

RESEARCH

Open Access



Roadside green spaces: role of tree diversity in carbon storage and thermal comfort

Alok Kumar^{1,2}, Manjul Panwar¹ and Usha Mina^{1*}

*Correspondence:

Usha Mina

ushamina@jnu.ac.in

¹Agroecology Laboratory, School of Environmental Sciences, Jawaharlal Nehru University,

New Delhi 110067, India

²Interdisciplinary Centre for Water Research, Indian Institute of Science, Bengaluru 560012, India

Abstract

Roadside green spaces (RGS) are an essential part of urban environments. These provide a variety of ecosystem services, including biodiversity conservation, carbon storage, and microclimate regulation. This study aims to assess RGS for tree diversity, carbon stock, and thermal comfort along four major roads of the Jawaharlal Nehru University campus, New Delhi. An extensive belt transect survey was employed with a total of 59 plots (10 m × 5 m each) covering a 5.5 km stretch of road. RGS supported 27 tree species from 27 genera and 15 families, comprising 19 native, 6 introduced and 2 invasive species. The diversity indices indicated low dominance ($D=0.16$), moderate diversity ($H'=2.47$), and moderately high evenness ($J'=0.75$). The Fabaceae family was the most dominant, with *Cassia fistula* having the highest IVI. However, invasive species (*Leucaena leucocephala* and *Prosopis juliflora*) accounted for 47.17% of the individuals. Despite the abundance, these invasive species contributed minimally to carbon stock (0.59 and 0.23 tC/m², respectively), underscoring that these are neither ecologically nor sustainably beneficial. Overall, the RGS stored 0.312 tC/m² of carbon. These also contributed to thermal comfort regulation, with on-field measurements showing reductions in air temperature by 0.80 to 2.24 °C and land surface temperature by 3.80 to 8.37 °C during April and May 2025. This research highlights the multifunctional role of RGS while emphasizing the urgent need to manage invasive species to secure their ecological and sustainability benefits. These findings confirm the role of RGS as an effective natural cooling system for megacities such as Delhi, which experiences intensifying heat waves and rising heat stress. For urban policy and planning, this underscores the need to integrate invasive species control and proactive RGS management into city-scale heat adaptation strategies.

Keywords Urban green spaces (UGS), Tree diversity, Thermal comfort, Carbon stock, Ecosystem services, Invasive species

1 Introduction

Urban green spaces (UGS) are vegetated public spaces within urban settings that serve as active or passive recreational places that have long-lasting impacts on the urban environment, eventually benefiting the public [7]. UGS include forests, residential yards, meadows, public parks, grassy lawns, roadside green spaces, rain gardens and green roofs and provide a variety of ecosystem services [5, 69, 72]. Roadside greenbelts, including avenue



© The Author(s) 2026. **Open Access** This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit <http://creativecommons.org/licenses/by/4.0/>.

trees and traffic lanes dividing green areas, are examples of roadside green spaces (RGS) [85]. RGS are an essential part of UGS that provide services such as air purification, noise reduction and habitat for fauna and significantly contribute to biodiversity conservation [3, 29, 67]. Trees in the RGS are essential in mitigating climate change impacts and sequestering carbon, serving as significant carbon sinks by storing it within their biomass [76]. This contributes to keeping global warming below 1.5 °C, as per the Paris Climate Agreement. These contributions to carbon sequestration occur through mechanisms such as photosynthesis and by enhancing soil carbon storage through processes such as leaf litter decomposition and root exudation [10, 68].

[]. Trees in RGS also reduce the amount of sunlight reaching the ground and therefore result in better thermal comfort needed for public [77]. The ecological advantages of RGS go well beyond cooling and shading when seen through the lens of human thermal perception (Zou and Zhang et al. 2021). Since it influences people's preferences for the selection and long-term usage of green spaces, outdoor thermal comfort is one of the most crucial factors of green space quality [46]. These also enhance the visual appeal of urban landscapes, promote recreation and reduce stress among residents [25]. RGS management has also increasingly prioritized the support of preserving culturally significant plant species [38]. RGS can also help in attaining the goals under international frameworks such as the Sustainable Development Goals of the United Nations and other global policy initiatives [69].

However, all UGS are frequently linked to biotic homogenization, a process whereby diverse native plant species are gradually replaced by a few widespread invasive plant species, disturbing the composition of community structure, leading to loss of functional diversity, and long-term ecosystem degradation [20]. When plants are purposefully or inadvertently brought by people into areas outside of their natural range, they harm biodiversity, interfere with ecosystem services, and have a detrimental effect on human welfare and economies [44, 45]. RGS can exacerbate this issue by facilitating the spread of non-native plant propagules into nearby natural habitats [59]. Therefore, monitoring the health of the RGS ecosystem is essential for making informed decisions [58]. However, only a few alien invasive species can invade intact and undisturbed ecosystems [81]. These are known to decrease biodiversity, lower productivity, degrade wildlife habitats, displace native species, and disrupt ecosystem functions [86]. One of the main causes of biodiversity loss are thus invasive species [31]. In India, 54 invasive alien terrestrial plant species have been reported and *Prosopis juliflora* and *Leucaena leucocephala* are two such species [84].

In megacities, university campuses RGS can serve as a site for the conservation of biodiversity and also engage stakeholders in research and education [56]. These serve as living laboratories, generating awareness through community outreach and conservation projects [35]. Additionally, university RGS contribute significantly to carbon stock through green infrastructure [92]. By combining these efforts with policy advocacy, campuses not only enhance ecosystem services but also act as models of sustainable urban environments. Recent studies highlight that Delhi exhibits major disparities in the availability and accessibility of UGS, with lower-income neighbourhoods being particularly underserved [69]. This uneven distribution exacerbates social and ecological vulnerabilities. So, there is need for localized assessments of RGS on institutional campuses that may function as semi protected ecological zones providing essential ecosystem services.

Despite its importance, research on RGS and its role in India, particularly in Delhi, in providing ecosystem services is limited. Therefore, this study aims to (1) assess RGS tree diversity on a 56-year-old university campus in Delhi, (2) estimate the carbon stock of the studied RGS, and (3) quantify the impact of RGS on thermal comfort.

2 Methodology

2.1 Study site

The study was carried out at Jawaharlal Nehru University (JNU) Campus (which covers around 405 ha, i.e., an area of approximately 4 km²) between 28°31′37″–28°33′12″ N and 77°09′08″–77°10′46″ E. The JNU campus (established in 1969) falls within the Delhi Ridge, which is part of the Aravalli range [23] and is classified as semiarid open scrub [12]. The region has a semiarid environment with 728 mm of annual rainfall on average (1984–2015), of which approximately 600 mm (82%) occurs during the summer monsoon. The total road length of the campus is approximately 34.38 km (Fig. 1). Four major roads of the JNU campus were selected as the sampling sites on the basis of their different levels of mobility. These roads include Ring Road (A), North Gate Road (B), East Gate Road (C), and Stadium Road (D), covering stretches of 2.1, 1.2, 1.5 and 0.7 km, respectively (Fig. 1). Road A is the main road that encircles the academic blocks, and there is more mobility during working hours on working days. Additionally, road A is well maintained in terms of the road structure as well as the roadside green spaces. Road B is the busiest road for almost all days and all hours because it connects all residential and academic blocks to the main gate of the campus. Road C is the third busiest road, as this road connects academic blocks for visitors and is mostly used by private vehicles.

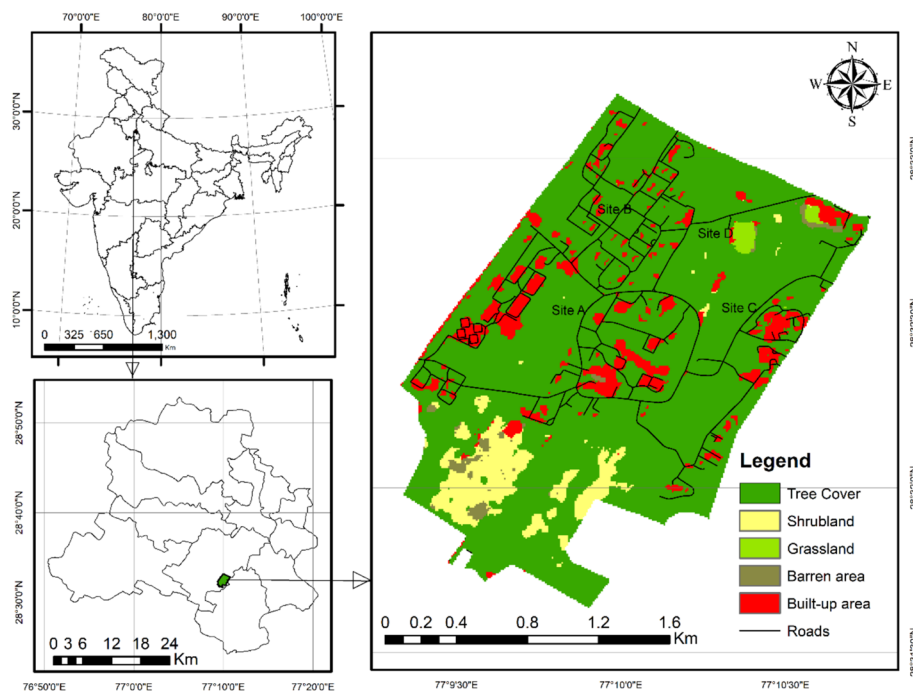


Fig. 1 Study area map of Jawaharlal Nehru University (JNU), New Delhi, showing four roadside green space (RGS) sites (A–D). Road network data were obtained from OpenStreetMap, and land use/land cover (LULC) classes were extracted from ESA WorldCover 2022. The campus is dominated by tree cover (301.61 ha), followed by built-up areas (30.17 ha), shrublands (21.97 ha), barren land (3.66 ha), and grasslands (2.38 ha). The total road length across the campus is approximately 34.38 km.

Road D, although it is the least busy road on average in terms of vehicular mobility, experiences increased pedestrian activity in the morning and evening, as this road leads to the stadium.

2.2 Tree diversity and carbon stock assessment

The tree diversity assessment was carried out via the belt transect methodology (Fig. 2). In each transect, three plots 10×5 m in size were laid from the point where the concrete construction ended, with 50 m distance between two subsequent plots. Another transect was laid on the alternate side of the road, with the two transects separated by a distance of 100 m. The width of each plot was selected to be 5 m, as it was not feasible to go deeper due to the topography of the study site and the presence of massive quartzite rock blocks.

A total of 59 plots were laid across these four sites. 27, 12, 12 and 8 plots were laid at the corresponding sites, A, B, C, and D. The standard belt transect methodology was used across the four sampling sites, resulting in a variable number of plots at each site. However, to nullify the effect of this variation on the diversity indices, a rarefaction curve was employed to validate the diversity estimated using indices. Within the laid plot area, the total number of tree species and each individual tree were counted. Trees were recognized at the species level via a field guide [53]. An advanced clinometer (Suunto Opti Height Meter Clinometer PM-5) was used to measure the height of the tree, and the diameter at breast height (DBH) was calculated by measuring the circumference at breast height (CBH) with a measuring tape. A height of 1.5 m was used as the reference point for DBH measurements. Various diversity indices were used to evaluate tree diversity across the four sites (A, B, C, and D).

The Simpson index (D') was used to evaluate species dominance.

$$D' = \sum_{i=1}^S p_i$$

where, $p_i = n/N$

where "S" stands for species richness, "n" for the total number of individuals in the i^{th} species, and "N" for the total number of individuals found. This formula gives a value between 0 and 1, where 0 indicates infinite diversity (theoretically, if every individual belongs to a different species) and 1 indicates no diversity, which means that all individuals belong to the same species [57].

Shannon index (H') was employed to evaluate species diversity and community equity using the formula:

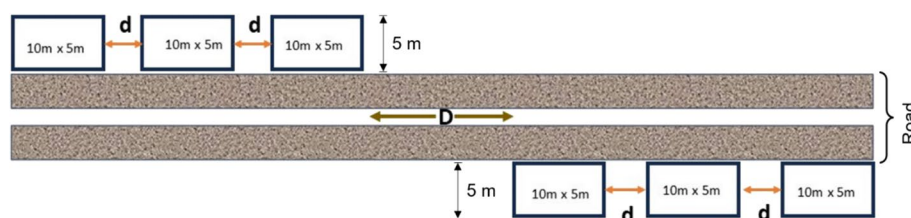


Fig. 2 Schematic layout of belt transects along roadside green spaces. Each plot measured $10 \text{ m} \times 5 \text{ m}$ and was extended 5 m beyond the road edge. The plots were placed at 50 m intervals (d) along the same side of the road, whereas opposite transects were separated by 100 m (D).

$$H' = - \sum_{i=1}^S (p_i) \cdot \ln(p_i)$$

where 'S' is the total number of species and ' p_i ' is the proportion of individuals belonging to the 'ith' species. Here, higher values indicate greater diversity. This index can reach zero to any positive value. Zero indicates no diversity, and higher values indicate greater diversity [57].

Pielou's evenness index (J') was used to assess the distributional evenness of species within the community.

$$J' = \frac{H'}{\ln(S)}$$

where "S" stands for species richness and "H" for Shannon index. The range of this index is 0 to 1, with 1 indicating maximum evenness [57].

2.3 Importance value index (IVI)

The importance value index (IVI) was calculated via relative frequency (RF), relative density (RD), and relative dominance (RDom), which were summed to obtain an IVI score with a maximum score of 300 [19].

$$IVI = \sum (RF, RD, RDom)$$

Relative frequency

$$RF(\%) = \frac{(\text{Number of occurrences of the species})}{(\text{Total number of occurrences})} \times 100$$

Relative density

$$RD(\%) = \frac{(\text{No. of individuals of the species})}{(\text{No. of individuals of all species})} \times 100$$

Relative dominance

$$RDom(\%) = \frac{(\text{Basal area of the species}(BA))}{(\text{Total basal area of all species}(TBA))} \times 100$$

where

$$BA = \pi \times (DBH/2)^2$$

$$TBA = (\text{No of individuals of the species}) \times (\text{Mean basal area of species})$$

2.4 Familial value index (FVI)

The FVI was calculated via the relative diversity (RDiv), relative density (RD) and relative dominance (RDom) of families, which were summed to obtain an FVI score with a maximum value of 300 [62].

$$FVI = \sum (RDiv(\%), RD(\%), RDom(\%))$$

Relative diversity

$$RDiv(\%) = \frac{(\text{Number of species in a family})}{(\text{Total number of species in the community})} \times 100$$

Relative density

$$RD(\%) = \frac{(\text{No of trees in a family})}{(\text{Total number of trees of all families})} \times 100$$

Relative dominance

$$RDom(\%) = \frac{(\text{Basal area of a family})}{(\text{Total basal area of the community})} \times 100$$

2.5 Thermal comfort

In situ temperature measurements were taken in the first week of May 2025 between 12:00 and 15:00. The day time was selected for capturing the typical summer day temperature. The method is used under the assumption that trees regulate the cooling effect beneath their canopy through evapotranspiration and shading. This leads to a decrease in air and surface temperatures under its canopy. A hand-held digital air temperature sensor (ANMOL 4201 Version: 8901-EN-00, range: 0 to 45 °C ± 2 °C) was used for measuring the air temperature 1.5 m above the ground's surface, which was close to human height, reflecting a vertical atmospheric zone interacting with our body [65]. A hand-held infrared thermometer (WORKZONE IR-950, range: – 50 to 950 °C) was employed in order to gauge the surface temperature. The surface temperature was measured by pointing the IR sensor at an angle of 90° (perpendicular) to the ground surface until the temperature readings stabilized. The surface temperature measurements were taken along roads at different locations under the shade of trees and under direct sunlight.

2.6 Tree biomass and carbon stock

Destructive and non-destructive methods are generally used for tree and crop biomass estimation. In the present study, the non-destructive method, followed by an allometric equation, was used to determine the standing biomass [8]. Various tree variables need to be measured to develop allometric equations and biomass tables, like wood density, total tree height, and diameter at breast height (DBH) [8]. Tree species-specific allometric equations and wood density were used for estimating biomass (Table 1). For tree species lacking specific gravity data, a default value of 0.6 g/cm³, as suggested by the USDA Forest Service, was employed to calculate carbon stocks and biomass [99].

The following formula was used to calculate the diameter at breast height (DBH) from the circumference at breast height (CBH):

$$DBH = CBH/\pi$$

Some equations estimate total biomass (TB), whereas others calculate aboveground biomass (AGB) exclusively. For equations providing only AGB, belowground biomass (BGB) was derived via an empirical relationship, suggesting a fixed ratio of 26% between BGB and AGB [9].

Table 1 Species-specific allometric equations used for estimating biomass of observed tree species

S.No	Scientific Name	Wood Density	Citation For Wood Density	Allometric Equations	Citation For Allometric Equations
1	<i>Aegle marmelos</i>	0.75	FAO [28]	$AGB = \{p \times \exp(-0.667 + 1.784 \times \ln(D) + 0.207 \times (\ln(D))^2 - 0.0281 \times (\ln(D))^3)\}$	Chave et al. [13]
2	<i>Albizia lebbeck</i>	0.66	FAO [28]	$TB = \{0.4 \times (\text{Diameter})^2 \times \text{Height} \times \text{Wood Density}\}$	Kumari et al. [52]
3	<i>Alstonia scholaris</i>	0.36	FAO [28]	$AGB = \exp\{-5.014 + 3.068 \ln(D)\}$	Liddell et al. [55]
4	<i>Azadirachta indica</i>	0.69	FAO [28]	$TB = \{0.4 \times (\text{Diameter})^2 \times \text{Height} \times \text{Wood Density}\}$	Kumari et al. [52]
5	<i>Bauhinia variegata</i>	0.67	FAO [28]	$AGB = 0.0673 \times (p \times D^2 \times H)^{0.976}$	Chave et al. [13]
6	<i>Bombax ceiba</i>	0.33	FAO [28]	Stem biomass (AGB (q tree-1)) = $\{10 \times SG \times \text{stem volume}\}$	Devi and Das [22]
7	<i>Callistemon viminalis</i>	0.6	Chave et al. [13]	$B = \{0.4 \times (\text{Diameter})^2 \times \text{Height} \times \text{Wood Density}\}$	Kumari et al. [52]
8	<i>Cassia fistula</i>	0.71	FAO [28]	$TB = \{0.7837(D^2 \times H) - 0.0004\}$	Tripathi [93]
9	<i>Cordia myxa</i>	0.53	FAO [28]	$TB = \{0.4 \times (\text{Diameter})^2 \times \text{Height} \times \text{Wood Density}\}$	Kumar et al. [52]
10	<i>Dalbergia sissoo</i>	0.62	Meghwal and Chauhan [60]	$TB = \{0.4 \times (\text{Diameter})^2 \times \text{Height} \times \text{Wood Density}\}$	Kumari et al. [52]
11	<i>Ehretia leavis</i>	0.46	Pati et al. [71]	$\ln AGB = \{(0.608 \times (\ln(D^2 \times H) \times p)) + 0.972\}$	Pati et al. [71]
12	<i>Ficus virens</i>	0.39	FAO [28]	$AGB = \{0.11 \times \text{Species Density} \times D^{2.62}\}$	Hendrayana et al. [40]
13	<i>Grevillea robusta</i>	0.81	Hernández and Genes [42]	$TB = \{0.4 \times (\text{Diameter})^2 \times \text{Height} \times \text{Wood Density}\}$	Kumari et al. [52]
14	<i>Holoptelea integrifolia</i>	0.64	Zanne et al. [32]	$TB = \{0.4 \times (\text{Diameter})^2 \times \text{Height} \times \text{Wood Density}\}$	Kumari et al. [52]
15	<i>Leucaena leucocephala</i>	0.64	FAO [28]	$TB = \{0.5 \times (DBH)^2 \times H \times p\}$	Kanazawa et al. [49]
16	<i>Nctanthes arbor-tristis</i>	0.88	FAO [28]	$\ln AGB = \{-3.206 + 1.337 \ln(p \times D^2 \times H)\}$	Chave et al. [13]
17	<i>Pithecellobium dulce</i>	0.5	Zanne et al. [32]	$TB = \{0.5825 \times (DBH)^{1.6178}\}$	Navar [64]
18	<i>Polyalthia longifolia</i>	0.86	Heckadka et al. [37]	$TB = \{34.4703 - 8.0671D + 0.6589D^2\}$	Pragasan [75]
19	<i>Pongmia pinnata</i>	0.609	Rajput et al. [79]	$AGB = \text{Exp. } \{-2.4090 + 0.9522 \ln(D^2 \times H \times S)\}$	Ahmedin et al. [2]
20	<i>Prosopis juliflora</i>	0.73	Zanne et al. [32]	$AGB = \{p \times \exp(-0.667 + 1.784 \ln(D) + 0.207 (\ln(D))^2 - 0.0281 (\ln(D))^3)\}$	Sundarapandian et al. [90]
21	<i>Syzygium cumini</i>	0.69	Zanne et al. [32]	$AGB = \{p \times \exp(-0.667 + 1.784 \ln(D) + 0.207 (\ln(D))^2 - 0.0281 (\ln(D))^3)\}$	Sundarapandian et al. [90]
22	<i>Tamarindus indica</i>	0.75	FAO [28]	$AGB = \{p \times \exp(-0.667 + 1.784 \ln(D) + 0.207 (\ln(D))^2 - 0.0281 (\ln(D))^3)\}$	Sundarapandian et al. [90]
23	<i>Tecoma stans</i>	0.6	Chave et al. [13]	$TB = \{0.4 \times (\text{Diameter})^2 \times \text{Height} \times \text{Wood Density}\}$	Kumari et al. [52]
24	<i>Tectona grandis</i>	0.67	Adi et al. [1]	$AGB = \{0.0904 \times DBH^{2.551}\}$	Kinyanjui et al. [51]
25	<i>Terminalia Arjuna</i>	0.68	FAO [28]	$B = \{0.372 + \{0.246D^2 \times H\}\}$	Srivastava et al. [89]
26	<i>Acacia leucophloea</i>	0.76	FAO [28]	$AGB = \{p \times \exp(-0.667 + 1.784 \ln(D) + 0.207 (\ln(D))^2 - 0.0281 (\ln(D))^3)\}$	Sundarapandian et al. [90]
27	<i>Acacia nilotica</i>	0.77	U.S. Forest Service [97]	$TB = \{0.4 \times (\text{Diameter})^2 \times \text{Height} \times \text{Wood Density}\}$	Kumari et al. [52]

The sum of AGB and BGB yielded TB. Total biomass values from different equations may be expressed in varying units (e.g., kg, quintal, or ton), necessitating conversion into a uniform unit.

The carbon stock (CS) was determined for each species via an empirical relationship between the TB and total carbon stock via an empirical equation [73].

$$\text{Carbon stock} = (\text{Total Biomass}/2)$$

Biomass was measured in 'ton/m²', and the carbon stock was measured in 'tC/m²' for the stretches of different study sites.

Using the mean diameter at breast height and mean height values as independent variables, the total biomass and carbon stock were calculated for 27 species within the study area and scaled by their respective species populations to obtain the total biomass and carbon stock from the study area. Familial contributions to total biomass were assessed by aggregating and analysing the TB and CS of species belonging to the same family.

2.7 Statistical analysis

2.7.1 Rarefaction curve

To account for differences in sampling effort, rarefaction curves were generated via individual-based rarefaction. This approach standardizes species richness by randomly resampling individuals to a common sample size, thereby allowing comparison of diversity across sites independent of sampling intensity [83]. Rarefaction analysis was used in to evaluate and compare species richness across different sites with unequal sampling areas.

The individual-based rarefaction method was used, where the expected number of species $E(S_n)$ in a random subsample of people selected from a bigger pool of N individuals (containing S species) is estimated via the following formula:

$$E(S_n) = \sum_{i=1}^S \left[1 - \left(\frac{\binom{N-n_i}{n}}{\binom{N}{n}} \right) \right]$$

where, $E(S_n)$ = expected number of species in a random sample of ' n ' individuals. S = total number of species in the full sample. N = total number of individuals in the full sample. n_i = number of individuals of species i .

The expressions included in the innermost parentheses are combinations rather than fractions.

Rarefaction curves were generated via the iNEXT (iNterpolation and EXTrapolation) tool in the R programming language [78], which is specifically designed for biodiversity estimation through rarefaction and extrapolation (Hsieh and Chao, 2016).

3 Results and Discussion

3.1 Tree diversity and composition

Along the roadside RGS in the study region, a total of 27 tree species from 27 genera and 15 families were identified (Table 2). The overall diversity of the study area across all four sites had a D of 0.16, H' of 2.47, and J' of 0.75, indicating high dominance, moderate

abundance, and high evenness, respectively. Among the 27 tree species recorded, 19 were native, 6 were introduced, and 2 were invasive.

The present study's tree diversity ($H' = 2.47$; $J' = 0.75$; species richness = 27) was comparable to that of other academic institutions in northern India. Singh et al. [87] reported species richness values of 21 ($H' = 2.897$, $J' = 0.967$) at Banaras Hindu University and 10 ($H' = 2.137$, $J' = 0.214$) at Uday Pratap Autonomous College, Varanasi, Uttar Pradesh, whereas Sharma et al. (2024) recorded 68 species ($H' = 1.9$, $J' = 0.72$) at the IISER, Mohali, Punjab, highlighting that university campuses can maintain significant biodiversity and serve as effective conservation sites in urban areas.

The five species with the highest IVI scores were *Leucaena leucocephala* (84.02), *Prosopis juliflora* (31.23), *Cassia fistula* (30.83), *Acacia nilotica* (30.35), and *Azadirachta indica* (18.54), contributing 28.01%, 10.41%, 10.27%, 10.11%, and 6.18%, respectively, to the total species importance value index.

3.2 Dominant species and families

Fabaceae was the most dominant family, accounting for 61.82% of the FVI values, with 11 genera and 11 species (Fig. 3). This family's ecological success is linked to adaptive traits such as divided leaves, which reduce water loss during dry seasons [41], and nitrogen fixation, allowing survival in nutrient-poor soils [47]. The nutrient-poor colluvial and aeolian soils of the campus [94] likely favour Fabaceae dominance. Other notable families included Meliaceae (4.97%), Myrtaceae (4.88%), Boraginaceae (3.73%), and Annonaceae (3.51%). Myrtaceae and Boraginaceae each had two genera and two species, whereas one genus and one species represented each of the other ten families (Table 2).

3.3 Evergreen vs. Deciduous trees

Seven species were evergreen (Table 2), including *Alstonia scholaris*, *Azadirachta indica*, *Grevillea robusta*, *Polyalthia longifolia*, *Pongamia pinnata*, *Tamarindus indica*, and *Syzygium cumini* [53, 70]. Evergreen species have a long visual appeal of lush greenery along the roadside, whereas deciduous tree species shed their leaves in the leaf fall season. These trees also have superior particulate matter (PM) reduction capabilities compared with deciduous trees [70, 100]. Year-long CO₂ removal from the ambient atmosphere, where vehicular emissions magnify the load of CO₂ in the ambient atmosphere, makes the choice of evergreen tree species along the roadside stand out significantly compared with deciduous trees [33]. These functional benefits support prioritizing evergreen species in RGS plantations in Delhi.

3.4 Functional and conservation values

Several species also have notable aesthetic, medicinal, and edible fruit value. *Alstonia scholaris* [21], *Bauhinia variegata* [54], *Callistemon viminalis* [82], *Cassia fistula* [63], *Nyctanthes arbor-tristis* [80], and *Tecoma stans* [88] are renowned for their aesthetic qualities. Native species such as *Aegle marmelos*, *Azadirachta indica*, and *Terminalia arjuna* hold traditional medicinal significance, as their fruits, seeds, leaves, and bark offer various health benefits [24, 34].

The recorded species included two conservation concerns: *Aegle marmelos* ('Near Threatened') and *Tectona grandis* ('Endangered') (IUCN Red List). Both are native to the region and intentionally planted in RGS to help conserve these species of concern, which

Table 2 Ecological characteristics and estimated biomass of the observed tree species

S.N	Common Name	Scientific Name	Family	Origin	Physiognomy	IUCN Red List Status	No. of Individuals	Tree Density (trees per 100 sqms)	IVI (%)	Total Basal Area (m ²)	Total Biomass (ton)	Total Carbon Stock (tC)	Carbon Stock per Unit Basal Area (tC/m ²)
1	Ronjh	<i>Acacia leucophloea</i>	Fabaceae	Native	Deciduous	LC	2.00	2.00	3.24	0.87	0.71	0.35	0.40
2	Indian Gum	<i>Acacia nilotica</i>	Fabaceae	Native	Deciduous	LC	15.00	3.33	21.03	6.55	2.99	1.49	0.23
3	Bael	<i>Aegle marmelos</i>	Rutaceae	Native	Deciduous	NT	3.00	2.00	4.46	1.31	1.80	0.90	0.69
4	Siris	<i>Albizia lebbeck</i>	Fabaceae	Native	Deciduous	LC	6.00	2.00	9.07	2.62	1.30	0.65	0.25
5	Saptarni	<i>Alstonia scholaris</i>	Apocynaceae	Native	Evergreen	LC	3.00	6.00	3.55	1.31	0.27	0.13	0.10
6	Neem	<i>Azadirachta indica</i>	Meliaceae	Native	Evergreen	LC	14.00	2.33	18.54	6.11	2.50	1.25	0.20
7	Kachnar	<i>Bauhinia variegata</i>	Fabaceae	Native	Deciduous	LC	1.00	2.00	2.51	0.44	0.25	0.13	0.30
8	Semal	<i>Bombax ceiba</i>	Malvaceae	Native	Deciduous	LC	2.00	4.00	4.35	0.87	0.46	0.23	0.26
9	Bottle Brush	<i>Callistemon viminalis</i>	Myrtaceae	Introduced	Deciduous	NE	4.00	2.67	4.73	1.75	0.18	0.09	0.05
10	Amaltas	<i>Cassia fistula</i>	Fabaceae	Native	Deciduous	LC	22.00	2.75	30.83	9.61	70.28	35.14	3.66
11	Lasura	<i>Cordia myxa</i>	Boraginaceae	Native	Deciduous	LC	3.00	3.00	2.54	1.31	0.11	0.06	0.05
12	Shisham	<i>Dalbergia sissoo</i>	Fabaceae	Native	Deciduous	LC	1.00	2.00	1.93	0.44	0.01	0.01	0.01
13	Harandi	<i>Ehretia leavis</i>	Boraginaceae	Introduced	Deciduous	DD	4.00	8.00	2.88	1.75	21.66	10.83	6.20
14	Pilkhan	<i>Ficus virens</i>	Moraceae	Native	Deciduous	LC	9.00	9.00	8.53	3.93	0.39	0.19	0.05
15	Silver Oak	<i>Grevillea robusta</i>	Proteaceae	Introduced	Evergreen	LC	2.00	4.00	3.31	0.87	0.69	0.34	0.39
16	Kanju	<i>Holoptelea integrifolia</i>	Ulmaceae	Native	Evergreen	LC	6.00	2.40	7.26	2.62	0.81	0.41	0.16
17	Subabool	<i>Leucaena leucocephala</i>	Fabaceae	Invasive	Deciduous	LR	88.00	7.04	84.02	38.43	45.30	22.65	0.59
18	Harsingar	<i>Nyctanthes arbor-tristis</i>	Oleaceae	Native	Deciduous	LC	3.00	6.00	3.33	1.31	0.72	0.36	0.28
19	Madras Thorn	<i>Pithecellobium dulce</i>	Fabaceae	Introduced	Deciduous	LC	2.00	4.00	1.92	0.87	0.15	0.07	0.08
20	Ashoka	<i>Polyalthia longifolia</i>	Annonaceae	Native	Evergreen	LC	4.00	4.00	8.45	1.75	3.56	1.78	1.02
21	Karanj	<i>Pongamia pinnata</i>	Fabaceae	Native	Deciduous	LC	6.00	1.71	8.45	2.62	22.91	11.45	4.37
22	Vilayati Kikar	<i>Prosopis juliflora</i>	Fabaceae	Invasive	Deciduous	LC	29.00	4.14	31.22	12.66	5.87	2.93	0.23
23	Jamun	<i>Syzygium cumini</i>	Myrtaceae	Native	Evergreen	LC	4.00	2.67	6.95	1.75	5.15	2.58	1.48
24	Imli	<i>Tamarindus indica</i>	Fabaceae	Introduced	Evergreen	LC	2.00	2.00	2.38	0.87	2.90	1.45	1.66
25	Cape Honey Suckle	<i>Tecoma stans</i>	Bignoniaceae	Introduced	Deciduous	LC	3.00	3.00	4.01	1.31	0.09	0.04	0.03

Table 2 (continued)

S.N	Common Name	Scientific Name	Family	Origin	Physiognomy	IUCN Red List Status	No. of Individuals	Tree Density (trees per 100 sqms)	IVI (%)	Total Basal Area (m ²)	Total Bio-mass (ton)	Total Carbon Stock (tC)	Carbon Stock per Unit Basal Area (tC/m ²)
26	Teak Tree	<i>Tectona grandis</i>	Lamiaceae	Native	Deciduous	EN	2.00	2.00	2.48	0.87	1.54	0.77	0.88
27	Arjun Tree	<i>Terminalia Arjuna</i>	Combretaceae	Native	Deciduous	LC	7.00	3.50	9.27	3.06	3.30	1.65	0.54

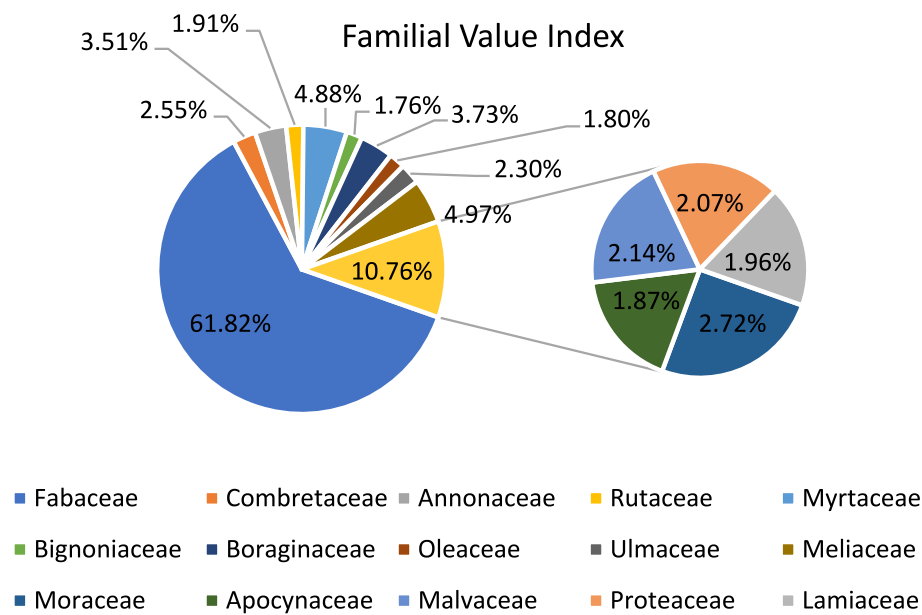


Fig. 3 Relative contributions of different tree families to the familial value index (FVI) across roadside green spaces (RGS) in the study area

Table 3. Comparison of Tree Density, Tree Diversity, and Thermal Comfort Metrics across Selected Study Sites

Study site		Ring Road	North Gate Road	East Gate Road	Stadium Road
Site Code		Site A	Site B	Site C	Site D
Path Length (km)		2.10	1.20	1.50	0.70
No of Plots		27	12	12	8
Tree Species Richness		18	17	15	10
Tree Abundance		83	65	66	32
Tree Density (trees per 100m ²)		61	11	11	8
Tree Diversity	Simpson (D)	0.21	0.10	0.09	0.28
	Shannon (H')	2.11	2.00	1.94	1.75
	Evenness (J')	0.73	0.71	0.72	0.41
Cooling Effect	Air Temp. of open area (°C)	37.63	38.13	38.53	36.87
	Air Temp. under Shade (°C)	36.65	36.2	36.29	36.07
	Δ Air Temp. (°C)	0.98	1.93	2.24	0.80
	Surface Temp. of open area (°C)	48.97	52.58	52.24	42.44
	Surface Temp. under shade (°C)	44.53	44.21	44.03	38.64
	Δ Surface Temp. (°C)	4.44	8.37	8.21	3.80

aligns with SDG 15 (Life on Land)-Target 15.9, demonstrating the potential of RGS as ex situ conservation sites for rare and threatened taxa [95].

3.5 Site-wise diversity patterns

Site A presented the maximum tree diversity ($D = 0.21$; $H' = 2.11$; $J' = 0.73$) (Table 3.). The total path length of Site A was 2.1 km, which was the longest among all the sites. The longer path length of the road is also one of the major reasons why the site is highly

diverse in tree communities because, generally, with increasing area, the diversity also increases [17]. Among its 18 species, 14 were native, 2 were introduced, and 2 were invasive. However, Site D, with 10 tree species, presented the lowest diversity (Table 3.) ($D = 0.28$; $H = 1.75$; $J' = 0.41$) and shortest path length (0.7 km), hosting 7 native, 1 introduced, and 2 invasive species. Site B (1.2 km) presented moderate diversity ($D = 0.10$; $H = 2.0$; $J' = 0.71$), with 12 native, 3 introduced, and 2 invasive species. Site C (1.5 km) also presented moderate diversity ($D = 0.09$; $H' = 1.94$; $J' = 0.72$), with 11 native, 2 introduced, and 2 invasive species.

3.6 Rarefaction analysis

Rarefaction analysis was employed to standardize species richness across sites by accounting for unequal sampling efforts. For a given number of individuals randomly selected from each group, the curves (Fig. 4) show the predicted number of species, allowing for objective comparisons of diversity. Site A consistently presented the highest richness, followed by Site B and Site C, whereas Site D presented markedly lower richness.

3.7 RGS biomass and carbon stock—a regulating ecosystem service

Estimating biomass and carbon stocks is frequently done using basal area, which is the total of cross-sectional areas of all trees at breast height. It serves as a strong predictor, as it accounts for both tree size and density [6]. Across the study sites, the carbon stock values were 0.020 tC/m² (Site A), 0.502 tC/m² (Site B), 0.606 tC/m² (Site C) and 0.021 tC/m² (Site D) with a total carbon stock of 0.312 tC/m². *Ehretia leavis* presented the highest carbon stock per unit basal area (6.2 tC/m²). Although this species was introduced and not particularly abundant within the study area, the results highlight its

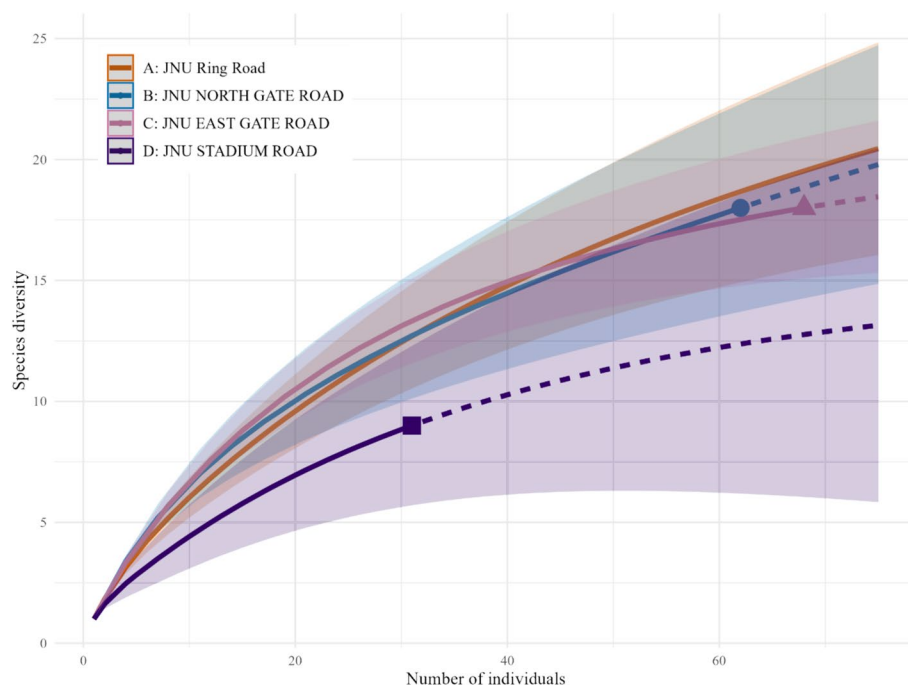


Fig. 4 Rarefaction curves depicting the expected species richness in RGS tree communities at the study sites, demonstrating site-wide variation in diversity independent of sampling bias.

significant potential for carbon sequestration. While not currently classified as invasive in India, continuous monitoring is advised to ensure that it does not threaten native biodiversity. The Fabaceae family contributed the highest total carbon stock (2.59 tC/100 m²; 77.92%). Even when the two invasive Fabaceae species were excluded, the family still accounted for 51.8% of the total carbon stock, which aligns with the high Fabaceae diversity previously reported in Delhi's urban forests and the Aravalli range [30].

3.8 Thermal comfort

Trees play a vital role in cooling through shading and transpiration, especially along roadside pavements, improving walking comfort during peak summer months [15]. By releasing water vapour, trees lower their surrounding temperatures, much like humans sweat [91]. The results highlight the contribution of RGS to microclimate regulation, as shown by variations in air and surface temperatures across sites. The largest air temperature reduction was observed at Site C (2.24 °C), followed by Sites B (1.93 °C), A (0.98 °C), and D (0.80 °C) (Table 3). These differences suggest that canopy density and spatial arrangement strongly influence cooling. Site C's moderate tree density (10.8 trees/100 m²) with optimal canopy cover likely increased shade and reduced ambient air temperatures. The surface temperature reductions were also greater at Sites B (8.37 °C) and C (8.21 °C). This finding provides evidence that dense canopies reduce surface heating by intercepting solar radiation [96, 102]. Notably, Site A, despite having the highest density (61.4 trees/100 m²), exhibited weaker cooling, suggesting that the species composition, canopy form, or site layout might have limited shading efficiency and airflow. This finding indicates that cooling is not a simple function of tree density alone but rather depends on structural traits such as crown spread, leaf texture, vertical stratification, and spacing relative to built surfaces. Sites dominated by tall narrow crowns or poorly layered canopies can accumulate heat and restrict ventilation despite high stem density. Conversely, species with broad crowns and staggered spatial arrangements can enhance convective cooling and surface shading even at lower densities. Overall, these findings demonstrated that the university RGS significantly regulates urban microclimates while also supporting biodiversity, underscoring their value as conservation sites in rapidly urbanizing landscapes [16, 98].

3.9 Invasive species

All four sites are heavily invaded by *Leucaena leucocephala* and *Prosopis juliflora*, although invasion levels vary with human intervention. These species thrive in disturbed soils [27, 53], spreading rapidly through efficient seed dispersal and forming dense monocultures that displace native plants [48]. Originally introduced for afforestation in the early twentieth century, they now dominate many degraded landscapes, including Sanjay Van [53]. The proportions of individuals at Sites A, B, C, and D were 60.71%, 47.08%, 30.77%, and 52.94%, respectively, averaging 47.17% across the study area. Despite its high IVI (28.02%), *L. leucocephala* stores only 0.59 tC/m², while *P. juliflora* sequesters even less (0.23 tC/m²), underscoring its poor contribution to the carbon stock. Ecologically, these invasives alter light availability, nutrient cycling, and water use efficiency [11], suppress native regeneration, and outcompete planted species [39]. Prolific self-sowing and shading further impoverish the regenerating tree community [50].

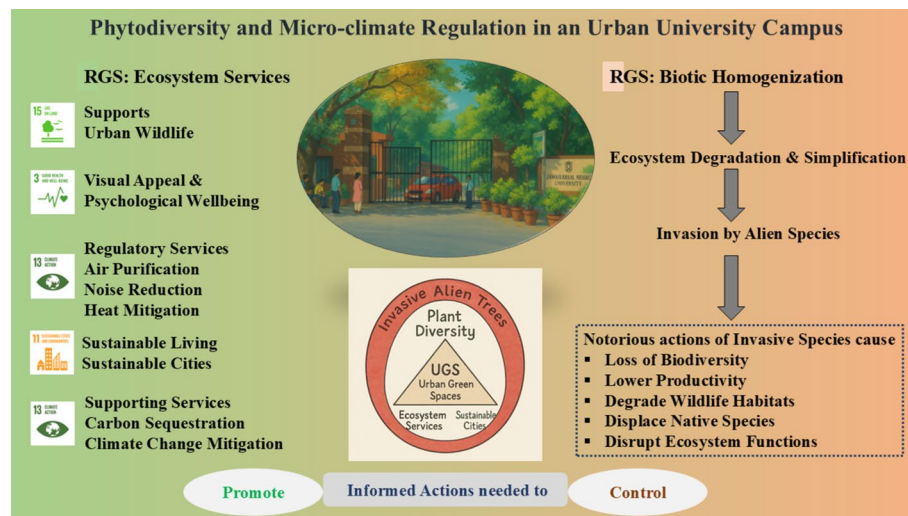


Fig. 5 Conceptual diagram illustrating roadside green spaces: sites for phytodiversity, carbon stock and microclimate regulation

Thus, managing and gradually removing invasives is critical for sustaining RGS biodiversity and carbon storage.

3.10 Policy implications

Although the studied RGS are characterized by relatively high tree density, their biomass and carbon stock are low due to the dominance of invasive species. These species occupy extensive areas and occur in large numbers, yet their carbon contribution and CO₂ sequestration potential are minimal compared with those of native taxa. This imbalance reduces the long-term effectiveness of RGS as a carbon sink. Addressing this challenge requires systematic removal of invasives, restoration of native vegetation, and targeted planting of high-biomass native trees such as *Cassia fistula*, *Pongamia pinnata*, and *Ehretia laevis*. Such interventions should be embedded within India's National Biodiversity Action Plan (NBAP) and implemented locally under the National Urban Forestry Programme (NUFP), both of which emphasize biodiversity-sensitive management and urban greening.

At the global level, the Kunming–Montreal Global Biodiversity Framework provides additional alignment, particularly with Target 6 (reduction of invasive alien species) and Target 12 (promotion of urban green spaces) [18]. Integrating these priorities into Delhi's urban ecological planning will be critical for enhancing carbon storage, improving ecosystem services, and building climate resilience. They also support India's commitment to the Net Zero Target by 2070 [61]. The findings also help achieve the Sustainable Development Goals (SDGs), particularly SDG 15.8 (preventing invasive alien species), SDG 13.1 (increasing resilience to climate-related impacts), and SDG 11.7 (ensuring access to safe and inclusive green spaces). By positioning campuses as semiprotected ecological zones and integrating biodiversity data into planning, Delhi can advance toward a more resilient, inclusive, and climate-adaptive urban future (Fig. 5).

4 Conclusion

In megacities, RGS provides crucial ecosystem services, such as the conservation of plant diversity, climate change mitigation by reducing CO₂, and thermal comfort by cooling and shading. These services are underutilized because of the nonmanagement of invasive plant species. The diversity was moderate, with an overall 47.17% invasion by *Leucaena leucocephala* and *Prosopis juliflora*. Despite the high abundance of invasive species, their contribution to the carbon stock was minimal (total estimated at 0.312 tC/m²) compared to native species, which was attributed to their low basal area and poor wood density. Furthermore, the overgrowth and trunk fall of *L. leucocephala* during strong winds hinder its ability to achieve a large basal area. The RGS significantly enhanced urban thermal comfort, as evidenced by air temperature reductions ranging from 0.80–2.24 °C and land surface temperature reductions ranging from 3.80–8.37 °C. These results highlight the importance of tree density and canopy cover in thermal comfort. To fully realize the potential of RGS, invasive management should be integrated into routine urban green space policy, followed by post intervention ecological monitoring to track the recovery of native species and improvements in ecosystem service delivery. Future research should extend such assessments to public roadside greens beyond protected campuses to generate scalable, city-wide guidance.

4.1 Limitations and future work

This study intentionally focuses on protected institutional roadside greens, which serve as a controlled model system to understand the ecological potential of managed RGS before comparisons are extended to heterogeneous public roadsides. By establishing baseline conditions in a low-disturbance setting, this work provides a reference frame against which future studies in more degraded or high-pressure sites can be meaningfully compared. Building on this foundation, future research will expand to unprotected urban roadside greens and evaluate how management interventions (e.g., invasive species control and planting schemes) translate into measurable gains in ecosystem service delivery at broader city scales.

Acknowledgements

Authors thank Dr. Senthil Kumar Umapathy (Assistant Professor, Madras Christian College, Chennai) for expert consultation for the identification of doubtful plant species, and also extend their gratitude to the anonymous reviewers for their valuable comments and suggestions.

Author contributions

AK and MP contributed equally to this work and are joint first authors. AK prepared the original draft in collaboration with MP. They jointly conducted the field surveys and carried out data analysis. AK made the figures and MP prepared the maps. AK, MP and UM revised the manuscript. UM conceptualized the study, supervised the research, critically reviewed the manuscript, and provided final checks.

Funding

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Data availability

Records of the tree species sampled during this study have been incorporated into a broader laboratory-managed database, which is publicly accessible via the following portal: [<https://sites.google.com/view/jnucampusflora/>].

Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Competing interests

The authors declare no competing interests.

Received: 18 August 2025 / Accepted: 26 November 2025

Published online: 31 December 2025

References

1. Adi, D. S., Himmi, S. K., Amin, Y., Darmawan, T., & Dwianto, W. Radial variation of wood properties of eight years-old fast-growing teak (*Tectona grandis*-Platinum teak wood). In IOP Conference Series: Earth and Environmental Science 2020;591(1):012035.
2. Ahmedin AM, Bam S, Siraj, KT, & Raju AS. Assessment of biomass and carbon sequestration potentials of standing *Pongamia pinnata* in Andhra University, Visakhapatnam, India. *Biosci. Dis.* 2013;4(2):143–148.
3. Akbari H, Pomerantz M, Taha H. Cool surfaces and shade trees to reduce energy use and improve air quality in urban areas. *Sol Energy.* 2001;70(3):295–310. [https://doi.org/10.1016/S0038-092X\(00\)00089-X](https://doi.org/10.1016/S0038-092X(00)00089-X).
4. An S, Dedekorkut-Howes A. A review of adaptation strategies to increased urban temperatures and heat island effect. *Discover Cities.* 2025;2(1):1–21.
5. Aronson MF, Lepczyk CA, Evans KL, Goddard MA, Lerman SB, MacIvor JS, et al. Biodiversity in the city: key challenges for urban green space management. *Front Ecol Environ.* 2017;15(4):189–96. <https://doi.org/10.1002/fee.1480>.
6. Balderas Torres A, Lovett JC. Using basal area to estimate aboveground carbon stocks in forests: La Primavera Biosphere's Reserve, Mexico. *Forestry.* 2013;86(2):267–81. <https://doi.org/10.1093/forestry/cps084>.
7. Baycan, T., van Leeuwen, E. S., Rodenburg, C. A., & Nijkamp, P. (2002). Development and management of green spaces in European cities: a comparative analysis.
8. Bhardwaj DR, Navale MR, Dogra R, Verma T, Sharma P, Keprate A. Biomass tables and allometric equations for predicting the fodder and fuelwood production of prominent tree resources in agricultural landscapes of the mid-hills of the North-Western Himalayas. *Agroforest Syst.* 2024;98(8):3129–44. <https://doi.org/10.1007/s10457-024-01078-4>.
9. Cairns MA, Brown S, Helmer EH, Baumgardner GA. Root biomass allocation in the world's upland forests. *Oecologia.* 1997;111:1–11. <https://doi.org/10.1007/s004420050201>.
10. Canadell JG, Raupach MR. Managing forests for climate change mitigation. *Science.* 2008;320(5882):1456–7. <https://doi.org/10.1126/science.1155458>.
11. Castro-Diez P, Vaz AS, Silva JS, Van Loo M, Alonso Á, Aponte C, et al. Global effects of non-native tree species on multiple ecosystem services. *Biol Rev.* 2019;94(4):1477–501. <https://doi.org/10.1111/brv.12511>.
12. Champion HG, Seth SK. A revised survey of the forest types of India. Manager of publications; 1968.
13. Chave, J., et al. Tree allometry and improved estimation of carbon stocks and balance in tropical forests. *Oecologia,* 2005;145(1):87–99.
14. Chave J, Muller-Landau HC, Baker TR, Easdale TA, ter Steege H, Webb CO. Regional and phylogenetic variation of wood density across 2456 Neotropical tree species. *Ecol Appl.* 2006;16(6):2356–67.
15. Cheela VS, John M, Biswas W, Sarker P. Combating urban heat island effect—a review of reflective pavements and tree shading strategies. *Buildings.* 2021;11(3):93. <https://doi.org/10.3390/buildings11030093>.
16. Colding J, Barthel S. The role of university campuses in reconnecting humans to the biosphere. *Sustainability.* 2017;9(12):2349. <https://doi.org/10.3390/su9122349>.
17. Connor EF, McCoy ED. The statistics and biology of the species-area relationship. *Am Nat.* 1979;113(6):791–833. <https://doi.org/10.1086/283438>.
18. Convention on Biological Diversity. (2022). *Kunming-Montreal global biodiversity framework*. Secretariat of the Convention on Biological Diversity. <https://www.cbd.int/article/cop15-final-text-kunming-montreal-gbf>
19. Cottam G, Curtis JT. The use of distance measures in phytosociological sampling. *Ecology.* 1956;37(3):451–60. <https://doi.org/10.2307/1930167>.
20. Cubino JP, Avolio ML, Wheeler MM, Larson KL, Hobbie SE, Cavender-Bares J, et al. Linking yard plant diversity to homeowners' landscaping priorities across the US. *Landsc Urban Plann.* 2020;196:103730. <https://doi.org/10.1016/j.landurbplan.2019.103730>.
21. De S, Das R, Adhikari M, Ghosh P, Mohanty JP, Sharma C. An updated review on *Alstonia scholaris*: a delightful therapeutic plant. *J Med Plants Stud.* 2024;12(2):43–51.
22. Devi, R. C., & Das, D. K. (2021). Biomass yield and carbon sequestration after six years of *Bombax ceiba* L. plantations in relation to stand density. *Indian Journal of Agroforestry,* 23(2).
23. Department of Forests & Wildlife, GNCT of Delhi. (2022). Plants of the Northern Aravalli Range in Delhi: A guide. https://forest.delhi.gov.in/sites/default/files/generic_multiple_files/plants_of_the_northern_aravalli_range_in_delhi.pdf
24. Dwivedi S, Chopra D. Revisiting *Terminalia arjuna*—an ancient cardiovascular drug. *J Tradit Complement Med.* 2014;4(4):224. <https://doi.org/10.4103/2225-4110.139103>.
25. Elsadek M, Liu B, Lian Z. Green façades: their contribution to stress recovery and well-being in high-density cities. *Urban For Urban Green.* 2019;46:126446. <https://doi.org/10.1016/j.ufug.2019.126446>.
26. European Space Agency. (2022). WorldCover 10 m 2022. <https://worldcover.org>
27. Fernández M, Alaejos J, Andivia E, Madejón P, Díaz MJ, Tapias R. Short rotation coppice of leguminous tree *Leucaena* spp. improves soil fertility while producing high biomass yields in Mediterranean environment. *Ind Crops Prod.* 2020;157:112911. <https://doi.org/10.1016/j.indcrop.2020.112911>.
28. Food and Agriculture Organization of the United Nations. (1997). State of the world's forests 1997. FAO. <https://www.fao.org/4/w4345e/w4345e00.htm>
29. Gallo T, Fidino M, Lehrer EW, Magle SB. Mammal diversity and metacommunity dynamics in urban green spaces: implications for urban wildlife conservation. *Ecol Appl.* 2017;27(8):2330–41. <https://doi.org/10.1002/eap.1611>.
30. Gaury PK, Devi R. Plant species composition and diversity at the Aravalli Mountain range in Haryana, India. *J Biodiversity.* 2017;8(1):34–43. <https://doi.org/10.1080/09766901.2017.1336306>.
31. Gentili R, Schaffner U, Martinoli A, Citterio S. Invasive alien species and biodiversity: impacts and management. *Biodiversity.* 2021;22(1–2):1–3. <https://doi.org/10.1080/14888386.2021.1929484>.
32. Gonzalez, G., Coomes, D. A., Ilic, J., Jansen, S., Lewis, S. L., Chave, J. (2009). Data from: Towards a worldwide wood economics spectrum. Dryad. <https://cir.nii.ac.jp/crid/1883398392629282560>

33. Gratani L. Understanding the benefits from green areas in Rome: the role of evergreen and deciduous species in carbon dioxide sequestration capability. *Am J Plant Sci.* 2020;11(8):1307–18. <https://doi.org/10.4236/ajps.2020.118093>.
34. Grover JK, Yadav S, Vats V. Medicinal plants of India with anti-diabetic potential. *J Ethnopharmacol.* 2002;81(1):81–100. [https://doi.org/10.1016/S0378-8741\(02\)00059-4](https://doi.org/10.1016/S0378-8741(02)00059-4).
35. Gunnels IV, C. W., Abercrombie, M. I., Bovard, B. D., Croshaw, D. A., Drummond, J., Everham III, E. M., et al. (2021). Campus as a living laboratory: conservation areas that create a community who then ensure its sustainability. In *Making the Sustainable University: Trials and Tribulations* (pp. 133–149). Singapore: Springer Nature Singapore. https://doi.org/10.1007/978-981-33-4477-8_9
36. Gupta H, Sanodiya P, Singh A, Dogra R. Land-use systems for biomass, carbon storage, and carbon credit: implications for climate change mitigation in subtropical pockets of Vindhyan region, India. *Biofuels Bioprod Biorefin.* 2024;18(4):1047–64. <https://doi.org/10.1002/bbb.2664>.
37. Heckadka, S. S., Nayak, S. Y., Rao, S., Samant, R., L K, S., & Salunkhe, K. M. (2021). Two body wear characteristics of polyalthia longifolia/mangifera indica/jute fiber reinforced epoxy composites using taguchi technique. *Materials Research*, 24,e20200323.
38. Hedblom M, Gunnarsson B, Iravani B, Knez I, Schaefer M, Thorsson P, et al. Reduction of physiological stress by urban green space in a multisensory virtual experiment. *Sci Rep.* 2019;9(1):10113. <https://doi.org/10.1038/s41598-019-46099-7>.
39. Hejda M, Hanzelka J, Kadlec T, Štrobl M, Pyšek P, Reif J. Impacts of an invasive tree across trophic levels: species richness, community composition and resident species' traits. *Divers Distrib.* 2017;23(9):997–1007. <https://doi.org/10.1111/ddi.12596>.
40. Hendrayana, Y., Adhya, I., & Ismail, A. Y. (2018). Diversity and Carbon Stocks of Genus Ficus In Gunung Tilu Kuningan District, West Java Province, Indonesia. *Journal of Forestry and Environment*, 1(01). <https://doi.org/10.25134/jfe.v1i01.1046>
41. Hossain A, Farooq M, El Sabagh A, Hasanuzzaman M, Erman M, Islam T. Morphological, physiobiochemical and molecular adaptability of legumes of fabaceae to drought stress, with special reference to *Medicago Sativa* L. *Plant Family Fabaceae*, 2020. pp 289–317.
42. Hernández, M. A., & Genes, P. Y. (2016). Wood density at breast height as estimate of the whole treedensity in *Grevillea robusta*. *Australian Forestry*, 79(3), 168–170.
43. Hsieh TC, Ma K, Chao A. iNEXT: an R package for rarefaction and extrapolation of species diversity (Hill numbers). *Methods Ecol Evol.* 2016;7(12):1451–6. <https://doi.org/10.1111/2041-210X.12613>.
44. International Union for Conservation of Nature (IUCN). Invasive alien species. IUCN. Assessed by April 12, 2025. 2025. <https://www.iucn.org/our-work/topic/invasive-alien-species>
45. International Union for Conservation of Nature (IUCN). The IUCN Red List of Threatened Species. Retrieved April 13, 2025. 2025. <https://www.iucnredlist.org/>
46. Javadi R, Nasrollahi N. Urban green space and health: the role of thermal comfort on the health benefits from the urban green space; a review study. *Build Environ.* 2021;202:108039. <https://doi.org/10.1016/j.buildenv.2021.108039>.
47. Jhariya MK, Banerjee A, Yadav DK, Raj A. Leguminous trees an innovative tool for soil sustainability. *Legumes Soil Health Sustain Manage*, 2018. pp. 315–345.
48. Kamiri HW, Choge SK, Becker M. Management strategies of *Prosopis juliflora* in eastern Africa: what works where? *Diversity.* 2024;16(4):251. <https://doi.org/10.3390/d16040251>.
49. Kanazawa, Y., Sato, A., & Orsolino, R. S. (1982). Above-ground biomass and the growth of giant ipil-ipil [*Leucaena leucocephala* (Lam.) de Wit] plantations in northern Mindanao island, Philippines. *JARQ (Japan)*, 15(3). <https://scispace.com/pdf/above-ground-biomass-and-the-growth-of-giant-ipil-ipil-2ydzjfw0u.pdf>
50. Kawaletz H, Mölder I, Annighöfer P, Terwei A, Zerbe S, Ammer C. Back to the roots: how do seedlings of native tree species react to the competition by exotic species? *Ann For Sci.* 2014;71:337–47. <https://doi.org/10.1007/s13595-013-0347-z>.
51. Kinyanjui, M. J., Latva-Käärylä, P., Bhuwaneswar, P. S., Kariuki, P., Gichu, A., & Wamichwe, K. (2014). An inventory of the above ground biomass in the Mau Forest ecosystem, Kenya. *Open Journal of Ecology*, 4(10), 619–627
52. Khuman, Y. S. C., Sokhi, J., & Nigam, A. (2023). Assessment of biomass and carbon stock of trees within the campus of IGNOU, New Delhi (India). *Sustainability, Agri, Food and Environmental Research-DISCONTINUED*, 12(1). <https://doi.org/10.7770/safer-V12N1-art2627>
53. Krishen P. *Trees of Delhi: a field guide*. Penguin Books India; 2006.
54. Kumar S, Baniwal P, Kaur J, Kumar H. *Kachnar (bauhinia variegata)*. Antioxidants in fruits: properties and health benefits, 2020. pp. 365–377.
55. Liddell, M. J., Nieullet, N., Campoe, O. C., & Freiberg, M. (2007). Assessing the above-ground biomass of a complex tropical rainforest using a canopy crane. *Austral Ecology*, 32(1), 43–58.
56. Liu J, Zhao Y, Si X, Feng G, Slik F, Zhang J. University campuses as valuable resources for urban biodiversity research and conservation. *Urban For Urban Green.* 2021;64:127255. <https://doi.org/10.1016/j.ufug.2021.127255>.
57. Magurran AE. *Measuring biological diversity*. John Wiley & Sons; 2013.
58. McDonnell MJ, Hahs AK. The future of urban biodiversity research: moving beyond the 'low-hanging fruit' Urban Ecosyst. 2013;16:397–409. <https://doi.org/10.1007/s11252-013-0315-2>.
59. McLean P, Gallien L, Wilson JRU, Gaertner M, Richardson DM. Small urban centres as launching sites for plant invasions in natural areas: insights from South Africa. *Biol Invasions.* 2017;19(12):3541–55. <https://doi.org/10.1007/s10530-017-1600-4>.
60. Meghwal, S., & Chauhan, K. (2020). Variation in fibre dimensions of some angiosperm woods of South-East Rajasthan. *The Pharma Innovation Journal* 9(10), 557–559.
61. MoEFCC. (2022). India's long-term low-carbon development strategy. Ministry of Environment, Forest and Climate Change, Government of India.
62. Mori SA, Boom BM, de Carvalho AM. Ecological importance of Myrtaceae in an eastern Brazilian wet forest. *Biotropica.* 1983;15(1):68–70. <https://doi.org/10.2307/2388002>.
63. Mwangi RW, Macharia JM, Wagara IN, Bence RL. The medicinal properties of *Cassia fistula* L: a review. *Biomed Pharmacother.* 2021;144:112240. <https://doi.org/10.1016/j.biopha.2021.112240>.
64. Navar, J. (2009). Allometric equations for tree species and carbon stocks for forests of northwestern Mexico. *Forest ecology and Management*, 257(2), 427–434.

65. Ndem P, Biose O, Effiong E, Udegbe S, Ukebor JE, Ifijen IH, et al. Electrochemical sensor-based assessment of CO₂ and CH₄ levels in Benin City under extreme heat wave conditions in Nigeria. *Environ Monit Assess*. 2025;197(8):1–21. <https://doi.org/10.1007/s10661-025-14356-0>.
66. OpenStreetMap contributors. OpenStreetMap. 2025. <https://www.openstreetmap.org>
67. Nowak DJ, Crane DE, Stevens JC. Air pollution removal by urban trees and shrubs in the United States. *Urban For Urban Green*. 2006;4(3–4):115–23. <https://doi.org/10.1016/j.ufug.2006.01.007>.
68. Pan Y, Birdsey RA, Fang J, Houghton R, Kauppi PE, Kurz WA, et al. A large and persistent carbon sink in the world's forests. *Science*. 2011;333(6045):988–93. <https://doi.org/10.1126/science.1201609>.
69. Panwar M, Mina U, Kumar K, Kumar M. Urban Green Space Assessment Index (UGSAI): a novel GIS-based measure for assessing green spaces in Delhi. *Environ Urban Asia*. 2025. <https://doi.org/10.1177/09754253251337350>.
70. Panwar M, Smiti K, Khatri R, Sailo FL, Tripathi A, Mina U. Optimizing plant species selection for alleviating air pollution: modified anticipated performance index–based evaluation in Delhi India. *Environ Monitor Assessm*. 2025;197(5):566. <https://doi.org/10.1007/s10661-025-13947-1>.
71. Pati, P. K., Kaushik, P., Maurya, D., Adhikari, C., Bishwas, A. J., Khan, M. L., & Khare, P. K. (2024) Evaluating the role of roadside vegetation in atmospheric carbon dioxide mitigation: a case study. *Arboricultural Journal*, 46(2), 97–119
72. Papastergiou E, Kalogeris A, Latinopoulos D, Ballas D. The greener, the better? A comprehensive framework for studying the effect of urban green spaces on subjective well-being. *Discover CITIES*. 2025;2(1):23.
73. Pearson TRH, Brown S, Ravindranath NH, MacDicken K, Shoch D, Murthy IK. Integrating carbon benefit estimates into GEF projects. UNDP, GEF, 2005; 1–56.
74. Plant Species of JNU Campus. JNU Campus Flora. Retrieved April 13, 2025. 2025. <https://sites.google.com/view/jnucampus/flora/>
75. Pragasam, L. A., Kumar, K. M., & Karthika, T. A. (2025). Tree carbon stock dynamics of riparian forests from the Western Ghats, India. *Ecological Frontiers*, 45(3), 749–755.
76. Psistaki K, Tsantopoulos G, Paschalidou AK. An overview of the role of forests in climate change mitigation. *Sustainability*. 2024;16(14):6089. <https://doi.org/10.3390/su16146089>.
77. Qiu GY, Zou Z, Li X, Li H, Guo Q, Yan C, et al. Experimental studies on the effects of green space and evapotranspiration on urban heat island in a subtropical megacity in China. *Habitat Int*. 2017;68:30–42. <https://doi.org/10.1016/j.habitatint.2017.07.009>.
78. R Core Team (2020). R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. <https://www.R-project.org/>.
79. Rajput, S. S., Shukla, N.K., & Gupta, V. K. (1985). Specific gravity of Indian timbers. <https://www.cabidigitallibrary.org/doi/full/10.5555/19860607795>
80. Rani C, Chawla S, Mangal M, Mangal AK, Kajla S, Dhawan AK. *Nyctanthes arbor-tristis* Linn.(Night Jasmine): A sacred ornamental plant with immense medicinal potentials. 2012
81. Rejmánek M, Robinson GR, Rejmánková E. Weed-crop competition: experimental designs and models for data analysis. *Weed Sci*. 1989;37(2):276–84. <https://doi.org/10.1017/S0043174500071903>.
82. Sales TA, Car-doso MG, Guimarães LGL, Camargo KC, Rezende DACS, Brandão RM, et al. Essential oils from the leaves and flowers of *Callistemon viminalis*: chemical characterization and evaluation of the insecticide and antifungal activities. *Am J Plant Sci*. 2017;8:2516–29. <https://doi.org/10.4236/ajps.2017.810171>.
83. Sanders HL. Marine benthic diversity: a comparative study. *Am Nat*. 1968;102(925):243–82. <https://doi.org/10.1086/282541>
84. Sandilyan S, et al. Invasive alien species of India. *Nat Biodiv Author*. 2018;22:9–15.
85. Si M, Mu Y, Han Y. Road landscape design: harmonious relationship between ecology and aesthetics. *Forests*. 2024;15(11):2008. <https://doi.org/10.3390/f15112008>.
86. Simberloff D. Nonnative species do threaten the natural environment! *J Agric Environ Ethics*. 2005;18:595–607. <https://doi.org/10.1007/s10806-005-2851-0>.
87. Singh AK, Singh JS, Singh H, Mishra RK. Quantifying carbon stock and tree species diversity of green infrastructure of Varanasi, India. *Int J Plant Environ*. 2023;9(01):15–23. <https://doi.org/10.18811/ijpen.v9i01.03>.
88. Singh S, Miller CT, Singh P, Sharma R, Rana N, Dhakad AK, et al. A comprehensive review on ecology, life cycle and use of *Tecoma stans* (bignoneaceae). *Bot Stud (Taipei)*. 2024;65(1):6. <https://doi.org/10.1186/s40529-024-00412-4>.
89. Srivastava, N., Goel, V. L., & Behl, H. M. (1999). Influence of planting density on growth and biomass productivity of *Terminalia arjuna* under sodic soil sites. *Biomass and Bioenergy*, 17(3), 273–278.
90. Sundarapandian, S. M., Dar, J. A., Gandhi, D. S., Kantipudi, S., & Subashree, K. (2013). Estimation of biomass and carbon stocks in tropical dry forests in Sivagangai District, Tamil Nadu, India. *Int J Environ Sci Eng Res*, 4(3), 66–76.
91. Taib N, Abdullah A. The cooling effects of plants on the built environment. *Renewable Energy and Sustainable Technologies for Building and Environmental Applications: Options for a Greener Future*, 2016. 151–165.
92. Thompson OP, Kosoe EA, Xu J. Green Infrastructure and Urban Planning for Sustainable Clean Air. In *Sustainable Strategies for Air Pollution Mitigation: Development, Economics, and Technologies* (pp. 343–375). Cham: Springer Nature Switzerland. 2024. <https://doi.org/10.1007/978-2024-1122>
93. Tripathi, M. (2015). *Cassia fistula*: Biomass functions and physiology of carbon dynamics. *International Journal of Applied Engineering and Technology*, 5(4), 16–22.
94. Tripathi JK, Rajamani V. Geochemistry of the loessic sediments on Delhi ridge, eastern Thar desert, Rajasthan: implications for exogenic processes. *Chem Geol*. 1999;155(3–4):265–78. [https://doi.org/10.1016/S0009-2541\(98\)00168-5](https://doi.org/10.1016/S0009-2541(98)00168-5).
95. Ucella-Filho JGM, Lucas FMF, Almeida DDM, Silva BRFD, Almeida DDM, Brito DYOD, et al. Biodiverse neighborhoods: an ex situ conservation tool. *Ornam Hort*. 2022;28(1):8–18. <https://doi.org/10.1590/2447-536X.v28i1.2388>.
96. Upreti M, Kumar A. Evaluating functional traits of urban green spaces in mitigating land surface temperature in megacities. *Discover CITIES*. 2025;2(1):31. <https://doi.org/10.1007/s44327-025-00074-2>.
97. U.S. Forest Service. (2024, October 31). Emission Factor Database. Missoula Fire Sciences Laboratory, U.S. Department of Agriculture. <https://research.fs.usda.gov/firelab/projects/emissionfactor>
98. Wang J, Zheng L, Liu H, Xu B, Zou Z. The effects of habitat network construction and urban block unit structure on biodiversity in semiarid green spaces. *Environ Monit Assess*. 2020;192(3):179. <https://doi.org/10.1007/s10661-020-8115-7>.

99. Warran A, Patwardhan A. Carbon sequestration potential of trees in and around Pune city. Case study Department of Environmental Sciences, University of Pune. 2001
100. Wang X, Xiang Y, Peng C, Teng M, Ma B, Zhou Z, et al. Impact of tree growth form on temporal and spatial patterns of particulate matter with various particle sizes in urban street canyons. *Landscape Ecol.* 2025;40(1):1–13. <https://doi.org/10.1007/s10980-024-02023-7>.
101. Yu X, Yang Z, Xu D, Wang Q, Peng J. Urban green spaces enhanced human thermal comfort through dual pathways of cooling and humidifying. *Sustain Cities Soc.* 2025;118:106032. <https://doi.org/10.1016/j.scs.2024.106032>.
102. Ziter CD, Pedersen EJ, Kucharik CJ, Turner MG. Scale-dependent interactions between tree canopy cover and impervious surfaces reduce daytime urban heat during summer. *Proc Natl Acad Sci U S A.* 2019;116(15):7575–80. <https://doi.org/10.1073/pnas.1817561116>.
103. Zou, M., & Zhang, H. (2021). Cooling strategies for thermal comfort in cities: a review of key methods in landscape design. *Environmental Science and Pollution Research*, 28(44), 62640–62650.

Publisher's Note

Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.