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# Journal of Threatened Taxa



Open Access



10.11609/jott.2024.16.1.24451-24614  
[www.threatenedtaxa.org](http://www.threatenedtaxa.org)

26 January 2024 (Online & Print)  
16(1): 24451-24614  
ISSN 0974-7907 (Online)  
ISSN 0974-7893 (Print)



ISSN 0974-7907 (Online); ISSN 0974-7893 (Print)

Publisher  
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www.wild.zooreach.org

Host  
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www.zooreach.org

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Cover: Green Sea Turtle *Chelonia mydas* watercolour by Elakshi Mahika Molur.



## Use of remote sensing and GIS in assessing the impact of *Prosopis juliflora* proliferation on land use, land cover and diversity of native flora at Point Calimere Wildlife Sanctuary, India

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**Abstract:** It is crucial to accurately quantify land use and land cover (LULC) within a protected area to understand the implications of habitat changes on biodiversity. Today's remote sensing and GIS technologies greatly facilitate analysis of LULC, especially with regards to tracing changes over space and time. This study uses remote sensing and GIS to examine the impact of climate, herbivore, and anthropogenic pressures including invasive Mesquite *Prosopis juliflora* on native plant communities at Point Calimere Wildlife Sanctuary. Classification of satellite images revealed that dry evergreen, mudflat, and water bodies had transformed into open scrub from 1995 to 2018 and the shift in LULC is detected with optimal accuracy (85%). Changes in LULC are largely attributable to a rise in open scrub caused by the growth in *P. juliflora* from 3 to 6 km<sup>2</sup> since 1995. GLM-based regression to examine the influence of climate, herbivores, and anthropogenic pressure including *P. juliflora* on native flora show native tree density, shrub density, shrub diversity, herb, and grass cover decreasing with *P. juliflora* cover or density. These findings imply that as the *P. juliflora* spreads the native plant diversity and density at Point Calimere Wildlife Sanctuary will continue to decline. *P. juliflora* is being eradicated in phases through management efforts, however, here we recommend a coordinated effort to curb further expansion in order to reverse ecological decline.

**Keywords:** Alien invasive species, diminishing grasslands, LULC accuracy and changes, NDVI, reduced native plant communities, mesquite impact.

**Editor:** C.P. Singh, Space Applications Centre, ISRO, Ahmedabad, India.

**Date of publication:** 26 January 2024 (online & print)

**Citation:** Gupta, S., S. Arandhara, S. Sathishkumar & N. Baskaran (2024). Use of remote sensing and GIS in assessing the impact of *Prosopis juliflora* proliferation on land use, land cover and diversity of native flora at Point Calimere Wildlife Sanctuary, India. *Journal of Threatened Taxa* 16(1): 24451–24462. <https://doi.org/10.11609/jott.8164.16.1.24451-24462>

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**Funding:** The project was funded by the Science and Engineering Research Board [SERB], Department of Science and Technology, New Delhi, Government of India, [Grant File. No. EMR/2016/001536].



**Competing interests:** The authors declare no competing interests.

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**Author contributions:** SG—data collection, analyses, and draft preparation. SA—data collection, analyses, and draft preparation. SS—data collection and draft preparation. NB—conceptualizing, supervising and final draft preparation.

**Acknowledgements:** We would like to acknowledge the Department of Science and Technology, Government of India, for funding [Grant File. No. EMR/2016/001536] this study under the SERB Extramural Research Category. We express our sincere thanks to the Tamil Nadu Forest Department, especially its former Chief Wildlife Warden, Mr. P.C. Thyagi, I.F.S., Mr. S.K. Srivatsava, I.F.S., and the Wildlife Wardens Point Calimere, Nagapattinam, for granting permission [Ref. No. WL(A)/21321/2017, Permit No44/2017] to conduct the study and support it. We are also thankful to the management and the Principal of A.V.C. College for their constant support of this project.

## Introduction

To meet global conservation goals, protected areas must preserve native features. Human-induced land use, including the introduction of alien invasive is triggering significant changes in tropical forests, leading to a drastic decline in wildlife and the local extinction of native species (Felker 2003). It's important to periodically assess a protected area's environmental preservation and identify barriers to success. Alien species invasions can change ecosystem functions and community structure among other negative effects (Vitousek 1990; Myers & Bazely 2003; Simberloff et al. 2013). Understanding the factors that control invasions is essential for describing the spread of invasive species and predicting their spread into new areas based on land-use patterns, vegetation, soil, and animal interactions (Wiens 1989; Richardson & Bond 1991; Hulme 2003; Rouget et al. 2004). Many exotic plant introductions were deliberate for habitat improvement, ornamental purposes, wood or fiber production, soil conservation, livestock forage production, or other crop uses (Harrod 2001). Invasive exotics are hard to control due to their aggressive expansion. The management of their growth, including an adaptation of alien species to non-native ecological niches is poorly understood (Dellinger et al. 2016).

*Prosopis juliflora* (Mesquite) is a Central and South American shrub. According to the global invasive database (<http://www.iucngisd.org/gisd>), it is one of the most invasive tropic species. Many countries introduced it to provide local communities with fodder and wood (Gallagher & Merlin 2010). Subsequently, unprecedented natural seed dispersal by livestock, wildlife, and water led to its spread (Mwangi & Swallow 2008; Mworio et al. 2011; Muturi et al. 2013). It now dominates many plant communities and is considered a weed. It is highly aggressive and coppices so well that it crowds out native vegetation (Tiwari 1999; Al-Rawai 2004). Invasion factors include land use change, deforestation, and climate change (Pasiiecznik et al. 2001).

This fast-growing leguminous species was introduced in 1940–1960 at Point Calimere Wildlife Sanctuary. It has since invaded many habitats, becoming dominant at the sanctuary (Ali 2005; Arasumani et al. 2019; Krishna et al. 2019; Baskaran et al. 2020; Murugan et al. 2020). This has had a negative impact on the sanctuary and will continue to have an adverse effect on the native flora and fauna by reducing open grasslands and creating physical barriers that prevent animals, especially large herbivores, from moving about freely (Ali 2005; Baskaran et al. 2016; Murugan et al. 2020).

Research on the effects of exotic species on LULC suggests that *P. juliflora* is expanding its territory into Kenya, displacing native plant life in the process (Muturi et al. 2013). According to one study, the amount of coastal grassland habitats has decreased as the amount of land dominated by *P. juliflora* has increased at Point Calimere (Ali 2005). A recent experimental study in the same area suggests the removal of some of the *P. juliflora* to increase native ground cover and diversity indices, especially for grasses. This is because the invasive species alters ecosystem processes by influencing the dynamics of soil organic carbon and nutrients (Murugan et al. 2020).

There is a significant information gap concerning the impact of *P. juliflora* on the temporal change in LULC and native floral composition. By utilising field surveys, remotely sensed satellite imagery, and GIS-based applications, our goals were to: (i) estimate the transition in LULC and (ii) assess the ecological impact of the invasive on the native flora at Point Calimere Wildlife Sanctuary.

## MATERIALS AND METHODS

### Study area

Point Calimere is a Wildlife Sanctuary (PCWS) (spread over 26.5 km<sup>2</sup>) off the coast of Tamil Nadu, India at lat.—10.300°N & long.—79.850°E (Figure 1). The Great Vedaranyam Swamp is included, and it is bounded to the north-east by the Bay of Bengal and to the south-west by Palk Strait. Because of rampant poaching and a lack of legal protection, the sanctuary was established in 1967 to house Blackbuck *Antelope cervicapra*. In 2002, it was designated a Ramsar Site (Ramsar Site No. 1210). The Greater Flamingo and other long-distance migratory water birds make it well-known. The sanctuary is home to the largest population of southern India's endemic Blackbuck. At present, 198 different species of medicinal plants have been identified in the sanctuary's grassland, mudflats, backwaters, and sand dunes (Ramasubramaniyan 2012). Soil and water salinization, the loss of wetland habitat, the spread of the invasive species, i.e., *P. juliflora*, the presence of cattle, and a lack of fresh water are the most pressing issues in Point Calimere (Ali 2005).

### Geospatial data acquisition

The administrative boundary in vector polygon was obtained from the forest department. Archived satellite imageries were downloaded from USGS (United States

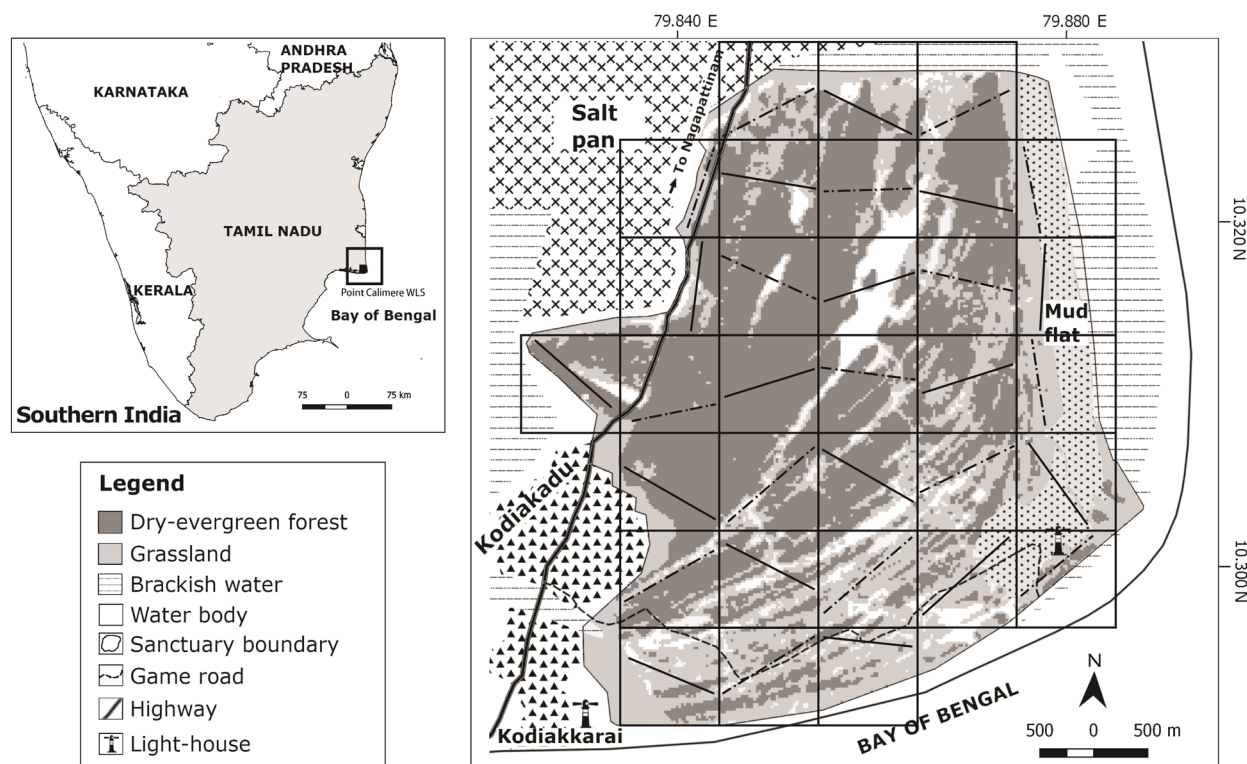


Figure 1. Map showing the study area - Point Calimere Wildlife Sanctuary, India.

Geological Survey) site, at a spatial resolution of 30 m for the years 1995 (5-TM/8 January) and 2018 (2 OLI-TIRS/8 July) (given in S-Table 1). While temporally comparable imageries prevent seasonal effects in LULC changes over several years (Im & Jensen 2005), quality images meeting this criterion were unavailable. Thus, quality images, especially those with low clouds, were used closer to the required dates. Each image was projected to WGS 84 and UTM-Zone 35 North. For the georectification process, 25 Ground Control Points (GCPs) was used along with the landsat image, tie points were established between the two images. Later, layer-stacking was done to combine the three landsat TM and landsat 8 bands (4, 3, 2, and 5, 4, 3). ArcMap 10 and ENVI 5 programs were used for geospatial processing.

#### Ground-truthing

The study area map was overlaid with a grid consisting of 1 km<sup>2</sup> cells, resulting in a total of 39 grid cells. In each grid cell, two plots of 30 x 30 m were placed to sample for tree species composition. From the 78 vegetation plots and also from nearby areas 1,280 ground-truthing points (GTP) were obtained. At every GTP that corresponds to a specific land-cover type, we recorded the geo-coordinate using a global positioning system (GPS) device. From

these GTPs, five major LULC elements were identified: (i) tropical dry-evergreen, (ii) open-scrub (with and without *P. juliflora*), (iii) grassland, (iv) mudflat, and (v) water body.

#### Temperature and humidity

Temperature and humidity data are collected from each grid cell physically using HTC HD-303 digital thermometer cum hygrometer.

#### Image classification and accuracy assessment

LULC elements were classified in ENVI 5.0 using a supervised classification based on a maximum likelihood algorithm. These were integrated into a matrix table showing four different types of accuracy results (given in S-Table 2,3). Accuracy assessment requires a sufficient number of samples per map class and comparison with actual ground conditions. Standard LULC map accuracy are between 85% and 90% (Lins & Kleckner 1996). Overall, classification accuracy was 85% for 1995 and 92% for 2018 (S-Table 3).

#### Change detection

After classification, the two images were compared using change-detection analysis. The matrix table of

transition change class was obtained using a change-detection statistical tool in ENVI (Peiman 2011).

### NDVI analysis

The NDVI imagery in this case was obtained by using a landsat image, which is a multiband dataset. The normalised difference vegetation index (NDVI) was calculated as per the following equation:

$$\text{NDVI} = (\rho_{\text{NIR}} - \rho_{\text{RED}}) / (\rho_{\text{NIR}} + \rho_{\text{RED}})$$

where,  $\rho_{\text{NIR}}$  is the reflectance of near-infrared band, and  $\rho_{\text{RED}}$  is the reflectance of red band. For landsat 4-5 TM, the NIR band is 4 and for RED, it is 3, but for landsat-8 OLI it is band 5, and band 4, respectively.

Following the derivation of the NDVI image as a single band raster, a threshold of pixel values were applied in

order to segment the data in various classes using the quantile reclassification option in ARC GIS.

As NDVI depicts vigour of the vegetation, two additional elements, viz., grasslands and *P. juliflora* were considered. For *P. juliflora*, a total of 100 GTPs (ground truthing points) were also collected systematically in plots with the presence of *P. juliflora*. After NDVI processing, four different NDVI elements were identified using the GTPs as threshold: (i) tropical dry-evergreen (0.300 to 0.700), (ii) open-scrub without *P. juliflora* (0.238 to 0.300), (iii) grasslands (0.090 to 0.146), and (iv) *P. juliflora* area (0.146 to 0.238). Water bodies and mudflats, both of which lack vegetation, were categorised as 'non-vegetation'. NDVI images from 1995 and 2018 were compared using change-detection analysis as

**Table 1A. Native vegetation attributes (dependent variables) used in the study.**

| Variables                      | Sampling unit                    | Description                                                                                                                                                                                                                 |
|--------------------------------|----------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <b>Tree</b>                    |                                  |                                                                                                                                                                                                                             |
| Tree density/km <sup>2</sup>   | Two 30×30 m plots/<br>grid cell  | At each grid cell diagonally opposite side, two plots of mentioned size were laid and counted all trees with >20 cm GBH. Density was calculated following number of tree/unit area                                          |
| Tree diversity                 | As above                         | Data collected from the above description following Shannon diversity index                                                                                                                                                 |
| <b>Shrub</b>                   |                                  |                                                                                                                                                                                                                             |
| Shrub density /km <sup>2</sup> | Four 5×5 m plots/<br>grid cell   | In each grid cell, four plots of the mentioned size were laid diagonally opposite side in each of two tree plots and counted all the shrubs species. Density was calculated following number of shrub/unit area             |
| Shrub diversity                | As above                         | Data collected from the above description following Shannon diversity index                                                                                                                                                 |
| <b>Grass and herb</b>          |                                  |                                                                                                                                                                                                                             |
| Herb cover                     | Eight 1×1 m plots/<br>grid cells | In each grid cell, eight plots of the mentioned size were laid diagonally opposite side in each of four shrub plots. From each plot % cover of herb was arrived as percentage of area of the plot covered by herb visually. |
| Grass cover                    | As above                         | Same as above                                                                                                                                                                                                               |

**Table 1B. Independent variables used in the study.**

| Variables                                      | Sampling unit                        | Description                                                                                                                                                                                   |
|------------------------------------------------|--------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <b>Temperature and humidity</b>                |                                      |                                                                                                                                                                                               |
| Temperature (Celsius)                          | 05 locations /grid-cells             | Measured at 05 locations per grid cell with one each at four corners and one at the middle of two tree plots digital thermometer-cum-hygrometer device in degree Celsius.                     |
| Humidity (%)                                   | As above                             | As above description and measured using digital thermometer-cum-hygrometer in %                                                                                                               |
| <b><i>P. juliflora</i> pressure</b>            |                                      |                                                                                                                                                                                               |
| <i>P. juliflora</i> cover %                    | Two 30×30 m plots/<br>grid-cell      | Estimated from the two tree plots in each grid cell by multiplying the crown length × crown width of each <i>P. juliflora</i> and arriving at mean % cover of <i>P. juliflora</i> /unit area. |
| <i>P. juliflora</i> density/ km <sup>2</sup> . | As above                             | Estimated from the two tree plots in each grid cell by counting the number of <i>P. juliflora</i> and arriving at number of <i>P. juliflora</i> /unit area.                                   |
| <b>Anthropogenic pressure</b>                  |                                      |                                                                                                                                                                                               |
| Number of people                               | Per grid-cell                        | Measured counting number of people observed per grid cell during the survey time.                                                                                                             |
| Distance to human settlements (m)              | One/grid-cell                        | Measured from the centre of the grid cell to the nearest human settlement using GIS-ArcMap 10 program.                                                                                        |
| <b>Herbivore pressure</b>                      |                                      |                                                                                                                                                                                               |
| Spotted Deer density/km <sup>2</sup>           | One 1-km line<br>transect /grid-cell | In each grid cell, animal surveys were conducted for three walks employing the line-transect distance sampling method (Burnham et al. 1980, Buckland et al. 2001 ).                           |
| Blackbuck density /km <sup>2</sup>             |                                      |                                                                                                                                                                                               |
| Feral horse density / km <sup>2</sup>          |                                      |                                                                                                                                                                                               |

separate thresholds were found based on GTPs. The GIS methodology flow chart is given in S-Figure 1.

### Vegetation survey

Vegetation attributes: (i) tree density/km<sup>2</sup>, (ii) tree diversity, (iii) shrub density/km<sup>2</sup>, (iv) shrub diversity, (v) herb cover, and (vi) grass cover, were sampled by laying plots of different sizes at 1 km<sup>2</sup> grid cells. Density and diversity were calculated in software PAST Version 3.23 for each grid cell (the dependent variables are described in Table 1A).

### Evaluation of the temperature & humidity effect, anthropogenic pressure, herbivore density, and *Prosopis* pressure on native flora

To assess the effect of temperature, humidity, anthropogenic pressure, and *P. juliflora* pressure on native flora, sampling was done using different plot sizes for the tree, shrub, herb and grass as described in (Table 1B) for each grid cell. The measure of covariates including *P. juliflora* species was recorded first followed by the measure of the entire indigenous vegetation in the plots. We assessed two covariates (i) temperature (Celsius), (ii) humidity (%); two covariates from *P. juliflora* pressure [(iii) *P. juliflora* cover %, (iv) *P. juliflora* density/km<sup>2</sup>]; two from anthropogenic pressure [(v) number of people (visual count), (vi) distance to human settlements (m)], and three belonging to herbivore density [(vii) spotted deer density/km<sup>2</sup>, (viii) Blackbuck density/km<sup>2</sup>, and (ix) feral-horse density/km<sup>2</sup>].

### Statistical analysis

We used the R-program (Version 3.3.1) for statistical analyses. First, a Shapiro-Wilk test was conducted to test the homogeneity of variance and normality of the dependent factors (Shapiro & Wilk 1965). Normality was not obtained for the six dependent factors related to the native tree, shrub, herb, and grass. Following this, the non-normal variables were transformed using log, arsine, negative exponential, and square root transformations. Normality was not achieved using any of the transformations, thus we used non-parametric tests for further analysis for the dependent variables, viz., tree density, tree diversity, shrub density, shrub diversity, herb cover, and grass cover. Normality test results are reported in S-Table 4.

### Difference in vegetation attributes between the levels of temperature and humidity, anthropogenic pressure, herbivore density, and *Prosopis* pressure

Mann-Whitney U-test was used to examine the

difference in vegetation attributes (dependent factor) between the levels of covariates (independent factor) by splitting them into two categories, for example, low level with *P. juliflora* cover <25%, and high level with *P. juliflora* cover >25%.

### Influence of temperature and humidity, anthropogenic pressure, herbivore density, and *Prosopis* on native vegetation

To evaluate the influence of covariates on native flora, six dependent factors related to the native tree, shrub, herb, and grass and nine covariates belonging to temperature and humidity, anthropogenic pressure, herbivore and *P. juliflora* parameters were subjected to regression analysis following generalised linear model (GLM) (McCullagh & Nelder 1989; Dobson 1990) in the *R-program* (R Core team 2019). Since the covariates were continuous variables, they were assumed to be Poisson error distribution and logarithmic functions (McCullagh & Nelder 1989). In other analyses, an F-test was used since the deviance was under-dispersed and covariates were evaluated separately up to a polynomial of the third order (Hastie & Pregibon 1993).

## RESULTS

### Land-use and Land-cover in 1995 & 2018

The land use and land cover (LULC) components assessed within the study region in 1995 and 2018 demonstrate the presence of four primary elements: tropical dry-evergreen, open-scrub, mudflat, and water bodies (Figure 2). In 1995, the most dominant among these was the tropical dry-evergreen (36.8%) category, succeeded by open-scrub (28.5%), mudflat (21.6%), and water bodies (13.1%) (Table 2). Conversely, by 2018, the open-scrub (44.4%) element had become the most prevalent, followed by tropical dry-evergreen (33.6%), mudflat (13.5%), and water bodies (10.5%) (Table 2).

**Table 2.** Area and percentage of different land cover classes of 2018 classified image at Point Calimere Wildlife Sanctuary.

|   | Class         | 1995                    |          | 2018                    |          |
|---|---------------|-------------------------|----------|-------------------------|----------|
|   |               | Area (km <sup>2</sup> ) | Area (%) | Area (km <sup>2</sup> ) | Area (%) |
| 1 | Dry-evergreen | 9.74                    | 36.77    | 8.91                    | 33.64    |
| 2 | Open-scrub    | 7.55                    | 28.52    | 11.23                   | 44.40    |
| 3 | Mudflat       | 5.73                    | 21.65    | 3.57                    | 13.47    |
| 4 | Water         | 3.46                    | 13.06    | 2.78                    | 10.50    |

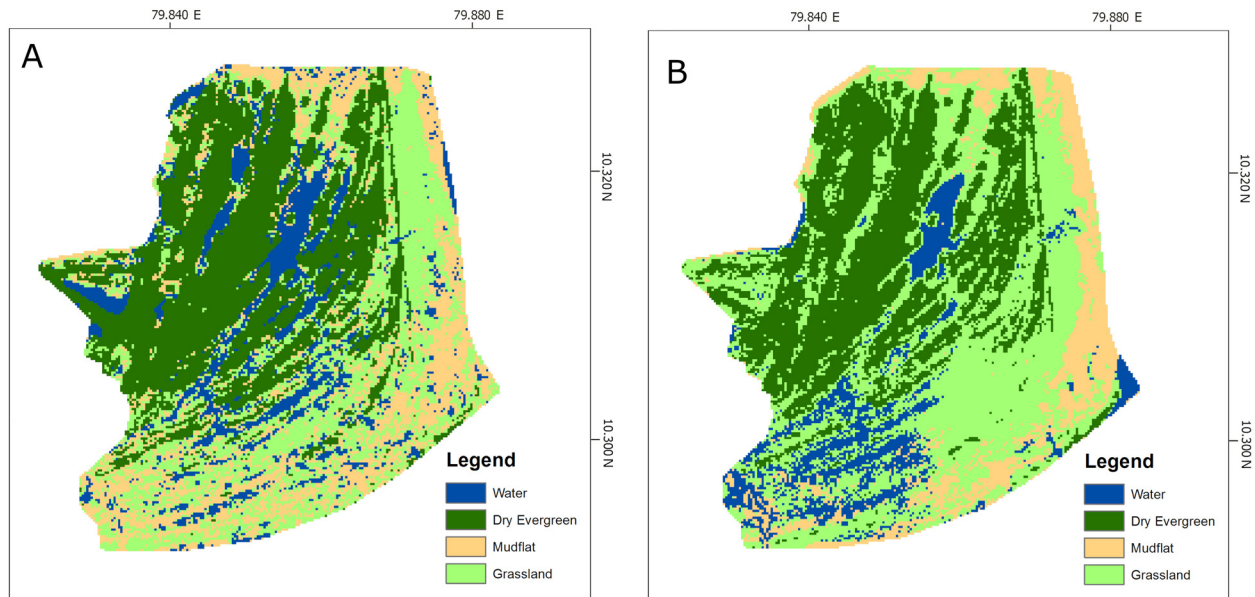


Figure 2. Map showing the land use and land cover of Point Calimere Wildlife Sanctuary during 1995 (A) and during 2018 (B).

### Land-use and land-cover (LULC) changes

The image processed through the post-classification change detection technique is given in Figure 3 and statistical summaries on the spatial distribution of different land-cover transitions and unchanged areas are tabulated in S-Table 5. The results showed that 6.5 km<sup>2</sup> area changed from dry evergreen (2.3 km<sup>2</sup>), mudflat (2.5 km<sup>2</sup>), and water (1.7 km<sup>2</sup>) to open scrub between 1995 and 2018.

### Invasion of *Prosopis*

Normalised Difference Vegetation Index for *P. juliflora* abundance map (Figure 4) illustrates changes in *P. juliflora* coverage between 1995 (Figure 4A) and 2018 (Figure 4B). Over the past 23 years, *P. juliflora* has expanded its range, most noticeably into open scrub. The elements also show that the area covered by *P. juliflora* in 1995 was 3.03 km<sup>2</sup> and has since doubled to 6.16 km<sup>2</sup>; meanwhile, the area covered by open-scrub has shrunk from 6.79 km<sup>2</sup> to 4.06 km<sup>2</sup> over the same time period (Table 3).

### Difference in vegetation attributes in relation to covariate level

Among temperature and humidity, no significant difference was seen in vegetation attributes, except for tree density, which was higher in higher humidity areas than that at a lower level of humidity ( $U = 768$ ,  $p < 0.05$ ). In relation to the levels of *P. juliflora* cover, the following vegetation attributes differed significantly revealing lower mean vegetation attributes at higher levels of *P.*

*juliflora* cover than that of at lower level of *P. juliflora*; tree density, shrub density, herb density, and grass cover ( $p < 0.05$ ). Similarly, at higher levels of *P. juliflora* density, tree diversity, shrub density, shrub diversity, and herb cover were significantly lower ( $p < 0.05$ ) compared to plots with low level of *P. juliflora* density. In relation to herbivore density, no significant difference was seen in any vegetation attributes, except for shrub diversity, which was significantly lower at a higher level of Blackbuck density ( $p < 0.05$ ). Herb cover was significantly lower at higher population levels ( $p < 0.05$ ), while shrub density, herb cover, and grass cover ( $p < 0.03$ ) were higher away from human settlements (Table 4).

### Influence of covariates on native flora

In models of GLM-based regression analysis, the influence of temperature and humidity, *P. juliflora*, herbivore density, and anthropogenic attributes on native vegetation revealed that tree density reduced significantly only with *P. juliflora* cover (pseudo- $R^2 = 0.21$ ), but no variables turned significant in the case of tree diversity (Table 5). Shrub density decreased significantly with *P. juliflora* cover, and density (pseudo- $R^2 = 0.25$ ) and shrub diversity with *P. juliflora* density (pseudo- $R^2 = 0.19$ ). The herb and grass cover decreased significantly with *P. juliflora* cover, but increased with distance to human settlements (herb; pseudo- $R^2 = 0.43$  and grass pseudo- $R^2 = 0.37$ ).

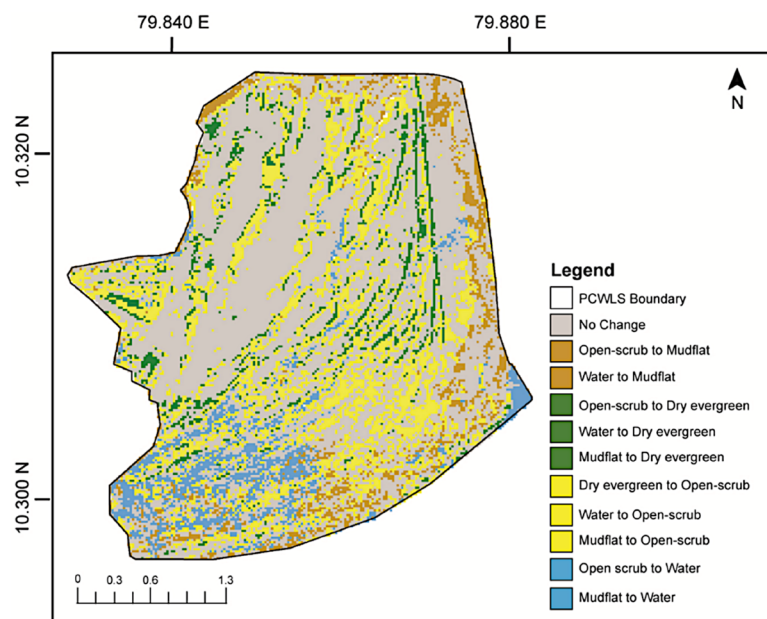


Figure 3. Map showing the change detection in LULC from 1995 to 2018 at Point Calimere Wildlife Sanctuary.

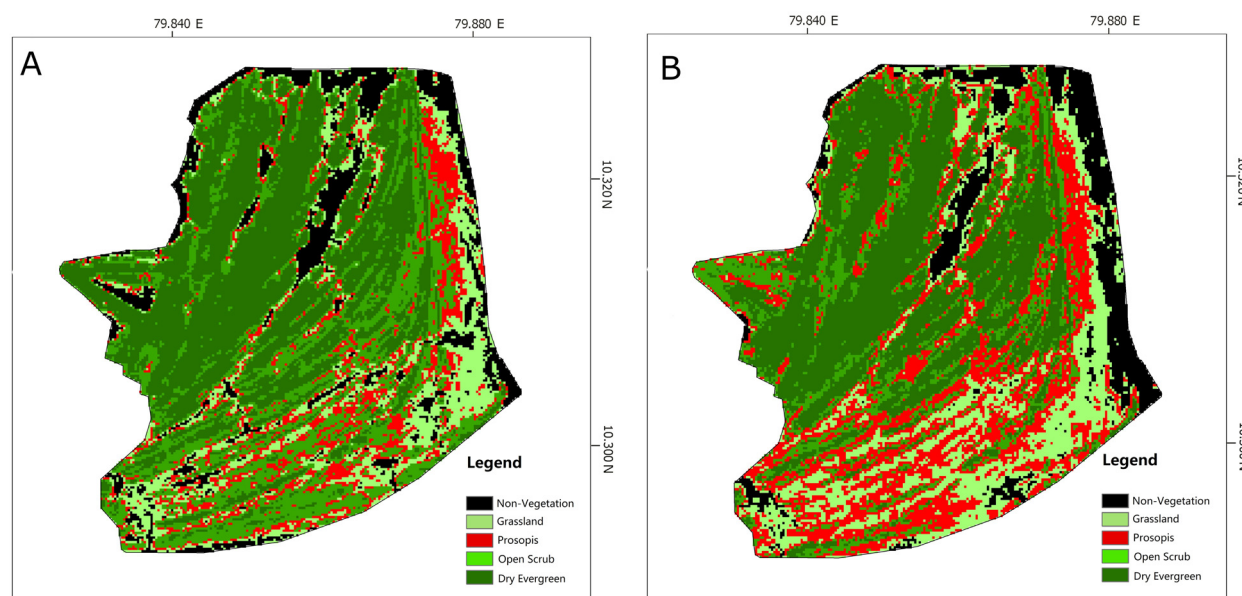


Figure 4. Map showing the changes in the abundance of *Prosopis juliflora* from 1995 (A) to (B) 2018 at Point Calimere Wildlife Sanctuary.

Table 3. Range and area of different classes of NDVI arrived for 1995 and 2018 period at Point Calimere Wildlife Sanctuary.

|   | Class               | 1995             |                         | 2018             |                         |
|---|---------------------|------------------|-------------------------|------------------|-------------------------|
|   |                     | NDVI Range       | Area (km <sup>2</sup> ) | NDVI Range       | Area (km <sup>2</sup> ) |
| 1 | Grasslands          | > 0.000 to 0.100 | 3.69                    | > 0.000 to 0.100 | 4.49                    |
| 2 | Open-scrub          | > 0.200 to 0.400 | 6.79                    | > 0.200 to 0.300 | 4.06                    |
| 3 | <i>P. juliflora</i> | > 0.100 to 0.200 | 3.03                    | > 0.100 to 0.300 | 6.16                    |
| 4 | Dry-evergreen       | > 0.400          | 9.89                    | > 0.300 to 0.500 | 9.18                    |
| 5 | Non vegetation      | < 0.000          | 3.10                    | < 0.000          | 2.61                    |

## DISCUSSION

### Land-use and land-cover change

Since 1995, the study area has seen a significant shift in the extent of various LULC elements. The loss of dry-evergreen, mudflat, and water areas, as measured by satellite imagery and a change area matrix, has resulted in an open-scrub expansion of 6.5 km<sup>2</sup>. Further, NDVI analysis has revealed that the extent of *P. juliflora* increased from 3.03 km<sup>2</sup> in 1995 to 6.16 km<sup>2</sup> in 2018. The LULC classification shows an increasing trend in open-scrub, while the *P. juliflora* abundance (NDVI) map shows a decreasing trend in open-scrub with *P. juliflora* proliferation. This suggests that *P. juliflora* proliferated significantly in the study area's LULC elements especially in open scrub. *P. juliflora* is well-known for its ability

to thrive in open areas rather than occupied ones. Compared to dry-evergreen, mudflat and water areas, open-scrub, which also includes grasslands, has a greater empty niche that allows the invasive to exhibit effective succession. This is supported by the propagule pressure hypothesis, which states that *P. juliflora* grows rapidly because of its ruderal characteristics (Williamson 1996). During times of seasonal resource stress, ungulates may rely heavily on fruits from browse species like *P. juliflora*. There is, however, a hidden cost in the proliferation of invasive species in open habitats such as grasslands, where territorial males and harems defecate in the grasslands, causing open grasslands to become open scrub (Ranjitsinh 1986; Jhala 1997; Jadeja et al. 2013).

**Table 4. Dependent factors level recorded in relation to the level of each covariate.**

| Covariates                                   | Level        | Dependent factor              |                |                                |                 |              |               |
|----------------------------------------------|--------------|-------------------------------|----------------|--------------------------------|-----------------|--------------|---------------|
|                                              |              | Tree density /km <sup>2</sup> | Tree diversity | Shrub density/ km <sup>2</sup> | Shrub diversity | Herb cover % | Grass cover % |
| Temperature (Celsius)                        | Low (<30)    | 69.4 ± 6.31                   | 1.1 ± 0.11     | 4185 ± 572.0                   | 1.3 ± 0.07      | 7.6 ± 0.89   | 12.9 ± 1.07   |
|                                              | High (>30)   | 51.7 ± 9.16                   | 0.9 ± 0.15     | 3455 ± 463.5                   | 1.2 ± 0.11      | 6.3 ± 1.09   | 12.7 ± 1.78   |
|                                              | U (p)        | 532 (0.070)                   | 501 (0.340)    | 877 (0.600)                    | 459 (0.170)     | 505 (0.670)  | 546 (0.890)   |
| Humidity (%)                                 | Low (<40)    | 52.0 ± 6.41                   | 1.1 ± 0.11     | 3738 ± 518.9                   | 1.3 ± 0.08      | 7.0 ± 0.89   | 13.4 ± 1.19   |
|                                              | High (>40)   | 75.5 ± 9.19                   | 1.1 ± 0.15     | 4360 ± 735.5                   | 1.3 ± 0.10      | 7.6 ± 1.17   | 11.8 ± 1.39   |
|                                              | U (p)        | 768 (0.050)                   | 766 (0.560)    | 423 (0.900)                    | 510 (0.770)     | 467 (0.500)  | 578 (0.700)   |
| <i>P. juliflora</i> cover %                  | Low (<20)    | 74.9 ± 9.28                   | 1.0 ± 0.11     | 4615 ± 612.0                   | 1.4 ± 0.07      | 9.2 ± 0.84   | 14.4 ± 1.04   |
|                                              | High (>20)   | 58.6 ± 6.23                   | 1.2 ± 0.14     | 2670 ± 207.4                   | 1.1 ± 0.11      | 3.3 ± 0.72   | 9.6 ± 1.64    |
|                                              | U (p)        | 733 (0.040)                   | 792 (0.350)    | 531 (0.020)                    | 760 (0.200)     | 472 (0.010)  | 663 (0.030)   |
| <i>P. juliflora</i> density /km <sup>2</sup> | Low (<1400)  | 72.4 ± 6.21                   | 1.2 ± 0.11     | 4253 ± 585.1                   | 1.4 ± 0.07      | 9.0 ± 0.83   | 13.9 ± 1.04   |
|                                              | High (>1400) | 43.6 ± 8.76                   | 0.7 ± 0.13     | 3261 ± 249.9                   | 1.1 ± 0.11      | 3.0 ± 0.89   | 10.3 ± 1.75   |
|                                              | U (p)        | 709 (0.690)                   | 529 (0.010)    | 796 (0.040)                    | 614 (0.050)     | 401 (0.000)  | 641 (0.090)   |
| Spotted Deer density /km <sup>2</sup> .      | Low (<1.5)   | 64.0 ± 6.67                   | 1.0 ± 0.11     | 3868 ± 456.8                   | 1.3 ± 0.07      | 7.3 ± 0.81   | 12.5 ± 1.12   |
|                                              | High (>1.5)  | 64.2 ± 8.42                   | 1.2 ± 0.16     | 4172 ± 910.6                   | 1.3 ± 0.12      | 7.0 ± 1.36   | 13.7 ± 1.57   |
|                                              | U (p)        | 865 (0.090)                   | 806 (0.500)    | 877 (0.920)                    | 877 (0.950)     | 835 (0.670)  | 745 (0.230)   |
| Blackbuck density /km <sup>2</sup> .         | Low (<2)     | 78.0 ± 10.17                  | 1.2 ± 0.17     | 4123 ± 571.2                   | 1.5 ± 0.11      | 7.8 ± 1.18   | 14.4 ± 1.59   |
|                                              | High (>2)    | 58.1 ± 5.99                   | 1.0 ± 0.10     | 3600 ± 476.7                   | 1.2 ± 0.07      | 7.0 ± 0.87   | 12.2 ± 1.10   |
|                                              | U (p)        | 643 (0.080)                   | 743 (0.340)    | 760 (0.430)                    | 760 (0.050)     | 750 (0.340)  | 775 (0.480)   |
| Feral horse density /km <sup>2</sup>         | Low (>1.5)   | 76.7 ± 10.87                  | 1.2 ± 0.18     | 3885 ± 589.8                   | 1.5 ± 0.12      | 7.4 ± 1.31   | 13.6 ± 1.56   |
|                                              | High (<1.5)  | 60.2 ± 5.96                   | 1.0 ± 0.10     | 3991 ± 524.9                   | 1.2 ± 0.07      | 7.2 ± 0.83   | 12.6 ± 1.09   |
|                                              | U (p)        | 567 (0.130)                   | 634 (0.380)    | 537 (0.740)                    | 537 (0.070)     | 699 (0.800)  | 718 (0.100)   |
| People (count)                               | Low (<2)     | 60.5 ± 7.61                   | 1.1 ± 0.13     | 4269 ± 0.1                     | 1.4 ± 0.08      | 8.8 ± 0.94   | 14.3 ± 1.24   |
|                                              | High (>2)    | 66.4 ± 6.98                   | 1.0 ± 0.13     | 3605 ± 0.1                     | 1.2 ± 0.09      | 5.4 ± 1.00   | 11.1 ± 1.31   |
|                                              | U (p)        | 498 (0.070)                   | 677 (0.800)    | 478 (0.700)                    | 600 (0.900)     | 655 (0.050)  | 723 (0.800)   |
| Distance to human settlements (m)            | Low (<100)   | 65.5 ± 6.30                   | 1.1 ± 0.11     | 3488 ± 387.8                   | 1.1 ± 0.11      | 4.3 ± 0.83   | 12.1 ± 1.13   |
|                                              | High (>100)  | 61.3 ± 9.58                   | 1.0 ± 0.15     | 5003 ± 993.3                   | 1.3 ± 0.09      | 8.6 ± 1.29   | 14.3 ± 12.50  |
|                                              | U (p)        | 744 (0.560)                   | 533 (0.340)    | 553 (0.003)                    | 533 (0.340)     | 477 (0.030)  | 456 (0.030)   |

Table 5. GLM regression model to determine predictors of vegetation attributes at Point Calimere Wildlife Sanctuary.

| Dependent factor | Covariate                     | $\beta \pm SE$      | z       | p      | Adj R <sup>2</sup> |
|------------------|-------------------------------|---------------------|---------|--------|--------------------|
| Tree density     | Intercept                     | 4.561 $\pm$ 0.0454  | 100.50  | 0.00   | 0.21               |
|                  | <i>P. juliflora</i> cover     | -0.246 $\pm$ 0.0277 | -9.12   | 0.00   |                    |
| Shrub density    | Intercept                     | 8.834 $\pm$ 0.0048  | 1833.00 | 0.000  | 0.25               |
|                  | <i>P. juliflora</i> cover     | -0.067 $\pm$ 0.0003 | -230.30 | 0.010  |                    |
|                  | <i>P. juliflora</i> density   | -0.001 $\pm$ 0.0007 | -120.74 | 0.000  |                    |
| Shrub diversity  | Intercept                     | 2.309 $\pm$ 0.0146  | 256.47  | 0.001  | 0.19               |
|                  | <i>P. juliflora</i> density   | -0.196 $\pm$ 0.0431 | 5.60    | -0.013 |                    |
| Herb cover       | Intercept                     | 2.629 $\pm$ 0.1006  | 26.13   | 0.000  | 0.43               |
|                  | <i>P. juliflora</i> cover     | -0.036 $\pm$ 0.0052 | -6.81   | 0.000  |                    |
|                  | Distance to human settlements | 0.185 $\pm$ 0.0778  | 2.37    | 0.018  |                    |
| Grass cover      | Intercept                     | 3.038 $\pm$ 0.0756  | 40.18   | 0.000  | 0.37               |
|                  | <i>P. juliflora</i> cover     | -0.031 $\pm$ 0.0039 | -7.81   | 0.000  |                    |
|                  | Distance to human settlements | 0.001 $\pm$ 0.0002  | 2.80    | 0.005  |                    |

### Impact of *P. juliflora* parameters on the native flora

The GLM-based regression in this study shows that *P. juliflora* has a negative impact on the density of native tree, shrub, and herb and grass species at Point Calimere (Ali 2005). This is because the ruderal characteristics of *P. juliflora* allow it to spread over time. To put it another way, the amount of open space with sunlight, which is essential for the regeneration of native species such as trees and shrubs, is decreasing. Ecological studies have shown that invasive plants have a negative effect on native species by decreasing species richness, diversity, and displacing indigenous species. (e.g., Smith et al. 1999; Brooks & Pyke 2001; Kedzie-Webb et al. 2001; Lesica & Miles 2001; Prieur-Richard et al. 2002; Badano & Pugnaire 2004). *P. juliflora* in Ethiopia created an impenetrable bush that restricted the native herbivores and livestock from grazing in the area, as well as displacing the native trees (Kebede et al. 2009; Rot et al. 2023). Similarly, *P. juliflora* invasion in the riverine forest habitat of Kenya showed reduced herbaceous cover and diversity (Muturi et al. 2013).

An experimental study at Point Calimere (Murugan et al. 2020) demonstrated the detrimental effects of *P. juliflora*, including herb and grass species' diversity, on local vegetation. Invasive plant species disrupt soil organic matter due to changes in the quality and quantity of litter inputs (Ehrenfeld 2010; Kaur et al. 2012). According to this research, the subsequent removal of *P. juliflora* facilitated the recolonization of local vegetation in terms of species composition and ground vegetation cover, as compared to an unremoved site, including (i) decline in the accumulation of soil organic matter C, total Nitrogen

due to enhanced microbial respiration and Nitrogen mineralisation rates, (ii) loss of plant canopy suppressed microbial biomass and enzyme activities indicating decline in soil quality while enhanced mineralisation of soil organic matter, (iii) higher metabolic quotient at *P. juliflora* removed site indicate that microbial C pools declined at a faster rate than soil organic matter C, resulting in a drop in microbial biomass C/soil organic matter C- ratio due to stress caused by plant removal and presence of allelopathic phenolic compounds released by invasive plant species roots and litter. Further, the authors have pointed that although the magnitude of invasive removal on local plant diversity and few ecosystems were examined, they speculate uncertainty as to how long these observed results may persist. Thus, suggesting long term and periodic monitoring experiments that evaluate the effects of invasive species removal on the environmental conditions.

### Impact of anthropogenic pressure on the native flora

This study found that grass and herb cover decreased noticeably as distance increased from human settlements, indicating a negative effect on grass and herb cover. It is not uncommon for cattle from nearby human settlements to wander into the forest in search of grazing. Because of this, cattle are more likely to graze and trample areas near human settlements as opposed to more remote areas. Therefore, grass and herb cover increase as one moves further away from anthropogenic populated areas (Baskaran 1998; Baskaran et al. 2012).

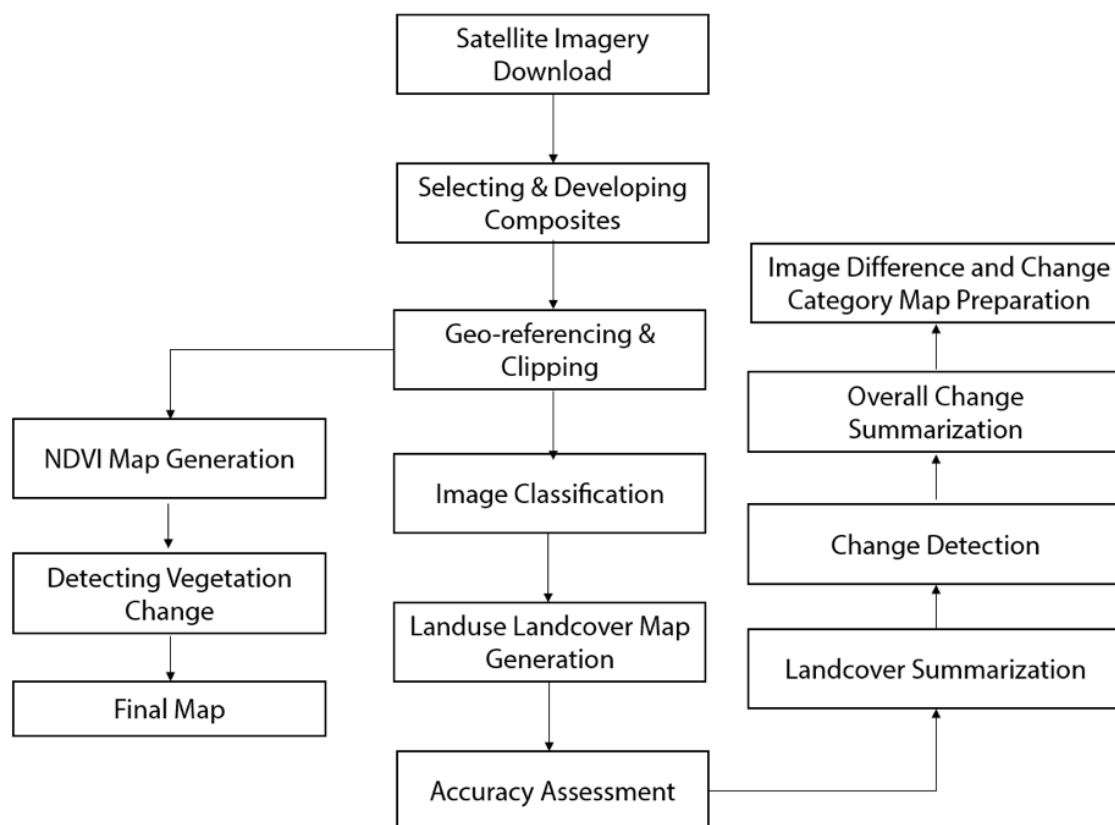
## CONCLUSION

From 1995 to 2018, findings show a transition from dry evergreen, mudflat, and water bodies to open scrub at Point Calimere Wildlife Sanctuary. The dramatic increase in *P. juliflora* from 3.03 km<sup>2</sup> to 6.16 km<sup>2</sup> since 1995, as revealed by this study, is a major cause of LULC shifts and thus the primary cause of the expansion of open-scrub. The detrimental effects of *P. juliflora* on native tree, shrub, herb, and grass species were revealed through a comparison of the effects of temperature and humidity, human activity, herbivores, and *P. juliflora*. The study found that the native flora at Point Calimere Sanctuary was reduced due to the proliferation of *P. juliflora*. Therefore, effective control of invasive species is necessary to save native species. To restore native ecological processes, the study recommends a concerted effort to slow the spread of *P. juliflora* at the same time that it is being eradicated. Other vegetation indices, such as SAVI (Soil-adjusted vegetation index) and similar indices, could address differences due to vegetation and soil fraction in future research. In addition to LANDSAT TM and LANDSAT 8 OLI data, Sentinel data can also be utilised to better comprehend spatial and temporal changes.

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S-Figure 1. GIS methodology flowchart.

**S-Table 1. Image acquisition details.**

| Details              | Landsat-TM                                                                       | Landsat-8                                                                        |
|----------------------|----------------------------------------------------------------------------------|----------------------------------------------------------------------------------|
| Data download source | USGS <a href="https://earthexplorer.usgs.gov">https://earthexplorer.usgs.gov</a> | USGS <a href="https://earthexplorer.usgs.gov">https://earthexplorer.usgs.gov</a> |
| Data catalogue       | WRS path/row: 142/053                                                            | WRS path/row: 142/053                                                            |
| Sensor               | SAM                                                                              | OLI                                                                              |
| Spatial coverage     | 170 km north-south by 183 km east-west                                           | 170 km north-south by 183 km east-west                                           |
| Date of acquisition  | 08-01-1995                                                                       | 02-07-2018                                                                       |
| Spatial resolution   | 30 m                                                                             | 30 m                                                                             |
| Bands associated     | B4, B3, and B2                                                                   | B5, B4, and B3                                                                   |

**S-Table 2. Confusion matrix and accuracy measures for the classification of land cover classes 2018.**

| Classified | Actual (%)            |       |               |         |           |       | User Accuracy (%) |
|------------|-----------------------|-------|---------------|---------|-----------|-------|-------------------|
|            |                       | Water | Dry evergreen | Mudflat | Grassland | Total |                   |
|            | -                     | 1     | 0             | 0       | 0         | 1     |                   |
|            | Water                 | 89    | 0             | 0       | 5         | 94    | 98                |
|            | Dry-evergreen         | 0     | 97            | 0       | 0         | 97    | 100               |
|            | Mudflat               | 5     | 0             | 94      | 8         | 107   | 91                |
|            | Grassland             | 5     | 3             | 6       | 87        | 101   | 79                |
|            | Total                 | 100   | 100           | 100     | 100       | 400   |                   |
|            | Producer Accuracy (%) | 89    | 100           | 94      | 87        |       |                   |

**S-Table 3. Accuracy statistics for the classification of various LULC of Point Calimere Wildlife Sanctuary.**

| Class Name    | Accuracy (%) |      |       |          |
|---------------|--------------|------|-------|----------|
|               | Producer     | User | Kappa | Over-all |
| 1995          |              |      |       |          |
| Dry-evergreen | 100          | 100  | 97    | 85       |
| Open-scrub    | 99           | 79   | 71    |          |
| Mudflat       | 78           | 91   | 71    |          |
| Water         | 73           | 98   | 85    |          |
| 2018          |              |      |       |          |
| Dry-evergreen | 100          | 100  | 96    | 92       |
| Open-scrub    | 87           | 79   | 82    |          |
| Mudflat       | 94           | 91   | 92    |          |
| Water         | 89           | 98   | 93    |          |

**S-Table 4. Normality test using Shapiro-Wilk Statistic and significance value.**

| Dependent factor | Shapiro-Wilk statistic (p) |
|------------------|----------------------------|
| Tree density     | 5.97 (0.037)               |
| Tree diversity   | 7.20 (0.011)               |
| Shrub density    | 8.82 (0.003)               |
| Herb cover       | 12.18 (0.007)              |
| Grass cover      | 10.15 (0.032)              |

**S-Table 5. Change area matrix of Point Calimere: 1995–2018 (Area in km<sup>2</sup>).**

|                      | 2018 km <sup>2</sup> |               |         |       |
|----------------------|----------------------|---------------|---------|-------|
| 1995 km <sup>2</sup> | Open-scrub           | Dry-evergreen | Mudflat | Water |
| Open-scrub           | -                    | 0.9           | 1.1     | 0.9   |
| Dry Evergreen        | 2.3                  | -             | 0.0     | 0.2   |
| Mudflat              | 2.5                  | 0.4           | -       | 0.8   |
| Water                | 1.7                  | 0.3           | 0.5     | -     |

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ISSN 0974-7907 (Online) | ISSN 0974-7893 (Print)

January 2024 | Vol. 16 | No. 1 | Pages: 24451–24614

Date of Publication: 26 January 2024 (Online & Print)

DOI: 10.11609/jott.2024.16.1.24451-24614

[www.threatenedtaxa.org](http://www.threatenedtaxa.org)

## Article

**Use of remote sensing and GIS in assessing the impact of *Prosopis juliflora* proliferation on land use, land cover and diversity of native flora at Point Calimere Wildlife Sanctuary, India**

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