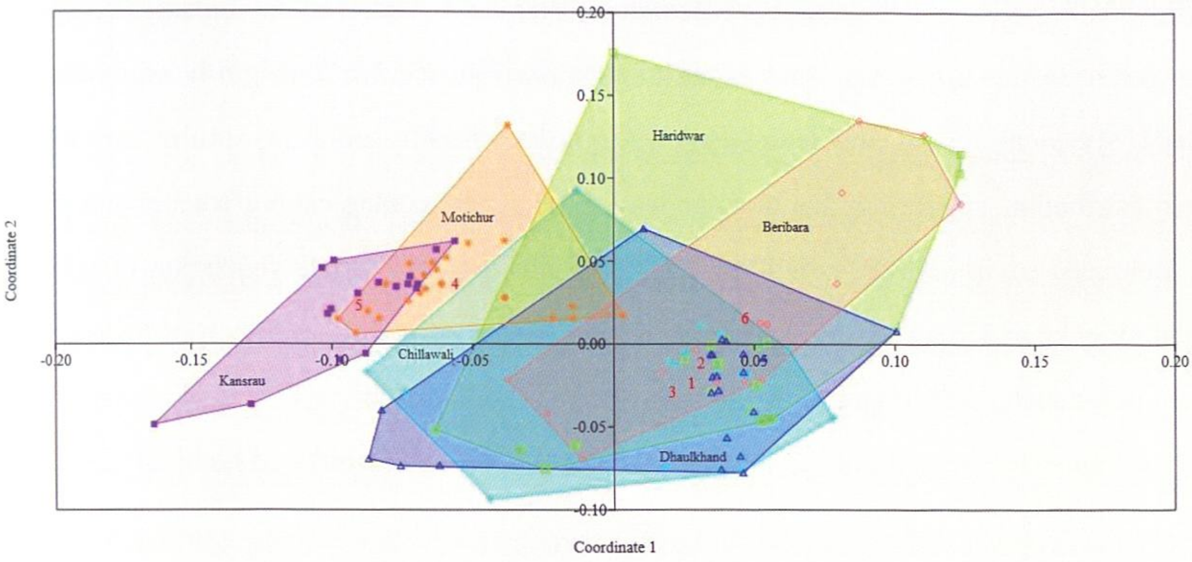


Figure 7: Similarity in species composition across different forest ranges in Western Rajaji.

4.1.2 Invasive species clustering and native flora insights

In order to understand distribution of invasive species and native vegetation, Canonical Correspondence Analysis (CCA) revealed distinct clustering of most invasive species in a single coordination. The ecologically significant finding of clustering the most invasive species in one coordination in CCA indicates a pattern of co-occurrence or shared environmental preferences among these invasive plants in the area. This spatial clustering suggests that these invasive species such as *Lantana camara*, *Ageratum conyzoides* and *Senna tora* might likely respond to similar ecological conditions, such as soil types, or other environmental factors that favor their establishment and growth (**Figure 8**). The observed clustering of major invasive species in a single coordination as per CCA gives rise to the intriguing concept of an invasional meltdown, the process by which two or more non-native species facilitate each other's establishment or exacerbate each other's impact on native species. This ecological phenomenon suggests that the co-occurrence and shared environmental preferences among invasive plants may amplify the impact of their invasion. The spatial clustering implies a potential synergistic effect, where these invasive species respond to similar ecological conditions, possibly soil types or other environmental factors that facilitate their establishment and growth. As such, the findings of the present study underscore the need for comprehensive management strategies to mitigate the potential long-term consequences of multiple invasions on the native vegetation in the area. In addition, the analysis conducted through CCA also reveals intriguing insights into native species dynamics. Species such as *Shorea robusta, Mallotus philippensis, Ehretia laevis, Syzygium cumini,* and *Holoptelea integrifolia* whereas, exhibit a similar tendency in their distribution, suggesting that they too may share certain ecological preferences or respond to analogous environmental conditions. If that is the case, the native vegetation in Western Rajaji may be experiencing consequences of multiple invasions where effects of invasion are more pronounced with co-occurring invasive plants. The cumulative effects of invasion may lead to future decline of native plant species, homogenization and reduced herbivory.

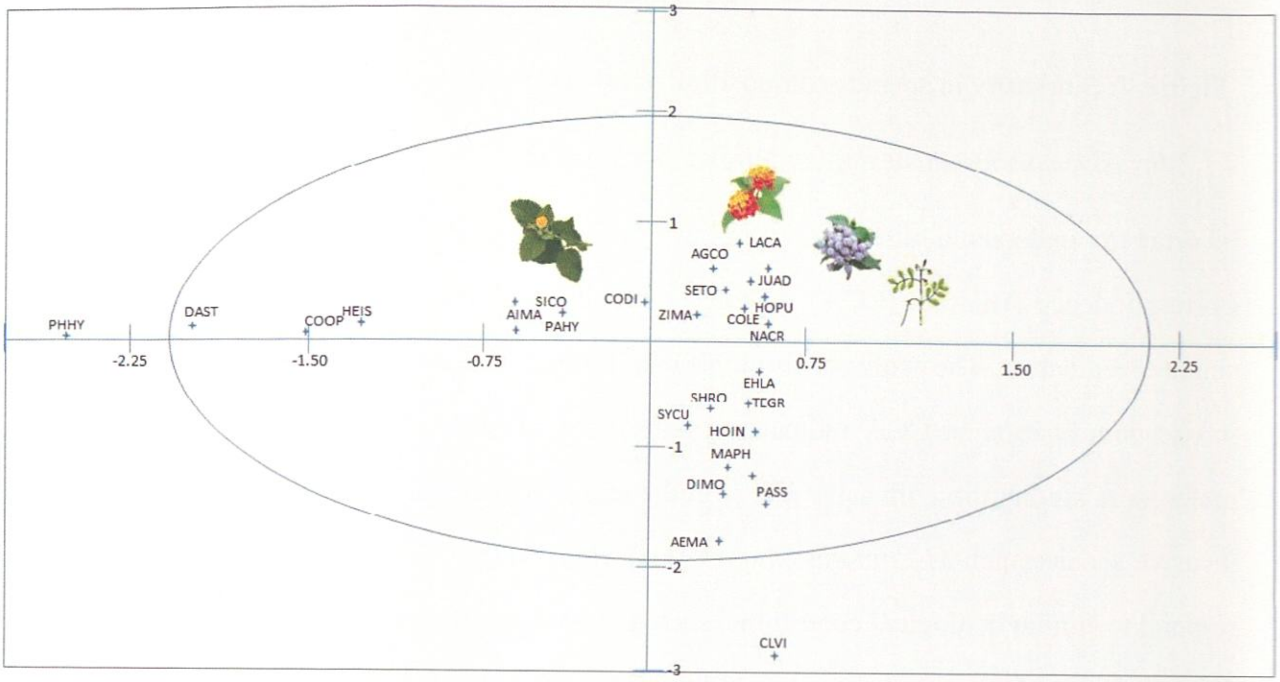


Figure 8: Plant species clustering in the Western Rajaji using Canonical Correspondence Analysis.

4.1.3 Invasion pattern across different forest ranges

Analyzing the ratio of abundance (A) and frequency (F), wherein an A/F ratio below 0.025 signifies regular distribution, values between 0.025 and 0.05 suggest a random distribution and ratios exceeding 0.05 indicate a contagious distribution (Cottam and Curtis, 1956), unveils the intricacies of plant spatial arrangement, providing ecologists with a quantitative lens through which to understand the ecological dynamics of diverse ecosystems. Against this backdrop, this study delves into the distribution pattern of invasive species within the Beribara, Chillawali, Dhaulkhand, Kansrau, Motichur, Haridwar, and Ramgarh forest ranges. The range wise information on the forest type, species composition and invasion pattern is as follows:

In the Beribara range, the principal forest types observed are classified as Tropical Dry Deciduous, and these forests are distinguished by a moderately dense forest. The landscape showcases dominance in Moist Siwalik Sal forest and northern dry mixed deciduous forest, thriving in relatively steeper and stable habitats. Notable features include tall, exposed cliffs adorned with tufts of grass, *Anogeissus* forest, mixed forest, and riverine habitats dominated by one or more species of *Saccharum* and *Zizyphus.* In this forest range, *Lantana camara* and *Parthenium hysterophorus* was observed as prominent invasive species, displaying densities of 5400 stems/ha (2700 individual/ha) and 814.29 individuals/ha, respectively. *Lantana camara* (0.8) and *Parthenium hysterophorus* (0.25) showed contiguous distribution across the entire range. Other prevailing invasive species, namely *Ageratum conyzoides*, *Senna tora*, and *Sida cordifolia* exhibit varying densities of 428.56, 657.16, and 1103.57 individuals/ha. The relatively low density albeit contiguous distribution of these species as compared to *Lantana camara* and *Parthenium hysterophorus* poses a significant threat to the native vegetation. Within the Beribara range, the A/F ratios point to a predominantly contagious distribution for most of the species.

Chillawali, a distinctive region within the forest landscape is characterized by diverse plant species. The forest typology of Chillawali is a remarkable intersection of ecosystems, primarily falling under the category of Tropical Dry Deciduous with moderately dense forest. Noteworthy features include the dominance of Moist Siwalik Sal forest and northern dry mixed deciduous forest, creating a habitat characterized by its steep and unstable nature. Tall and exposed cliffs adorned with tufts of grass contribute to the unique ecological dynamics of the region. Mixed forests, riverine habitats, and remnants of old Teak (*Tectona grandis*) and *Eucalyptus* plantations are one of the major habitats of this range. The present study sheds light on the thriving presence of *Lantana camara* and *Parthenium hysterophorus*, displaying notable densities of 3830.76 stems/ha (1915.38 individual/ha) and 123.07 individuals/ha, respectively. In addition, the landscape is invaded by other impactful albeit native species such as *Justicia adhatoda* and *Sida cordifolia* that exhibit varying densities 2619.23 and 188.46 individuals/ha, respectively. *Ageratum conyzoides* exhibits remarkable adaptability to different habitats, reaching its high density in Chillawali at 953.84 individuals/ha. This versatility suggests that *Ageratum conyzoides* is not confined strictly to moister environments but rather thrives in both slightly drier and more humid settings. It indicates that certain invasive species such as *Ageratum conyzoides* can flourish across a range of environmental conditions, contributing to its resilience and success in the region. In the Chillawali forest range, the A/F ratios indicate a contagious distribution pattern for *Ageratum conyzoides* (0.28), *Lantana camara* (0.32), *Senna tora* (0.22), *Justicia adhatoda* (0.54), and *Sida cordifolia* (0.35).

In the Dhaulkhand range, the forest types fall under Tropical Moist Deciduous, featuring moderately dense forests. The landscape is characterized by the dominance of Moist Siwalik Sal forest, thriving in steeper and stable habitats. Tall, exposed cliffs adorned with tufts of grass, Sal Forest, mixed forest, riverine tracts, and remnants of old Teak plantations further enrich the diverse ecological diversity within this range. The range is marked by the prevalence of invasive species, notably *Lantana camara* and *Ageratum conyzoides*, with recorded densities of 4800 stems/ha (2400 individual/ha) and 1163.64 individuals/ha, respectively. These invasive species form dense patches across the area. Concurrently, native species such as *Justicia adhatoda* densely populate the region, with 2700 individuals/ha, engaging in competitive interactions with invasive such as *Lantana camara*. Dhaulkhand forest showcases a contagious distribution for *Ageratum conyzoides* (0.19), *Lantana camara* (0.51), *Parthenium hysterophorus* (0.44), *Senna tora* (0.12), *Justicia adhatoda* (0.58), and *Sida cordifolia* (0.79). From a scientific standpoint, this spatial arrangement may suggest a lack of strong interactions or influences shaping the dispersion of these species, leading to a more unpredictable distribution pattern.

The forest types within the Kansrau range fall under Tropical Moist Deciduous, featuring very dense forests. The landscape is characterized by the dominance of Moist Siwalik Sal forest, highlighting the region's rich biodiversity and intricate ecological balance. The presence of *Lantana camara, Ageratum conyzoides,* and *Parthenium hysterophorus* adds a layer of complexity to the forest ecosystem. In this range, *Lantana camara* stands out with a density of 2566.64 stems/ha (1283.32 individual/ha). Additionally, other dominant invasive species in the area include *Ageratum conyzoides* and *Parthenium hysterophorus*, displaying varying densities of 166.64 and 41.66 individuals/ha, respectively. In the Kansrau forest, most species exhibit a regular distribution, except for *Ageratina adenophora* (0.15) and *Ageratum conyzoides* (0.06), which displays a contagious distribution pattern.

In the Motichur Range, the forest types fall under Tropical Moist Deciduous, characterized by moderately dense forests. The landscape is marked by the dominance of Moist Siwalik Sal forest, reflecting the region's diverse flora and fauna. The prevalence of *Lantana camara*, along with the presence of *Parthenium hysterophorus*and *Sida cordifolia*, underscores the complex interplay in shaping the ecological balance of the range. In this Range, *Lantana camara* asserts its dominance with a notably high density of 1835.28 stems/ha (917.64 individual/ha). Additionally, *Parthenium hysterophorus* and *Sida cordifolia* are present in the area, albeit with lower but comparable densities of 70.56 individuals/ha. Motichur forest predominantly displays regular distribution for *Ageratum conyzoides* (0.03), and *Justicia adhatoda* (0.02) whereas *Lantana camara* (0.07) has contiguous distribution. Ecologically, this implies an even spacing of these species, reflecting a balanced distribution across the habitat.

The forest types within the Haridwar Range fall under Tropical Dry Deciduous, characterized by moderately dense forests. The landscape is marked by the dominance of Moist Siwalik Sal forest and northern dry mixed deciduous forest, thriving in steeper and unstable habitats. Tall and exposed cliffs, mixed forest, and riverine habitats dominated by *Zizyphus* spp. contribute to the diverse ecological matrices within the Haridwar range. The coexistence of dominant invasive species alongside native vegetation emphasizes the complex interactions influencing the overall ecological balance of this range. In the Haridwar range, the *Lantana camara* takes center stage, dominating the landscape with a high density of 6033.33 stems/ha (3016.66 individual/ha). Following closely, *Parthenium hysterophorus* exhibits a density of 1583.33 individuals/ha, while *Senna tora* and *Ageratum conyzoides* contribute with densities of 633.34 individuals/ha and 600 individuals/ha, respectively. Further, *Justicia adhatoda* (955.56 individuals/ha) and *Sida cordifolia* (450 individuals/ha) contribute significantly to the plant community in the area. The trend of habitat preferences continues with *Senna tora* and *Parthenium hysterophorus* showing their highest densities in Haridwar. *Senna tora*, known for its adaptability, is commonly found in disturbed areas, along roadsides, in agricultural fields, and in open, sunny locations. This observation underscores the idea that *Senna tora* and *Parthenium hysterophorus* thrive in environments that may include drier components, as evidenced by their prevalence in the Haridwar range. Haridwar forest demonstrates a contagious distribution pattern for *Ageratum conyzoides* (0.6), *Lantana camara* (0.53), *Parthenium hysterophorus* (0.63), and *Senna tora* (0.41). From an ecological perspective, this suggests spatial clustering of these species, possibly influenced by factors such as seed dispersal mechanisms or localized environmental conditions that favor their growth in proximity. The outer fringes of the Haridwar Range serve as a crucial interface between the forest ecosystem and human activities. Agricultural lands, Van guzzars and the presence of villagers' livestock introduce significant disturbances, creating pathways for cattle to infiltrate the forested areas. This intrusion not only disrupts the natural ecological balance but also contributes to the proliferation of invasive species, as the cattle grazing activity inadvertently supports the spread of seeds and facilitates the establishment of opportunistic plants, further impacting the contagious distribution pattern observed in the Haridwar Range.

The forest types within the Ramgarh Range fall under Tropical Moist Deciduous, characterized by very dense forests. The landscape is defined by the dominance of Moist Siwalik Sal forest, reflecting the region's rich biodiversity. The existence of *Lantana camara, Ageratum conyzoides, Parthenium hysterophorus,* and *Justicia adhatoda* underscores the intricate interaction between invasive and indigenous species, influencing the ecological equilibrium of the Ramgarh Range within this dynamic forest environment. In the Ramgarh Range, *Lantana camara* is observed with a density of 1024 stems/ha (521.32 individual/ha). Other notable invasive species include *Ageratum conyzoides*, with a density of 900 individuals/ha, *Parthenium hysterophorus* at 433.34 individuals/ha, and *Justicia adhatoda* with a substantial density of 1200 individuals/ha. Ramgarh forest exhibits a contagious distribution for *Ageratum conyzoides* (0.8), *Lantana camara* (0.06), *Ageratina adenophora* (0.09), and *Justicia adhatoda* (0.27). From a scientific standpoint, this suggests localized clusters of these species, potentially influenced by factors such as seed dispersal dynamics or specific micro-environmental conditions that promote their aggregation.

The prevalence of *Lantana camara* in various forest ranges, such as Chillawali, Beribara, Kansrao, Motichur, Haridwar, and Ramgarh, underscores its adaptability across different forest types. In Chillawali, Beribara, Haridwar, Dahaulkhand and Motichur ranges, where Tropical Dry Deciduous forests dominate, *Lantana camara* exhibits resilience and high densities (**Figure 9**), suggesting an affinity for the characteristics of these ecosystems. The invasive species competes with native vegetation, potentially impacting the ecological balance in these dry deciduous areas. Conversely, in Kansrao and Ramgarh ranges, characterized by Tropical Moist Deciduous forests, *Lantana camara* not remains prevalent as other ranges, but some of the part which is drier and less dense forest indicating its prevalent. Still *Lantana* thrives alongside Moist Siwalik Sal forest and other vegetation types, influencing the composition and structure of these moist and dry deciduous ecosystems. In contrast, Ramgarh Range, with its moist deciduous forest, shows a relatively lower density of *Lantana camara*, suggesting potential variations in its ecological interactions and competition with native species. This dynamic distribution of *Lantana camara* highlights its ecological adaptability across distinct forest types, with implications for biodiversity and ecosystem stability in each range.

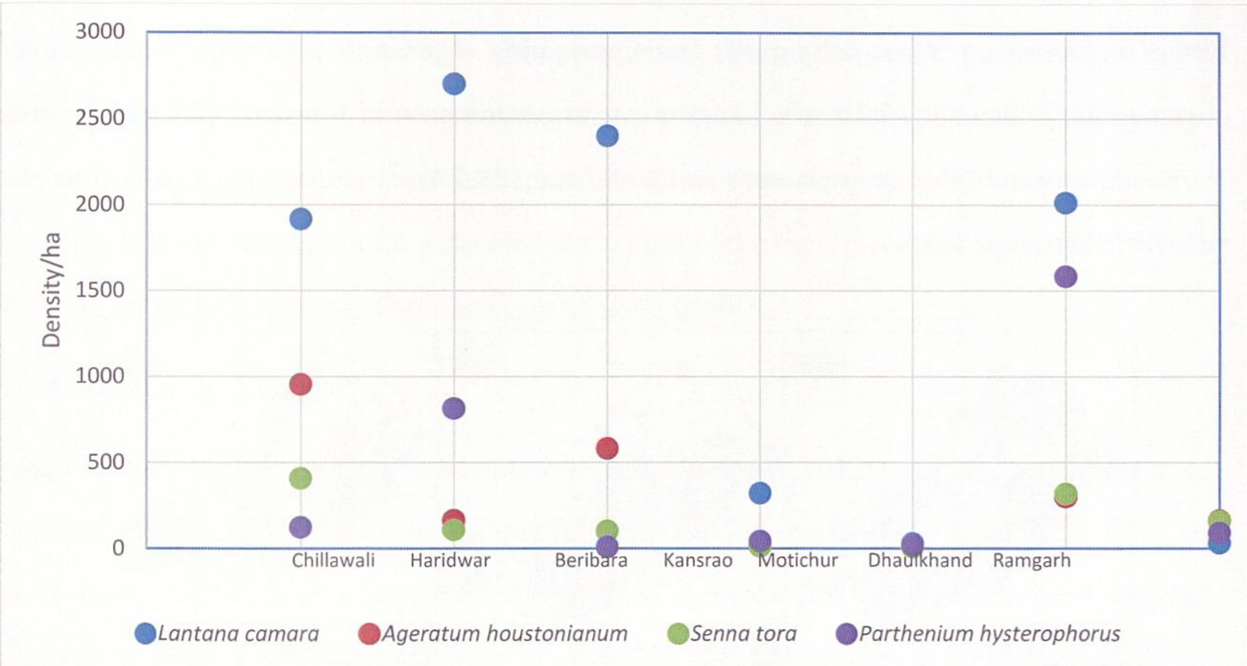


Figure 9: Density per hectare of major invasive species reported across different forest ranges in Western Rajaji.

4.1.4 Spatial distribution of selected invasive species

In Western Rajaji, the detailed analysis of invasive species revealed significant variations in the distribution pattern of *Lantana camara, Ageratina adenophora* and *Parthenium hysterophorus* (**Figure 10**). These variations in their prevalence across different forest ranges within the reserve underscore the ecological importance of understanding their impact on native ecosystems. The distinct percentages of these invasive species within each range highlight the need for control management strategies to address their ecological impact. By recognizing the ecological significance of each range and the specific challenges posed by these invasive species, the study spatially analyzed the distribution of these species in Western Rajaji. Employing a predictive model, the assessment focuses on *Lantana camara, Ageratina adenophora* and *Parthenium hysterophorus,* demonstrating robust predictive capabilities. The model performance is quantified through Area Under the Curve (AUC) values, with *Lantana camara* scoring 0.827, *Ageratina adenophora* at 0.847, and *Parthenium hysterophorus* at 0.813. Additionally, True Skill Statistic (TSS) values are provided, with *Lantana* at 0.658, *Ageratina* at 0.669, and *Parthenium* at 0.633. The distribution patterns of invasive species are further explored on a range-by-range basis, revealing *Ageratina adenophora* substantial coverage in Chillawali (19.2 km^2), *Lantana camara* dominance in Haridwar (23.5 km^2), and *Parthenium hysterophorus* prevalence in Dholkhand (28.5 km^2) showcasing distinct range-wise distribution patterns.

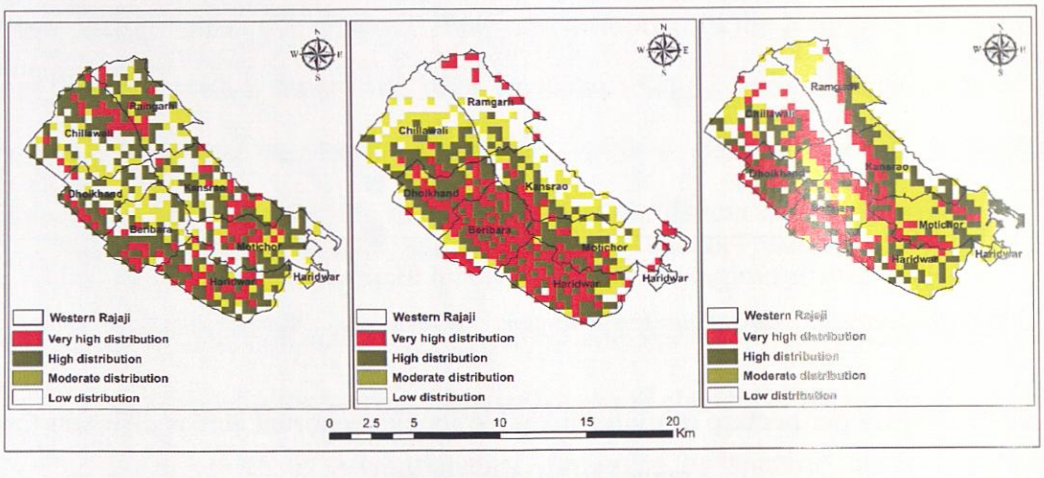


Figure 10: Distribution pattern of selected invasive species (i) *Ageratina adenophora* (ii) *Lantana camara* and (iii) *Parthenium hysterophorus*

Certainly, in Western Rajaji, the range-wise percentage distribution of the studied invasive species provides valuable insights into their ecological significance. *Ageratina adenophora* occupies varying percentages across the different ranges, with Chillawali covering 21.03%, Beribara 14.24%, Dholkhand 8.77%, Haridwar 19.78%, Kansrao 5.72%, Motichur 22.32%, and Ramgarh 8.14%. Similarly, *Lantana camara* exhibits distinct percentages within each range, ranging from 4.30% in Kansrao to 27.87% in Haridwar. *Parthenium hysterophorus* also presents variations in distribution, with percentages ranging from 6.84% in Haridwar to 23.08% in Dholkhand. Understanding the range-wise distribution percentages is crucial for recognizing the ecological significance of each range and the impact of these invasive species on the park's ecosystems. This knowledge forms the basis for shaping effective management strategies specific to the ecological needs of each range, thereby facilitating the preservation of native biodiversity and the maintenance of ecological balance within Western Rajaji.

4.2 Ecological impacts of invasive alien plant species on native flora

Soil sampling was conducted in the years 2021 and 2022 in selected *Lantana*-invaded and uninvaded sites, with the primary aim of assessing soil nutrient levels such as organic carbon (OC), organic matter (OM), nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), and sodium (Na). Additionally, measurements of soil pH and electrical conductivity (EC) were carried out to scrutinize the potential impact of *Lantana* on soil quality. This comprehensive sampling laid the foundation for a detailed evaluation of the multifaceted influence of *Lantana* invasion on various aspects of soil composition and quality.

4.2.1 Nutrient analysis

Based on consecutive two-year soil sampling during 2021 and 2022, the present study revealed that *Lantana*-invaded (LI) sites have higher pH (6.66±0.29) compared to uninvaded (UI) sites (6.45±0.60). Apart from the impact on plant growth, it is expected that the higher soil pH in LI sites can alter soil nutrient cycles, which further can affect the quality and productivity of the soil in the long run. For instance, LI had lower organic matter (1.91±0.93%) and phosphorus content (1.106±0.57ppm) as compared to UI sites (2.209±2.09% and 2.23±2.01ppm, respectively), whereas LI areas had higher sodium (37.57±11.81kg/ha) and nitrogen content

(0.09±0.013%) as compared to UI sites (36.63±9.54kg/ha and 0.1±0.05%, respectively), indicating that *Lantana* has a negative impact on soil nutrient composition.

It is evident that *Lantana* quickly colonizes different areas and out competes native plant species, leading to a decrease in overall plant diversity. Based on the comparative analysis of LI and UI sites, the current study revealed that the average number of plant species 15 and 21, respectively Also noted the density native species were significantly higher in UI sites than in LI sites. It shows that the *Lantana* has a negative impact on native plant species in terms of diversity, structure, and composition, for instance, areas with *Lantana* had lower plant density than uninvaded areas.

The soil parameters comparison between LI and UI sites (**Figure 11; Table 2**) revealed notable differences in key factors influencing soil quality. In LI areas, the pH is slightly higher at 6.66, compared to 6.45 in UI areas. This shift in pH, along with a lower electrical conductivity (EC) of 18.12 S/m in LI areas compared to 20.99 S/m in UI areas, indicates an alteration in the soil's chemical composition by *Lantana* invasion. Organic carbon (OC) and organic matter (OM%) are lower in LI areas (1.11% and 1.91%, respectively) compared to UI areas (1.55% and 2.21%, respectively). This suggests that *Lantana* invasion may contribute to a reduction in soil organic content. In terms of nutrient content, LI areas exhibited lower average potassium (235.62 kg/ha) compared to UI areas (274.74 kg/ha). The same trend is observed in average phosphorus content (1.11 ppm in invaded vs. 2.23 ppm in uninvaded). LI areas also showed slightly lower total nitrogen (0.096%) compared to UI areas (0.110%).

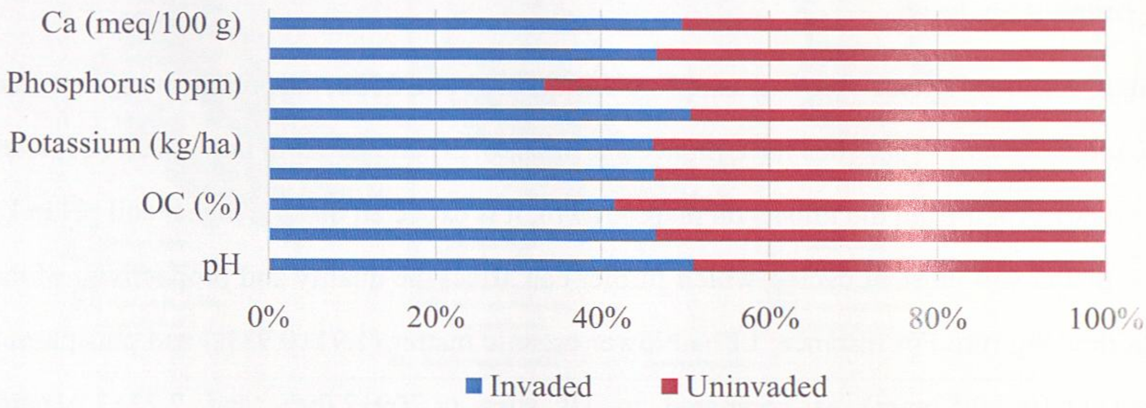


Figure 11: Soil parameters observed in *Lantana* invaded (LI) and uninvaded sites (UI).

Table 2. The soil parameters observed between *Lantana*-invaded (LI) and uninvaded areas (UI).

S.no.	Soil parameters	LI	UI
1.	pH	6.6553125	6.4478125
2.	EC (mS/m)	18.12083438	20.994769
3.	OC (%)	1.108091481	1.5525618
4.	OM (%)	1.910349714	2.2092343
5.	Potassium (kg/ha)	235.6186439	274.73585
6.	Na (kg/ha)	37.57268892	36.639761
7.	Phosphorus (ppm)	1.106015951	2.2306473
8.	Nitrogen (%)	0.09575	0.1097188
9.	Ca (meq/100 g)	168.6869673	171.46953

The t-tests were employed to discern differences in OC, OM, N, P, K, Ca, Na, soil pH and EC between *Lantana*-invaded and uninvaded sites. The t-tests comparing soil pH, OC, and P levels between invaded and uninvaded *Lantana* sites revealed significant differences (**Figure 12**), while OM, N, K, Ca, Na and EC showed insignificant differences (**Figure 13**). The soil pH t-value of -1.92477 (p= 0.031894), indicates a substantial difference in pH levels between the two sites. Similarly, the OC t-value of 4.81448 (p=0.00002), and the P t-value of 2.60029 (p=0.007159) suggest significant disparities in OC and P levels. These results imply that the invasion of *Lantana* can cause notable alterations in soil parameters, potentially carrying ecological implications. Studies conducted within the biogeographic province of North Western Himalaya exhibited similar results where *Lantana* invaded sites showed a decrease in their soil nutrient levels. Invaded sites in Western Rajaji were mostly dominated by *Lantana* as well as *Justicia adhatoda.* A decrease in the nutrient concentration of Phosphorus and Nitrogen in invaded soils may be possibly due to the co-occurrence of two species in a single zone (Bhatt et al., 1994; Dobhal et al., 2010; Rastogi et al., 2023). Consequently, sharing the same zone in the invaded area may be indicating that *Lantana* might be competing with *Justicia* for uptake of P and N. Furthermore, sharing the similar root system with *Lantana* might be indicative of a negative allelopathic effect of *Lantana* on *Justicia*. The observed changes in soil pH, OC, and P due to *Lantana* can significantly impact soil fertility, nutrient cycling, and microbial activity, influencing overall ecosystem dynamics as also indicated by Fan et al., 2010; Kumar et al., (2016). Notably, other tested parameters did not exhibit statistically significant differences. The research findings align with existing studies on *Lantana's* impact on soil nutrient dynamics in Uttarakhand. For instance, Dobhal et al., (2010) observed a significant decrease in nitrogen (N) and phosphorus (P) levels due to *Lantana* invasion. This trend is consistent with the findings in our study, where invaded areas exhibited lower nitrogen and phosphorus content compared to uninvaded areas. Similarly, Bhatt et al., (1994) reported a decrease in N and P levels in *Lantana*-invaded areas in the Kumaon Himalaya, aligning with the observed nutrient decrease in our study.

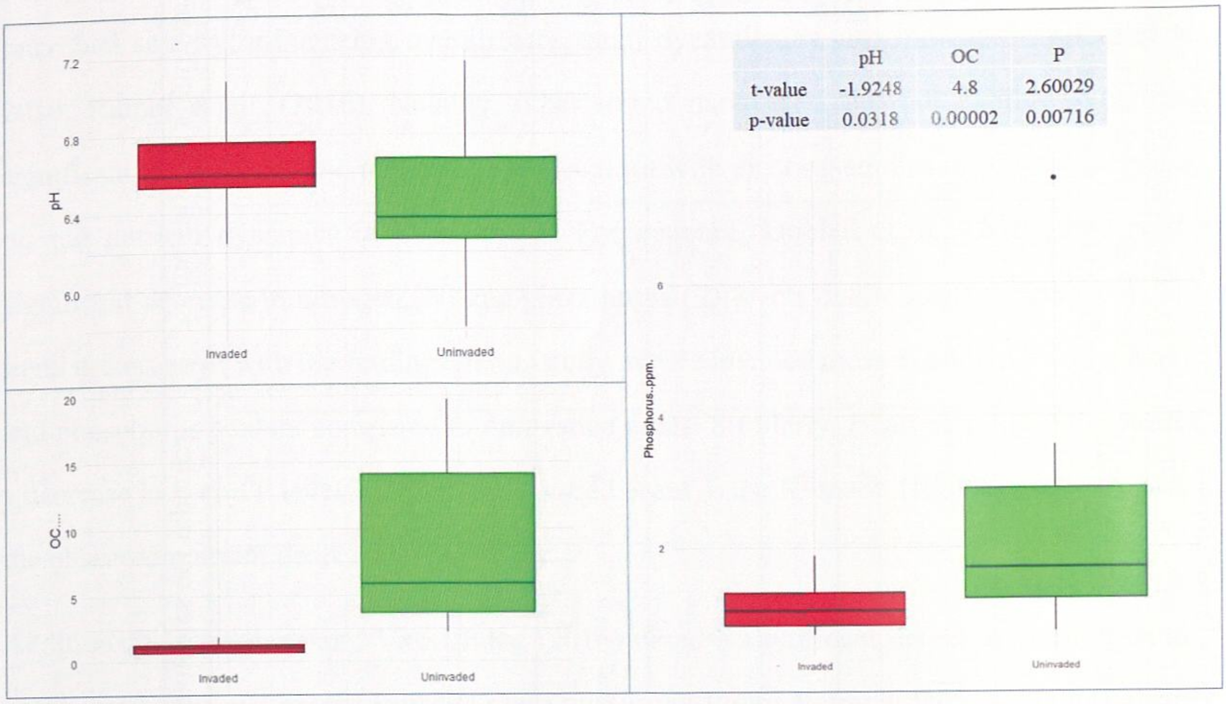
Additionally, Chandane and Vashishtha, (2015) noted a significant decrease in nitrogen and potassium levels in *Lantana*-invaded areas within the Rajaji National Park, providing further support to the trends identified in our investigation. Contrastingly, Mandal and Joshi (2015) observed an increasing trend in nitrogen, phosphorus, and potassium in *Lantana*-invaded areas of the Doon Valley. This was specifically in areas where neighbouring plants were removed and *Lantana* was the sole species in the invaded area. Therefore, the lowered concentration of nitrogen and phosphorus obtained in the present study might have been suppressed due to the presence of other plant species like *Justicia adhatoda* in the vicinity of *Lantana* invaded areas. A comparative analysis on effect of *Lantana camara* on soil physico-chemical properties across different tropical dry deciduous forests of India is provided in **Table 3**.

Table 3. Effect of *Lantana camara* on soil physico-chemical properties across different tropical dry deciduous forests of India.

S. no.	pH	Nitrogen	Carbon	Phosphorus	Potassium	Calcium	Magnesium	Sodium	Electrical Conductivity	Moisture Content	References
1	*	↓	*	↓	*	*	*	*	*	*	Bhatt et al., (1994)
2	↑	*	*	*	*	*	*	*	*	*	Sharma and Raghubanshi, (2007)
3	*	↑	*	↑	*	*	*	*	*	*	Rajwar, (2007)
4	*	↑	↑	*	*	*	*	*	*	↓	Raizada et al., (2008)
5	↓	↑	↑	*	*	*	*	*	*	↑	Sharma and Raghubanshi, (2009)
6	*	↑	↑	*	*	*	*	*	*	↑	Sharma and Raghubanshi, (2010)
7	*	↓	*	↓	×	↓	×	*	*	*	Dobhal et al., (2010)
8	×	↑	↑	*	*	*	*	*	*	*	Sharma and Raghubanshi, (2011)
9	*	*	×	*	↑	*	*	*	*	×	Rastogi et al., (2023)
10	↑	×	↓	↓	×	×	×	×	×	×	**Present study**

↓- indicates decrease	↑-indicates increase	*- indicates not reported	×- indicates no significant change

In summary, the existing literature and current study collectively underscore the diverse impacts of *Lantana* invasion on soil nutrient levels, emphasizing the need for context-specific ecological management strategies to mitigate its effects on native ecosystems.



	pH	OC	P
t-value	-1.9248	4.8	2.60029
p-value	0.0318	0.00002	0.00716

Figure 12: Soil physio-chemical properties observed for Soil pH, Organic Carbon and Phosphorus.

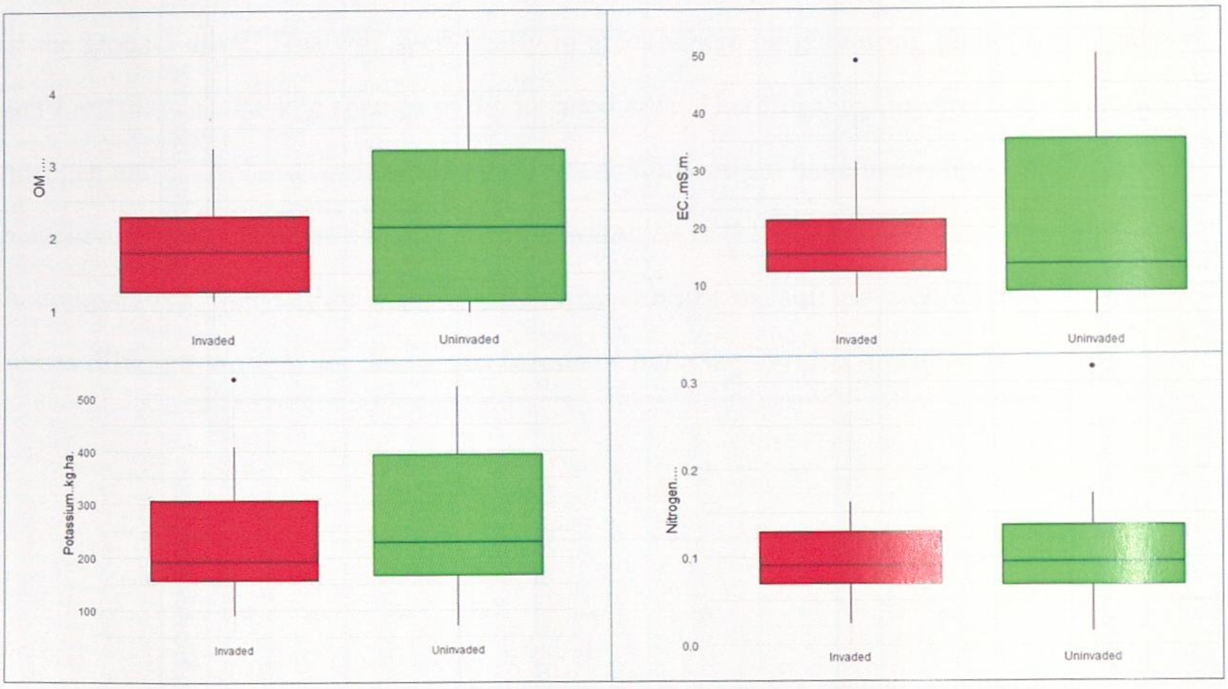


Figure 13: Soil physio-chemical properties observed for Organic Matter, Electrical Conductivity, Potassium and Nitrogen.

Understanding these alterations is crucial for comprehending the ecological consequences of *Lantana* invasion, as it may affect plant community composition, disrupt nutrient regimes, and potentially lead to cascading effects on other biotic components. Therefore, these scientifically significant findings underscore the necessity for comprehensive management strategies to mitigate the ecological impact of *Lantana invasion* on soil parameters and overall ecosystem health.

The rapid colonization of diverse areas by *Lantana* is evidently resulting in the outcompeting of native plant species, consequently leading to a decline in overall plant diversity. Through a comparative analysis of *Lantana*-invaded (LI) and uninvaded (UI) sites, the current study unveils significant differences. These findings emphasize the ecological repercussions of *Lantana* invasion, indicating a clear association between its presence and a reduction in native plant species diversity and density. This insight is crucial for understanding the ecological dynamics influenced by *Lantana* and underscores the need for effective management strategies to mitigate its impact on native vegetation.

4.2.2 Statistical analysis

Using Pearson correlation and t-tests, it was determined that sodium (Na) and potassium (K) levels in *Lantana*-invaded (LI) sites exhibited positive correlations with electrical conductivity (EC), organic carbon (OC), and organic matter (OM) (**Figure 14**). Conversely, phosphorus demonstrated positive correlations with OC and OM, while displaying a negative correlation with soil pH. Additionally, calcium displayed negative correlations with EC and potassium. In uninvaded (UI) sites, nitrogen (N), phosphorus (P), and potassium (K) manifested a positive relationship with each other (**Figure 15**). These findings indicate that invasive plants exert a significant influence on soil nutrient availability and composition, resulting in alterations to soil properties. For instance, the invasion of non-native plants may stimulate the accumulation of specific nutrients, such as Na and K, crucial for the growth of many invasive species. This could be attributed to invasive plants releasing more organic matter into the soil, introducing additional nutrients and fostering a positive correlation with soil organic carbon (OC) and organic matter (OM). Conversely, the negative correlation between calcium (Ca) and EC, and potassium suggests that invasive plants may competitively exclude other plants for these nutrients, diminishing their availability in the soil. The positive correlation observed between nitrogen, phosphorus, and potassium in UI sites indicates interdependence and the impact of similar environmental factors on their levels. In essence, the study underscores the intricate relationships between invasive plant species and soil nutrients, emphasizing the significance of monitoring soil composition in both invaded and uninvaded sites for ecological understanding and management.

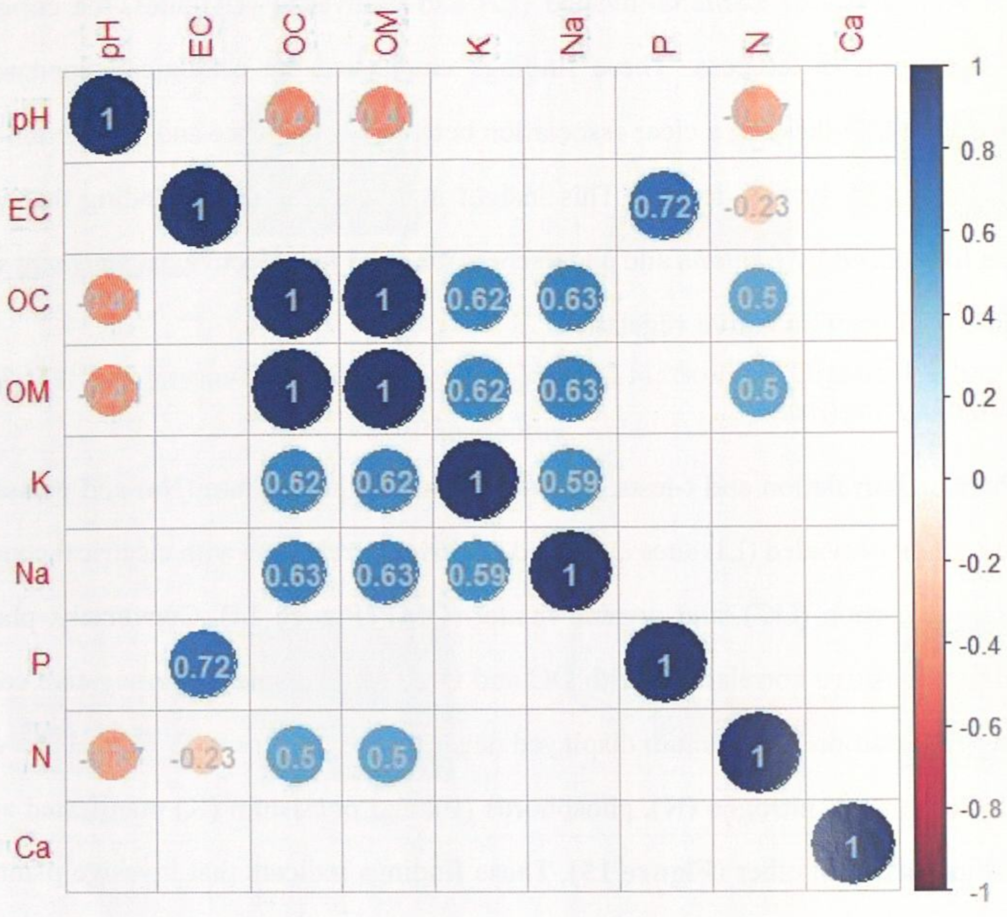


Figure 14: Correlation between soil parameters in *Lantana* invaded sites

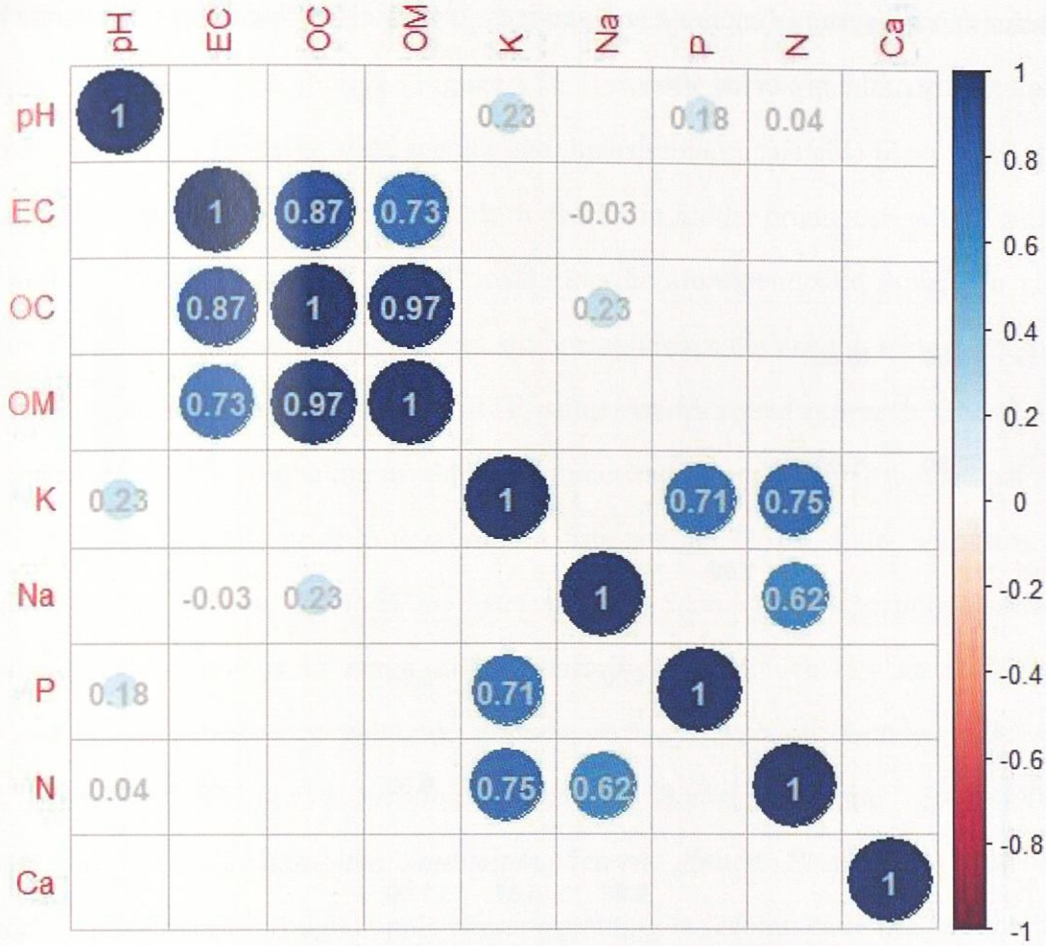


Figure 15: Correlation between soil parameters in uninvaded sites

The study highlights a noteworthy correlation between canopy cover and soil pH in both invaded and uninvaded sites, revealing an inverse relationship (**Figure 16**). However, non-invasive plant species, excluding *Lantana*, did not exhibit any discernible changes concerning canopy cover. This implies that the presence of *Lantana* in an ecosystem is intricately linked to reduced canopy cover and lower soil pH, potentially posing adverse effects on other plant species and the overall health of the ecosystem. *Lantana's* presence is associated with detrimental impacts on both soil and vegetation in the examined sites. The observed outcomes indicate a reduction in native plant diversity and alterations in soil chemistry, suggesting potential consequences such as decreased soil fertility, heightened erosion risks, and potential negative effects on soil physiochemical properties. These repercussions may, in turn, lead to modifications in ecosystem functions and services, ultimately influencing the overall health and sustainability of the protected site.

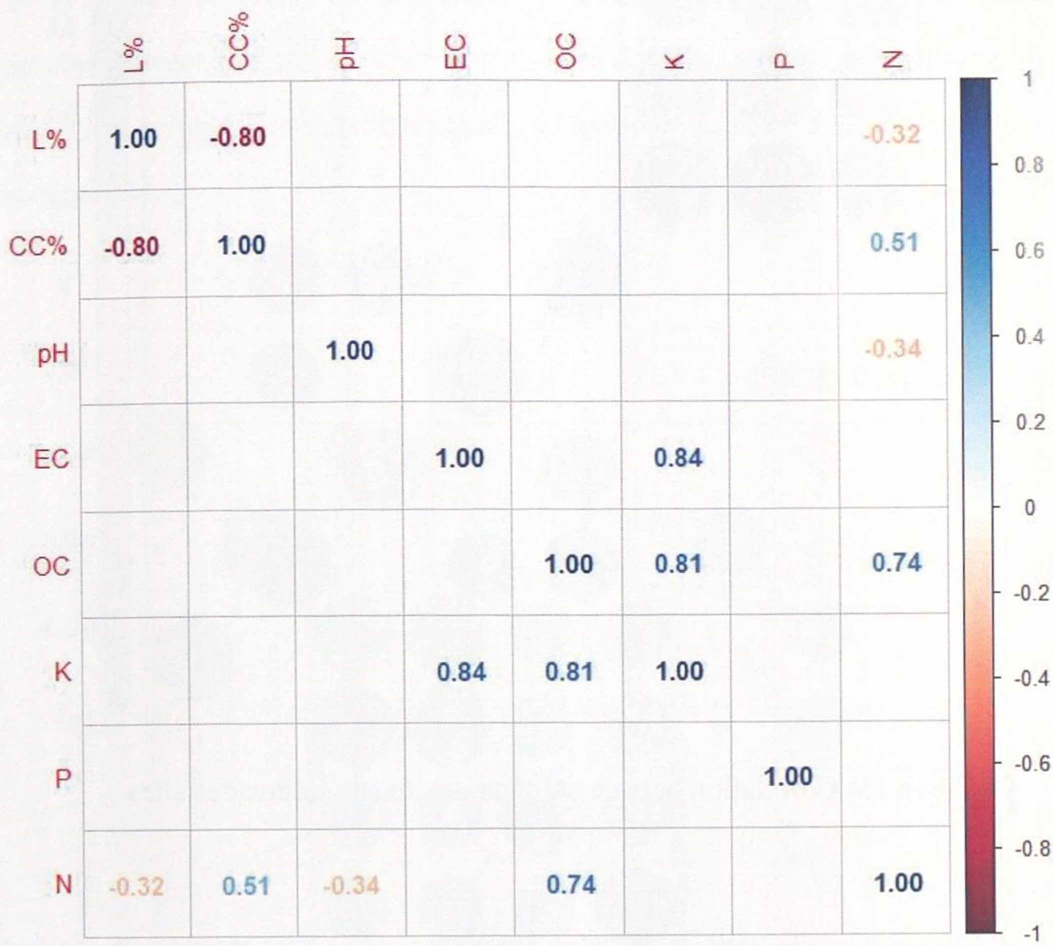


Figure 16: Correlation between soil parameters and canopy cover in *Lantana* invaded sites.

4.3 Ecological restoration measures

Globally, biological invasion is a major driver for decline in species and habitat diversity. India, located at the junction of Palearctic and Indo-Malayan realm, represents 03 of the 25 global biodiversity hotspots. It is also one of the few countries to adopt biogeography-based protected area planning. Considering the rising concern about the management of invasive species in the country, strategies on the management of invasive alien plant species have been included in National Biodiversity Action Plan since 2008. However, the lack of proactive efforts on management and regulation of invasive species in the country is a matter of grave concern.

The RTR management has been making conscious efforts to maintain the forested areas including grasslands of the reserve (**Figure 17**). However, these habitats are quite prone to infestation by several invasive alien species and undesirable/unpalatable plant species. Dense cover of unpalatable invasive species results in decline in fodder production which will in turn affect herbivore populations and tiger. Considering the aforementioned aspects in view and based on the field observations, the current study emphasises the need to restore and preserve the forested areas including grasslands of RTR using a multifaceted approach. One of the most important strategies for combating invasive and undesired plant species is the manual removal of such species, especially prior to flowering or fruit setting. This includes uprooting species such as *Lantana camara, Parthenium hyterophorus, Senna* spp., *Ageratina adenophora, Mesosphaerum suaveolens* to name a few, ensuring periodic checks on their invasion. Subsequently, introduction of palatable grasses such as *Cynodon dactylon, Chrysopogon fulvus, Vetiveria zizanoides, Heteropogon contortus, Bothriochloa* spp., *Sporobolus* spp., *Sorghum halepense, Dichanthium annulatum, Setaria glauca, Paspalidium flavidum* and *Neyraudia arundinacea* through supplementary planting is recommended to replace invasive species and enhance nutritional value. Simultaneously, the control of unpalatable species such as *Artemesia scoparia, Datura* spp., *Sida* spp. and *Senna* spp. should be carried out along the roads and near human habitations, emphasizing the importance of manual de-weeding and the introduction of desirable grass species. Furthermore, adapting the grassland composition to include dwarf palatable species such as *Chrysopogon fulvus* and *Cynodon dactylon* above the flood line to cater the forage requirements of small ungulates during high flood regimes. De-weeding of unpalatable weeds, monitoring woody ingression, and developing inspection paths for rigorous staff oversight further underscore the commitment to a comprehensive and adaptive restoration plan. Furthermore, addressing the invasive species issue should be integrated into the broader framework of conservation and management practices. This includes revisiting past decisions regarding exotic plantations, emphasizing the restoration of native vegetation, and implementing effective strategies for invasive species control to safeguard the park's biodiversity and ecological balance.

Currently, a nursery (0.42 hectare) prepared under CAMPA exists in Chillawali forest range where native and naturalized grasses such as *Cynodon dactylon, Imperata cylinderica, Chrysopogon fulvus, Heteropogon contortus, Saccharum spontaneum* and *Neyraudia arundinacea* of RTR are raised. In order to mitigate the effect of forest fire, invasive species control and to fortify the restoration initiatives in RTR, the establishment of grass and native tree saplings at each range is recommended. These nurseries will serve as vital repositories, ensuring a consistent supply of planting material crucial for the restoration of areas affected by invasive species, including those impacted by the removal of *Lantana* and areas recuperating from forest fires. Further, maintenance of detailed journals, akin to plantation journals will provide a structured approach for documenting activities, work completed, and financial information, fostering effective tracking and analysis of invasive species management efforts. Additionally, community engagement is advocated, allowing locals to contribute to invasive species control by cutting mature invasive plants in buffer areas on a quid pro quo basis. This collaborative approach should particularly target the outer fringes of all the forest ranges.

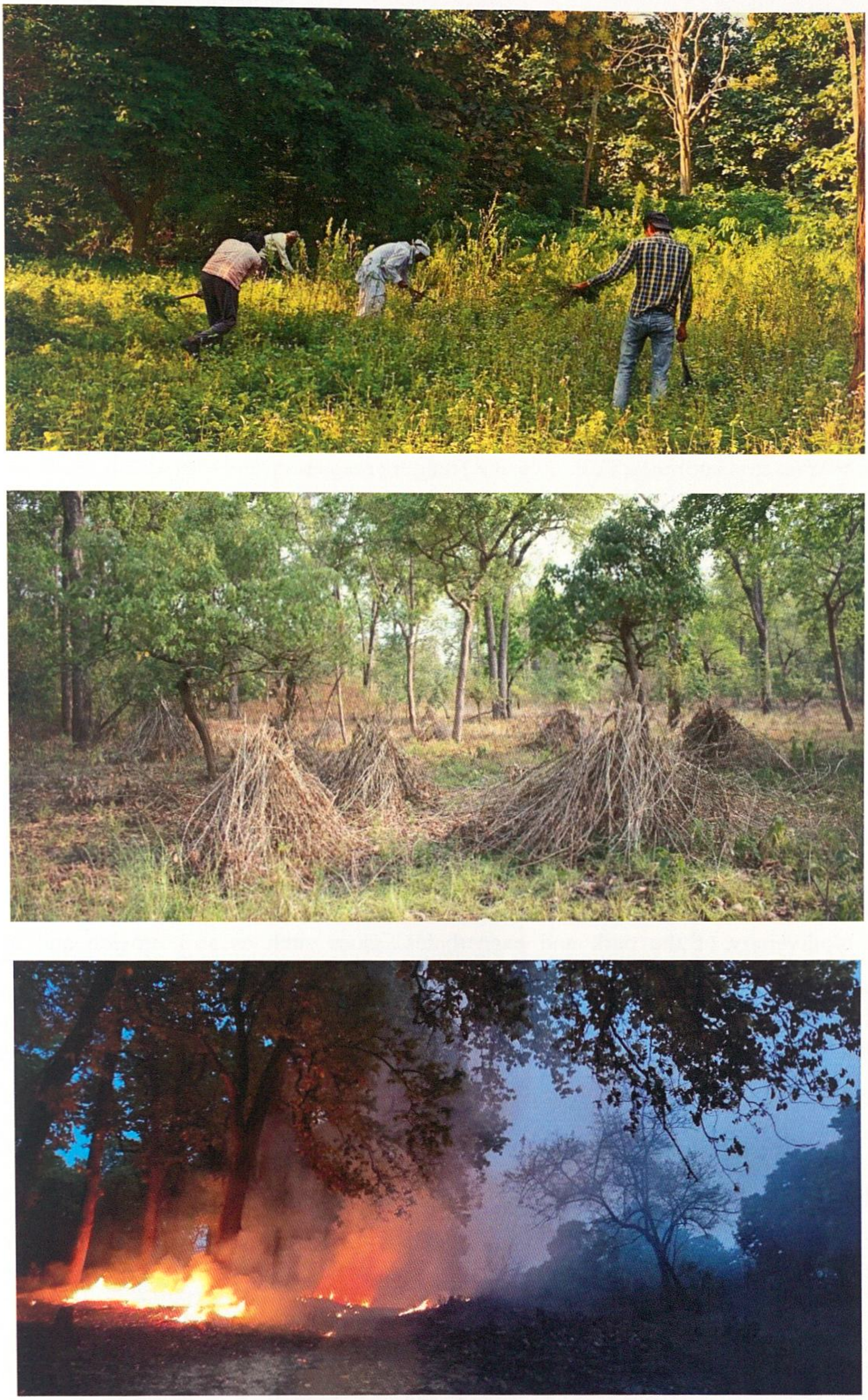


Figure 17: Invasive plant species removal and control burning in Rajaji TR.

4.4. Efficacy of various management practices in controlling the invasion of alien species

4.4.1 Management History

The Rajaji Tiger Reserve, like many other Protected Areas, faces the constant challenge of invasive alien plants encroaching on its diverse forest ecosystems. In response to this threat, the park management has implemented various strategies over the years to mitigate the impact of the non-native invaders such as *Lantana camara*, *Parthenium hysterophorus*, *Senna tora*, to name a few and preserve the integrity of native flora. This objective deals with the results of a comprehensive assessment aimed at understanding the efficacy of past management strategies in the reserve.

The historical overview of management practices in Rajaji Tiger Reserve reveals a significant focus on maximizing timber, bamboo, and other commercially valuable forest produce, leading to the implementation of silvicultural practices favoring the conversion to uniform stands for efficient timber production (Raiselly, 2022). Unfortunately, this approach, combined with the introduction of species such as Teak and *Eucalyptus*, has had adverse ecological consequences. The large-scale clearing of natural forests for plantations has not only reduced the effective habitat area but also created favorable conditions for the invasion of non-native species, particularly *Lantana*. This invasive plant, along with other non-native species, poses a threat to the biodiversity of the park and exacerbates issues such as soil erosion and habitat degradation. Furthermore, the presence of *Van Gujjars* within the park, engaged in buffalo rearing, has led to habitat disruption, promoting the spread of invasive species such as *Lantana, Parthenium, Ageratum* and compromising conservation efforts. The lack of concrete efforts due to invasive species and the proliferation of non-palatable species highlight the challenges faced by the park in maintaining its ecological balance.

Though, the management plan by Pandey (2010), attempted to shift the focus towards biodiversity conservation, habitat protection, and soil & moisture conservation, the non-execution of crucial administrative recommendations within the buffer zone, highlights challenges in implementing these conservation-oriented strategies. While, mechanical control measures, such as manual removal (Cut Root-Stock method) and mechanical clearing, have been employed to address localized infestations, which suggest that these methods have shown success in smaller areas (Love et al., 2009). But their scalability and cost-effectiveness on a larger scale are limited and can be questioned. Despite this, they remain a crucial component of integrated management strategies, contributing to the overall reduction of IAP abundance (Pascual et al., 2009). As per latest working plan (Raiselly, 2022) and *Lantana* eradication register maintained by park, the information gathered on the invasive species management including removal and monitoring is provided in detail.

4.4.1.1 Lantana infestation trends

The data shows that in previous management plan (Raiselly, 2022), the total area under *Lantana* infestation was 35.97% of the total park area, signifying a substantial presence of this invasive species. Whereas, according to Raiselly (2022) significant efforts were made to eradicate *Lantana*, resulting in a reduction of 50.26% of the total park area. Notably, despite eradication efforts, the forest ranges continue to experience a high proportion of *Lantana* infestation, indicating the challenges associated with completely eliminating this invasive plant.

4.4.1.2 Variability across ranges

According to latest working plan (Raiselly, 2022) the forest ranges such as Dhaulkhand and Chillawali exhibited relatively high proportions of *Lantana* infestation in 2001 and continued to face challenges in eradication efforts. Conversely, areas such as Haridwar and Motichur, have witnessed significant success in reducing *Lantana* infestation, showcasing the effectiveness of management practices.

4.4.1.3 Ecological implications

The reduction in *Lantana* infestation, as seen in some eastern ranges, is ecologically positive as it allows for the recovery of native vegetation, benefiting both flora and fauna (Raiselly, 2022). High proportions of *Lantana* in certain western ranges, even after eradication efforts, may suggest the need for adaptive management strategies to address persistent challenges.

4.4.2 Current Management Challenges

The current management challenges majorly include:

4.4.2.1 Acquisition of funds and their distribution

In Rajaji Tiger Reserve, funding from agencies such as the Compensatory Afforestation Fund Management and Planning Authority (CAMPA), Uttarakhand Forest Department, Project Tiger, Project Elephant and CLL are the major contributors towards *Lantana* removal. On an average, 50-60 hectares in each range has been cleared for *Lantana* removal. The cost of uprooting *Lantana* ranges from Rs. 15,000 to 20,000 per hectare. However, the eradication of *Lantana* varies by range due to availability of funding, which fluctuate throughout time. Furthermore, the uniformity of funds available to each range is not constant. Nevertheless, based on the allotment of funds, the current management strategy involves the removal of *Lantana* in all the forest ranges. Therefore, the effort towards management practices involved towards the removal of *Lantana* and other invasive species varies throughout the year and depend on the availability of funds.

4.4.2.2 Timing of invasive species removal

In a general practice, one of the most important strategies for combating invasive and undesired plant species is the manual removal of such species, especially prior to flowering or fruit setting. A major issue with invasive species removal efficacy is the timing of removal. Field observations reveal that removing species including *Parthenium hysterophorus, Lantana camara, Ageratina adenophora, Cassia* spp., *Mesosphaerum suaveolens* during their fruiting phase has resulted in overgrowth. As a result, it is critical to manage the invasive species removal areas and monitor them regularly. Furthermore, soil quality parameters should be assessed in such areas to identify the implications of invasive species removal on native vegetation.

4.4.2.3 Anthropogenic pressure

Based on the field observations, a significant involvement of *Van Gujjars* as well as local villagers near the fringes of western ranges, where lopping of trees for fodder, cattle grazing and collection of fuelwood from forests was observed. This has resulted in the gradual loss of indigenous vegetation, resulting in an increase of invasion cover near forest edges, mainly in outer fringes of the reserve.

4.4.2.4 Regular monitoring

Lantana removal sites need to be monitored for at least 3 to 5 years before implementation of restoration projects. The efficacy of removal areas needs to be assessed (for example – soil quality parameters need to be evaluated in *Lantana* removed sites before planting native vegetation for restoration purposes.

4.4.3 Current Management Strategies

4.4.3.1 Establishment of nurseries for habitat restoration

In a proactive initiative to combat invasive species and promote ecosystem restoration, the Rajaji Tiger Reserve has established grass nurseries strategically utilized during the rainy season. These nurseries play a pivotal role in the rehabilitation of areas affected by both *Lantana* uprooting and forest fires, which collectively contribute to invasive species control. The nursery focuses on cultivating local or native and naturalized grass species such as *Cynodon dactylon, Imperata cylinderica, Chrysopogon fulvus, Heteropogon contortus, Saccharum spontaneum* and *Neyraudia arundinacea* adapted to the unique ecological conditions of the reserve. The use of these indigenous grasses serves a dual purpose: firstly, it aids in stabilizing the soil and preventing erosion in areas where *Lantana* has been uprooted, facilitating the natural regeneration of native vegetation. Secondly, in areas affected by forest fires, the grass nursery provides a means to swiftly re-establish ground cover, minimizing the potential for invasive species re-infestation and supporting post-fire ecological recovery. This integrated approach showcases the reserve's commitment to holistic invasive species management, leveraging local plant species for both ecological restoration and sustained control of invasive threats within the Rajaji Tiger Reserve.

4.4.3.2 Lantana eradication programme

More than 25% of the area of Rajaji Tiger Reserve is under thickets of weeds (Raiselly, 2022), the dominant being *Lantana*. Starting from core to buffer, riverbank to grassland, road to fire lines, forest to non-forest, *Lantana* is found everywhere, due to its aggressive behavior and wide range of adaptation. Currently, *Lantana* eradication followed by ecological restoration is a principal activity in the reserve which is proactively being carried out with an objective to make the reserve *Lantana* free. Notably, *Lantana* उन्मूलन (eradication) register maintained at each forest range of the reserve, revealed that there is a considerable *Lantana* removal practice in place in each range of the reserve. For instance, a total of 385-hectare *Lantana* invaded area was cleared in Chillawali range during 2017-2021, year wise area of *Lantana* cleared is provided in **Figure 18**. Similarly, 680-hectare *Lantana* invaded area was cleared in Dhaulkhand range during 2013-2022 (**Figure 19**).

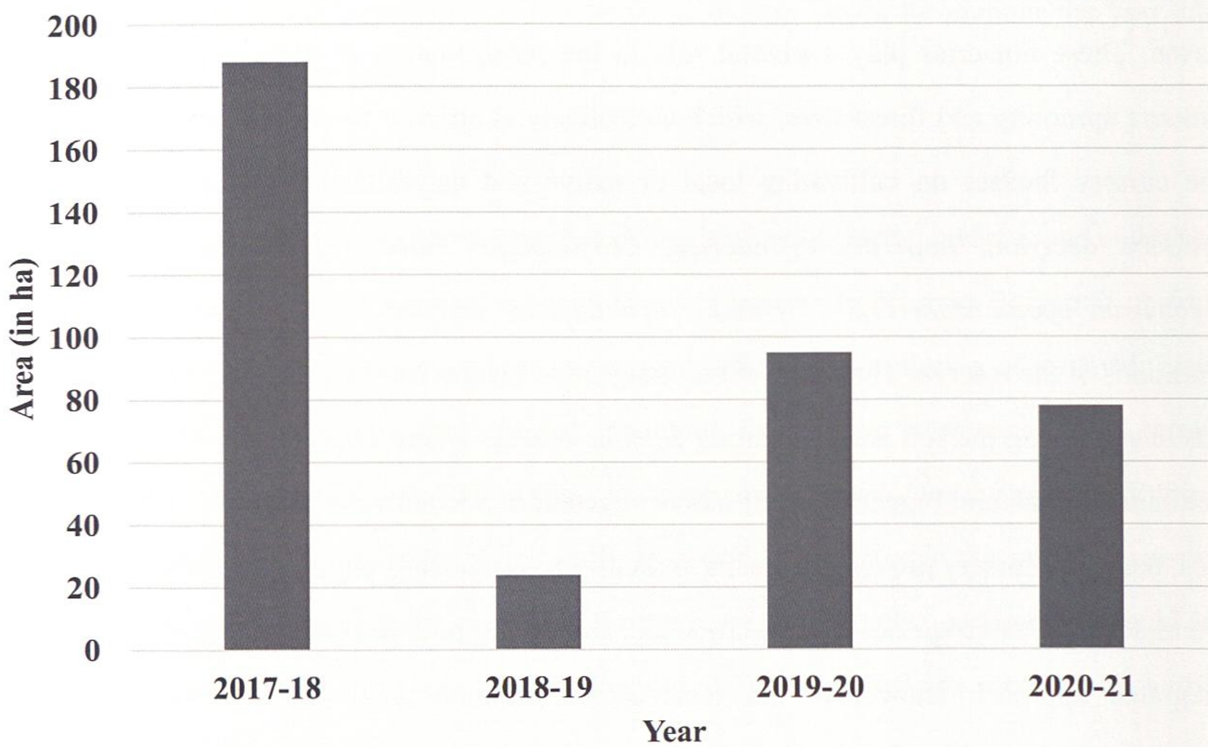


Figure 18: Year-wise *Lantana* removal in Chillawali range of Rajaji TR.

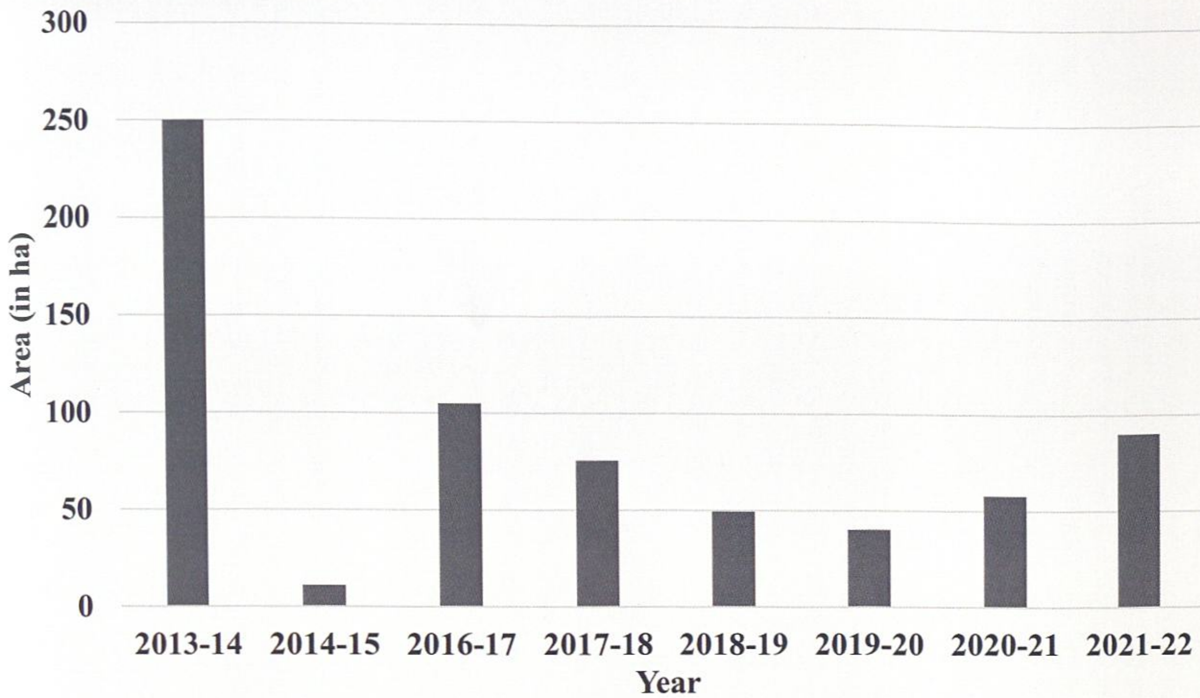


Figure 19: Year-wise *Lantana* removal in Dhaulkhand range of Rajaji TR.

4.4.3.3 Tourism through integrated approach

During the tourist period (November to June), alongside regular management efforts, the park management implements additional measures to enhance the ecological integrity of the landscape. A proactive approach is taken to eradicate invasive weeds, with particular attention given to clearing patches of *Lantana* extending 20-25 meters on either side of the road for better visibility of wild animals. This initiative serves a dual purpose by not only addressing the aesthetic concerns associated with weed overgrowth but also promoting the safety and satisfaction of the park visitors. By creating visually appealing and well-maintained areas along tourist routes, the reserve aims to offer a more immersive and pristine experience. Simultaneously, this targeted weed removal strategy contributes to the broader invasive species management plan, ensuring that high-traffic zones remain resilient against the encroachment of invasive plants. This integrated approach aligns with the reserve's commitment to both conservation and visitor satisfaction.

Additionally, during the summer season, the Rajaji Tiger Reserve places a strong emphasis on controlling forest fires, recognizing its dual impact on both fire prevention and weed eradication. The dry conditions prevalent during this period elevate the risk of wildfires, posing a significant threat to the ecosystem. However, the strategic control of fire plays a pivotal role not only in preventing uncontrolled blazes but also in managing invasive weeds. Controlled burns are employed as a targeted tool for weed eradication, particularly in areas where invasive species pose a heightened risk. By carefully orchestrating controlled fires, the reserve not only mitigates the risk of uncontrolled wildfires but also leverages this ecological tool to suppress the growth of invasive plants. This integrated approach exemplifies the reserve's commitment to comprehensive land management practices, ensuring the preservation of native biodiversity while actively addressing the challenges posed by invasive species during the summer months.

Roadside invasion of *Parthenium hysterophorus* in Haridwar range of Rajaji TR.

5. KEY RECOMMENDATIONS

5.1 Invasive Species Management Plan: Area-specific and species-specific

In pursuit of ecological restoration within the Rajaji Tiger Reserve, a paramount imperative is the development of a comprehensive Invasive Species Management Plan (ISMP) specific to the landscape and the invasive plant species. This strategic framework, which is specific to the ecology of RTR, will aim to improve wildlife and habitats holistically. ISMP should stress on the need to strengthen the ecological restoration activities involving enrichment of *Lantana* invaded areas with native plant species, emphasizing leguminous plants such as *Atylosia, Phaseolus,* and *Cajanus.* This will not only aid in soil enrichment but also aligns with the diverse ecological dynamics of the reserve. Considering this in view, a unified approach for invasive species management in RTR is proposed, the major components of ISMP are as follows:

5.1.1 Strategic patch planning and focused eradication

Optimize the effectiveness of *Lantana* management by consolidating operational areas into compact patches rather than dispersed locations across different forest ranges. Implement *Lantana* and other invasive species eradication and eco-restoration initiatives in a targeted and focused manner rather than adopting a piecemeal approach. This approach ensures a focused and concentrated effort, enhancing the ecological impact of eradication and restoration measures.

5.1.2 Establishment of nurseries

The establishment of well-equipped grass along with native plant nurseries within invaded ranges would be the practical solution for invasive species management in RTR. These nurseries would serve as essential hubs for a consistent supply of vegetative stock (stolon) and seeds required for the restoration of impacted sites resulted due to *Lantana* or other invasive plant species.

Grass nursery developed at Chillawali Range of Rajaji TR.

5.1.3 Strategic transplantation and seed broadcasting

Emphasize the strategic transplantation of stolons of *Cynodon dactylon*, *Vetiveria zizanoides* and *Imperata cylinderica*, alongside the collection and broadcasting of seeds of grasses such as *Crysopogon fulvus, Dicanthium annulatum, Apluda mutica,* and *Setaria pumila.* Employ innovative techniques, such as bundling inflorescences, for seed distribution, and monitoring germination during the monsoon.

5.1.4 Topographical Lantana camara and other major invasive plant removal

As observed in **Figure 10**, prioritize the removal of very high distribution and high distribution areas due to *Lantana* and other major invasive species such as *Ageratina adenophora, Parthenium hysterophorus* across different forest ranges. As a general practice, it is suggested that the removal of these invasive species be carried out from upper slopes to down slopes to mitigate the dispersal of seeds through surface runoff. This topographical approach aids in preventing seed spread and encourages more controlled restoration efforts.

5.1.5 Manual uprooting with minimal soil disturbance

Recommend manual uprooting of *Lantana* and other major invasive species such as *Ageratina adenophora, Parthenium hysterophorus* to name a few, before flowering period, minimizing soil disturbance, and strongly discourage mechanized excavation and removal. Whereas, to minimize disturbance to wildlife from noisy instruments, light weight grass trimmers (fuel/oil/gas) with minimal noise level may be tried to curb the growth of *Parthenium, Senna* spp., *Artemisia scoparia* and *Sida* spp. at young stage before flowering or fruit setting especially along the road side infestation of these exotic invasive species. This approach ensures a gentler ecological footprint during eradication efforts.

5.1.6 Comprehensive year plan

Advocate for the development of a comprehensive 5-year plan instead of a 3-year time frame to achieve complete control over species such as *Lantana camara*. This extended plan allows for a thorough and sustainable approach to eradication, with adequate funding arrangements. Furthermore, *Lantana* removal should be substituted with adequate restoration of native trees and shrubs. Since, *Lantana* acts as shelters for herbivores as well as forms a major diet of generalist species, restoration measures should also consider that adequate habitat is restored for the native fauna in the region.

5.1.7 Timely operation and funding

Stress the importance of conducting all operations in a time-bound manner, emphasizing that scheduled activities should not be skipped due to fund constraints. Ensure a continuous provision of funds to maintain the momentum of operations and facilitate a seamless continuum in the restoration process. Propose ad hoc funding arrangements from the CAMPA, State Forest Department, Project Elephant and NTCA to ensure the continuity of operations.

5.1.8 Rigorous monitoring and scientific documentation

Call for rigorous monitoring, incorporating photographic record and periodic vegetation plot assessments. Implementing measures to prevent the introduction of invasive species and detecting new infestations early on can be crucial in managing their impact. Additionally, the creation of a dedicated wing for invasive species management within the reserve is suggested to ensure focused attention, with officers and staff assigned for proper monitoring, assessment, and follow-up actions. Intensive restoration efforts, spanning a minimum of five consecutive years are imperative for areas affected by invasive plant species. Further, regular training and capacity-building programs for field staff is recommended for invasive species infestation, native seed collection, storage, propagation techniques, biomass management, grazing control, and nursery management. This holistic approach, attuned to the specific ecological intricacies of the reserve will lay the foundation for a resilient and thriving ecosystem in the face of invasive species challenges.

5.2 Recommendations for Adaptive Management Strategies in Rajaji TR

The strategies for invasive species eradication employ a multi-faceted approach to effectively combat such species.

(i) Develop forest range specific and invasive species-specific management plan for three to five years to complete removal and eco-restoration of the targeted sites.

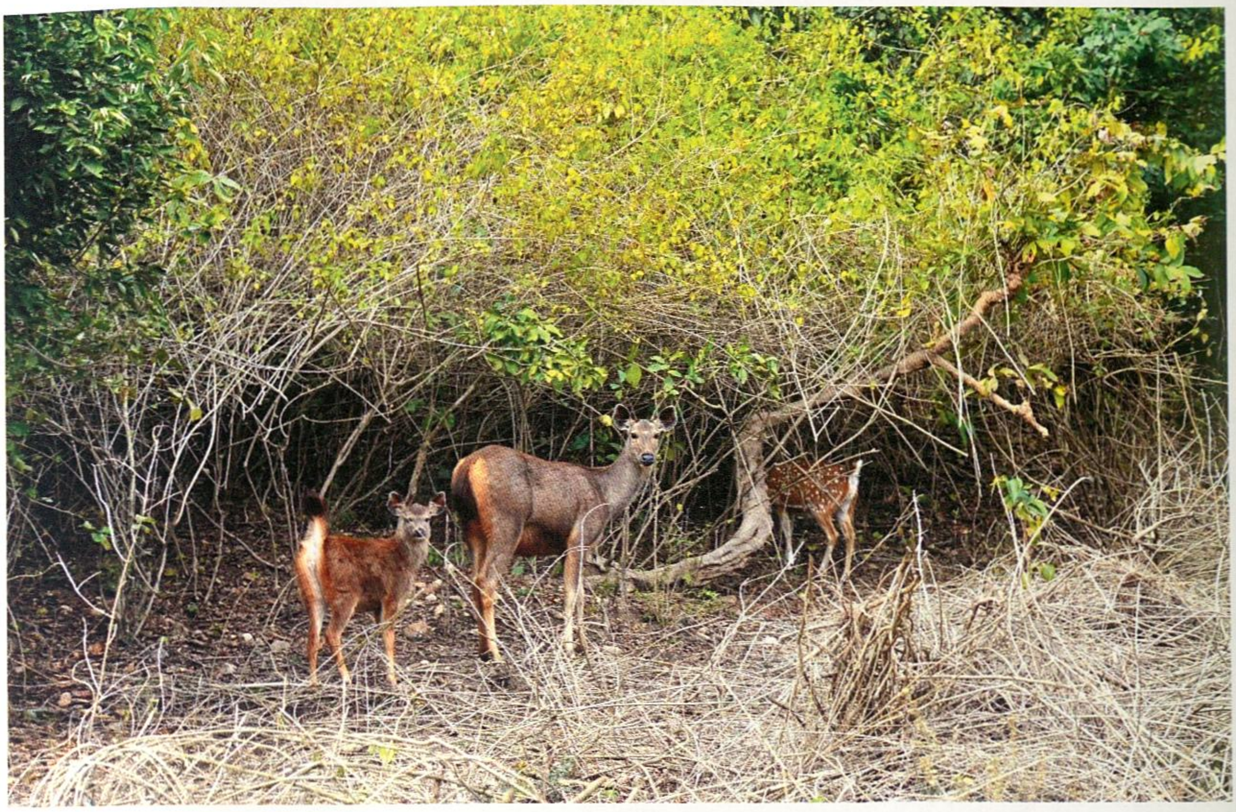
(ii) Mapping the forest range with invasive species infestation in order to identify invasion hotspots and a comprehensive understanding of their distribution across the range.

(iii) Holistic and time-phased approach: Removal of invasive species in the 1st year followed by monitoring for at least three to five years.

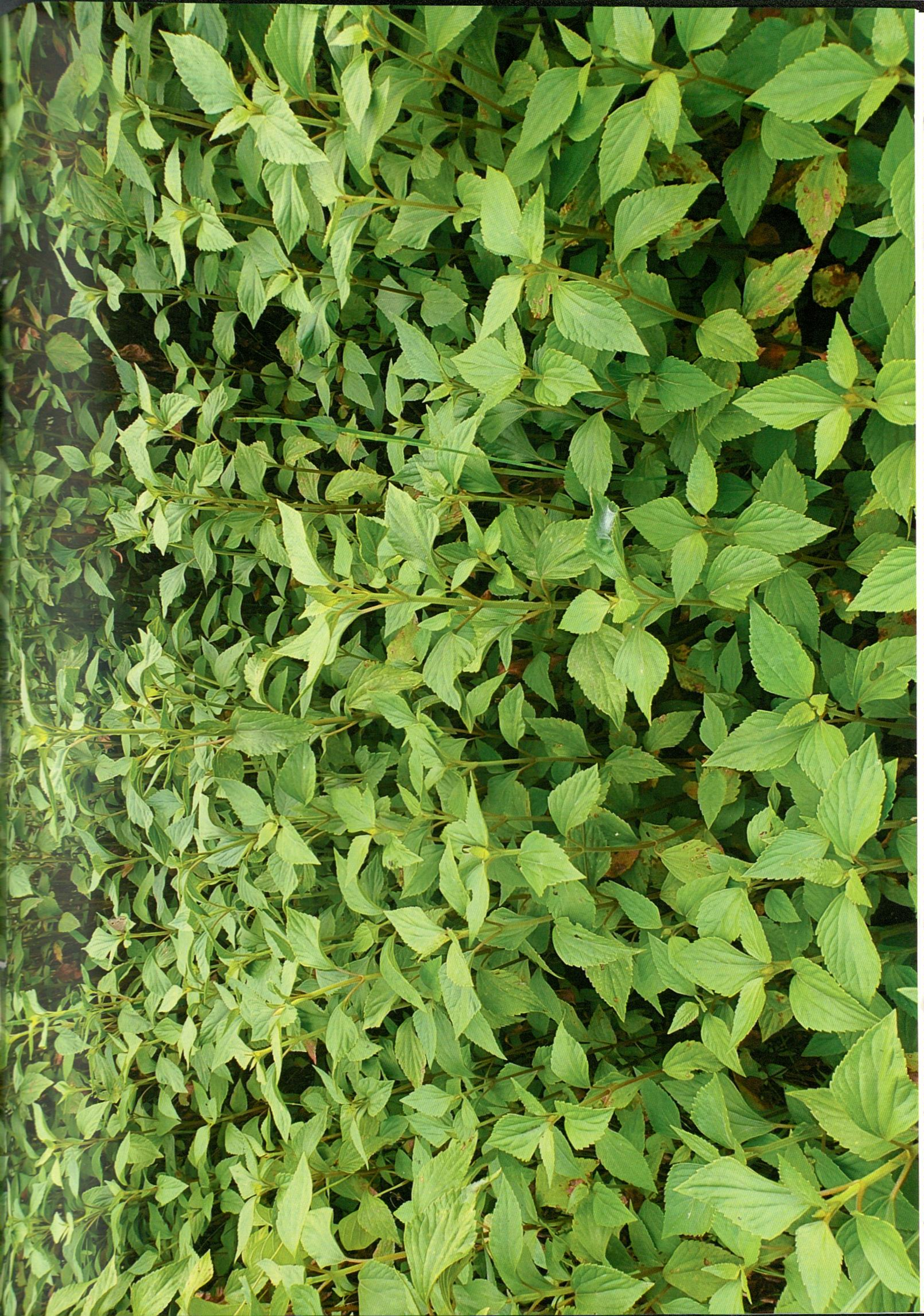
(iv) Timing of removal: Ensure removal of invasive species prior to flowering or fruit setting.

(v) Control burning of slashes and supplementary planting with grasses such as *Cynodon dactylon, Chrysopogon* spp., *Apluda mutica, Vetiveria zizanoides, Heteropogon contortus, Bothriochloa* spp., *Sporobolus* spp., *Sorghum halepense, Dichanthium annulatum, Setaria* spp., *Paspalidium flavidum* and *Neyraudia arundinacea* and subsequent monitoring for three years.

(vi) Strengthen the ecological restoration activities involving enrichment of invaded areas with native plant species, emphasizing leguminous plants such as *Atylosia, Phaseolus,* and *Cajanus* to enhance nutritional value.



Top: Proliferation of *Lantana camara*. **Bottom:** Grassland patch amidst forested area



6. REFERENCES

Akash, N. & Bhandari, B. S. (2018). Phytosociological studies, biodiversity conservation in a subtropical moist deciduous forest of Rajaji Tiger Reserve; Uttarakhand, India. *Int J Res Anal Rev*, 5(3): 39-51.

Bhagwat, S. A., Breman, E., Thekaekara, T., et al. (2012). A battle lost? Report on two centuries of invasion and management of *Lantana camara* L. in Australia, India and South Africa. *PLoS One*, 7(3): e32407.

Bhatt, Y. D., Rawat, Y. S., & Singh, S. P. (1994). Changes in ecosystem functioning after replacement of forest by *Lantana* shrubland in Kumaun Himalaya. *Journal of Vegetation Science*, 5(1): 67-70.

Champion, H. G., & Seth, S. K. (1968). A Revised Survey of Forest Types of India, Govt. of India Press, New Delhi, 404p.

Chandane, G., & Vashishtha, H. B. (2015). Impact of *Lantana camara* on vegetation and soil in Tropical Moist Deciduous Forest of Rajaji National Park, Uttarakhand. International Conference on "Ethical Prospects: Economy, Society and Environment.

Cottam, G., & Curtis, J. T. (1956). The use of distance measures in phytosociological sampling. *Ecology*, 37(3): 451-460.

Das, K. K., Ravan, S. A., Negi, S. K., et al. (1996). Forest cover monitoring using remote sensing and GIS- A case study in Dhaulkhand range of Rajaji National Park, Uttar Pradesh. *Journal of the Indian Society of Remote Sensing*, 24: 33-42.

Dobhal, P. K., Kohli, R. K., & Batish, D. R. (2010). Evaluation of the impact of *Lantana camara* L. invasion, on four major woody shrubs, along Nayar river of Pauri Garhwal in Uttarakhand Himalaya. *International Journal of Biodiversity and Conservation*, 2(7): 155-161.

Dogra, K. S., Kohli, R. K., & Sood, S. K. (2009). An assessment and impact of three invasive species in the Shivalik hills of Himachal Pradesh, India. *International Journal of Biodiversity and Conservation*, 1(1): 4-10.

Fan, L., Chen, Y., Yuan, J. G., et al. (2010). The effect of *Lantana camara* Linn. invasion on soil chemical and microbiological properties and plant biomass accumulation in southern China. *Geoderma*, 154(3-4): 370-378.

Gupta, S. (2018). Invasive Alien Species in the Flora of Jammu, Jammu and Kashmir.

Hijmans, R. J. & Elith, J. (2011). Species distribution modeling with R. Retrieved from http://cran.r-project.org/web/packages/dismo/vignettes/.

ICFRE. (2020). A Handbook on Invasive Species. Indian Council of Forestry Research and Education, Dehradun, India.

INBAP. (2019). India's National Biodiversity Action Plan 2019. Ministry of Environment, Forest and Climate Change.

Jones, A., Smith, B., & Johnson, C. (2020). Invasive Species Management: A Handbook of Principles and Techniques. Oxford University Press.

Kannan, R., Shackleton, C. M. & Uma Shanker, R. (2013). Reconstructing the history of introduction and spread of the invasive species, *Lantana*, at three spatial scales in India. *Biological Invasions*, 15: 1287–1302. https://doi.org/10.1007/s10530-012-0365-z

Kaushik, M. (2014). Influence of habitat structure and anthropogenic disturbances on diurnal raptor community in Rajaji National Park, India. *Raptor Research & Conservation Foundation project completion report*, 1-36.

Kimothi, M. M., Anitha, D., Vasistha, H. B., et al. (2010). Remote sensing to map the invasive weed, *Lantana camara* in forests. *Tropical Ecology*, 51(1): 67-74.

Kumar, H. & Subudhi, S. P. (2013). Assessment of grass species diversity and wild animals occurrence in *Van Gujjars* relocated site of the Rajaji National Park in Uttarakhand, northern India. *Journal of Zoology*, 2(1): 30-39.

Kumar, R., Jinnah, Z., Khan, A. H., et al. (2016). Impact of alien invasive plant species on crop fields and forest areas of Hawalbag Block of Kumaun Himalaya-people's perceptions. *Imp. J. Interdiscip. Res*, 2: 632-635.

Lamsal, P., Kumar, L., Aryal, A., et al. (2018). Invasive alien plant species dynamics in the Himalayan region under climate change. *Ambio*, 47(6): 697-710.

Langmaier, M. & Lapin, K. (2020). A systematic review of the impact of invasive alien plants on forest regeneration in European temperate forests. *Frontiers in Plant Science*, 11: 524969. doi: 10.3389/fpls.2020.524969

Love, A., Babu, S. & Babu, C. R. (2009). Management of *Lantana*, an invasive alien weed, in forest ecosystems of India. *Current Science*, 1421-1429.

Mandal, G. & Joshi, S. P. (2015). Eco-physiology and habitat invasibility of an invasive, tropical shrub (*Lantana camara*) in western Himalayan forests of India. *Forest Science and Technology*, 11(4), 182-196.

Manly, B. F. J. (2009), Statistics for Environmental Science and Management, Chapman & Hall/CRC.

Mondal, T., Bhatt, D. & Ramesh, K. (2021). Distribution modeling of *Lantana camara* and identification of hotspot for future management of the species in the lower Shivalik region of Uttarakhand, India. bioRxiv, 2020-12.

Mondal, T., Bhatt, D. & Ramesh, K. (2023). Bioclimatic modelling of *Lantana camara* invasion in the Shivalik landscape of Western Himalaya. *Tropical Ecology*, 64(2): 249-263.

Mungi, N. A., Coops, N. C., Ramesh, K., et al. (2018). How global climate change and regional disturbance can expand the invasion risk? Case study of *Lantana camara* invasion in the Himalaya. *Biological Invasions*, 20: 1849-1863.

Naithani, H.B., Shah, R. & Rasaily, S.S. (2017). Study on qualitative and quantitative survey of invasive species in Dehradun District. Uttarakhand Biodiversity Board, Dehradun.

Pandey, S. (2010). Working Plan (2000-2010) of Rajaji National Park, Uttarakhand Forest Department.

Pathak, R., Negi, V. S., Rawal, R. S., et al. (2019). Alien plant invasion in the Indian Himalayan Region: state of knowledge and research priorities. *Biodiversity Conservation*, 28: 3073–3102. https://doi.org/10.1007/s10531-019-01829-1

Perkins, L. B. & Nowak, R. S. (2013). Native and non-native grasses generate common types of plant–soil feedbacks by altering soil nutrients and microbial communities. *Oikos*, 122(2): 199-208.

R Core Team (2021). R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. URL https://www.R-project.org/.

Rai, P. K. & Singh, J. S. (2020). Invasive alien plant species: Their impact on environment, ecosystem services and human health. *Ecological Indicators*, 111: 106020.

Raiselly, S. S. (2022). Working Plan (2012-2022) of Rajaji Tiger Reserve, Uttarakhand Forest Department.

Raizada, P., Sharma, G. P. & Raghubanshi A. S. (2008). Ingress of *lantana* in dry tropical forest fragments: Edge and shade effects. *Current Science* 94(2): 180-182.

Rajwar, G. S. (2007). Invasive effects of *Lantana camara* in the forests of Southern Garhwal Himalaya. *Progress in Environmental Science and Technology*, 1.

Ramaswami, G., Prasad, S., Westcott, D., et al. (2014). Addressing the management of a long-established invasive shrub: the case of *Lantana camara* in Indian forests. *Indian Forester*, 140(2): 129-136.

Rastogi, R., Qureshi, Q., Shrivastava, A., et al. (2023). Multiple invasions exert combined magnified effects on native plants, soil nutrients and alters the plant-herbivore interaction in dry tropical forest. *Forest Ecology and Management*, 531: 120781.

Ravi, B.A. (2016). Rajai Tiger Reserve: A conservation odyssey in the Shivaliks. M/s Bisen Singh Mahendra Pal Singh, Dehradun. 158p.

Rishi, V. (2009). Wildlife habitat enrichment for mitigating human-elephant conflict by biological displacement of *Lantana. Indian Forester*, 135(4); 439.

Rishi, V. (2010). A note on 1995 wildlife habitat enrichment plantation by biological displacement of *Lantana* in Rajaji National Park. *Indian Forester*, 136(10): 1424-1425.

Rodgers, W. A., Panwar, H. S. & Mathur, V. B. (2002). Wildlife Protected Area Network in India: A Review, Executive Summary. Wildlife Institute of India, Dehradun, 1-51.

Roura-Pascual, N., Richardson, D. M., Krug, R. M., et al. (2009). Ecology and management of alien plant invasions in South African fynbos: accommodating key complexities in objective decision making. *Biological Conservation*, 142(8), 1595-1604.

Sagoff, M. (2005). Do non-native species threaten the natural environment? *Journal of Agricultural and Environmental Ethics*, 18.

Schelhas, J., Alexander, J., Brunson, M., et al. (2021). Social and cultural dynamics of non-native invasive species. Invasive species in forests and rangelands of the United States: A comprehensive science synthesis for the United States forest sector, 267-291.

Seebens, H., Blackburn, T. M., Dyer, E. E., et al. (2018). Global rise in emerging alien species results from increased accessibility of new source pools. *Proceedings of the National Academy of Sciences*, 115(10), E2264-E2273. https://doi.org/10.1073/pnas.1719429115

Sharma, G. P. & Raghubanshi, A. S. (2007). Effect of *Lantana camara* L. cover on local depletion of tree population in the Vindhyan tropical dry deciduous forest of India. *Applied Ecology and Environmental Research*, *5*(1), 109-121.

Sharma, G. P. & Raghubanshi, A. S. (2009). *Lantana* invasion alters soil nitrogen pools and processes in the tropical dry deciduous forest of India. *Applied Soil Ecology*, *42*(2), 134-140.

Sharma, G. P. & Raghubanshi, A. S. (2010). How *Lantana* invades dry deciduous forest: a case study from Vindhyan highlands, India. *Tropical Ecology*, 51(2), 305-316.

Sharma, G. P. & Raghubanshi, A. S. (2011). *Lantana camara* L. invasion and impact on herb layer diversity and soil properties in a dry deciduous forest of India. *Applied Ecology and Environmental Research*, 9(3), 253-264.

Simberloff, D., Martin, J.L., Genovesi, P., et al. (2013). Impacts of biological invasions: What's what and the way forward. Trends in Ecology & Evolution 28: 58– 66. https://doi.org/10.1016/j.tree.2012.07.013.

Smith-Ramesh, L. M. (2017). Invasive plant alters community and ecosystem dynamics by promoting native predators. *Ecology*, 98(3), 751-761.

Upadhyay, S., Mondal, T., Pathak, et al. (2019). A network theoretic study of potential invasion and spread of *Lantana camara* in a part of Rajaji Tiger Reserve, India. *Ecological complexity*, 40, 100793.

Veitch, C. R. & Clout, M. N. (2002) Turning the tide: The eradication of invasive species. Gland, Switzerland and Cambridge, UK: IUCN Species Specialist Group.

Wei, T. & Simko, V. (2021). R package 'corrplot': Visualization of a correlation matrix (Version 0.92). Available from https://github.com/taiyun/corrplot

Wickham, H. (2016). ggplot2: Elegant graphics for data analysis, Springer-Verlag New York.

Yadav, S. P., Tiwari, V. R., Mallick, et al. (2023). Management effectiveness evaluation of Tiger Reserves in India, Fifth Cycle, 2022. Wildlife Institute of India, Dehradun and National Tiger Conservation Authority, Government of India