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What influences the plant community composition on Delhi ridge? The role played by *Prosopis juliflora* and anthropogenic disturbances

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Abstract: Scientific studies in the past have highlighted the effects of *Prosopis juliflora* on native vegetation. However, most of these studies do not consider the influence of external factors like disturbances on the vegetation community under *P. juliflora* canopy. Thus, this study expands the discussion on the effects of invasive species on native vegetation under two human disturbance intensities (low and high) on Delhi Ridge. Vegetation characteristics like species composition and diversity, functional traits of ground vegetation and the regeneration of tree species were studied, to assess the role played by *P. juliflora* in conjunction with anthropogenic disturbances like grazing, cutting and trampling. We found that while *P. juliflora* had no adverse influence on native plant biodiversity, grazing and other forms of anthropogenic disturbance had the most significant negative effects on the vegetation. The *P. juliflora* canopy showed no or low influence on the vegetation characteristics studied. Indeed, the coverage of native trees was positively correlated with the cover of *P. juliflora* implying that *P. juliflora* acts as a nurse tree facilitating the regeneration of native species under its canopy. These findings contradict the common assumption that *P. juliflora* causes a decline in native plant biodiversity. However, in the forests of New Delhi this relationship, in conjunction with the influence of anthropogenic disturbances, has been sparingly studied. Future research should focus on the monitoring of strictly protected areas with and without *P. juliflora*.

Key words: Delhi ridge, disturbances, exotic species, nurse effect, *Prosopis juliflora*, regeneration.

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Introduction

The rapid increase in global human population has led to an overall rise in the demand for wood products. Exotic tree species with high growth rates have been planted extensively to meet this increasing demand (Dodet & Collet 2012). However, these exotic plantations have led to conflicts among stakeholders in many parts of the world. The main argument for exotic tree plantations, besides biomass production, is for the provision of additional services depending on taxa

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and location (Dickie *et al.* 2014; Wilgen & Richardson 2014). For instance, the roles played by exotic tree species in reforesting degraded sites and facilitating the restoration of native ecosystems has been widely recognized by scientists and practitioners (Fischer *et al.* 2009; Senbeta & Teketay 2001). On the other hand, many exotic species spread into native ecosystems altering their composition and structure, which is perceived as a negative influence in many cases (Kumar and Mathur 2014; Maundu *et al.* 2009; Mwangi & Swallow 2005). Globally 434 tree species are recognized as having such an impact (Rejmánek & Richardson 2013). The question of how to manage these exotic species causes conflicts between those wanting to conserve native ecosystems and the growing need for ecosystem products (Dickie *et al.* 2014). The management question is further exacerbated by a lack of knowledge regarding the effects of establishing species outside their native range (Fischer *et al.* 2009). In this study we analysed the impact of the exotic tree species *Prosopis juliflora* on the semi-arid forest plant community in New Delhi.

Prosopis juliflora (Sw.) DC has been introduced in a number of tropical countries (Maheshwari 1997; Pasiecznik *et al.* 2001). Its natural distribution covers the arid and semiarid regions of Central and South America where it is one of the most economically and ecologically important species (Chaudhary *et al.* 2009; Gallaher & Merlin 2010; Pasiecznik *et al.* 2001; Zare *et al.* 2011). *P. juliflora* is a light demanding, early successional tree species with a strong colonizing ability in arid and semiarid areas (Maheshwari 1997; Pasiecznik *et al.* 2001; Troup 1921). Humans as well as domestic and wild herbivores are largely responsible for its wide distribution today (Pasiecznik *et al.* 2001; Reddy *et al.* 2007). It is widely planted for its production of high quality fuel wood, wood charcoal, fertilizer, pods as fodder, flowers for bee honey and gum (Laxén 2007; Pandey *et al.* 2012; Pasiecznik *et al.* 2001; Walter 2011).

There are reports of serious negative impacts that arise from the rapid spread of the species including invasion of agricultural land (Mwangi & Swallow 2005), inhibiting the natural flora (Andrade *et al.* 2009; El-Keblawy & Al-Rawai 2007; Singh *et al.* 2008), habitat loss for native fauna (Dayal 2007), decreasing soil moisture (Bhojvaid *et al.* 1996; Chaudhary *et al.* 2009; Jain & Garg 1996; Suwalka & Qureshi 1995; Tiedemann & Klemmedson 1973) and releasing allelopathic biochemicals (El-Keblawy & Al-Rawai 2007). However, other studies showed that *P. juliflora* also had positive effects on existing ecosystems, emphasizing its ability to foster the regeneration of other species under its canopy (Kahi *et al.* 2009; Tiedemann & Klemmedson 2004; Vera 2007), provide habitat for birds and other fauna (Pandey *et al.* 2012) and increase soil fertility in degraded areas (Chaudhary *et al.* 2009; Jain & Garg 1996; Mishra *et al.* 2013; Singh *et al.* 2014; Suwalka & Qureshi 1995; Tiedemann & Klemmedson 1973). Many Fabaceae species including *P. juliflora* are hosts to rhizobia, which have the ability to fix nitrogen thereby changing the soil fertility (Maheshwari 1997; Pasiecznik *et al.* 2001; Suwalka & Qureshi 1995; Walter 2011). The reason for a lack of consensus regarding the impact of *P. juliflora* on ecosystems might be because the studies were conducted under different environmental conditions or differing approaches and possibly with the unintentional biases of some authors. Additionally, many of the studies did not clarify if the impact of disturbances like overgrazing, cutting and fire had been excluded or controlled. We hypothesized that these anthropogenic disturbances interact with the effects *P. juliflora* has on ecosystems. To try and separate or at least include these anthropogenic effects is especially important when evaluating the effects of *P. juliflora* because this species has often been planted in areas which were considered degraded with the intention of improving soil fertility (Chaudhary *et al.* 2009; Mishra *et al.* 2013; Singh *et al.* 2014). For example, in our study area the species was introduced in the early 20th century for the afforestation and restoration of the then barren, semi-arid Delhi Ridge (Crowley 2011). Since then it has spread over the entire region and is now the most abundant tree species on the ridge (Crowley 2011; Kalpvriksha 1991; Krishen 2006). There have been numerous reports in the popular media describing the alarming spread of *P. juliflora* in Delhi and its negative impact on native flora (Hashmi 2012; Tiwari & Rahmani 1999). The strong negative opinion about the species has led to costly eradication programs in Delhi and others parts of India (Dayal 2007).

However, grazing, browsing, trampling and wood cutting are the three main disturbances on the Delhi Ridge and these have a significant impact on the plant community. To develop efficient adaptive management plans for the maintenance and restoration of the regional forest, it is crucial to understand the role of anthropogenic disturbances on the plant community under the canopy of *P. juliflora*.

We tested the hypothesis that anthropogenic impacts have a stronger negative effect on the plant community under *P. juliflora* canopy than does the species itself. Therefore, our objectives were to quantify the impact of *P. juliflora* as well as the anthropogenic disturbances on: 1) understory vegetation composition, 2) functional traits of the ground vegetation, 3) tree species compositions, 4) tree density.

Materials and methods

Study area

The northern end of the 1500 million year old Aravalli mountain range, which spans the north-western part of India, is known as the Delhi Ridge. This highly undulating ridge is composed of unconsolidated micaceous rocks and sandy soil (Kalpvirksha 1991). The ridge, situated at the heart of the national capital of India, covers a total area of 1474.88 km² (MoEF 2010) and is surrounded by a heavily urbanized landscape.

The climate of Delhi is described as subtropical humid characterized by extremely hot and long summers (from April to June with maximum temperatures as high as 45 °C) giving way to a monsoon season (most of the average annual rainfall of 714 mm is concentrated in July and August), followed by a short autumn and winter (January is the coldest month with a mean daily minimum temperature of 7 °C during daylight) (Pletcher 2011).

The Ministry of Environment and Forests of India stated that the ridge forest of Delhi contributes to a clean environment in the city by purifying air pollution (MoEF 2010). However, an empirical base for such a statement is not available since a specific study on the ecosystem services provided by the Delhi Ridge forest has not been conducted yet.

Sampling design and data collection

To test our hypothesis we selected six *P. juliflora* forests with varying degrees of human disturbance. The selected stands were divided into two disturbance intensities, high disturbed (HD) stands (including the South Central Ridge, Sanjay Van, and Tughlakabad Forest) and low disturbed (LD) stands (including Central Delhi Ridge, Jahanpanah City Forest, and National Zoological Park). The categorization of stands was based on the official protection status of the forest as per the forest department, the Delhi Development Authority and on evidence of human activities like cutting, lopping, coppicing and on the amount of undergrowth in the stands. Although we made exhaustive efforts to locate undisturbed stands of *P. juliflora* to serve as a control, to our knowledge such stands do not exist. However, we strove to ensure that the site conditions in the selected stands were as similar as possible and that at least 40% of the total canopy cover was comprised of *P. juliflora*.

The vegetation assessment plots were systematically located 30 m apart along transects. In total 60 plots were assessed, ten in each stand. To avoid the edge effect, a distance of at least 20 m was maintained from roads, forest edges, and trails. A nested plot design was used for collecting vegetation data in different layers. The canopy layer (trees > 3.0 m height) was assessed in a large (10 × 10 m) plot, nested within this plot was a 7 × 7 m plot for assessing the middle tree layer (trees > 1.3 m to 3.0 m) as well as the upper (1.3–3.0 m) and lower (< 1.3 m) ground vegetation. Additionally, a circular plot (1.0 m radius) was placed at the plot center where the tree seedlings and saplings (< 1.3 m) by species were counted.

For ground vegetation we combined all shrubs, herbs, grasses, and creepers that were found in the understory. The vegetation cover was estimated by observing the percentage of ground area covered in a plot for each of the layers as well as the cover by species. For each tree in the middle and canopy layers the height, diameter at breast height (DBH) and the diameter at root collar (DRC) were measured. The nomenclature of the species follows Maheshwari (1997).

Depending on the type, disturbance indicators were recorded in different ways. In the smaller plots signs of coppice cutting were noted if present and the proportion of the plot affected by livestock trampling was estimated. Signs of grazing and browsing *(G)*, cutting (*C,* complete removal of the above ground biomass of woody plants at the base of stem, or cutting of herbs and grasses depending on the layer) and lopping (*L,* partial removal of biomass by cutting branches of woody plants) were recorded for each individual plant according to Schmerbeck (2003); damage classes were assessed as: 1- no damage, 2- damage evident but the plant retained its original shape, 3- damage obvious and affected the plant's development as seen in its changed growth form.

Damage indexes (DI) for grazing/browsing and cutting were calculated for each plot based on the number of individuals with particular damage using the following formula:

DI = sum (number of individuals x damage class)/ total number of individuals

Functional traits of species were taken from the literature (Maheshwari 1997). The traits included were life span (annuals/ biennials or perennials) and spinescence (presence or absence of spines) additionally we analyzed the geographic origin of the species (native or exotic). We could only include a very small selection of traits because information for most of the species was not available. However, life span and spinescence, as well as the geographic origin gave additional insight into the degree to which the vegetation was disturbed.

Data analysis

Indicator Species Analysis (ISA) (McCune *et al.* 2002) was used to determine if there were any species specifically related to one of the two disturbance intensities. The resulting Indicator Value (IV) is a combination of the relative abundance and relative frequency of the species in the plots belonging to one or the other group (here disturbance intensity) and ranges from 0 (no indication) to 100 (perfect indication) (McCune *et al.* 2002).

The influence of *P. juliflora* in the canopy and the impact of the different disturbances (DI-trampling, DI-cutting and DI-grazing) on the ground vegetation composition were tested using permutational multivariate analysis of variance (PERMANOVA) (Anderson 2001). The analysis is partitioning sums of squares of a multivariate dataset analogous to the multivariate analysis of variance but is based on distance matrices. In this case, we used the Bray-Curtis distance to measure the dissimilarity between the plots based on their species composition. Significance tests (α = 0.05) were done using F-tests based on sequential sums of squares from permutations of the raw data. Additionally, a nonmetric multidimensional scaling (NMDS) was performed to visualize the relationships between the plots and disturbance influences. We used NMDS based on Bray-Curtis distance. A step-across procedure was used to replace the dissimilarities for plots that had no species in common, and zero dissimilarities were changed to 0.0012 (a randomly selected number lower than all non-zero dissimilarities).

We examined the effects of *P. juliflora* cover and disturbance indicators on the coverage of species with different functional traits applying the fourth-corner analysis (see Dray & Legendre 2008). This analysis describes the relationships between species traits and environmental variables (here disturbance indicators) through a link provided by a dataset of species coverage. The basis for calculating a statistical measure were three tables: a table L ($n \times p$) containing the coverage of p species at n sites, a second table R ($n \times m$) with the measurements of m environmental variables (here disturbance indicators) for the n sites, and a third table Q ($p \times s$) describing s species traits for the p species. The fourth-corner analysis calculates the relationship between each pair of traits and the environmental variables (here disturbance indicators). The test statistic is returned depending on the type of data being analyzed. When both variables are quantitative (ordinal or continuous data), a Pearson correlation coefficient, r, describes the strength of the relationship. When one variable is nominal and the other quantitative, a Pseudo-F and Pearson r is returned for the global association between the pair of variables. The relationship between each level of the nominal variable and the quantitative variable is provided by a correlation coefficient. The significance of each test was assessed by permutation using model 5 and simultaneously permuting the rows of tables R and Q. Permutation is performed by exchanging the values of species among sample units in table L, while preserving the number of sites at which a species was found. When the overall test was significant, p-values were adjusted for multiple tests. We used seven environmental (disturbance indicating) variables in the fourth-corner analysis: one nominal and six continuous variables describing the potential impact of *P. juliflora* and the different disturbances. The nominal variable was the disturbance intensity used for stratification with two levels (low or high disturbance). For a more quantitative description of the disturbance impacts, the quantitative variables we used were the canopy cover of *P. juliflora* (%) and the cover of trampled area within the plot (trampling). We calculated DI using damage codes (given above) to quantify grazing and browsing on lower ground vegetation (DI_G130) and upper ground vegetation (DI_G300). For the direct impact of firewood collection, an index was calculated based on species individuals with signs of cutting, in the lower ground vegetation (DI_C130) and the upper ground vegetation (DI_C300). The fourth-corner analysis was used simultaneously to evaluate the effects of disturbances on the abundance of native and exotic plant species using the disturbance intensity, percent *Prosopis* canopy cover and trampling as explanatory variables.

Vegetation diversity (Shannon diversity index and species richness) in low disturbed (LD) was compared to high disturbed (HD) stands using the T-test for normally distributed data and Mann-Whitney U test for data not showing normal distribution.

Furthermore, generalized linear models (GLM, Poisson distribution and log-link function; using R (R Foundation for Statistical Computing, Vienna, AT; www.r-project.org) were performed for assessing the influence of *P. juliflora* and other disturbances on the overall tree density (in the middle and lower layer, stems/ ha) and especially native tree density. Additionally, a comparison between the density of regenerating trees (stems/ha), under the canopy of *P. juliflora*, was made between the low disturbed and high-disturbed plots using a Mann-Whitney U test.

Results

Understory vegetation composition under P. juliflora *canopy and the influence of anthropogenic disturbances*

Altogether 36 plant species were found in the understory (Supplementary Table I). *Adhatoda vasica, Capparis sepiaria, Carissa spinarum, Chloris dolichostachya, Lantana camara, Urena lobata* were the most frequent species. Other than *Adathoda vasica* and *Lantana camara,* all

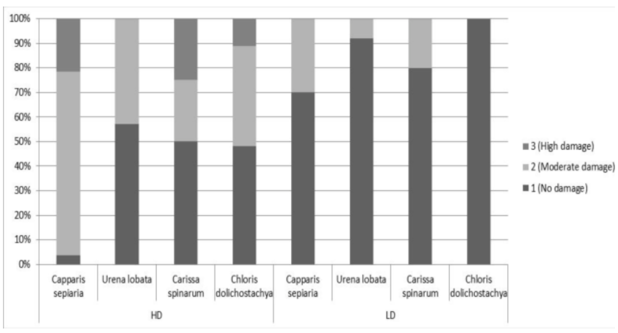

Fig. 1. Relative proportions of frequently occurring species (detected using Indicator species analysis) in the ground vegetation, found under different disturbance intensities in low-disturbed (LD) and high-disturbed (HD) stands.

Table 1. Results of PERMANOVA testing for the effects of *P. juliflora* cover (Pj_canopy) and the disturbance-indicating variables (trampling, C300 (cutting; height 1.3–3 m), C130 (cutting; height > 0–1.3 m), G300 (grazing/browsing, height 1.3–3 m), and G130 (grazing/ browsing, height > 0–1.3 m) on the ground vegetation composition**.**

	Df	F. model	R^2	*P*
Pj_canopy	1	19.717	0.029	0.069
Trampling	1	14.629	0.022	0.174
C300	1	20.315	0.031	0.056
C130	1	31.256	0.047	0.008
G300	1	53.654	0.081	0.000
G130	1	0.35	0.005	0.936
Residuals	52		0.784	

frequently occurring species were grazed or browsed in both LD and HD stands (Fig. 1).

These species occurred in the LD as well as in the HD stands but with differences in abundance. *Leptadaenia reticulata* (IV = 75.5) and *Ipomea arachnosperma* (IV = 64.1) were identified as the indicator species for LD stands and *Aerva lanata* (IV = 33.3) and *Blepharis mollunginifolia* (IV = 28) for HD stands. The LD stands showed significantly higher mean species richness (mean = 6.5, standard deviation = 1.7 in LD, mean = 2.4, standard deviation = 2.6 in HD) and mean Shannon diversity (mean = 1.1, standard deviation = 0.18 in LD, mean = 0.6, standard deviation = 0.29 in HD) compared to the HD stands (T-test, $P < 0.00$) in the upper ground vegetation. The highest impact of grazing and browsing was in the upper ground vegetation layer (G300; height: > 1.3–3 m) followed by cutting of the lower ground vegetation layer (C130; height: > 0–1.3 m). The canopy cover of *P. juliflora* had only a low and non-significant impact on the ground vegetation composition (Table 1).

There was a clear differentiation in species composition among disturbance intensities (LD and HD) (Fig. 2). In HD stands, grazing (G130) and browsing (G300) as well as cutting in the middle layer (C300) were dominant (Fig. 2). While in stands with low disturbance trampling and cutting of the lower vegetation (C130) had the highest effect.

Functional traits of ground vegetation related to the disturbances

Overall the associations or relationships between plant functional traits and the damage indicating variables were weak. According to the fourth-corner analysis, the cover of native species was positively correlated with the cover of *P. juliflora* in the canopy and also with the grazing of the ground and shrub layer (Table 2). The exotic species cover was negatively related to these influences. Also, there was no relationship between the life span of the species and the disturbance indicating variables. Species with spines tended to show a positive relation with cutting of the ground layer, but were negatively correlated with grazing and browsing of the ground and the shrub layer. Species without spines had the opposite associations (Table 2).

Tree species composition

A total of 21 tree species were recorded during the study (Supplementary Table II). The indicator species analysis showed that *Pongamia pinnata* (IV = 49.5) and *Leucaena leucocephala* (IV = 40) were indicator species for LD stands whereas in HD stands no indicator species could be identified. Amongst the regenerating tree species *P. juliflora* was found in 62% of all plots, followed by *Pongamia pinnata* (30%) and *Leucaena leucocephala* (25%). *P. juliflora* was the most abundantly regenerating species in the HD stands, found in 80% of total plots, however, in the case of LD stands it was found regenerating only in 35% of the plots. On the other hand, 94.2% of the total individuals *of P. juliflora* regenerating in HD stands were stump sprouts originating from coppice cutting as opposed to 5% in LD stands. Only 4 and 2 seedlings of *P. juliflora* were found in HD and LD stands respectively. The most frequent damage of trees resulted from cutting and lopping. Comparative analysis for both tree saplings (> 0 – ≤ 130 cm) and middle tree layer (> 130 – ≤ 300 cm) showed a significantly higher mean Shannon diversity (tree saplings: 0.25 in LD, 0.0 in HD; middle tree layer: 0.5 in LD, 0.0 in HD) (Mann-Whitney U test, $P < 0.05$) and mean species richness (tree saplings: 0.85 in LD, 0.15 in HD; middle tree layer: 2.2 in LD, 1 in HD) (Mann-Whitney U test, $P < 0.001$) in LD stands as compared to HD stands.

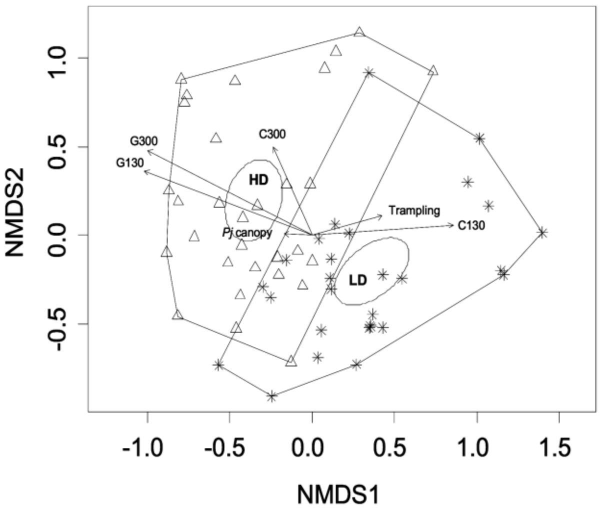

Fig. 2. Results of NMDS ordination visualizing ground vegetation composition. The composition dataset was based on species cover by plot (the ordination used Bray Curtis distance, 15 random starts, was iterated for two dimensions, nonmetric fit r^2 : 0.98, linear fit r^2: 0.827. Symbols represent individual plots coded by disturbance level (HD = high disturbed; LD = low disturbed). Disturbance levels (HD = high disturbed; LD = low disturbed) show the averages of factor levels (class centroids), and the continuous variables (*Pj* canopy, trampling, G300, G130, C300, C130) were added as arrows. The arrow shows the direction of the (increasing) gradient, and the length of the arrow is proportional to the correlation between the variable and the ordination.

Tree density and the influence of disturbance

The mean number of stems ha^{-1} were significantly higher (Mann-Whitney U test, $P <$ 0.0) for LD areas compared to HD areas for both saplings (417.03 stems/ ha in LD, 204.8 stems/ ha in HD) and middle layer (0 – < 1.30 m, 666.67 stems/ ha in LD, 460.2 stems/ ha in HD) (Fig. 3).

The GLM shows that *P. juliflora* canopy had very low impact on the tree density in the middle layer and no impact on the density in the lower layer (Table 3). Browsing, however, had a stronger negative impact on the density of trees. The tree regeneration was affected by browsing in both layers. Cutting also had some influence on tree density; however, it was much less than that of browsing.

The density of regenerating native tree species was highly influenced by the different disturbances. Again, browsing in the shrub layer followed by cutting in this layer heavily reduced the density of native trees.

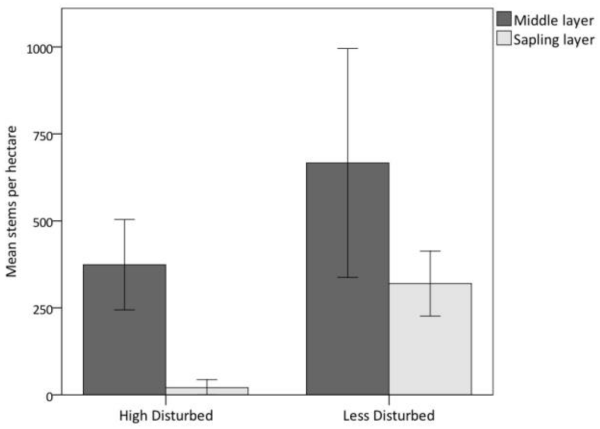

Fig. 3. Mean number of stems per hectare in the sapling (0–1.3 m) and middle layer (>1.3–3 m) in high disturbed and low-disturbed stands; Error bars: 95% CI.

Discussion

Our results showed that anthropogenic disturbances had a significant impact on the ground vegetation composition. Disturbances like grazing and browsing have been known to shape ground vegetation structure and composition (i.e. Landsberg *et al.* 1999; Seis *et al.* 2014; Bhatt *et al.* 2015). Notably, we found that *P. juliflora* cover had no significant influence on the ground vegetation. This was in contrast to the loss in diversity of the ground vegetation layer under *P. juliflora* canopy reported by others (Andrade *et al.* 2009; El-Keblawy & Rawai 2007; Singh *et al.* 2008). In none of these studies was it described how human disturbances were dealt with. Noteworthy positive effects of *P. juliflora* canopy include supporting the growth of native desert grassland species (Tiedemann & Klemmedson 2004), modifying the microclimate to facilitate germination of *Azadirachta indica* seedlings (Vera *et al.* 2007) and supporting the maximum herb species richness in the semiarid forests of Kenya as compared to the native *Acacia* species (Kahi *et al.* 2009).

Our second objective was to evaluate the effect of *P. juliflora* and anthropogenic disturbance on the functional trait composition of the ground

Table 3. Summary of the generalized linear model analyses of the effects of *P. juliflora* and the different anthropogenic disturbances on: a) tree density in the middle layer, b) tree density in the lower layer, and c) density of regenerating native trees.

Model	Independent variable	Coefficient estimate	z–value
a) Tree density (stems ha^{-1}) (middle layer)	(intercept)	5.5346934	133.364
	Pj canopy	0.0118698	23.169
	Trampling	–0.002491	–6.603
	C300	0.2017575	16.603
	C130	0.0109653^{NS}	0.804
	G300	–0.194879	–4.127
	G130	–0.069823^{NS}	–1.430
b) Tree density (stems ha^{-1}) (lower layer)	(intercept)	4.8774783	54.309
	Pj canopy	0.0003683	0.394
	Trampling	0.0056470	8.944
	C300	0.5903103	24.557
	C130	1.4311253	52.856
	G300	–1.004254	–7.999
	G130	–0.451952	–3.659
c) Native tree density (stems ha^{-1})	(intercept)	7.5749792	59.270
	Pj canopy	0.0094898	8.133
	Trampling	0.0016090^{NS}	1.865
	C300	–0.298829	–9.764
	C130	0.1218630	3.994
	G300	–3.889654	–26.380
	G130	1.1677484	7.882

NS - non-significant; all other values of Coefficient estimates are significant at $P<0.001$

vegetation. The functional traits of species in the understory vegetation are an indicator of the effect of disturbances on the plant community (Pedley & Dolman 2014; Mouillot *et al.* 2013). We found significantly less area covered by species with spines (e.g. *Carrisa spinarum, Capparis sepiaria, Ziziphus mauritiana*) with increasing grazing pressure. Initially this seems contradictory, but these were predominantly native species on which livestock feeds. The defense systems of these species do not always protect them from being grazed and browsed (Hanley *et al.* 2007) but does enable them to survive under this disturbance regime. Other plant species which were browsed but do not have any defense mechanism (e.g. *Urena lobata, Chloris dolichostachya*) showed reduced cover with increasing grazing pressure. The only species without spines, which was found to be abundant in both HD and LD areas, was *Adhatoda vasica*, which is unpalatable to cattle (Mishra & Rawat 1998). Browsing and grazing therefore play a role in determining the composition and abundance of species (Landsberg *et al.* 1999).

Our third objective was to quantify the effect of *P. juliflora* and the anthropogenic disturbances on the tree species composition. The first significant observation was that *P. juliflora* was the most abundant tree species regenerating in the high disturbed stands. Since *P. juliflora* is largely unpalatable, except for its pods, it withstands high browsing pressure (Mwangi and Swallow 2005; Pasiecznik *et al.* 2001; Reddy *et al.* 2007) compared to the native tree species. The high frequency of cutting and browsing in the HD areas promoted the re-sprouting of cut stems (Pasiecznik *et al.* 2001) and facilitated the mechanical scarification of seeds, through trampling, which is essential for their successful germination (Gallaher & Merlin 2010; Pasiecznik *et al.* 2001). Since *P. juliflora* is a light demanding pioneer tree species (Pasiecznik *et al.* 2001), the closure of the canopy shades out its own regeneration over time. However, this successional pathway is interrupted due to the constant cutting of wood which maintains open canopies in the HD stands. We found very little regeneration from seeds of *P. juliflora* under its own canopy in both HD and LD stands, possibly the result of auto-allelopathy. The inhibiting effect of *P. juliflora* allelopatic biochemicals has been reported to limit the germination of the species under itself (Pasiecznik *et al.* 2001; Warrag 1994). Other factors reported to limit species regeneration include heavy shade, a failure to scarify the seed and predation by seed eating insects (Gallaher & Merlin 2010; Pasiecznik *et al.* 2001). Although disturbances, especially browsing seem to support the germination and growth of *P. juliflora* in HD areas, we found a significantly higher number of other tree species like *Pongamia pinnata, Leucaena leucocephala, Acacia nilotica, Azadirachta indica* etc., regenerating under the *P. juliflora* canopy in LD stands. This finding contradicts the results of El-Keblawy and Rawai (2007), who reported that *P. juliflora* had a negative impact on the surrounding plant species richness, but importantly, their study did not take into consideration the interacting effects of anthropogenic disturbances. Our results are in agreement with a study by Vera *et al.* (2007), on the regeneration and development of Azadirachta indica (Neem) (a tree species also regenerating in our plots) under the canopy of *P. juliflora* in Venezuela. Vera *et al.* (2007) found that most of the Neem seedlings and saplings had established close to the trunk of *P. juliflora* trees showing that the germination of Neem was not inhibited. However, the species with the most abundant regeneration in LD stands were *Pongamia pinnata* and *Leucaena leucocephala.* Both species are light demanding and have wide ecological amplitudes (see Sangwan *et al.* (2010) for *P. pinnata* and Wolfe & Van Bloem (2012) for *L. leucocephala*) and are early successional species making them indicators of disturbance.

The impact of *P. juliflora* and other disturbances on overall tree density was the fourth objective of the study. We found that the density of trees per hectare in both the sapling and middle layers were significantly higher in LD stands than in HD stands (Fig. 3). Additionally, we did not find that the cover of *P. juliflora* had any influence on the regeneration of other tree species. On the contrary, the density per hectare of native trees was positively correlated with *P. juliflora* cover, thus demonstrating that it did not hinder the establishment of native tree species under its canopy (Table 3). The observation that exotic species can act as nurse species facilitating the regeneration of native flora has been made repeatedly (Alem & Woldemariam 2009; Feyera *et al.* 2002; Harikrishan *et al.* 2012; Selwyn & Ganesan 2009; Senbeta & Teketay 2001; Senbeta *et al.* 2002). Based on our results it can be assumed that *P. juliflora* would have a similar nurse effect on the regeneration of native flora in the absence of human driven disturbances.

Conclusion

Our results led us to conclude that the impact of *P. juliflora* on the native ecosystems of New Delhi was much more positive than is currently perceived. However, our results would be clearer if it was possible to exclude disturbances over a longer time period. An even better understanding could be gained from experimental studies that controlled the effect of *P. juliflora* and the grazing/ browsing pressure on the development of native ecosystems. However, to determine the extent to which *P. juliflora* is able to promote the biodiversity of Delhi Ridge, independent from human disturbances, requires further research. Establishment of permanent plots and designated long-term research areas which exclude anthropogenic disturbances are essential for such studies.

Adaptive management practices that use exotic species as nurse trees for the restoration of native forest (Senbeta & Teketay 2001; Senbeta *et al.* 2002), appear to be a feasible option on the Delhi Ridge. Such methods would lead to the establishment of shade tolerant native species as a secondary forest layer that could gradually replace the exotic species without any significant loss of ecological services like soil protection, air quality enhancement and carbon storage (Baggethun & Barton 2013; Young 2010). The present mind set focusing on the eradication of *P. juliflora* should be modified to include its use in the restoration of ecosystem functions.

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