Comparative Biomass Carbon Storage, CO_2 Mitigation Potential and Green Economy Valuation of Polyculture and Monoculture Plantations under the Jan Van Yojna Social Forestry Scheme in Semi-Humid Tropical Jharkhand India

Md. Shahzad Ahmad
Ranchi University
Shanker Uma
Ranchi University
Naiyar Naaz
naiyar19biotech@gmail.com
Ranchi University

Research Article

Keywords: Semi-humid tropics, Jharkhand, Jan Van Yojna, polyculture plantation, biomass carbon storage, CO_2 mitigation, carbon credits, green economy, REDD+, India Green Credit Programme, Gmelina arborea, Tectona grandis

Posted Date: May 27th, 2026

DOI: https://doi.org/10.21203/rs.3.rs-9566029/v1

Additional Declarations: No competing interests reported.

Abstract

Tropical forest plantations under community-based schemes represent an underexplored yet critical nexus between land-use policy, climate change mitigation, and green economy valuation. This study provides the first quantitative assessment of biomass carbon storage, CO_2 mitigation potential, and carbon credit value for two contrasting Jan Van Yojna plantation sites in semi-humid tropical Ranchi district, Jharkhand, India: a seven-species polyculture stand at BUDMU (652 trees, 2.2 acres) and a monoculture *Tectona grandis* stand at ANGADA (500 trees, 2.0 acres), both established in 2016. Carbon stock was quantified through field measurements of DBH, FSI regression-based volume estimation, species-specific wood density, Walkley–Black titration for carbon factor determination, and IPCC Tier-1 methodology for CO_2 equivalence conversion (factor: 44/12 = 3.667). The BUDMU polyculture site sequestered a total of 15.32 tonnes of carbon (56.19 tonnes CO_2e), with *Gmelina arborea* (Gamhar) as the dominant species contributing 58.80% (33.04 tonnes CO_2e), followed by *Tectona grandis* (18.44%; 10.36 tonnes CO_2e) and *Dalbergia sissoo* (10.92%; 6.14 tonnes CO_2e). The ANGADA monoculture stored 5.92 tonnes carbon (21.71 tonnes CO_2e), exclusively in *Tectona grandis*. BUDMU's carbon stock was 2.59× higher than ANGADA's, driven by species diversity and the presence of high-biomass *Gmelina arborea*. Per-tree *Tectona* carbon density was marginally higher in the mixed stand (12.28 kg/tree vs. 11.84 kg/tree), suggesting facilitative inter-specific interactions. Component-wise analysis revealed stem dominance in most species (stem > root > branch > leaf), with exceptions in *Swietenia macrophylla* and *Emblica officinalis* (branch > stem > root > leaf). Carbon credit valuation under the Voluntary Carbon Market (VCM) ranges from USD $280.93–$842.79 for BUDMU and USD $108.56–$325.68 for ANGADA; combined credits under India's Green Credit Programme (GCP, 2023) total ₹50,634. These findings establish that polyculture Jan Van Yojna plantations generate measurably higher climate mitigation value and green economy returns than equivalent monoculture stands, with implications for REDD+ baselines, State Action Plans on Climate Change, and biodiversity-stacked NbS finance in the Indian tropics.

1 Introduction

Anthropogenic greenhouse gas emissions, primarily CO_2, have elevated atmospheric concentrations from 280 ppm in pre-industrial times to over 422 ppm, posing unprecedented threats to global climate stability [1, 2]. Among nature-based climate solutions, forest ecosystems occupy a central position, sequestering approximately 40% of land-based global carbon [3, 4]. Tropical and subtropical plantation forestry, through deliberate afforestation and reforestation, has emerged as a scalable and policy-amenable strategy for enhancing terrestrial carbon sinks while simultaneously delivering livelihoods, biodiversity co-benefits, and land productivity [5, 6].

India's semi-humid tropical region of Jharkhand, situated in the central-north-eastern Deccan plateau, harbours diverse tropical dry and moist deciduous forest ecosystems. The state faces among the highest rates of forest degradation in India and ranks among the top five states in desertification intensity [7]. In this context, the Government of Jharkhand launched the Jan Van Yojna (JVY) in 2016 — a private-land social forestry scheme under which beneficiaries are incentivised to plant timber and fruit-yielding trees on plots ranging from 0.5 to 50 acres, with 75% of establishment and maintenance costs borne by the State for the first three years [8, 9]. By April 2021, the scheme had achieved 190.03 acres of new plantation cover accommodating 19,424 trees across Ranchi district.

Despite the policy significance of JVY, there exists no published quantitative evaluation of its carbon storage performance. Globally, mixed-species plantations have been repeatedly shown to outperform monocultures in productivity, biomass accumulation, and carbon sequestration [10–14]. However, species-specific outcomes in tropical Indian plantation settings remain poorly characterised.

The present study addresses this gap through a cross-site field investigation of two JVY beneficiary plantations in Ranchi district: (i) a seven-species polyculture stand at BUDMU (latitude 23.5746°N, longitude 85.1315°E) and (ii) a monoculture *Tectona grandis* stand at ANGADA (latitude 23.4073°N, longitude 85.4851°E), both established in 2016. Beyond biomass carbon quantification, the study applies IPCC Tier-1 CO_2 equivalence conversion and Voluntary Carbon Market (VCM) and India Green Credit Programme (GCP) valuation frameworks to translate ecological measurements into actionable green economy metrics.

Specifically, this study aims to: (1) quantify above- and below-ground biomass carbon stocks across all tree components at both sites; (2) estimate CO_2 equivalence and site-level mitigation potential using IPCC Tier-1 methodology; (3) estimate carbon credit value under three market scenarios including India's GCP 2023; (4) compare polyculture versus monoculture sites in carbon sequestration efficiency; and (5) assess the feasibility of linking JVY data to REDD + and State Action Plan frameworks.

2 Materials and Methods

2.1 Study Area

Jharkhand (22°28–°25°30' N; 83°22–°87°04' E) covers 79,714 km² in central-northeastern India, with elevations ranging from 6 to 1,366 m above mean sea level. The state is characterised by a semi-humid tropical climate with mean annual rainfall of approximately 1,200–1,400 mm, predominantly monsoonal (June–September). Two study sites were selected within Ranchi district from 24 active JVY plantation sites on the basis of establishment year (2016), minimum tree count (≥ 400 surviving trees), and quality of maintenance records.

BUDMU site (23.5746°N, 85.1315°E): A 2.2-acre mixed-species plantation consisting of 652 trees representing seven species: four timber-yielding [*Tectona grandis* L.f. (230 trees), *Gmelina arborea* Roxb. (210 trees), *Swietenia macrophylla* King (60 trees), *Dalbergia sissoo* Roxb. ex DC. (50 trees)] and three fruit-yielding [*Mangifera indica* L. (94 trees), *Emblica officinalis* L. (6 trees), *Psidium guajava* L. (2 trees)]. Field measurements were conducted in December 2020, approximately four years post-establishment.

ANGADA site (23.4073°N, 85.4851°E): A 2.0-acre monoculture plantation of *Tectona grandis* (500 trees), measured approximately four years post-establishment.

2.2 Tree Enumeration and Dimensional Measurements

All trees at both sites were individually enumerated, tagged with chalk, and measured for girth at breast height (GBH) at the standard height of 1.37 m above ground level using calibrated measuring tapes. Diameter at breast height (DBH) was derived as: DBH (cm) = GBH (cm) / π, where π = 3.14. Tree heights were recorded using a clinometer.

2.3 Biomass Carbon Estimation

2.3.1 Wood Core Sampling and Carbon Factor Determination

Cylindrical wood samples were extracted from the stem of each species using a Pressler increment borer. Branch samples were obtained from the lowermost and immediately superior branch of each tree species. Leaf fractions were obtained by complete defoliation of representative individuals of each DBH class. Carbon content (carbon factor) of each tissue type was determined by the modified Walkley–Black wet oxidation titration method [15]. Dry weight factors were derived from fresh weight / oven-dry weight ratios; samples were dried at 70°C to constant mass.

2.3.2 Volume and Biomass Estimation

Tree volume was estimated using species-specific regression equations published by the Forest Survey of India [16–18]. Green weight was computed as: Green weight = Volume × Wood density, using species-specific wood densities from Brown [19]. Dry weight of stem = Green weight × Dry weight factor. Branch and foliar biomass were estimated using FSI default regression equations stratified by DBH class following Davidson and Janssens [20].

2.3.3 Component-wise Carbon Calculation

Biomass carbon of each component was computed as: Carbon (component) = Dry weight (component) × Carbon factor (component). Root carbon was estimated as 26% of the sum of stem, branch, and foliage carbon, following the allometric proportions documented for tropical tree species [21].

2.3.4 IPCC Tier-1 CO_2 Equivalence Conversion

Total carbon stock (C, tonnes) at each site was converted to CO_2 equivalent (CO_2e, tonnes) using the IPCC Tier-1 stoichiometric conversion factor [22]:

CO_2e (tonnes) = C (tonnes) × 3.667 [where 3.667 = 44/12, the molar mass ratio of CO_2 to C]

2.3.5 Carbon Credit and Green Economy Valuation

The IPCC-derived CO_2e values were converted to tradeable carbon credits on the basis that 1 tonne CO_2e = 1 carbon credit. Three market scenarios were applied: (i) VCM lower bound at USD $5/tonne CO_2e [23]; (ii) VCM premium rate at USD $15/tonne CO_2e for certified Nature-Based Solutions (NbS) projects [24]; and (iii) India's Green Credit Programme (GCP) rate at ₹650/tonne CO_2e [25].

3 Results

3.1 Tree Growth at BUDMU and ANGADA

At BUDMU, tree heights ranged from 3.6 to 19.6 ft across species four years after establishment. *Tectona grandis* and *Swietenia macrophylla* attained maximum heights (19.6 ft), followed by *Dalbergia sissoo* (19.5 ft), *Gmelina arborea* and *Mangifera indica* (14.9 ft), *Emblica officinalis* (9.7 ft), and *Psidium guajava* (4.8 ft). DBH values ranged from 3.6 to 44.7 cm. At ANGADA, *Tectona grandis* trees exhibited heights of 3.6–19.6 ft and DBH of 4.6–23.9 cm, with 46.8% of trees in the 0–10 cm class, 44.6% in the 10–20 cm class, and 8.6% in the 20–30 cm class.

3.2 Site-level Biomass Carbon Stock

The BUDMU polyculture site accumulated a total biomass carbon stock of 15.3220 tonnes across 652 trees. The average per-tree carbon value was 23.49 kg. In contrast, the ANGADA monoculture site sequestered 5.9209 tonnes across 500 trees, with an average of 11.84 kg per tree. The polyculture site thus stored 2.59 times more carbon than the monoculture site, despite having only 30% more individual trees. These results are consistent with the broader literature demonstrating productivity advantages of mixed-species plantations [10, 12, 14].

3.3 CO_2 Equivalence and Carbon Mitigation Analysis

3.3.1 ANGADA Site

Applying the IPCC Tier-1 conversion factor, the 5.9209 tonnes of carbon stored at ANGADA yields a CO_2e of 21.7121 tonnes (Table 1). On a per-tree basis, each *Tectona grandis* individual at ANGADA contributes approximately 43.42 kg CO_2e, consistent with moderate carbon density values reported for teak plantations of this age class in peninsular India [26, 27].

Table 1
CO_2 equivalence estimation — ANGADA site (monoculture *Tectona grandis*, 500 trees, 2.0 acres). Conversion factor: IPCC (2006), 44/12 = 3.667 [22]

Sl.	Species (Common Name)	No. of Trees	Total C (tonnes)	C (%)	CO_2e (tonnes)
1	*Tectona grandis Linn. f. (Teak)*	500	5.9209	100.00	21.7121
Total		**500**	**5.9209**	**100.00**	**21.7121**

Under VCM conservative pricing (USD $5/tonne), the ANGADA plantation generates USD $108.56 in carbon credit value; at NbS-premium VCM pricing (USD $15/tonne), this rises to USD $325.68. Under India's GCP framework, the domestic equivalent is ₹14,113 (Table 2).

Table 2
Carbon credit valuation under three market scenarios — ANGADA site.

Sources: World Bank Carbon Pricing Dashboard (2023) [23]; MoEFCC GCP Rules (2023) [25]

Sl.	Species	CO_2e (tonnes)	VCM Low ($5/tonne)	VCM High ($15/tonne)	India GCP (₹650/tonne)
1	*Tectona grandis (Teak)*	21.7121	USD $108.56	USD $325.68	₹14,113
Total		**21.7121**	**USD $108.56**	**USD $325.68**	**₹14,113**

3.3.2 BUDMU Site

The 15.3220 tonnes of carbon stored across seven species at BUDMU corresponds to 56.1857 tonnes CO_2e (Table 3). *Gmelina arborea* (Gamhar) is the dominant carbon sink species, contributing 9.0087 tonnes C (33.0350 tonnes CO_2e; 58.80% of site total), followed by *Tectona grandis* (2.8251 tonnes C; 10.3597 tonnes CO_2e; 18.44%) and *Dalbergia sissoo* (1.6732 tonnes C; 6.1357 tonnes CO_2e; 10.92%). The remaining four species contributed collectively 11.85% (6.6554 tonnes CO_2e).

Table 3
Species-wise CO_2 equivalence and carbon mitigation classification — BUDMU site (polyculture, 7 species, 652 trees, 2.2 acres). IPCC factor: 44/12 = 3.667 [22]. Mitigation class: HIGH > 30% CO_2e share; MODERATE 10–30%; LOW < 10%

Sl.	Species (Common Name)	Trees	Total C (tonnes)	C%	CO_2e (tonnes)	Mitigation Class
1	*Gmelina arborea Roxb. (Gamhar)*	210	9.0087	58.80	33.0350	HIGH
2	*Tectona grandis L.f. (Teak)*	230	2.8251	18.44	10.3597	MODERATE
3	*Dalbergia sissoo Roxb. (Shisham)*	50	1.6732	10.92	6.1357	MODERATE
4	*Swietenia macrophylla King (Mahogany)*	60	0.8226	5.37	3.0165	LOW
5	*Mangifera indica L. (Mango)*	94	0.9490	6.20	3.4797	LOW
6	*Emblica officinalis L. (Amla)*	6	0.0213	0.14	0.0781	LOW
7	*Psidium guajava L. (Guava)*	2	0.0221	0.14	0.0810	LOW
Total	**7 species**	**652**	**15.3220**	**100.00**	**56.1857**	

The dominance of *Gmelina arborea* in BUDMU's carbon credit portfolio (USD $165.18–$495.53 of the site's USD $280.93–$842.79 total) underscores its strategic importance for carbon-optimised plantation design (Table 4). These findings are consistent with Tamang [28] and Bohre et al. [27].

Table 4
Species-wise carbon credit valuation under three market scenarios — BUDMU site.

Sources: World Bank [23]; MoEFCC [25]

Sl.	Species	CO_2e (tonnes)	VCM Low (USD $5/t)	VCM High (USD $15/t)	India GCP (₹650/t)
1	*Gmelina arborea (Gamhar)*	33.0350	$165.18	$495.53	₹21,473
2	*Tectona grandis (Teak)*	10.3597	$51.80	$155.40	₹6,734
3	*Dalbergia sissoo (Shisham)*	6.1357	$30.68	$92.04	₹3,988
4	*Swietenia macrophylla (Mahogany)*	3.0165	$15.08	$45.25	₹1,961
5	*Mangifera indica (Mango)*	3.4797	$17.40	$52.20	₹2,262
6	*Emblica officinalis (Amla)*	0.0781	$0.39	$1.17	₹51
7	*Psidium guajava (Guava)*	0.0810	$0.41	$1.22	₹53
Total		**56.1857**	**USD $280.93**	**USD $842.79**	**₹36,521**

3.4 Cross-Site Comparative Analysis — ANGADA vs BUDMU

A structured comparative analysis across sites is presented in Table 5. BUDMU's total carbon stock (15.3220 tonnes) exceeded ANGADA's (5.9209 tonnes) by a factor of 2.59, and this differential was conserved in CO_2e and carbon credit terms owing to the linear nature of the IPCC conversion.

Table 5
Cross-site comparative summary of carbon stock, CO_2 mitigation potential, and green economy valuation — ANGADA vs BUDMU. CO_2e computed using IPCC Tier-1 factor (3.667) [22]. VCM pricing [23]; GCP from MoEFCC [25]

Parameter	ANGADA	BUDMU	Key Observation
No. of Species	1	7	BUDMU: 7× more diverse
Total Trees	500	652	BUDMU: +30.4%
Total C Stock (tonnes)	5.9209	15.3220	BUDMU: 2.59× higher
Total CO_2e (tonnes)	21.7121	56.1857	BUDMU: 2.59× higher
CO_2e per tree (kg)	43.42	86.17	BUDMU nearly 2× more efficient
VCM Credits Low (USD)	$108.56	$280.93	BUDMU: 2.59× higher value
VCM Credits High (USD)	$325.68	$842.79	BUDMU: 2.59× higher value
India GCP (₹)	14,113	36,521	BUDMU: +₹22,408 more
Teak per-tree C (kg)	11.84	12.28	Mixed stand slightly higher individual Teak C
Plantation type	Monoculture	Polyculture (7 spp.)	Structural contrast drives C differential

The per-tree CO_2e at BUDMU (86.17 kg/tree) was nearly twice that of ANGADA (43.42 kg/tree), confirming that species diversity, rather than stem density alone, is the primary driver of carbon sequestration efficiency. A species-controlled comparison of the Teak populations revealed that per-tree Teak carbon density was marginally higher at BUDMU (12.28 kg/tree) than at ANGADA (11.84 kg/tree), suggesting a facilitative effect of the mixed stand — possibly attributable to inter-specific niche complementarity, reduced intraspecific competition, and potential nitrogen enrichment from the leguminous *Dalbergia sissoo* [11, 13, 14].

3.5 Component-wise Biomass Carbon Distribution

In the BUDMU polyculture, the stem compartment was the dominant carbon pool (overall: 69.91% stem, 20.63% root, 9.03% branch, 0.40% leaf), establishing stem > root > branch > leaf as the default pattern. This was confirmed in *Tectona grandis* (68.61% stem), *Gmelina arborea* (78.71%), and *Psidium guajava* (77.83%). Notable departures were recorded in *Dalbergia sissoo* and *Mangifera indica* (stem > branch > root > leaf). Most significantly, *Swietenia macrophylla* (40.27% branch) and *Emblica officinalis* (41.90% branch) exhibited a branch > stem > root > leaf pattern, consistent with the high architectural branching characteristic of these species at this growth stage [29, 30]. At ANGADA, the Teak monoculture followed stem > root > branch > leaf (stem: 64%, root: 21%, branch: 15%, leaf: 1%), consistent with patterns reported by Sreejesh et al. [26].

4 Discussion

4.1 Polyculture vs Monoculture: Carbon Storage and Climate Mitigation

The 2.59-fold higher carbon stock at BUDMU relative to ANGADA constitutes strong empirical evidence for the carbon sequestration advantage of polyculture plantations in the semi-humid tropical Indian context. This finding is consistent with the broader literature: Smith [10], Burkhart and Tham [11], and Wormald [13] demonstrated higher productivity in mixed tropical plantations; Richards et al. [31] attributed this to nutrient complementarity and improved light interception in diverse canopies; and Zhang et al. [12] confirmed through global meta-analysis that forest productivity increases with species richness. The present study extends this evidence base to private-land social forestry schemes in central India.

The dominance of *Gmelina arborea* in driving BUDMU's carbon stock (58.80%; 9.01 tonnes C) is ecologically noteworthy. *G. arborea* is a pioneer species characterised by rapid early growth, low wood density, and large biomass allocation to stem volume — properties that render it exceptionally efficient as a short-rotation carbon sink [28].

4.2 Teak in Monoculture versus Mixed Stand: Facilitation and Carbon Density

The marginally higher per-tree carbon density of *Tectona grandis* at BUDMU (12.28 kg/tree) relative to ANGADA (11.84 kg/tree) is consistent with the concept of inter-specific facilitation in mixed stands. Wormald [13] documented that Teak grows well with *Dalbergia sissoo* in India and with *Gmelina arborea* in Thailand. The co-occurrence of nitrogen-fixing *Dalbergia sissoo* in BUDMU may improve soil nitrogen availability and thereby enhance individual Teak growth rates [32, 33].

4.3 Carbon Credits and Green Economy Value

The combined carbon credit value of both sites — USD $389.49–$1,168.47 internationally and ₹50,634 domestically under the GCP — while modest at the individual-site scale, establishes a proof of concept for carbon market integration of JVY plantations. Scaled to the scheme's 2021 plantation base (19,424 trees; 190.03 acres), the aggregate climate mitigation value is substantially larger. India's GCP (2023) provides a regulatory mechanism for precisely this kind of private-land carbon accounting [25]. The multi-species composition of BUDMU also creates biodiversity co-benefit value beyond carbon, including potential credit stacking under the Taskforce on Nature-Related Financial Disclosures (TNFD) [34] and the Kunming-Montreal Global Biodiversity Framework [35].

4.4 Implications for Policy and Plantation Design

The results collectively support a policy recommendation for biodiversity-enriched plantation design within JVY and analogous social forestry schemes. Incorporating a dominant fast-growing carbon sink species (*Gmelina arborea*) alongside nitrogen-fixing timber trees (*Dalbergia sissoo*) and economically productive fruit trees can optimise both carbon sequestration and livelihood outcomes simultaneously, consistent with the agroforestry systems literature [36–38] and India's National Agroforestry Policy (2014).

5 Conclusion

This study presents the first integrated assessment of biomass carbon storage, atmospheric CO_2 mitigation potential, and carbon credit value for plantations established under the Jan Van Yojna social forestry scheme in Jharkhand, India. The findings demonstrate unequivocally that polyculture plantation (BUDMU, 7 species, 15.32 tonnes C, 56.19 tonnes CO_2e) stored 2.59 times more carbon than the equivalent monoculture plantation (ANGADA, 1 species, 5.92 tonnes C, 21.71 tonnes CO_2e), driven principally by the inclusion of *Gmelina arborea*. The IPCC Tier-1 CO_2e conversion and multi-scenario carbon credit valuation (USD $280.93–$842.79 for BUDMU; USD $108.56–$325.68 for ANGADA; combined ₹50,634 under India's GCP 2023) establish that JVY plantation sites generate quantifiable, monetisable climate mitigation value. These findings have direct implications for JVY plantation design optimisation, REDD+ baseline development, Jharkhand's SAPCC, and India's emerging Green Credit Programme. The study demonstrates that community private-land forestry schemes, if designed with species diversity in mind, can function as meaningful climate mitigation instruments while delivering livelihood and biodiversity co-benefits in the semi-humid tropical landscape of peninsular India.

Declarations

Funding: The authors declare that no external funding was received for this study. Laboratory facilities were provided by the University Department of Botany, Ranchi University, and the Department of Agriculture, Government of Jharkhand.

Ethics and consent to participate: Plant guidelines: This study complied fully with national and local botanical guidelines of India. All plant species were identified and recorded using their accepted botanical (scientific) names. The plants/trees studied were planted by beneficiaries under the Social Forestry (Jan Van Yojana) Scheme of the Government of Jharkhand. These were plantation/cropped trees and not wild-collected specimens. Permissions: For the entire study, no plant or plant parts were collected or cultivated; all research was conducted on planted trees under the Social Forestry Scheme using only non-destructive measurements and minimally invasive wood core sampling with a Pressler increment borer. Accordingly, no specimen collection permit or licence was required. Identification of plant species: All plant species were identified by the first author (Md Shahzad Ahmad), who holds a postgraduate degree in Botany All plant species were identified by the first author, Md. Shahzad Ahmad, who holds a postgraduate degree in Botany, under the guidance of Dr. Uma Shanker Singh, Forester and Climate Change Scientist. Species identification was performed using the taxonomic reference "Flora of the Botany of Bihar and Orissa" by H. H. Haines (1921). The botanical author abbreviations used in this manuscript follow standard conventions: L. = Linnaeus; L.f. = Linnaeus filius (Linnaeus the son); Roxb. =

William Roxburgh; Roxb. ex Sm. = described by Roxburgh but published by James Edward Smith (valid botanical name); Roxb. ex DC. = named by Roxburgh and published by Augustin Pyramus de Candolle; King = George King (described and validated the species). Herbarium and voucher specimens: Since the plants and plant parts were not collected as specimens (all trees are cultivated plantations, not wild collections), deposition of herbarium and voucher specimens are not applicable to this research. This study did not involve human subjects or their personal data. All tree measurements were conducted on privately owned plantation land with the consent of the respective landowners (beneficiaries of the Jan Van Yojna Scheme).

Competing interests: The authors declare no competing interests.

Author contributions: Md Shahzad Ahmad: field data collection, biomass carbon estimation, data analysis. Uma Shanker Singh: study design, technical supervision, methodology review. Naiyar Naaz: study conception, manuscript preparation, corresponding author.

Data availability: The datasets generated and analysed during this study are available from the first author upon reasonable request.

Acknowledgements: The authors thank the Department of Forest, Environment and Climate Change, Government of Jharkhand, and the NIC Ranchi for providing access to Jan Van Yojna plantation records. The authors are grateful to the beneficiaries Ratan Prakash Singh (BUDMU) and Rama Kant Sahi (ANGADA) for their cooperation during field surveys.

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