

Investigating the phenology and interactions of competitive plant species co-occurring with invasive *Lantana camara* in Indian Himalayan Region.

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Abstract

Invasive plant species are considered one of the significant drivers of habitat loss for endangered plants by strangling and covering native flora in various biogeographical zones. They have also been observed to alter the local ecology, resulting in a decline in the frequency and abundance of native inhabitants that the invaded region supports. The settlement of aggressively spreading invasive species is widely recognized as one of the most severe challenges to biodiversity conservation.

Lantana camara is an invasive that affects the local biodiversity and is considered one of the ten worst weeds by the International Union for Conservation of Nature (IUCN). Native and indigenous species may evolve to compete with invasive species, reducing invader fitness. It is observed that species competition fluctuates throughout environmental gradients, life phases, and abundances. Hence competition outcome is very context-dependent. In the present study, we conducted field surveys in Doon Valley of the Indian Himalayan Region (IHR) to screen the species growing and competing with *Lantana camara*. We identified the potential competitor species based on the Domin-Karajin scale and IVI. In our experiments, we observed phenological growth patterns (using the BBCH scale) for these species with *Lantana* and conducted experiments for intra and interspecific competition using RII (Relative Interaction Index). We suggest native species that can potentially reduce *Lantana*'s invasiveness. The present study will be helpful for policymakers and park management authorities to adopt the use of competitive native species for dealing with invasives in the IHR.

Introduction

Biological diversity is threatened by Invasive Alien Species (IAS), species that are introduced and/or spread outside their native range. Native plant species, crops, and natural water bodies are all at risk of habitat loss from IAS is a significant threat to global and local diversity (Early *et al.*, 2016). Both biological processes and human activity have contributed to the proliferation of alien plants. In the past, reluctance to identify positive uses for IAS species has undermined efforts to control plant infestations¹.

Several theories have been proposed to explore the mechanisms of plant invasions^{2,3}. When invasive plant species (IAS) breach natural dispersal barriers by several factors, their natural opponents possibly lose control of them, known as the enemy release (ER)⁴. It is a common notion that Invasive populations outcompete the native competitors in the environment, as per the Evolution of Increased Competitive Ability (EICA) hypothesis⁵. The impact and threat of IAS is a well-known phenomenon over time. Research has shown its impact on depleting biodiversity, and its ability to compete with native flora has resulted in major habitat loss⁶. When colonizing new places, invasive plant species generally outcompete native species, but the principles behind their success remain unknown⁷. IAS disturbs the balance of ecosystems by involving direct and indirect drivers responsible for biodiversity loss⁸. IAS uses a variety of strategies to establish itself in new environments and is supported by theories like EICA. Different biological invasion ideas, such as the "new weapon hypothesis,"^{9,10} and "biotic resistance hypothesis"¹¹, have

speculated that allelochemicals emitted by a root or leaf may interfere with neighbours. Interactions can occur where one invasive species may favor the invasion of another intrusive, known as an invasional meltdown¹². By modifying recipient community features and propagule pressure, invader–invader interactions could affect the success of future invaders¹³. Limiting similarity hypothesis states that plants compete within themselves when they occupy similar niche, and coexistence can be seen when niche differs.

On the contrary,¹⁴ states that related species flourish well when they co-exist based on functional traits according to phylogeny. However, trait-based niche descriptions could overlook interaction patterns between distinct species¹⁵. Emphasis on using traditional biological control to handle established invasive alien species causing environmental harm¹⁶. Biological control is an effective tool for managing invasive species in vulnerable settings.

However, all these theories have remained controversial; allelopathy can also help native species withstand invasion by improving their biotic resistance against invasives¹⁷.

One such pantropical invasive weed that harms ecosystems and results in enormous biodiversity loss is *Lantana camara*, considered native to Central and South America. An increase in the presence of *Lantana* in a tenure of thirty years and its expansion range over the years worldwide is depicted in (Fig. 1) IAS, like *Lantana*, can reach out to allelopathic substances in the soil, which directly resists the growth of native plants in the vicinity or indirectly depress native plants by disrupting beneficial belowground microbial mutualisms or altering soil resources¹⁸. Native plant allelopathic effects on exotic plants and interactions between conspecific and heterospecific invading plants have rarely been studied¹⁹.

Despite the costs involved in its removal, people have been using mechanical methods to weed out *Lantana*²⁰. Considering the opportunistic behaviour of this weed, it reestablishes itself by finding open canopies²¹. Cutting them, spraying herbicides, or using any biocontrol agent doesn't work well with these species²². The only natural process preventing its growth is establishing canopy cover using fast-growing native trees and grasses that can claim the open land, followed by mechanical removal²³. Numerous efforts have been made to control the spread of this invasive species through mechanical, chemical, and biological methods²⁴. However, out of these methods, the biological method was found to be more economical, sustainable, and evident²⁵. Studies have shown that fast-growing trees can be selected to restructure a community invaded by a weed majorly²⁶ focusing on envisioning a suitable crop competitive strategy to reduce *Lantana*'s invasiveness by introducing native species and mechanical removal. Based on the geographical location involving edaphic factors and climatic conditions, the selection of competitive species with the potential vigour to fight invasive must be chosen to prevent their reoccurrence by establishing a closed canopy^{27,28}. However, selecting a fast-growing tree would take some time until it creates its canopy cover, and what if the invasive retakes control after mechanical removal?²⁹. Study on in-depth invasion studies to clarify the cause and effect of native and invasive species have already been reviewed³⁰ suggesting that these studies combine observations of natural

environment invasions with well-controlled removal or addition studies. Henceforth, we used a consortium of native grasses to reclamation infested land and planted native species in our experiments.

The adaptive response of individual plants to biotic and abiotic stress is a typical driver of community assembly outcomes and is a crucial predictor of biological invasions when competitive ability traits are considered, stating that economic considerations influence the control strategy selected for invasive plant removal. Interaction between plants can range from facilitative to competitive and restoration ecology aims to promote native species flourishing in the long run to preserve biodiversity³¹ Few studies have focused on multiple plant interactions³², and more detailed studies are required to understand the underlying mechanisms of species coexistence. Moreover, there is a gap in relevant studies on plant interaction involving invasive species³³. In this study, we investigated whether selected invasive plants produce more biomass under the competitive pressure of native/indigenous competitors or vice-versa; and (ii) Are selected native/indigenous species better competitors than selected invasive species?

The rationale behind the study

Other than field observations, those plant species that grow fast, produce a significant amount of biomass, enrich the soil, and are native to the area were chosen for plantation. Apart from these benefits, fuel, fodder, and medicinal uses of these plants, including grasses, are added advantages other than restoration. The choice of a practical treatment approach and its use in the field can be improved by a better understanding of the biology and timing of invasive plant species phenology. Community ecologists have focused on understanding phenology, which is crucial in assigning competitive advantages to invasive alien species. Detection, control, and mitigation of invasive species may be aided by developing phenological calendars like BBCH³³. With this background, the objective of the present study was to monitor the growth and competition behaviour of six native species with *Lantana camara* in Doon Valley of IHR.

Methods and Experimental Design

Experimental Site

Two experimental sites were selected for the experiments in Dehradun district, Uttarakhand, an Indian Himalayan State. The first site is located in Forest Research Institute besides the climate observatory on the campus, and the second site is in Bhopalpani (compartment 08), located in the Raipur region, Mussoorie Forest Division of Doon Valley. Doon Valley is a part of the IHR. The Shivalik range of the Himalayas (lesser Himalayas) surrounds it. The vegetation in the region includes a mix of deciduous, lush green valleys and terraced fields. The climate of Dehradun is subtropical, humid with four distinct seasons: Winter (December to February), Summer (March to May), Monsoon (June to September), and Post-monsoon (October-November) are the four seasons, with an average yearly rainfall of about 168.75 mm. Doon Valley receives an average of 70–80% precipitation between June and September. The valley has fertile alluvial soil with sandy, clayey, and rocky components.

Methodology

During the field survey, it was observed that, in the landscapes dominated by *Lantana*, many native species co-exist and, in some case, appears to be competing with *Lantana*. We selected these species based on the Domin Karajin scale^{34,35}. We laid 10 quadrats of 10 m X 10 m at sixty locations in the Doon Valley and further screened suitable competitive species based on the IVI values to proceed with experiments. The ecological concept of competition describes the effects of species cohabitation in a resource-limited environment³⁶.

The experimental design consisted of young plants where three replicates for each species were studied for intraspecific competition in a ratio of 1:1, and twenty-seven replicates were analysed for interspecific competition in the same ratio. Fresh weight, an adequate indication of resource allocation to growth, was used to examine the intraspecific and interspecific competitive effects. The plant species used in our experiments do not fall in endangered/threatened/rare endangered threatened categories. These native plant species occur in natural conditions with *Lantana*. Seeds were collected along roadside and unprotected areas (sampling locations do not fall in any reserved/protected forests) and, we assured no disturbance to any of the conserved/protected areas. Prior permission was already taken from forest department through proper channel from Director FRI. Final permission was granted for conducting the experiments by Divisional Forest Officer, Mussoorie, Uttarakhand. We also declare that no native flora or habitat was harmed while collecting seeds from field sites. These seeds were sown in the nursery of Silviculture Division in June 2019. Saplings were grown in similar conditions inside the New Forest Campus nursery, Silviculture Division, Forest Research Institute, Dehradun. The pots were regularly watered every morning in the summer months and three times per week in other months by garden can sprinkler. The pots are randomly placed with a minimum spacing of 40 cm to avoid competition between the pots.

Some plants in the experiments died due to disturbance by wild animals, wind, or pot breakage. The experiments were carried out consecutively for four years, and data were recorded for the phenological growth stages. The same species were planted at two different geographical locations in Doon Valley to see the performance of species in field conditions.

Finding simple and affordable ways to execute restoration plantings is vital. Following the three-tier vegetation system, grasses that are fast growing and can cover up the soil were introduced³⁷. Henceforth, a consortium of four types of grass species was made by preparing seed balls. Farm yard Manure (FYM) composition was mixed in a 2:1:1 ratio with the seeds of *Penisetum pedicellatum*, *Panicum antidotale*, *Sachharum spontaneum*, and *Thysanolaena latifolia*. Seeds were spread by making seed balls in RBD design on field sites before the onset of rainy season. The research hypothesis was that the fast-growing grass would cover the field and prevent the regrowth of *Lantana*, limiting its opportunistic behaviour for open canopies. Nursery-grown seedlings of identified plant species were used for plantation after the mechanical removal of *Lantana* from the field sites. Outplanting was chosen rather than seeding because the survival rate of out planting is higher. We conducted field experiments of

planting selected native species with *Lantana camara* and observed the interaction and phenology in detail. Fresh weight was calculated for each species after the termination of experiments. It is stated here that all the authors comply with the IUCN Policy Statement on Research Involving Species at Risk of Extinction and the Convention on the Trade in Endangered Species of Wild Fauna and Flora.

Phenological observation of concerned species by Landmark BBCH scale

Plant phenology is closely related to biodiversity and environmental dynamics. It is impacted by habitat and climate change, which can vary the timing and frequency of phenological occurrences and many other elements of ecosystem functioning. As a result, phenology monitoring in many biomes has received more attention in recent years. The phenology of an organism provides one of the most apparent indicators of the effects of recent climate change, as it is an essential biological characteristic that determines its survival³⁸. It ultimately depends on the plant's inherent adaptability and its exposure to variations in temperature and rainfall if ecological stability is achieved over the long run.

Various monitoring techniques like remote sensing, carbon flux towers, citizen science approaches, drones, fixed cameras, dendrometers, high-resolution satellites, multi and hyperspectral sensors, and accelerometers are used to understand phenology better and how it affects ecosystems, and each of them has advantages and disadvantages³⁹. This experiment uses the BBCH scale (Biologische Bundesanstalt, Bundessortenamt und Chemische Industrie) to understand the phenology of other native plants and their phenological variation. It has been extremely helpful in simplifying and systematically studying the vegetative and reproductive stages of annual, biennial, and perennial plants⁴⁰.

Results and Discussion

Phenological documentation using BBCH scale for understanding the phenology

The scale uses bi-numeric codes to indicate important Principal Growth Stages (PGSs, 0–9) and related secondary growth stages (SGSs, 0–9). Following the previous study of the BBCH scale for *Lantana*⁴¹, we propose BBCH scale for five other native plants used in experiments in competition with *Lantana* for the first time (Fig. 5) following the pattern of PGS stages as mentioned in (Table 1). To precisely monitor these phases during the growing period, periodic visits are required at least once every two weeks. However, during the critical growth phase (phase change to reproductive growth), observation frequency can be reduced to at least once every week, or sometimes daily observations may be required. BBCH scale for *Aegle marmelos*⁴² and *Broussonetia papyrifera* have been documented earlier. However, a BBCH scale does not exist for *Pterospermum acerifolium*, *Urtica dioica*, *Pongamia pinnata*, *Adhatoda vasica*, and *Bauhinia variegata*.

From interfering with species dispersal and disrupting species interactions resulting in the alteration of the carbon cycle and, in turn, affecting global climate, changes in phenology can have far-reaching consequences. Changes in the phenology of these native species coupled with climatic variables lead ecologists and researchers to design and implement restoration plans for invasive species like *Lantana*.

Table 1
BBCH Codes for different PGS (0–9)

Code Description	
Principal growth stage 0: sprouting/bud development	
00	Dormancy: buds closed and covered by scales
01	Beginning of bud swelling
03	End of bud swelling
07	Beginning of sprouting or bud breaking; shoot emergence
09	Buds show green tips
Principal growth stage 1: leaf development	
10	Green leaf tips 10 mm above the bud scales
	Bud elongation
11	First leaves unfolded
15	More leaves unfolded, but not yet at full size. First leaves unfolded
17	Most leaves unfolded on majority of tree
19	Leaf expansion complete
Principal growth stage 3: stem elongation	
30	Beginning of stem elongation
31	Stem about 10% of final length
33	Stem about 30% of final length
35	Stem about 50% of final length
35a, 35b, 35c.....	Stages continue.
39	Stem about 90% of final length; cessation of stem growth
Principal growth stage 5: inflorescence emergence	
51	Inflorescence or flower buds visible
55	First individual flowers visible but still closed
59	First flower petals visible (in forms with petals)
Principal growth stage 6 : flowering (main shoot)	
60	First flowers open
61	Beginning of flowering, 10% flowers open

Code Description	
62	20% of flowers open
63	30% of flowers open
64	40% of flowers open
65	50% of flowers open, full flowering: first petals may be fallen
67	Flowering finishing; majority of petals fallen or dry
69	End of flowering: fruit set visible
Principal growth stage 7 : Fruit development	
72	Fruit 20% of final size
75	Fruit 50% of final size
78	Fruit 80% of final size
79	Fruit final size
Principal growth stage 8 : fruit ripening	
89	Fruit fully ripe
Principal growth stage 9 : senescence, beginning of dormancy	
91	Shoot growth completed; foliage still green and terminal buds developed
92	Beginning of leaf discoloration
93	Beginning of leaf fall
95	50% of leaves fallen
97	End of leaf fall

Major climatic variables governing phenology:

Average annual mean for different climatic variables have been recorded for four years, i.e., wind speed (2.35 m/sec) (Fig. 4), specific humidity (9.31 g/kg) (Fig. 4), rainfall (168.75 mm) (Fig. 3), relative humidity (59.51%) (Fig. 3), temperature max. (36.27°C), temperature min.(9.18°C) and temperature avg. (18.11°C) (Fig. 2).

Density of species based on IVI

The study areas was sampled using the nested quadrat method. Ten Quadrats were laid at sixty sites randomly selected for the study. Four quadrats of 5m x 5m and 1mX1m were nested within each quadrat

to study shrubs and herbs in each site (Fig. 7(a)). The data was analysed for Phyto-sociological attributes as per ⁴³.

The Importance Value Index (IVI) of species determined the dominance of the tree and shrubs. Basal cover ⁴⁴ was calculated by using the following formula; basal area = πr^2 , Where 'r' is the radius of the species. The following formulas were used for the calculation:

$$\begin{aligned} \text{Density} &= \frac{\text{Total number of individuals of a species}}{\text{Total number of quadrats studied}} \\ \text{Frequency (\%)} &= \frac{\text{Total number of quadrat of occurrence of species}}{\text{Total number of quadrats studied}} \times 100 \\ \text{Relative Frequency} &= \frac{\text{Frequency of a species}}{\text{Frequency of all the species}} \times 100 \\ \text{Relative Density} &= \frac{\text{Density of a species}}{\text{Density of all the species}} \times 100 \\ \text{Relative Dominance} &= \frac{\text{Basal area of a Species}}{\text{Basal area of all species}} \times 100 \end{aligned}$$

Importance Value Index (IVI) = Relative Frequency + Relative Density + Relative Dominance

The ratio of abundance to frequency (A/F) was worked out to determine the distribution pattern. This ratio indicates regular (< 0.025), random (0.025 to 0.05), and contagious distribution > 0.05. The data was used to interpret the distribution pattern of plant species and regeneration in the community.

$$\text{Abundance} = \frac{\text{Total number of individual of the species}}{\text{Total number of quadrats in which species occur}}$$

The cover-abundance of the invasive species was determined by Domin-Karajin scale (Table 2). The following scale value of Domin Karajin is absolute in so far as the values relate to a reference area.

Table 2
Domin Karajin Scale for cover abundance

Scale	Cover %	Details
10	≈ 100	Any number, with complete cover
9	> 75	Any number with more than $\frac{3}{4}$ but less then complete cover
8	50–75	Any number with $\frac{1}{2}$ - $\frac{3}{4}$ cover
7	33–50	Any number with $\frac{1}{3}$ - $\frac{1}{2}$ cover
6	25–33	Any number with $\frac{1}{4}$ to $\frac{1}{3}$ cover
5	10–25	Any number with $\frac{1}{10}$ to $\frac{1}{4}$ cover
4	5–10	Any number with $\frac{1}{20}$ – $\frac{1}{10}$ cover
3	1–5	Scattered with cover under $\frac{1}{20}$
2	< 1	Very scattered with small cover
1		Seldom with insignificant cover
+		Solitary with insignificant cover

Administrative boundaries of the Dehradun District were downloaded from the Diva GIS software. Raw field data was arranged in the .csv file format to input into the Arc GIS software. Critical variables used for each site were Latitude and Longitude, Elevation in meters, and Density per hectare covered by the specific species. Field survey data was analyzed and used as a data source to create this GIS map.

The IVI values used in Fig. 7 are calculated after Quadrat surveys in different locations of Doon Valley. Maps were created using Arc GIS software. These figures, i.e., a,b, and c, show the density of *Lantana* for shrubs and trees in Doon Valley. A comparative idea of how dense the *Lantana* invasion is in Doon Valley can be figured out from these GIS maps. The presence of shrubs and tree density concerning their IVI values according to the survey at different sites can be inferred from the respective maps in Fig. 6. Brown Layer shows the highest value of IVI. The presence of *Lantana* in Doon Valley can be seen clearly with the majority of green colour that signifies the mid-range of IVI value. The lower half of the Doon Valley map has a lower elevation and is heavily infested by *Lantana*, according to the survey, except for some areas that range from light blue to pink.

Shrubs with high IVI values are mainly present in the middle of the lower half of the map, depicted with brown colour, and the rest areas in green represent intermediate values of IVI. Furthermore, Orange, yellow, and green indicate that shrubs are present from the high to medium IVI range. The shades of Yellow to Brown show that tree density is high in the Doon Valley, with some green and yellow patches. When comparing Map c with a and b, one can infer that *Lantana* and other shrubs are present in the lower half of the Doon valley, i.e., from 250–850 m in abundance, and the middle portion (Fig. 6) with green and yellow colour has highest *Lantana* infestation. The above observation also supports the theory that

Lantana does not establish itself under closed canopies. It avoids the less-lit areas where trees are present and continues expanding its boundaries in sunlit or open environments.

Young plants of each species were planted in pots to check interspecific and intraspecific (control) combinations in the same water and nutrient availability conditions. AGB(Above Ground Biomass) and BGB(Below GroundBiomass) were measured for individuals of each species and observed their phenological characteristics throughout study period. After performing pot experiments to evaluate the performance by observing AGB and BGB of native species with the *Lantana* in specific conditions utilizing similar edaphic factors. Seven dominant native species i.e., *Urtica dioica*, *Adhatoda vasica*, *Broussonetia papyrifera*, *Pongamia pinnata*, *Bauhinia variegata*, *Pterospermum acerifolium* and *Aegle marmelos*.

RII

RII was used as a comparative index to measure the competition between selected natives and *Lantana*. It is suitable for parametric meta-analyses due to its solid statistical properties. This index measures the facilitative or competitive interaction between plants ⁴⁵. Negative values indicate that the interaction between plants is competitive and positive values indicate that interaction is facilitative. $RII = 0$ suggests no significant change of mixed monoculture on the plant's growth. The formula is also represented as $B_w = B_o + \Delta BF - \Delta BC$, where B_w is biomass observed by the target plant grown with other plants (treatment), and B_o is biomass potentially achieved without species interaction (control).

$$RII = (\Delta BF - \Delta BC) / ((\Delta BF + B_o) + (-\Delta BC + B_o))$$

$$= \Delta BFC / (\Delta BFC + 2B_o)$$

$$= (B_w - B_o) / (B_w + B_o), RII = [-1, 1]$$

ΔBF is denoted as an increase of biomass produced by facilitation (from 0 to $+\infty$), and ΔBC is a decrease in biomass due to competition. $\Delta BFC = \Delta BF - \Delta BC$, i.e., observed biomass change = absolute effect of the interaction. Therefore, $B_w - B_o = \Delta BFC$. Facilitation and competition would not be compared using these equations. Therefore, a new index, RII, is proposed as : (treatment – control) / (treatment + control)

RII shows negative values for PP, BP, BV, and UD. It clearly states that these plants have the potential to compete with *Lantana* (Fig. 8).

Figure 9 (a) Control experiments (Intraspecific competition): R1, R2 and R3 between seven native species. LC represents *Lantana camara*, PP represents *Pongamia pinnata*, BP represents *Broussonetia papyrifera*, AV represents *Adhatodavasica*, PA represents *Pterospermum acerifolium*, AM represents *Aegle marmelos*, BV represents *Bauhinia variegata*, and UD represents *Urtica dioica*.

This Fig. 9 (a) and (b) represent cluster analysis of all the species with respect to *Lantana* using Prism software Version 8. 4. 0 (455). It depicts how other species interact with *Lantana* and is represented in

Fig. 9 by a violin plot. The X-axis signifies the fresh weight observed in grams, respectively. Similarly, the y-axis represents twenty-seven replicates for interspecific competition showing their fresh weight average mean. It can be inferred that PP, BP, and BV outcompeted *Lantana* in controlled pot experiments. However, Fig. 9 (b) shows that AV, PA, and AM could not compete well with *Lantana*. UD showed the highest competitive nature and directly impacted *Lantana*'s growth in these controlled experiments. It leads to the establishment that high allelopathy in *Urtica dioica* regulated *Lantana*'s growth, which shows allelopathic potential. ANOVA was performed for eight groups, including *Lantana*, for twenty-seven replicates. The null hypothesis was rejected, and we state that all population means are unequal. The p-value is highly significant. Tukey post hoc test was performed by Web Agri Stat Package (WASP 2.0). The coefficient of variation value is 15.51, and Treatments found Significant at 1% and 5% level of significance $CD(0.01) = 29.620$ $CD(0.05) = 22.537$.

It is observed that BP, UD, PP, and BV have shown the best results in terms of growth with *Lantana*(Fig. 10). These native species have promising potential to compete with *Lantana* and give it a tough competition to flourish. Plantation strategy must be followed considering the phenology of individual species, and mechanical removal of the invasive is a pre-requisite before following these steps. *Urtica dioica* is a shade lover; however, *Lantana* flourishes well in open canopies. It is clear from (Fig. 8) that *Urtica dioica* is a potential competitor (Figs. 9 and 10), but since it loves to grow in shady conditions, we cannot count on it for experiments in the wild. It shows us a way to use allelochemicals present in UD. Chemical extraction of these allelochemicals can help us design a biological control method that can be sprayed or injected on *Lantana*.

Of the four types of grass used in our experiments, two species of grass, i.e., *Pennisetum pedicellatum* and *Sachharum spontaeum*, showed major success (Fig. 11). Their growth beyond the quadrats in which they were expected to grow may be due to the heavy rains that uniformly distributed their seeds. Apart from this, *Sorghum halpense* also grabbed the opportunity and expanded in the field, which didn't allow *Lantana* to prosper. Surprisingly, in January and February, *Pennisetum* again took hold of the other grasses and flourished well, while *Sachharum*, a perennial grass, formed tufts and stayed every month.

The above graphs show the significant fresh weight difference between the major grass species that have the potential to compete with *Lantana*(Fig. 11). However, *Sorghum halpense* is considered invasive, it may have grabbed the opportunity to flourish, and its seeds were introduced by extraneous environmental factors and its presence in the nearby areas of the field sites.

Conclusion

The significance of comprehending the ecological and evolutionary aspects that lead to the success of invasive species in non-native environments is shown by the substantial correlation between phenology and the higher competitive abilities of invasive plants. However, restoration ecologists have emphasized the strategies to tackle non-native plants by using natives (Hulme, 2006; Funk, 2008; Uprety, 2012). Over thousands of years, native plant communities have developed to live in harmony with one another and

other organisms in their habitats. They have intricate relationships and interactions with their surroundings, enabling them to survive and flourish (Strayer, 2006). Flory and Clay, 2009 suggested that Invaded habitats should be restored by removing invasive plants and re-establishing native plant communities. Therefore, strategic plantation of native plant species by studying the phenology in detail is of utmost importance as it helps us decide the correct time for the introduction of a specific species for its success in the longer run. It is impossible to eliminate invasive species, but managing and restoring ecosystems carefully and keeping them diverse to maintain healthy ecosystems is frequently necessary.

Countries worldwide have made ambitious restoration commitments, promising to support landscape restoration on 170 million hectares by 2030 (Chazdon&Brancilon, 2019). Parallely, United Nations announced 2021-30 as the decade for ecosystem ecorestoration that involves global investments worldwide, and controlling invasives is one of the primary targets for achieving these goals. Norton, 2009 stated that restoration measures for invasives might require long-term monitoring for adequate control. However, uncertainty still prevails in implementing these restoration measures as the costs associated with the restoration measures are high. An effective management strategy is needed after the mechanical removal of invasive *Lantana* as it may reappear in later stages. We used native tree species and grasses to reclaim the *Lantana*-infested field sites at two different geographical landscapes. Taylor *et al.*, 2020 stated that rehabilitation of degraded areas frequently depends on understanding the ecology of invasive plant species combined with timely control of them. Thus, studying the phenological growth stages of plants that have a competitive ability to survive with invasive like *Lantana* helped us successfully delineate effective control measures for this invasive weed. Combining native grasses and plant species and their timely introduction proved an effective management strategy. This study is rewarding in bringing down *Lantana*'s density after introducing natural competitors that limit its vigour and spread after delineating each individual's phenology. The present study will aid policymakers, farmers, stakeholders, researchers, and conservationists in adopting effective plans for invasive species management in the IHR.

Declarations

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Authors contributions

AK performed the experiments and prepared the manuscript. SS contributed equally, designed the experiments, and helped draft the manuscript. AKG, RKS, HBC and AK participated in helping with writing the manuscript and data collection from field sites. All authors read and approved the final manuscript.

Data availability statement

The datasets used and/or analysed during the current study will be available from the corresponding author at reasonable request.

Competing interests

The author(s) declare no competing interests.

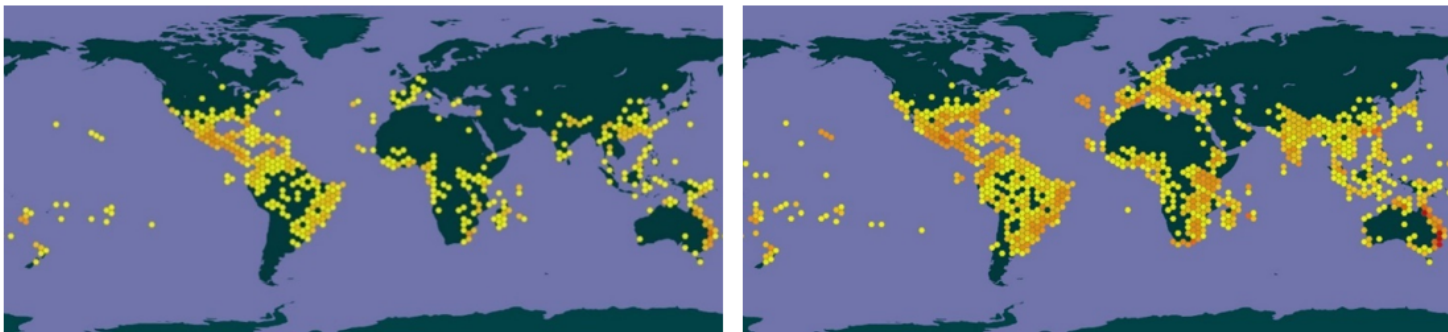
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Figures



Duration of years from 1770- 1993

After 30 years, till 2023

Figure 1

Map showing the pan-tropical presence of *Lantanain* different subcontinents. Yellow hexagons present the occurrence of *Lantana*. Hexagons with orange and red, where red is the upper end, show more observations recorded in the database, adapted from GBIF secretariat, 2022.

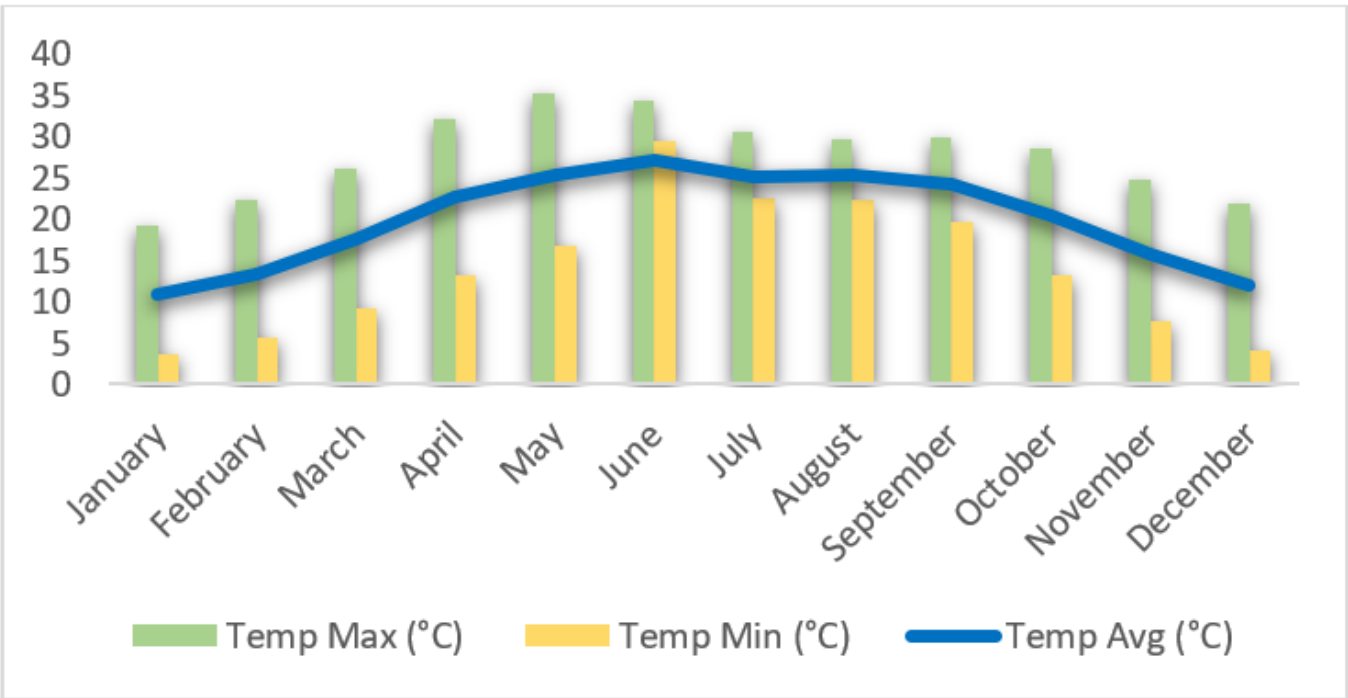


Figure 2

Average temperature (Maximum, Minimum, and Average) recorded for Doon Valley in the last four years

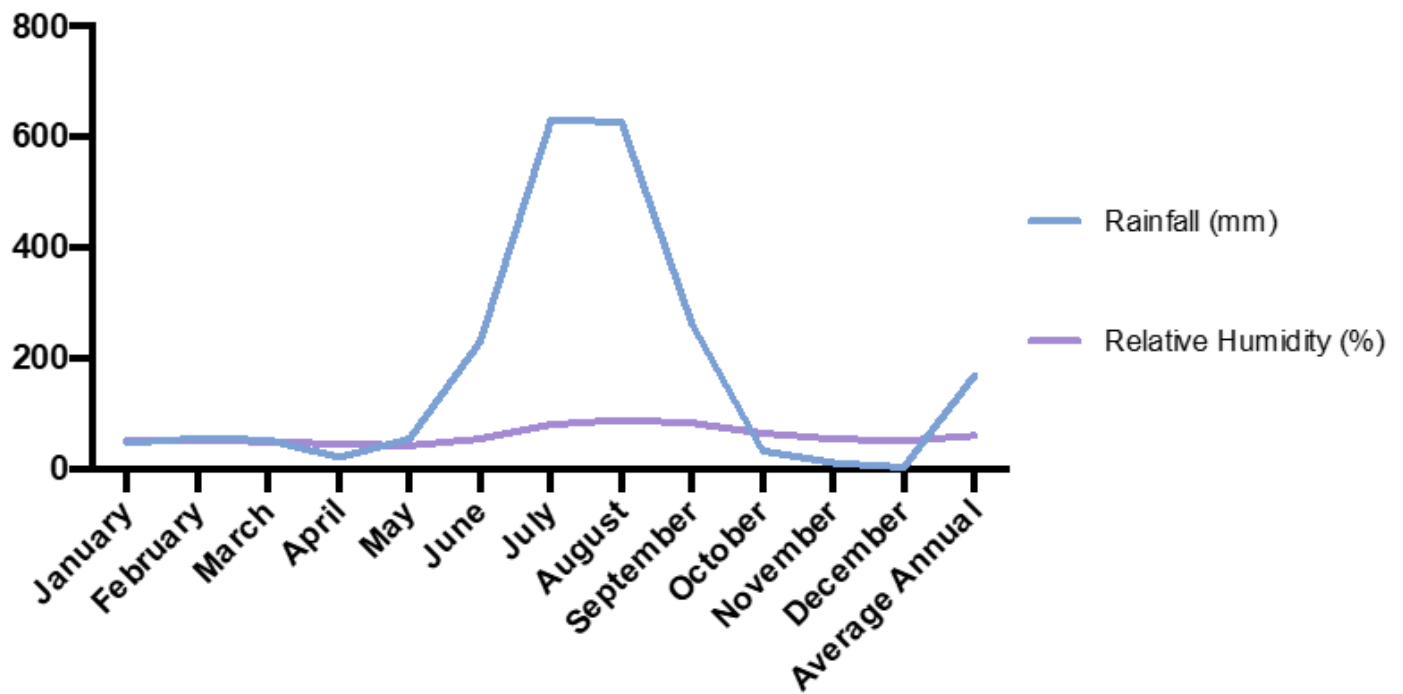


Figure 3

Average Rainfall (mm) and relative Humidity (%) recorded for Doon Valley in the last four years

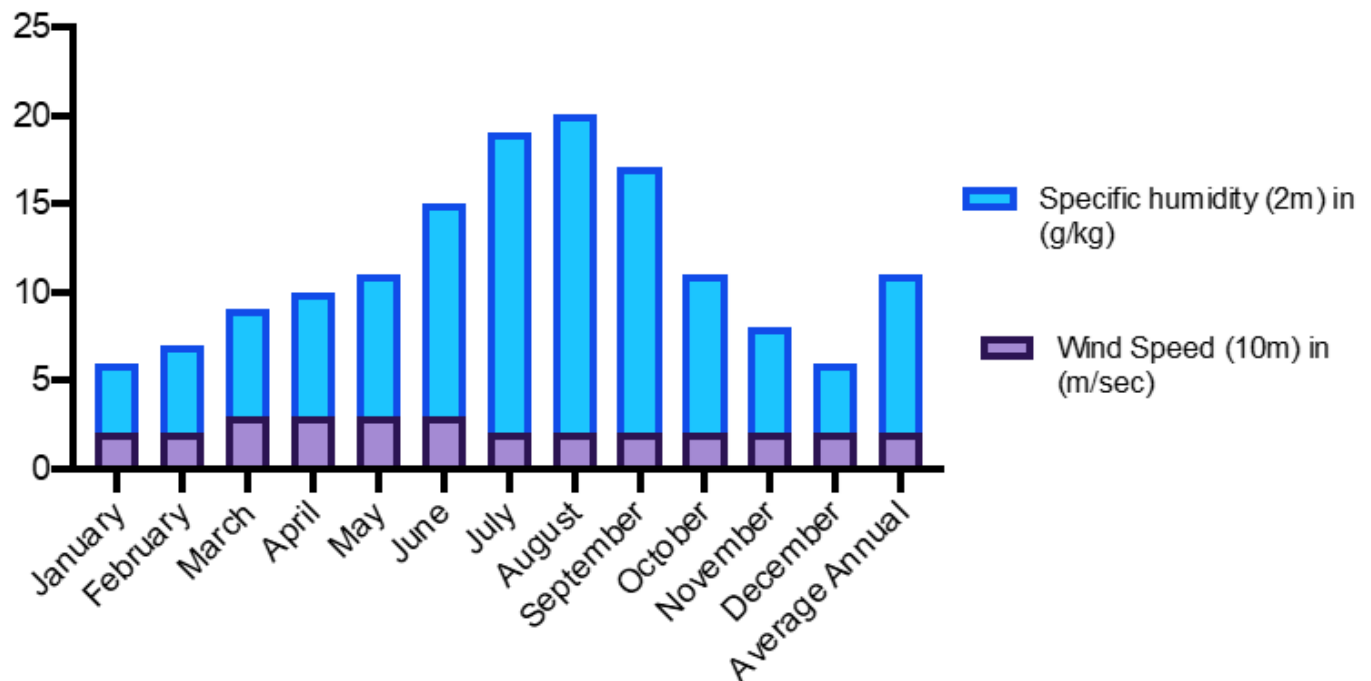


Figure 4

Specific humidity at (2m) in g/kg and Wind speed at 10m in (m/sec) were recorded for Doon Valley in the last four years.

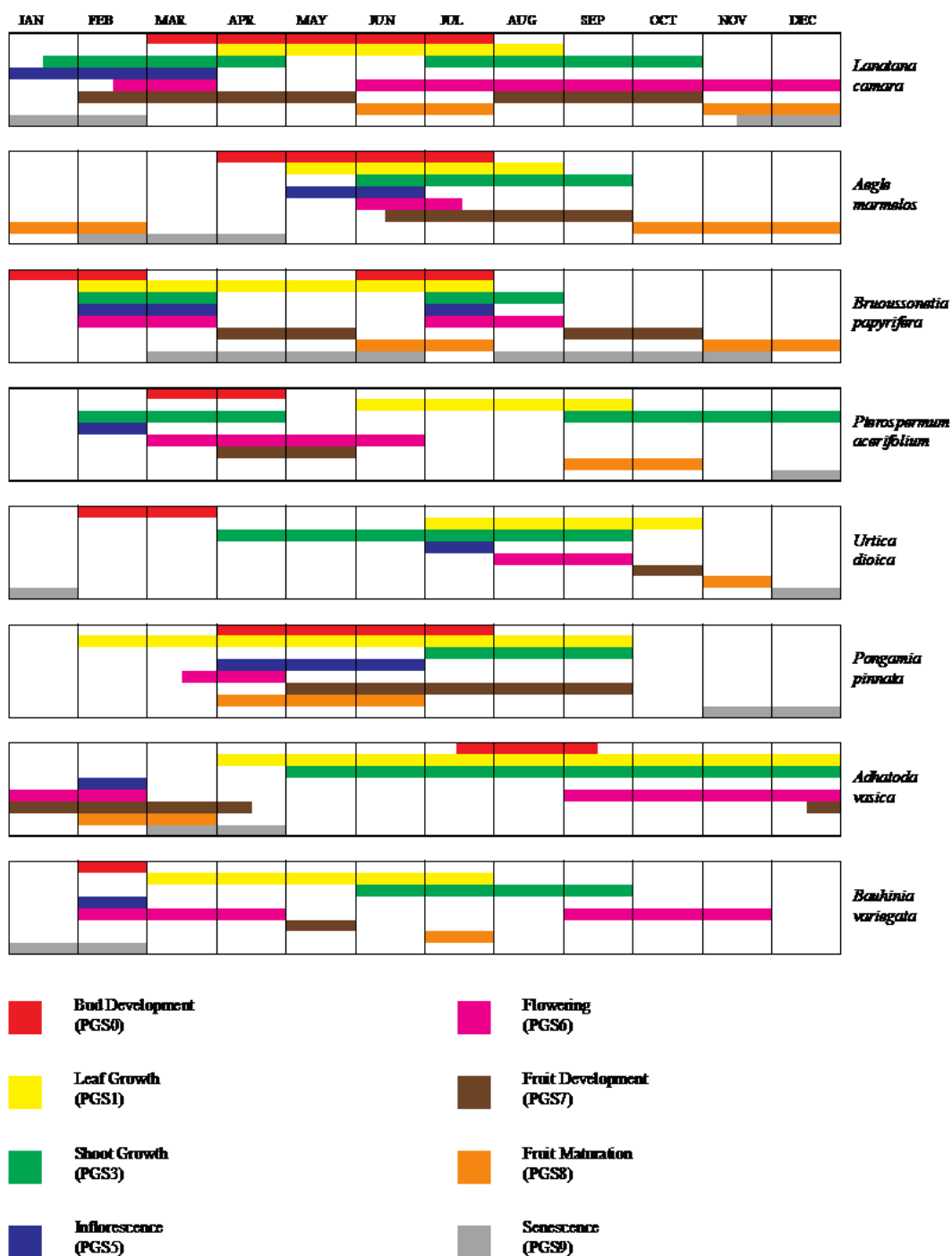


Figure 5

This figure represents a seven-species phenology comparison following the BBCH scale. Different PGS stages (0-9) for other plant species have been illustrated by different colour codes in the respective month of their occurrence. BBCH scale for *Pterospermum acerifolium*, *Urtica dioica*, *Pongamia pinnata*, *Adhatoda vasica*, and *Bauhinia variegata* is introduced here for the first time

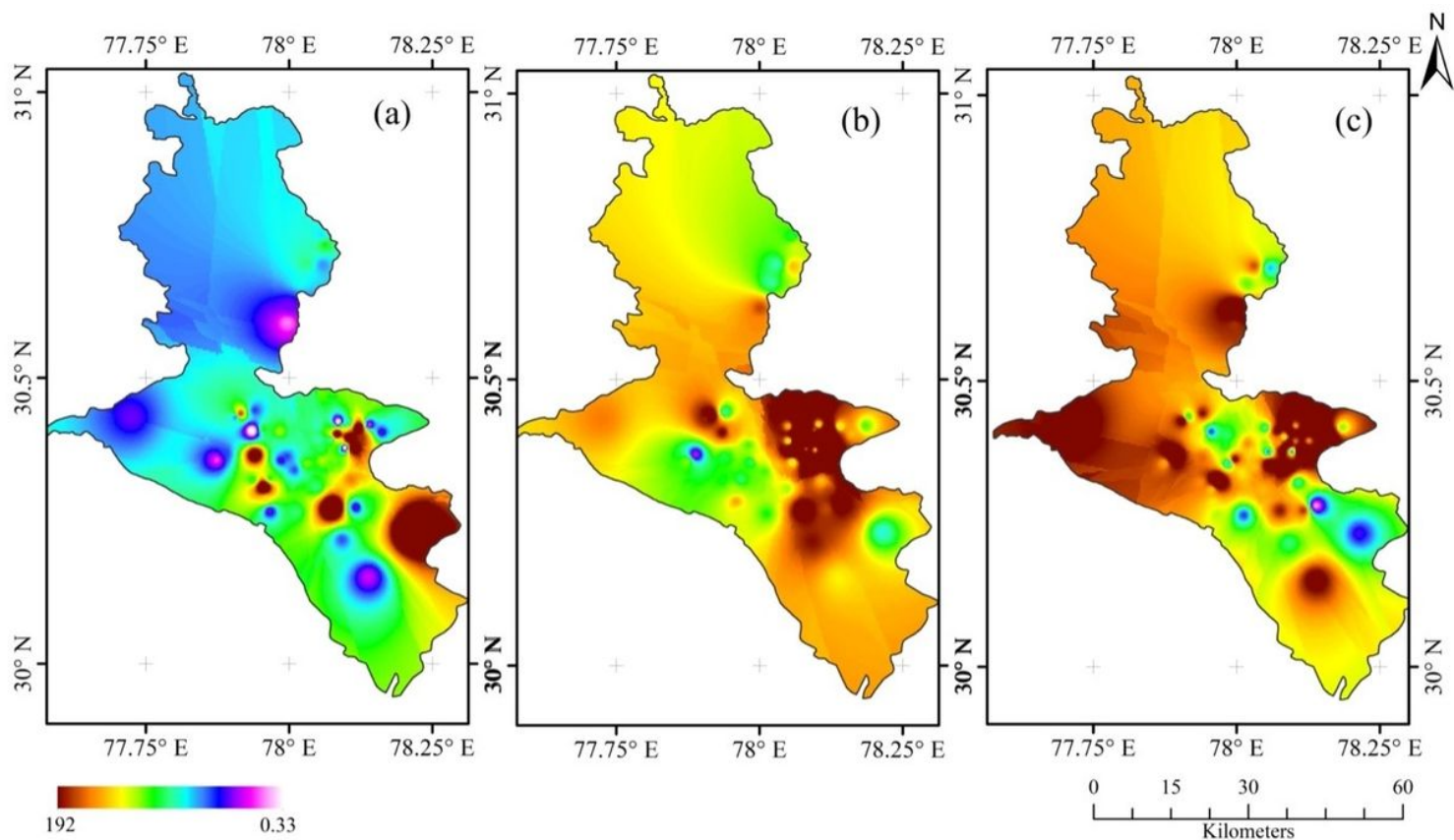


Figure 6

Map showing colour-coded raster layers depicts the Importance Value Index (IVI) for (a) *Lantana*, (b) shrubs, and (c) trees in the Dehradun district at various survey locations, with values ranging from 0.33 to 192.

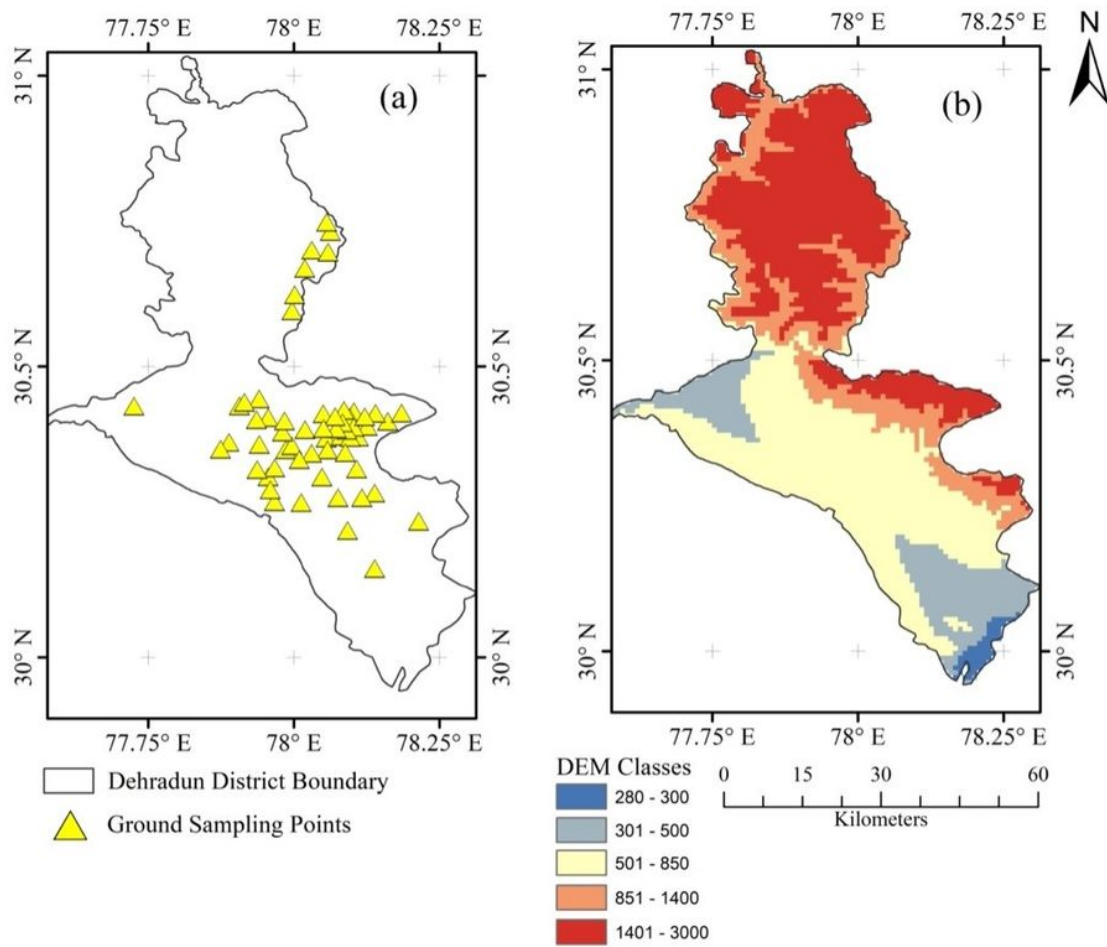


Figure 7

(a) Sampling points in Doon Valley, (b) Digital Elevation Map of Doon Valley.

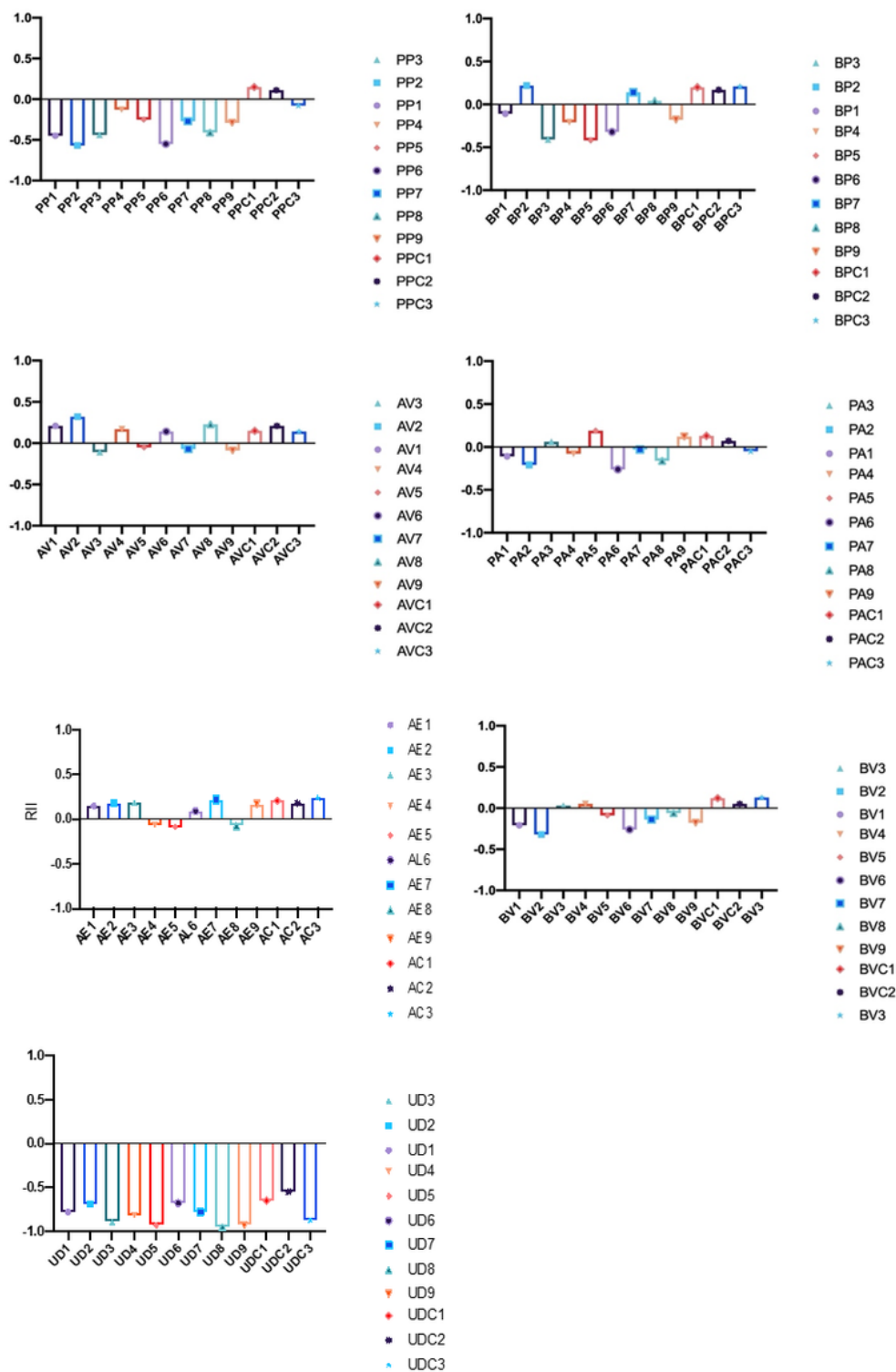


Figure 8

RII for different plant species was calculated for eight species. Each value from 1 to 9 with plant name initial (PP represents *Pongamia pinnata*, BP represents *Broussonetia papyrifera*, AV represents *Adhatodavasica*, PA represents *Pterospermum acerifolium*, AM represents *Aegle marmelos*, BV represents *Bauhinia variegata* and UD represents *Urtica dioica*) represents twenty-seven replicates. Each value is a sum of RII for three replicates. PP1 to PP9 are interspecific, and PP1-PP3 are interspecific (control).

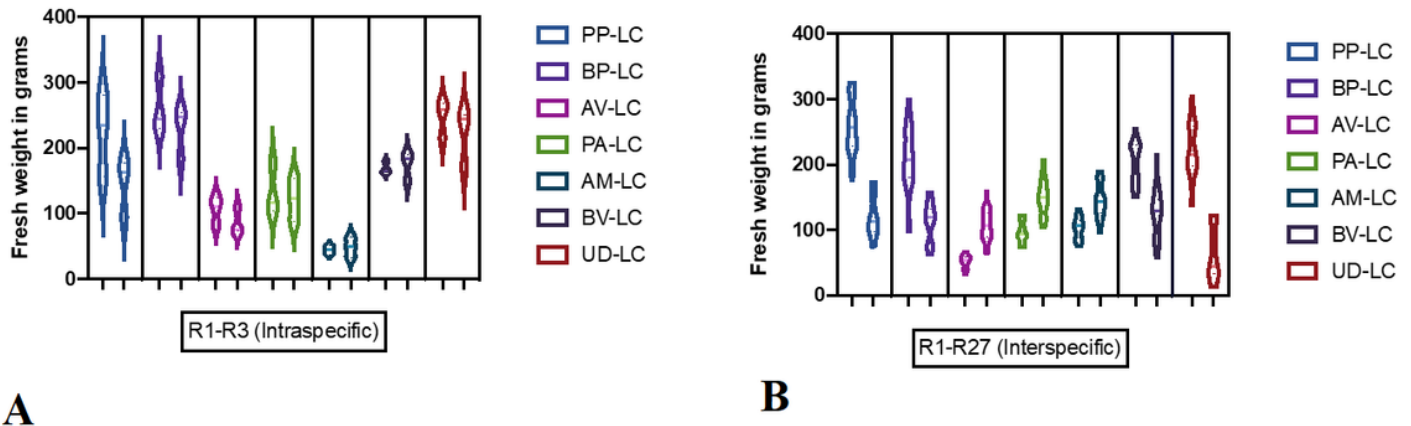


Figure 9

(a) Control experiments (Intraspecific competition): R1, R2 and R3 between seven native species. LC represents *Lantana camara*, PP represents *Pongamia pinnata*, BP represents *Broussonetia papyrifera*, AV represents *Adhatodavasica*, PA represents *Pterospermum acerifolium*, AM represents *Aegle marmelos*, BV represents *Bauhinia variegata*, and UD represents *Urtica dioica*.

(b) Cluster analysis of each plant's twenty-seven replicates (interspecific competition) with *Lantana* according to the fresh weight observed.

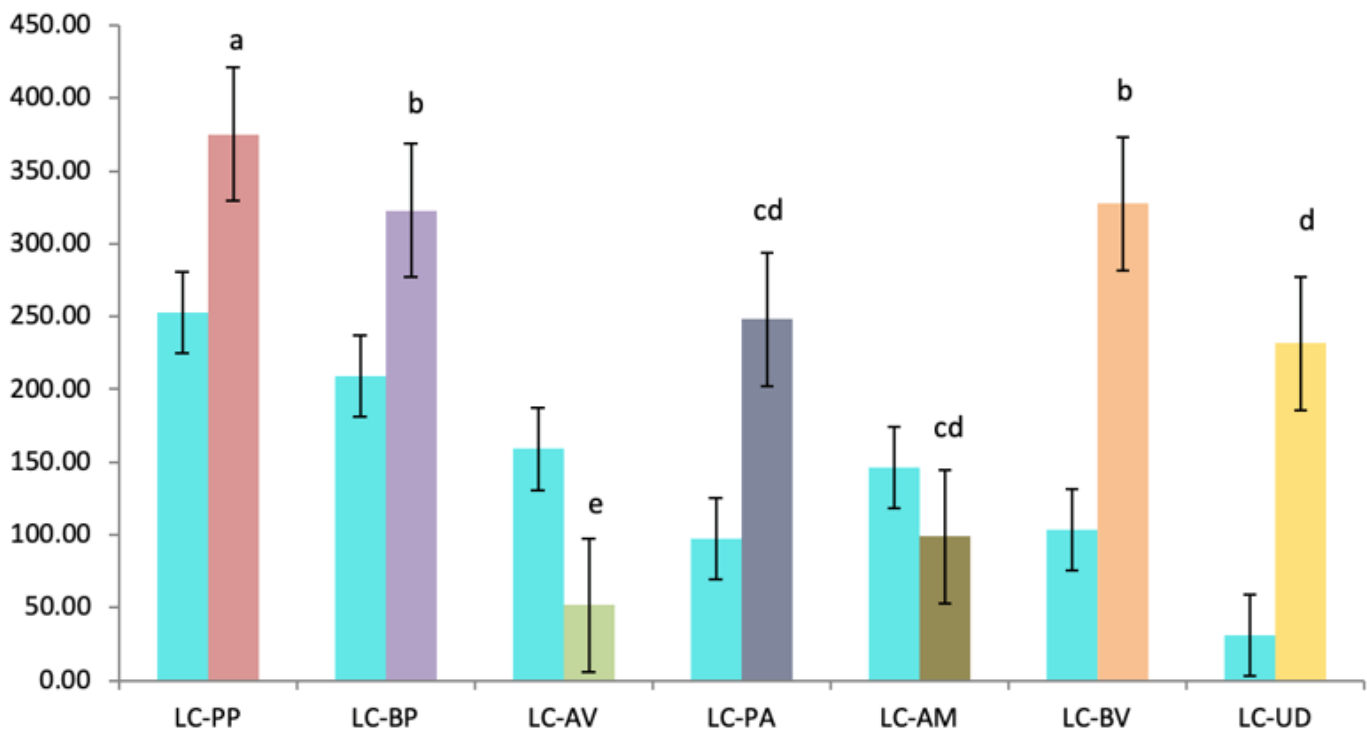


Figure 10

Mean values for each species (in gm) with respect to *Lantana* on X-axis. Blue represents *Lantana* growth with respect to other plants.

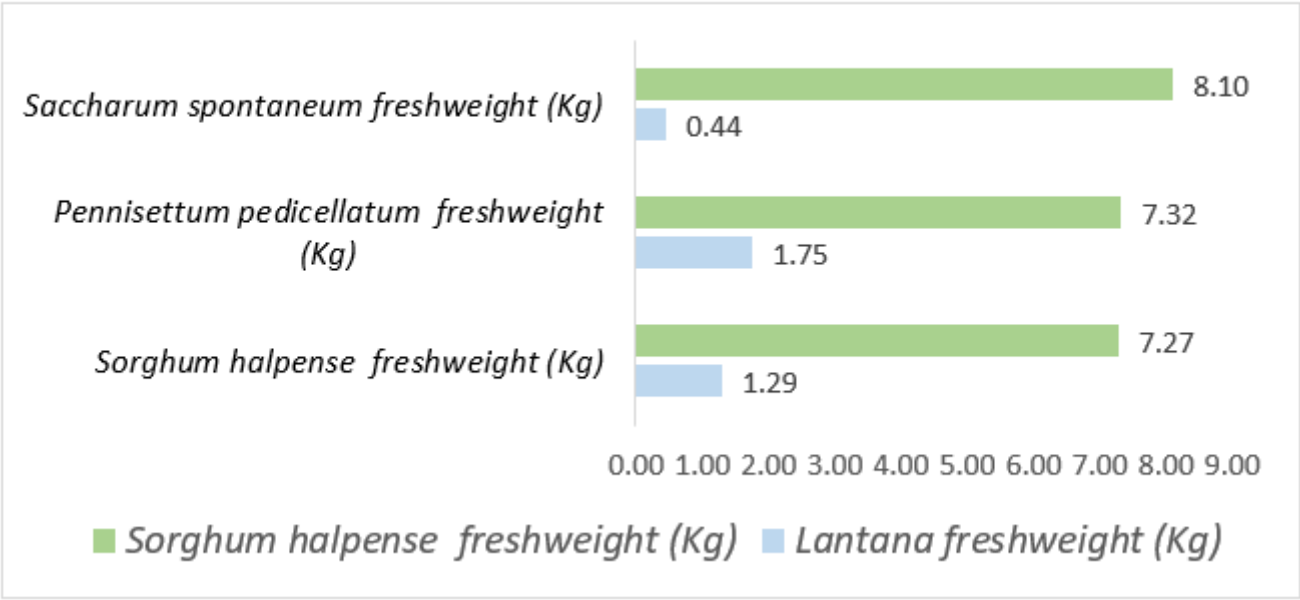


Figure 11

a) Mean fresh weight of *Lantana* with *Sorghum halpense*, (b) *Pennisetum pedicellatum* (c) and *Saccharum spontaneum* observed from field sites.