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Status and ecological significance of *Terminalia arjuna* (Roxb.) Wight & Arn., a keystone species in the riparian forest of Moyar River valley in Mudumalai Tiger Reserve, Southern India.

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Abstract

Terminalia arjuna (Roxb.) Wight & Arn. is a keystone species that supports vital ecosystem services in riparian forest and associated faunal communities in the Moyar River valley. The study assessed the ecological significance of these trees in five forest ranges of Mudumalai Tiger Reserve (MTR). A total of 10,127 trees (92.9% live and 7.1% dead) were enumerated. Its distribution ranged from 292m to 933m AMSL with high basal area (7,612.26 m^2), biomass (93,589.6 t) and carbon stock (46,794.8 t). We observed nests of White-rumped vulture *Gyps bengalensis* (n= 56) and Malabar giant squirrel *Ratufa indica* (n= 157) on these trees. This study highlights the importance of conserving large trees like *T. arjuna* due to their ecological significance and role in climate change mitigation.

Keywords: Carbon stock; Malabar giant squirrel, nesting sites; Western Ghats; White rumped vulture.

Introduction

Terminalia arjuna (Roxb.) Wight & Arn., locally called as "Marutham" or "Neer Marudhu", is an endemic plant species to the Indian subcontinent with a severely fragmented population (Sunil *et al.,* 2019; WFO 2025). *T. arjuna* trees are often considered as 'Large old trees' due to their large size, associated faunal communities and their invaluable ecosystem services. Large old trees are often referred to as "Keystone structures", supporting other biodiversity, livelihood of local community by offering economic and social benefits and contributing significantly to the climate change mitigation by carbon sequestration and storage (Manning *et al.,* 2006; Lindenmayer *et al.,* 2012; Lindenmayer & Laurance, 2017, Kauppi *et al.,* 2015; Hauck *et al.,* 2023). Large trees serve as shelter and nesting sites and food for many key species such as elephants, tigers, and leopards in tropical dry forest (Manning *et al.,* 2006; Lindenmayer 2017), and their canopies serve as shelters and nesting sites, particularly for raptors (Gibbons & Lindenmayer, 2002; Lindenmayer & Laurance, 2017). The decline of the large trees adversely impacts the ecosystem, and leads to the loss of many associated fauna and flora (Lindenmayer, 2017).

Large old trees hold immense ecological and cultural significance globally, but detailed regional studies on these keystone species, particularly from Asia, are negligible (Bar-Ness, 2013; Arzoo *et al.,* 2022). A few studies have focused on specific landscapes, *e.g.,* areas along the River Cauvery in Karnataka (Sunil *et al.,* 2010; Nagaraja *et al.,* 2014; Sunil *et al.,* 2019). *T. arjuna* plays a pivotal role in diverse ecosystems, underscoring its importance (Nagaraja *et al.,* 2014; Sunil *et al.,* 2019). A broader understanding of its ecology, distribution pattern, and carbon storage capacity is crucial but lacking, especially from India. Regional studies are very limited, especially in critical wildlife habitats.

The Moyar River Valley (MRV), located within Mudumalai Tiger Reserve (MTR), Tamil Nadu, is a dry tropical landscape, renowned for its rich biological diversity supporting numerous flagship species of flora and fauna. It is also known as one of the prime landscapes supporting the populations of tigers and elephants in the country (Thirumurugan *et al.,* 2021; Qureshi *et al.,* 2023; PE-MoEFCC-WII, 2024). Moreover, this landscape supports substantial vulture nesting colonies, particularly on the Segur plateau and MRV, where the *T. arjuna* trees are abundant along the riparian stretches. Sathya & Jayakumar, (2017) and Nagarajan & Bhaskar (2023) mapped the distribution of *T. arjuna* in MRV. Nesting population of vultures on *T. arjuna* trees have been previously studied by Venkitachalam & Senthilnathan, (2018), Anoop *et al.,* (2018), and Samson *et al.,* (2024) in MRV. Though there is a limited number of studies for understanding the status, distribution, and ecological significance of these key species in riverine habitats, including studies on associated or dependent faunal communities. Hence, the present study focused on i) assessing the population, distribution, and carbon storage of *T. arjuna* and ii)enumerating its ecological role and importance by documenting the nesting observations of White-rumped vulture (*Gyps bengalensis*) and Malabar giant squirrel (*Ratufa indica*) in the riparian forest of Moyar River valley in MTR.

Study Area

The Mudumalai Tiger Reserve (MTR) (Figure 1A) covers an area of 688.59 km², with its core area alone spanning 321 km² (NTCA 2025), situated in the Nilgiris Mountain of the Western Ghats and shares borders with other protected areas such as Bandipur Tiger Reserve, Sathyamangalam Tiger Reserve (STR), and Wayanad Wildlife Sanctuary (Baskaran & Boominathan, 2010). MTR is an integral part of Nilgiri Biosphere Reserve, the first Biosphere Reserve recognized by UNESCO in India (Daniels 1993), renowned for its rich biodiversity, and the diverse landscape experiences (Pushpakaran & Gopalan, 2014). According to Champion & Seth (1968), forest types of MTR is classified as Southern Tropical Dry Thorn Scrub Forest (6A/DS1), Southern Tropical Dry Deciduous Forest (5A/C3), Southern Tropical Moist Mixed Deciduous Forest (3B/C2), Southern Tropical Semi-Evergreen Forest (2A/C2), Moist Bamboo Brakes (2E3), and Tropical Riverine Forest (5/B1 & 4E/RS1). The present study was conducted in five forest ranges, such as Segur, Masinagudi, Nilgiri Eastern Slopes (NES), Theppakadu, and Singara in MTR.

Methods

The present study assesses the population status, distribution, and ecological significance of *T. arjuna* using a field inventory method (Avery & Burkhart 2015). During the study period, all individual trees on either side of the Moyar River and its tributaries (within 200-300 m perpendicular distance along the total stretch of 77.6 km length of river) in the Mudumalai Tiger Reserve, Tamil Nadu, were measured between February and July 2024. The status of each tree was marked either as live or dead, and the tree circumference was measured (in cm.) at girth at breast height (GBH) (1.37 m). Each tree was marked with a unique code to avoid double-counting and color-coded for identity. Geo-coordinates for all trees, photographs, and critical observations were recorded, and associated flora and fauna were documented. The flora (both native and invasive species) and faunal communities were documented within a 5-meter radius. Direct, indirect signs of faunal communities, nesting of birds and mammals, particularly the Indian giant squirrel and White-rumped vulture nests, were identified and documented. Vultures' nests were identified based on characteristics described by Venkitachalam & Senthilnathan (2018), Anoop *et al.,* (2018), and Samson & Ramakrishnan (2020). Nesting of the Indian Giant Squirrel was identified based on Baskaran *et al.,* (2011).

The basal area of each tree is a key indicator for tree density, biomass, and carbon storage (Babst *et al.,* 2014). Such indicators were calculated based on measurements using the standard formulas:

(1) Diameter at Breast Height (DBH) =
Girth at Breast Height (GBH)/π, and basal area (in cm. sq.) = π(DBH×DBH)/4 (Hein & Dhote, 2006; Thompson *et al.,* 2006). Trees were grouped into DBH classes and elevation classes (200 m to 1000 m) to assess age structure and vertical distribution.

(2) The carbon stock methods were estimated using standard protocols (Cairns *et al.,* 1997, IPCC, 2003; 2005; Chave *et al.,* 2009).

(3) Above-Ground Biomass (AGB) refers to the total mass of living plant material, including the entire shoot, branches, leaves, fruits, and flowers (Chave *et al.,* 2005). AGB (kg $tree^{-1}$) = $\rho \times \exp(-0.667 + 1.784 \ln(D) + 0.207(\ln(D))^2 - 0.0281(\ln(D))^3)$. Where ρ is the wood density, D is DBH.

(4) Wood density of *T. arjuna* is calculated as 0.94 kg/m³ by Zanne *et al.,* (2009).

(5) The Below-Ground Biomass (BGB) is the biomass of live roots, excluding fine roots having <2 mm diameter (Cairns *et al.,* 1997; IPCC, 2003) and BGB (kg $tree^{-1}$) = AGB × 0.26 (IPCC, 2005).

(6) Total biomass or living plant material in both above and below the soil was calculated based on the formula: Total biomass (kg $tree^{-1}$) = AGB (kg $tree^{-1}$) + BGB (kg $tree^{-1}$).

(7) Formula for total carbon stored in a tree: Carbon (kg $tree^{-1}$) = 0.5 × Total Biomass (kg $tree^{-1}$); wherein, 0.5 is a default conversion factor as 50% of its biomass is considered as carbon (IPCC, 2005).

(8) The total carbon dioxide (CO_2) sequestration by a tree was assessed based on the formula: CO_2 sequestered (kg $tree^{-1}$) = 3.67 × Carbon (kg $tree^{-1}$); wherein, 3.67 is the factor for CO_2 sequestration in trees (IPCC, 2005).

During the survey in Moyar, a total of 77.6 km distance was covered, and *T. arjuna* tree encounter rate (average number of trees per km) was estimated along 56 km stretch between 11.60828°N, 76.61684°E and 11.52538°N, 77.01463°E. The assessment mainly focused on the mainstem river of MTR, while minor streams and tributaries were excluded due to uneven distribution within these areas, and the survey was restricted to the state. Mapping of the spatial distribution of *T. arjuna* was carried out using ArcMap (Version 10.8). Data analysis and summarization (DBH and streams) were performed using R software (version 4.2.3, R core team 2024).

Results and Discussion

A total of 10,127 trees were counted in the entire study area (Figure 1B), out of which 9,415 trees were live (92.9%) and 712 trees were dead (7.1%) (Table 1). A total of 3,454 trees were recorded in the 56 km stretch of the mainstem of the Moyar river, wherein the tree encounter rate was estimated as 61.6 trees per km. (61.6±1.04 SE) *T. arjuna* is widely distributed in the riparian ecosystem along the MRV. It ranges from the highest elevation of 933 m to the lowest elevation of 292 m above mean sea level (AMSL) in MTR. DBH varied from 5 cm to 359 cm. *T. arjuna* covered a substantial total basal area of 7612.26 m², and it is stocking a total of 46794.8 tons carbon (Table 1). The tree presence and population in the present study are comparatively higher than the previous studies (Sunil *et al.,* 2010; Nagaraja *et al.,* 2014; Sunil *et al.,* 2019) in the neighboring landscapes.

The present study exhibits an exceptional carbon storage capacity of *T. arjuna* due to its large size. This large tree species

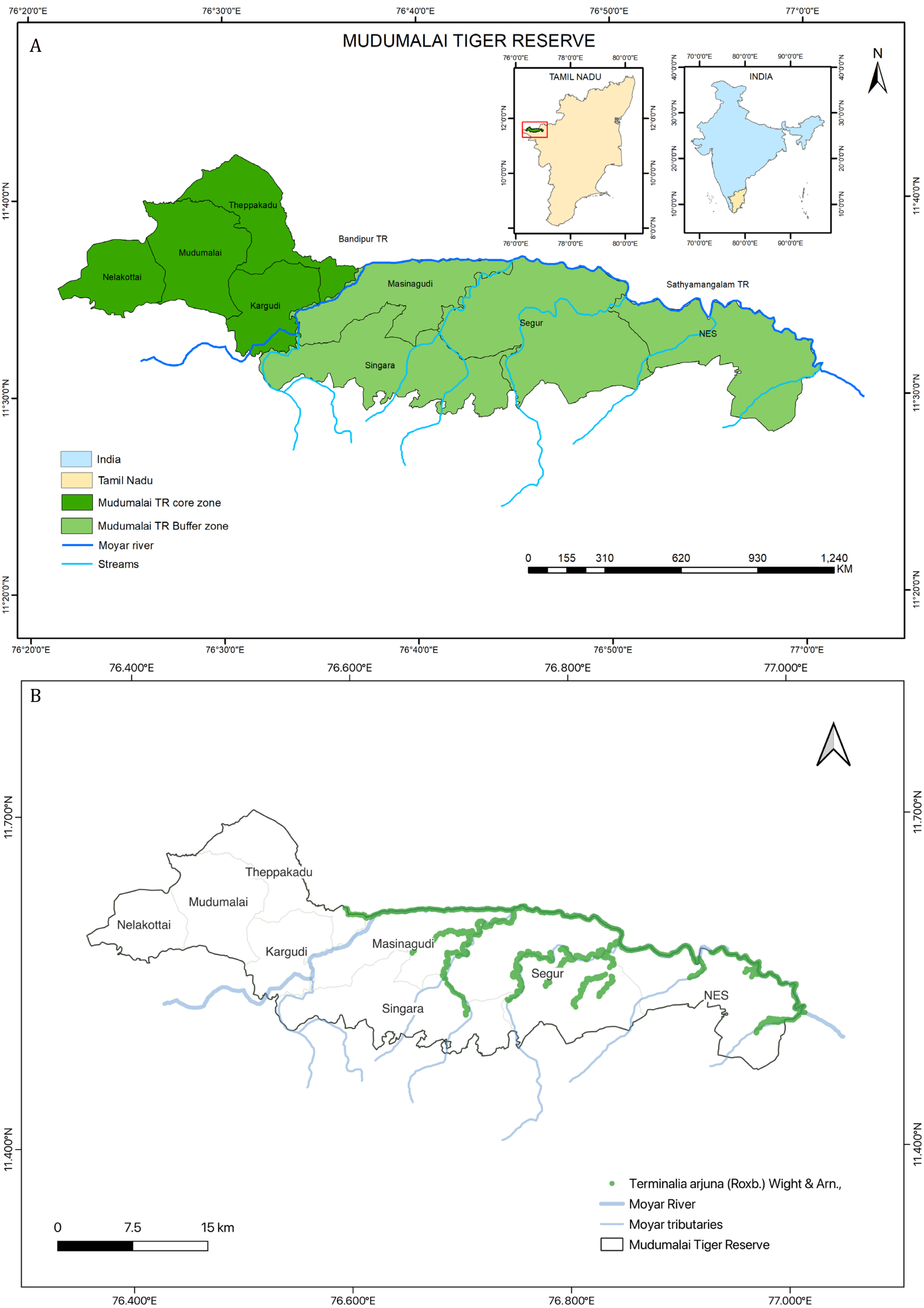

Figure 1 A: The study area map included different forest ranges along Moyar river and its tributaries in Mudumalai Tiger Reserve, Tamil Nadu. B: The distribution of *T. arjuna* trees along Moyar river in the Mudumalai Tiger Reserve.

Table 1: Details of quantitative summary of *T. arjuna* trees in the study area.

Habit		**Estimate**
Total individuals enumerated		10127
Tree condition	Live	9415
	Dead	712
Tree distribution elevation range		292–933m AMSL
Diameter at Breast Height range		5-359 cm
Average Diameter at Breast Height		74.35 cm
Total Basal area		7612.26 m^2
Above Ground Biomass		74277.5 t
Below Ground Biomass		19312.1 t
Total Biomass		93589.6 t
Carbon stock		46794.8 t
Carbon dioxide sequestration		171737 t
Average number of individuals in a 1 km stretch of *T. arjuna* habitat along Moyar River valley (Tamil Nadu portion)		61.6 individuals/ Km (61.6±1.04 SE)

with a high basal area contributes significantly to the potential carbon storage capacity in the MRV. The total carbon stock storage capacity of 93,589.6 tons (t) of total biomass amounting to 1,71,737 t of carbon dioxide sequestration in a single river valley of 77.6 km, highlights its significant role in mitigating climate change. Many other studies have also highlighted that these trees store large quantities of biomass and accumulate carbon in the riparian ecosystems (Chauhan *et al.,* 2019; Srinivas & Sundarapandian 2019; Kujur *et al.,* 2021).

Terrain type plays a significant role in tree distribution. Flat and stable terrain supports high tree distribution, as these areas have a favorable microclimate for growth and regeneration with greater soil depth and moisture retention. In contrast, the tree density was lower in stretches with rapid elevation change. The present study exhibits a healthy population with low mortality. Though, there are certain observations of drying branches and defoliation due to parasites and invasive species. The highest tree population was observed in the Segur Range (N= 4872), hn followed by Masinagudi Range (N= 2451). The lowest number of trees was observed in Singara Range (N= 53). Masinagudi and NES ranges (N= 1904) exhibited a fair presence of *T. arjuna* with very low tree mortality rate (<5%). On the other hand, no tree deaths were recorded in Theppakadu range, where all 135 individuals are alive (Figure 2). All five forest ranges showed a significant variation in different elevation ranges (Supplementary Figure S1). The highest number of trees was recorded in the elevation range between 300 m and 600 m AMSL (N=6622). Tree abundance was high in the elevation range between 400 m and 1000 m AMSL (N=7532), and *T. arjuna* had a widespread elevational distribution in Segur Forest Range. Tree Presence was low in the elevation range between 200 and 300 m AMSL (n = 159), observed in NES Range (Supplementary Figure S1).

Live trees had a similar median DBH (76.13±0.52) with dead trees DBH (75.18±1.86) in all the streams (Supplementary Figure S2), except Segurnallah stream and Siriyurallah stream. The Iyanmathi stream showed the largest range of DBH (11 to 286) for live trees (N = 56). Significantly, some of the trees in the Segur nallah stream and Siriyurallah stream had attained maximum DBH (318 and 259) before mortality. In some other streams, the median DBH of the dead trees was smaller than the DBH of the live trees, which indicates the presence of higher mortality in the smaller size classes. We noted that the DBH was almost equal for both live and dead trees in Edakkarapallam, Mukkuruthipallam, and Poochapallam streams (Supplementary Figure S2).

The number of trees in various size classes showed significant variation amongst the forest ranges. Masinagudi, Segur, and Theppakadu ranges showed an inverted 'J' shaped curve, indicating a healthy, regenerating forest with a considerable number of young trees (Supplementary Figure S3). In contrast, NES and Singara ranges showed a decline in the presence of smaller size class trees (5-50 cm DBH), indicating that these areas have slow recruitment and possible hindrance in the establishment of young trees. As the total number of trees in Singara range was too small (N= 53) to draw any conclusion, the situation of low recruitment in smaller size classes in the NES range needs further investigation. Invasive species such as *Prosopis juliflora*, *Lantana camara*, *Parthenium hysterophorus*, and *Chromolaena odorata* have caused severe degradation of native ecosystems in some ranges of STR (Sivakumar *et al.,* 2018). Presence of anthropogenic pressures such as lopping, cattle herbivory on edges, trampling of young plants, and severe invasion of *P. juliflora*, in the NES range may have led to the lower number of young trees with 0-50 cm of DBH. Several studies have documented the negative impact of *P. juliflora* in the Moyar river valley landscape (Sathya & Jayakumar 2017; Maheshnaik & Baranidharan 2018; Rajput *et al.,* 2019; Arandhara *et al.,* 2021).

T. arjuna has direct and indirect ecological associations with several floral and faunal communities in the riparian ecosystem (Figure 3). We observed association of *T. arjuna* with the plant species like: *Pongamia pinnata* (L.) Pierre, *Diospyros malabarica* (Desr.) Kostel. and *Syzygium cumini* (L.) Skeels (Supplementary Table T1), and wild animal species such as: *Axis axis* (Erxleben, 1777), *Crocodylus palustris* (Lesson, 1831), and *Elephas maximus indicus* Cuvier, 1798 (Supplementary Table T2). The Bengal tiger (*Panthera tigris tigris*) and leopards (*Panthera pardus*) use *T. arjuna* trees for sharpening their claws, and many mammals use the tree shade and rest beneath the trees; . These trees act as one of the most preferred nesting sites of Honey bees, as it provides space for large honeycombs, which also indicates their importance to pollinators. Tusk marks of the Indian elephant (*Elephas maximus indicus*) on these trees, basking of marsh crocodiles (*Crocodylus palustris*) near these trees in riparian habitat, the termites moulding on the dead tree trunks, and sloth bears (*Melursus ursinus*) feedings on these termites shows vital ecological interactions between animals and *T. arjuna*.

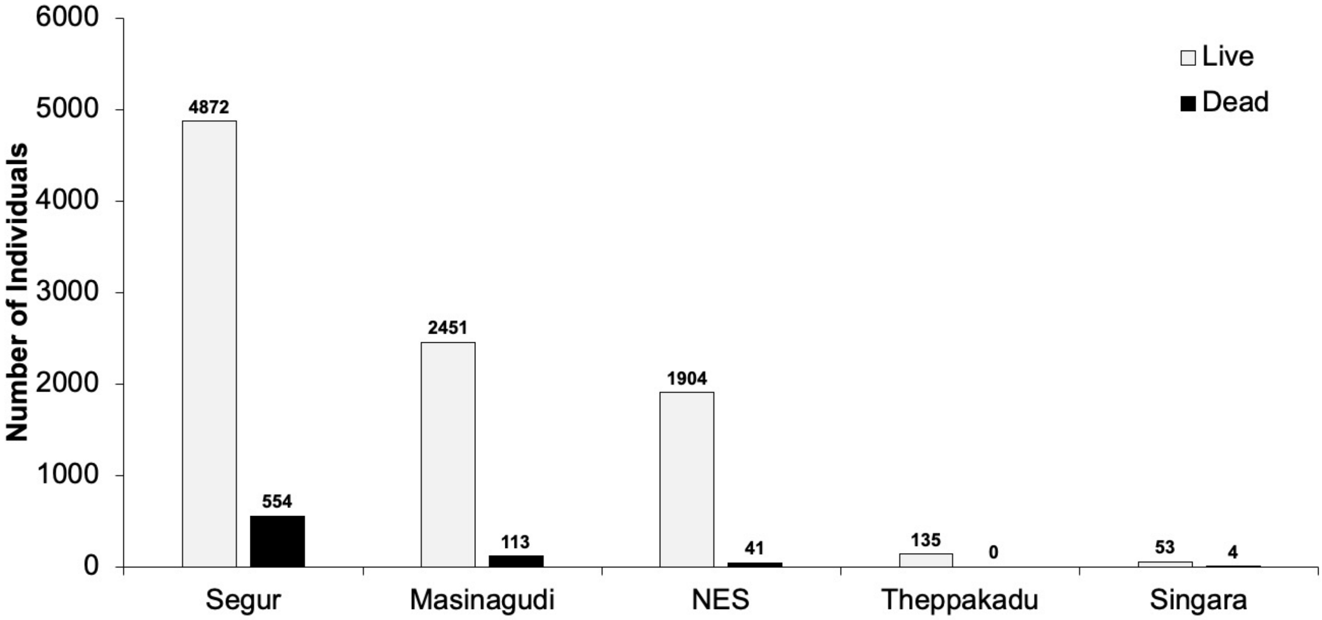

Figure 2: Distribution of live and dead *T. arjuna* trees in different forest ranges of the Mudumalai Tiger Reserve.

Figure 3: The direct and indirect sightings of faunal species associated with the *T. arjuna* tree.
a) White-rumped vulture (*Gyps bengalensis*) soaring.
b) The White-rumped vulture nesting and roosting on the *T. arjuna* tree.
c) Malabar giant squirrel (*Ratufa indica*).
d) A Malabar giant squirrel nest on *T. arjuna* tree.
e) Tiger claw scratch marks on the *T. arjuna* tree trunk, likely indicating territorial marking and claw sharpening behaviour.
f) Spot-bellied eagle-owl (*Bubo nipalensis*) roosting on *T. arjuna* tree.

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During the study, 56 nests of White-rumped vulture, a critically endangered species and 157 nests of Malabar giant squirrel were observed on *T. arjuna* trees in the Mudumalai Tiger Reserve (Figure 4, Supplementary Table T3). The observed 157 Malabar giant squirrel nest were higher than the earlier study (N = 83; Baskaran *et al.*, 2011). Sightings of White-rumped vultures are high in the Segur followed by Masinagudi ranges, whereas its nests were recorded as high in the Segur range (N = 44) followed by Masinagudi range (N = 13). Only one nest of White-rumped vulture was observed on a different tree species, Mitragyna parvifolia (Roxb.) Korth. Samson & Ramakrishnan (2020) also, recorded that the White-rumped vultures nests (N = 83) with preference of 97% *T. arjuna* trees and 3% nest on the trees of Spondias mangifera Willd. to build their nest; *T. arjuna* is preferred for shelter mainly because of its tall, large crown and wide canopy that provide protection from predators (Samson & Ramakrishnan 2020; Arockianathan, 2020).

The highest number of Malabar giant squirrel's nests on *T. arjuna* trees was observed from Segur range (N= 74), and the lowest was observed from Singara range (N= 01). The results were similar to earlier studies, *e.g.* Samson & Ramakrishnan (2020) observed 68 vulture nests, and Arockianathan (2020) observed 279 nests of Malabar giant squirrel in MTR.

Out of the total enumerated 10,127 individual trees in the present study, 92.9% were live and distributed in a wider elevational range between 292 m – 933 m, indicating a healthy population and widely fragmented in these landscapes. Carbon storage of 46,794.8 tons by these trees exhibits their importance in preventing CO_2 release and climate change mitigation. Limited branch death and defoliation showed its resilience to parasites, invasive species, and other disturbances. Observation of a large number of nesting sites of birds and mammals on *T. arjuna* showed its strong contribution to the ecological integrity.

This study identified and quantified some of the crucial associations of *T. arjuna*, providing crucial habitat for several native plant species and shelter and other services to wildlife in riparian areas, highlighting its high ecological significance to the landscape (Nagaraja *et al.,* 2014; Ramakrishnan *et al.,* 2014; Sunil *et al.,* 2019; Thirumurugan *et al.,* 2021; Nagarajan & Bhaskar, 2023). Though it is essential to adopt policies and management measures to invasive species, *P. juliflora*, in the Segur and NES forest ranges, as these invasions potentially disrupt the regeneration of *T. arjuna*. Anthropogenic disturbances should be restricted, and some of the activities like pollution and dumping waste must be regulated, particularly along the Segur and Masinagudi ranges, where the higher tree mortality rates were recorded. Establishing long-term monitoring plots to study factors affecting tree mortality and regeneration is highly recommended to conserve these large old heritage trees in the riparian ecosystems of Mudumalai Tiger Reserve.

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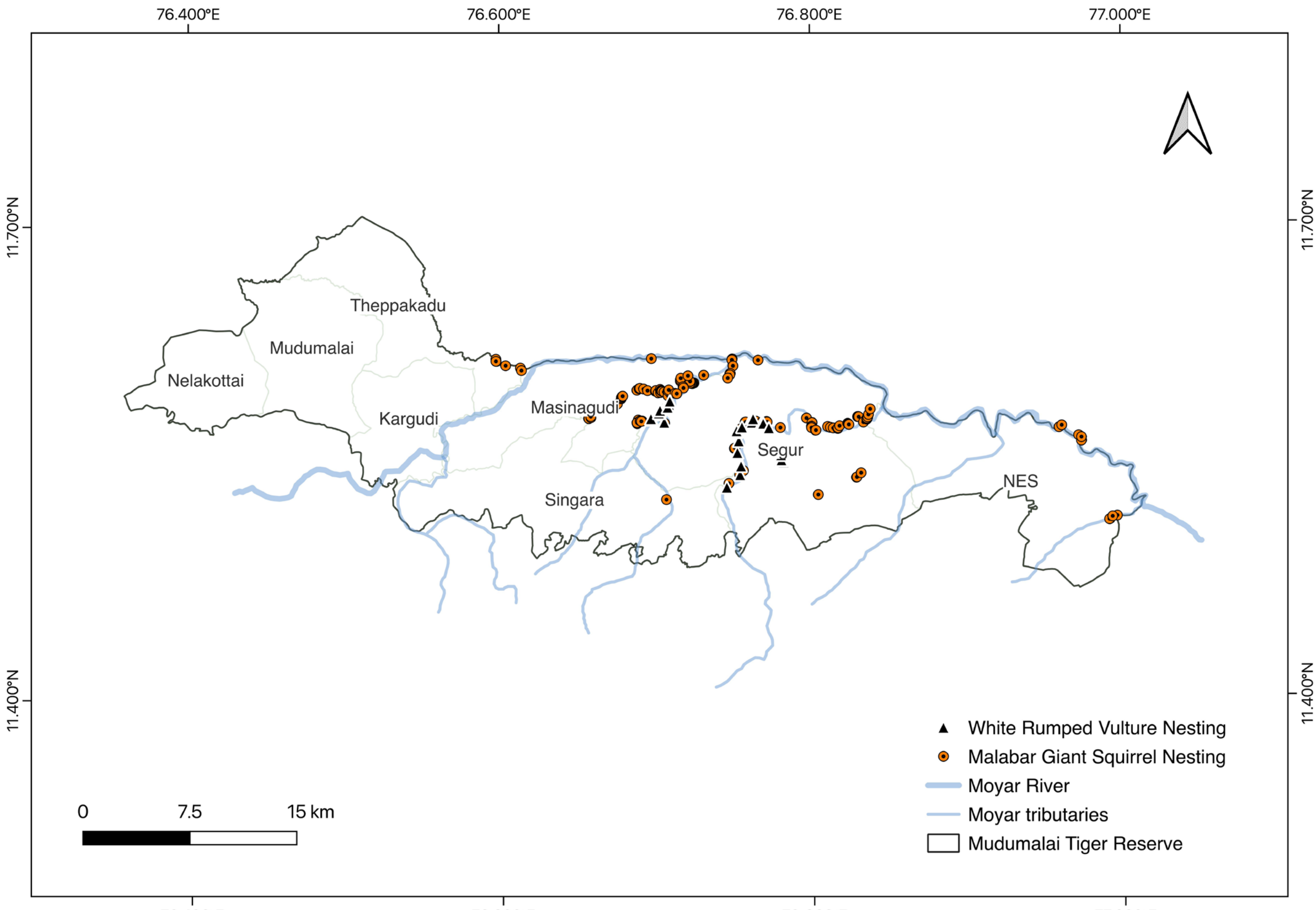

Figure 4: The distribution of White-rumped vultures and giant squirrel nesting sites in the Moyar River valley.

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CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

DATA AVAILABILITY

The data used in the study are available upon request from the corresponding author

AUTHOR CONTRIBUTIONS

T.V.: Data analysis; Writing - Conceptualization; original manuscript; review & editing; Investigation.
I.S.: Data Collection & analysis; Writing - review & editing.
N.M.S.: Data Collection & analysis; Writing - review & editing.
S.T.T.: Writing - review & editing.
S.R.S.: Supervision; Writing - review & editing.
A.P.: Funding; Supervision
S.S.: Funding; Supervision

ORIGINALITY STATEMENT

The submitted research work is original, and we confirm that the manuscript is neither published nor under consideration for publication elsewhere in whole or in part. No generative AI was used for the manuscript.

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