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RESEARCH ARTICLE

Sustainability index for bamboo utilization: a framework for balancing conservation and livelihood needs

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Abstract: Bamboo is a vital natural resource that helps keep the environment healthy and support rural living. Its long-term sustainability however, is becoming unclear due to shifting land-use patterns and market conditions. Base on field surveys and spatial analysis this study develops the Sustainability Index for Bamboo Utilization (SIB) to quantity the environmental, economic, and social aspects of bamboo utilisation in Karbi Anglong district, Assam, India. The index was built using household surveys (n=500), plot-based bamboo inventories, and remote sensing derived land use and land cover data. The indicators reflecting the three sustainability extents were aggregated into composite scores through assessments by respondent on a five-point Likert scale. The results indicate that a composite SIB score of 3.4 suggests that the use of bamboo in the district can be considered as sustainable. The social sustainability indicator scored the highest (3.9), reflecting that bamboo has served well across cultures, in constructions, and community resilience. Bamboo's soil, water, and carbon functions were reflected in its moderate environmental sustainability (3.4), which was countered by the loss of forests and the decline in biodiversity brought on by plantation expansion. The weakest dimension was economic sustainability (2.9), largely due to the decline in industrial demand following the closer of the Jagiroad/ Nagaon Paper Mill, unstable market conditions, and a lack of value addition within the bamboo value chains.

Keywords: Environmental indicators, spatial analysis, household income, resource management framework

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Introduction

Bamboo is well known as one of the most versatile plant resources used by rural communities worldwide. Being a grass plant (Poaceae), it grows fast, can regenerate itself, and thus is a valuable resource for any tropical and sub-tropical ecosystems. Worldwide, bamboo covers over 30 million hectares of forest and a significant contribution to rural economies, in Asia, Africa, and Latin America (Lobovikov *et al*., 2007; van der Lugt and King, 2019). Beyond the ecological benefits that bamboo supports, it sustains a broad spectrum of economic endeavours such as construction, handicrafts, furniture production, and emerging bio-economy usage. Socially, bamboo offers opportunities to create socio-ecological values as it rooted in cultural traditions, community practices, and sustenance systems.

Bamboo plays a significant role in daily life and the rural production structure in Northeast India. Most of the families rely on housing materials, farming equipment, handicrafts, and additional earnings. Despite its significance, the sustainability of bamboo utilisation (consumption and production) is threatened. The pace of land-use alteration,

uncontrolled harvesting, market efficiencies, and the lack of suitable processing technologies continue to affect both ecological balance and the long-term advantages of bamboo resources (Lobovikov *et al*., 2007; Nath *et al*., 2009; FAO, 2010). At the same time, the reliance of rural households on bamboo often results in uneven incomes and limited access to markets, raising questions about the socio-economic sustainability of bamboo-based livelihoods.

Most of the literature reviewed focuses on the ecological roles of bamboos, their economic value. The majority of studies however tend to describe individual aspects such as production, trade, or ecological services. Consequently, the broader sustainability of the bamboo utilisation system is rarely evaluated holistically. Evaluating sustainability requires consideration of environmental conditions, economic viability, and social dependence simultanesously. One element that help solve these problems is the use of a composite index approach in which various indicators are integrated into a single analytical framework.

The present study fills this gap by creating a Sustainability Index for Bamboo Utilisation (SIB). The index combines environmental, economic, and social indicators to evaluate the sustainability of bamboo use in a more holistic way. The framework is used in Karbi Anglong district, Assam, where bamboo resources are abundant, and livelihoods reliant on the bamboo-are high. The data for the analysis were obtained through household surveys, field observations, and secondary sources. The main objectives are to:

1. Develop and operationalise the SIB framework

2. Evaluate sustainability performance across the three dimensions.

Materials & methods

Study area

The study was carried out in Karbi Anglong district, Assam, Northeast India (Fig 1). Karbi Anglong covers an uneven central–southern area of Assam consisting of ridges, valleys, and riverine plains; the diverse topography supports a variety of forest types and agro-ecosystems contributing the extensive occurrence of bamboo in the district (Karbi Anglong District, n.d). The richness of bamboo species and the value of bamboo to local above ground biomass and soil organic pools are high in natural forested stands, managed homestead and private plantations within district (Singnar, 2019; Singnar *et al*., 2023). Forest products such as bamboo culms and bamboo shoots are very important to rural households for housing, storage, handicrafts and seasonal incomes, making bamboo a key part of household livelihood plans and local material culture (Nath *et al*., 2009). For these reasons, the sampling sites were selected in reserve forests, district council reserved forests (DCRF), and on private lands and homesteads to capture the full range of bamboo occurrence, management practices and socio-ecological functions of Karbi Anglong.

Environmental Indicator used in the study

The environmental aspect of the Sustainability Index of Bamboo Utilisation (SIB) was designed to indicate the availability of bamboo resources and their ecological productivity. To capture these aspects, the study employed an indicator reflecting the spatial distribution of bamboo and density of bamboo stand in the field. These indicators were based on two primary sources: multi-temporal land use/land cover (LULC) mapping and field-based measurement of bamboo stock. Integration of these datasets enabled the incorporation of the spatial extend of bamboo resources and their productivity capacity into the environmental evaluation.

Multi-temporal Land Use/Land Cover (LULC) Change Analysis

Preparation of land-use land cover (LULC) maps for the study area in 1993 and 2023/24 using remote sensing and GIS was conducted to investigate long-term changes in land use. In the case of 1993, the classification was made on medium-resolution images. Due to the spectral limits used in the previous dataset, bamboo was not identified as a distinct category and was thus lumped into the larger forest category.

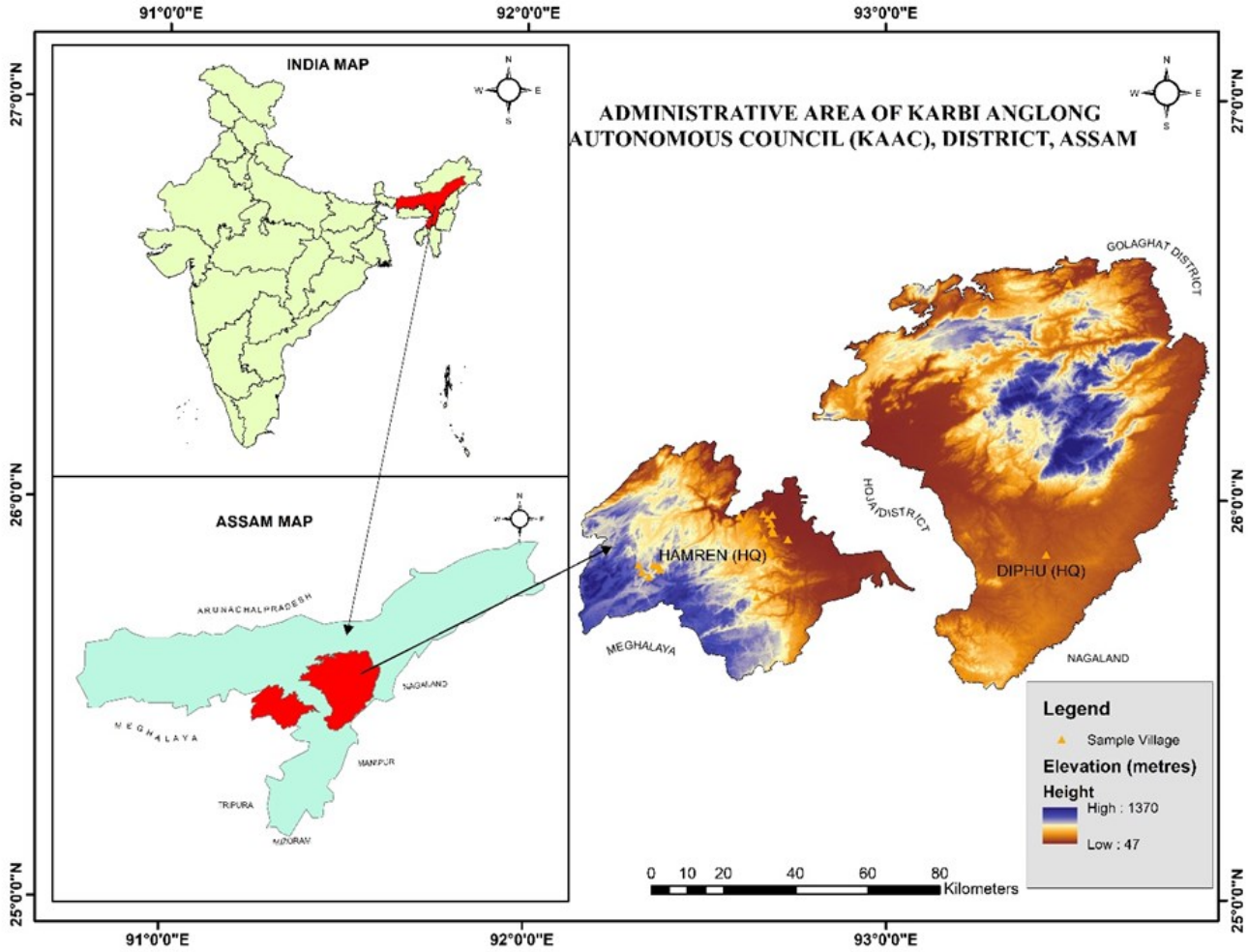

Fig 1. Showing the location Map of the Study area

On the contrary, the 2023/24 classification was based on higher-resolution images and enabled bamboo-dominated areas to be classified as an independent land-cover category. The two periods can be compared to give two helpful perspectives. First, it demonstrates the general changes that have occurred since 1993, such as the reduction of natural forest areas and the expansion of agriculture, plantations, and built-up land. Second, the new classification displays the current spatial distribution of bamboo-dominated landscapes in the district.

Spectral vegetation indices were used to enhance differentiation between vegetation classes, such as the Normalised Difference Vegetation Index (NDVI) and related measures (Rouse *et al*., 1973). The Random Forest (RF) algorithm was then used for supervised classification and has been widely used in landcover mapping in heterogeneous environments (Breiman, 2001).

Accuracy Assessment

The accuracy of the Land use/Land cover (LULC) classification was evaluated using an accuracy assessment following the standard methodology outlined by Congalton (1991) and Olofsson *et al*. (2014). Field survey data were used as ground truth for validation. A confusion matrix was prepared to compare the classified land cover categories with the reference points. According to this matrix, the total classification accuracy of 93.75% and the Kappa value of 0.87 indicate a strong degree of agreement between the classified map and the reference data, as recommended by Landis and Koch (1977). These outcomes confirm that the bamboo land cover class is sufficient to proceed with the spatial analysis.

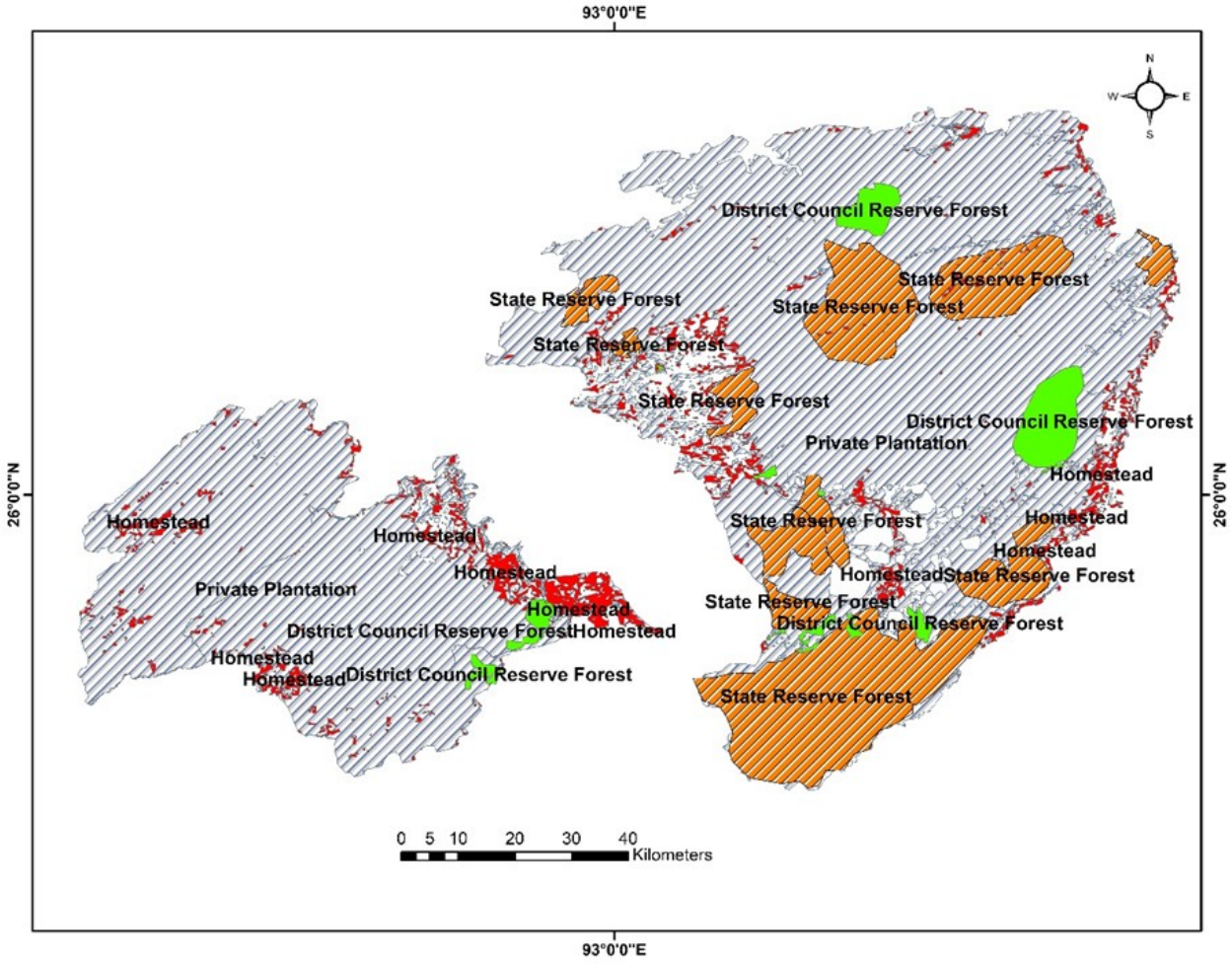

Fig 2. Sampling boundaries in the study area: State Reserved Forests (SRF), District Council Reserved Forests (DCRF), Homesteads, and Private lands. Source: Authors' analysis (2023–2024).

Field Sampling of Bamboo

To capture the ecological and land-use variability in the district, the study area was further divided into four broad categories: State Reserved Forests (SRF), District Council Reserved Forests (DCRF), homesteads, and private Lands (Fig 2). This stratification was carried out using remote sensing (RS) and Geographical Information Systems (GIS) analysis, which helped determine the spatial distribution of bamboo across various landscape units. The distribution of bamboo under these strata is shown in Fig 2. This stratified random sampling design was adopted to ensure that all land uses were fairly represented in the field survey. Standard circular/rectangular sample plots were placed in every stratum to record the characteristics of bamboo. A number of attributes of bamboo stands were measured during the field survey. The following measurements were recorded.

1. *Culm density (culms/ha):* Culm density (culms/ha): The quantity of bamboo culms found in each sample plot, subsequently converted into an estimation per hectares

2. *Clump density (clumps/ha):* The quantity of clumps in each plot, expressed in hectares.

3. *Bamboo area (ha):* Bamboo area (ha): based on LULC classification, the area of bamboo-dominated patches

4. *Estimated stock (culms):* Determined by multiplying the bamboo area for each stratum by the mean culm density.

The stock estimates derived from the sample plots were summed across strata to produce district-level

estimates of bamboo availability. The sample size was determined according to the principles of standard sampling theory as outlined by Cochran (1977). Moreover, allometric associations were used within the region to convert culm counts into biomass and carbon storage estimates where needed (Nath *et al*., 2009). Based on findings from the LULC analysis, classification accuracy evaluation, and field-based sampling, a list of environmental indicators was derived for the Sustainability Index of Bamboo Utilisation (SIB). These indicators are bamboo stock and regeneration, forest and land-use change, species integrity, soil fertility, water regulation, and carbon sequestration.

Environmental Indicator Framework

To measure the ecological aspect of using bamboo, a series of environmental indicators was designed to carry out the study. The indicators were chosen based on their significance to the ecosystem's functioning. The framework considered for the study is given in Table 1.

Methodology for Economic Indicators

Economic indicators such as household income, employment opportunities, and livelihood stability were taken to measure bamboo contributions in the study area. In Karbi Anglong, bamboo as a natural resource has supported livelihoods and local trade, which is why many households have depended on it for generations and especially choose this dimension to reflect the various ways people are involved in bamboo-related activities. The indicators are shown in Table 2.

Household Survey and Data Collection

The data on economic indicators were collected from a household survey conducted in 2023-2024. Five hundred households were randomly selected from the various strata of the study area to ensure sufficient representation of bamboo-dependent communities. The survey was conducted to record household participation in bamboo-related activities and bamboo-related income. The structured interviews were conducted using a questionnaire

Table 1. Environmental Indicators to evaluate the sustainability of Bamboo Utilisation

Indicator	Description	Implication
Bamboo regeneration and stock of bamboo	Determine the culm density, standing stock per hectare and rate of regeneration	It is imperative that extraction is not exceeding natural growth; this is essential after industrial exploitation
Changes to Land Cover	Maintain observing the dynamics of built-up areas, bamboo, natural forests, and agriculture	This will assist in determining whether the expansive bamboo is affecting landscape deforestation or destabilising it
Diversity of species and ecosystem integrity	Species and wildlife	Demonstrates the ecological trade between mixed natural
Land Productivity and Soil Fertility	Measures nutrient retention, erosion control and organic matter in bamboo regions	Important to the long-term land productivity when jhum or agriculture is substituted by bamboo
Hydological operations and Availability of water	The role of bamboo in regulating ground water and stream flows	Historically, it has been established that bamboo woods enhance downstream water flow in agriculture
Carbon and Climate Regulation	Bamboo will capture carbon and greenhouse gas emissions.	Recognize bamboo as a fast-growing carbon sink that may be used in the adaptation of climate change

Table 2. Economic Indicators to evaluate the sustainability of Bamboo Utilisation

Indicator	Description	Implication
Household income Bamboo sales and products	Share of household income in Bamboo sales and products	The paper mill demands historically important; currently narrowed to the local and regional markets
Market Access and Price Stability	Access to bamboo markets and time variation in price fluctuations	The winding down of the Jagiroad Paper Mill has caused a destabilising effect; singles out the necessity of diversified purchasers
Employment and Labour Opportunities	Follows employment opportunities in the fields of harvesting, transporting, processing, and handicraft production	Offers seasonal and part-time work; this matters to the rural livelihoods
Value Addition and Processing Extent	Bamboo application in processed products (furniture, mats, handicrafts, paper)	Concludes if bamboo can contribute to increased incomes or it will continue to be just a seller of raw materials
Economic Diversification	The degree to which the households depend on bamboo as compared to other crops and income	Diversified to rubber, tea and arecanut in 2017; the contribution of bamboo has become secondary
Livelihood Resilience	The role of the bamboo in the safety nets in the case of shocks (e.g., crop failure, floods)	Even as its cash position reduces, bamboo is an alternative

that incorporated both quantitative (income, volume sold, labour days) and qualitative (perceptions of market access, price stability) issues. The bamboo-related activities considered in the survey are presented in Table 3. The given activities depict the primary channels through which Karbi Anglong households earn income from the bamboo resource

Methodology for Social Indicators

The social factor of the Sustainability Index Bamboo Utilisation (SIB) aimed to evaluate the cultural, institutional, and community values of bamboo in Karbi Anglong. Bamboo in this area has been quite significant for livelihoods, cultural identity, traditional dwellings, and community practices. Data from the indicators were collected using a mixed-methods approach. Household surveys, focus group discussions (FGDs), and key informant interviews with local leaders, artisans, and elders provided further details on the social importance of bamboo. This combination ensured that both the quantitative and qualitative aspects of bamboo's social significance were presented. Table 4 summarises the selected indicators and gives information about their contextual relevance

Construction of the Sustainability Index for Bamboo Utilisation (SIB)

The Sustainability Index of Bamboo Utilisation (SIB) was constructed as a composite index to assess the sustainability of bamboo utilisation in Karbi Anglong. The index integrates measures in the three dimensions, environmental, economic, and social, to give a comprehensive evaluation of the role of bamboo in the ecological stability, livelihood security and cultural resilience. The choice of indicators was based on the existing frameworks, one of which was the Global Forest Resources Assessment (FRA) criteria and indicators by the Food and Agriculture Organisation (FAO, 2010). The supply-chain and socio-economic studies by the International Bamboo and Rattan Organisation (van der Lugt and King, 2019) and the wider methodological principles of composite

Table 3. Economic Indicators of Household Participation and Income Distribution

Activity	Households (n=500)	% of HH	Average annual Income (₹)
Sale of culms	43	11.1	10,000 -15,000
Handicraft sales	94	24.3	5,000 - 10,000
Bamboo shoot sales	68	17.6	3,000 - 6,000
Bamboo trading (middlemen)	42	10.9	15,000 - 20,000
Industrial wage labour	140	36.2	12,000 - 18,000

Table 4. Social Indicators to evaluate the Bamboo Utilisation sustainability

Indicator	Description	Implication
Cultural Identity and Practices	Bamboo goes hand in hand with rituals festival, and the daily traditional practices in Karbi community	Despite increasing land use change towards commercial crops, Karbi community continue to be a cultural favourite
Housing and Shelter Security	Bamboo in rural housing, fencing and grain storage buildings in villages	It is an affordable building material to much of the low-income population; it is still relevant in terms of shelter and grain storage
Equity and Access to Resources	The access of the bamboo resources by various households, including the poorer, and marginalised groups	Bamboo is usually available and, in many cases, it is distributed informally in communities which would minimise inequality
Community resilience	Bamboos as a form of emergency material in times of disaster like floods, crop failure	Due to its presence and multifunctional use, the bamboo is a practical support resource resource to rural household in times of disaster.
Knowledge and Skill Transformation	Traditional knowledge in regard to bamboo crafts, handicrafts and local techniques	The practice assists in sustaining native skills, as well as generate livelihood opportunities, to youth and women artisan.
Social Cohesion and Cooperation	Management and use of bamboo resources in village landscape	The use of bamboo is frequently controlled by the institutions and traditional practices within a community, which enhances the cooperation between families

sustainability indices and indicator-based structures (Rigby *et al*., 2001; OECD, 2008; Mayer, 2008; Singh *et al*., 2012). Besides, local empirical studies of bamboo biomass and ecological processes provided essential background in the development of indicators (Nath *et al*., 2009; Singnar *et al*., 2023).

In operationalising the SIB, 500 respondents from the household surveys were pooled, along with field-based measurements and secondary data. Every household respondent was requested to rank and assess the sustainability and importance of the chosen indicators on a five-point scale. Likert scale (Table 5). This participatory score meant that the index indicated both scientific community perceptions and assessment. The Likert scale was formulated as follows:

Table 5. Sustainability Interpretation of Likert Scale Scores

Score	Interpretation
1	Highly unsustainable
2	Unsustainable
3	Fairly sustainable
4	Sustainable
5	Highly sustainable

Source: Adapted from Likert (1932) and Artino (2013)

Note. The sustainability scores in the current study were based on the composite Sustainability Index on Bamboo Utilisation developed for the study. The Index values were scaled and grouped into five categories to facilitate easier interpretation. Mean values for each indicator were then converted into weights, which in turn enabled the relative significance of environmental, economic and social aspects of utilising bamboo to be represented in the final index.

The Sustainability Index was calculated using the following formula

$$SIB \frac{wE \times E + wEc \times Ec + wS \times S}{wE + wEc + wS}$$

Where,

SIB = Sustainability Index for Bamboo Utilisation

E = Environmental Sustainability Score

Ec = Economic Sustainability Score

S = Social Sustainability Score

wE, wEc,wS = represent the weight assigned to the environmental, economic and social components of the Sustainability Index for Bamboo Utilisation.

The Fig 3 illustrates the order of steps used to build the sustainability index. In the household survey, respondents rated each indicator on a scale of 1-5, and the results were later converted into weights to reflect the relative importance of the individual dimensions.

Results of the Sustainability Index for Bamboo Utilisation (SIB)

Environmental Sustainability Scores: Land Use/ Land cover (LULC) analysis for 1993, 2014, and 2023-24 shows major changes in the Karbi Anglong landscape (Fig 4, 5 and 6). The forest cover was reduced by 58, 663 hectares between 1993 and 2014. In the meantime, the jhum area and built-up area declined by 194,796 ha and increased by 6,103 ha, respectively (Table 6). The 2014 classification was also the first instance in which bamboo was declared a distinct land-cover group, comprising 257,954.65 ha, constituting 24.76 per cent of the district's area. According to the latest classification (2023-2024), bamboo still occupies a significant portion of the district, covering 258243 ha (24.75%). Nonetheless, other categories of land use have increased over the last few years. The area under rubber plantations has already expanded to 138,940 ha (13.31%), and tea and arecanut plantations cover 99,361 ha (9.52%). The area of built-up land has also grown to 150,561 ha (14.42 per cent). Agriculture currently occupies 108,095 ha (10.36 per cent), and water bodies have decreased by approximately 6,790 ha (0.65 per cent). The picture shows a transition from mixed-forest-jhum to permanent plantation (Arecanut/rubber/tea) and settlement, but bamboo maintains its present range, though it is difficult, as the communities opted for more economical plantations

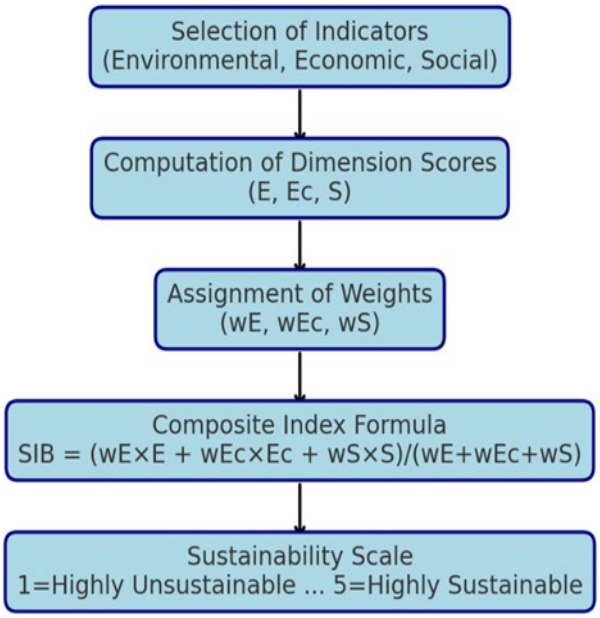

Fig 3. Workflow for Developing the Bamboo Sustainability Index (SIB)

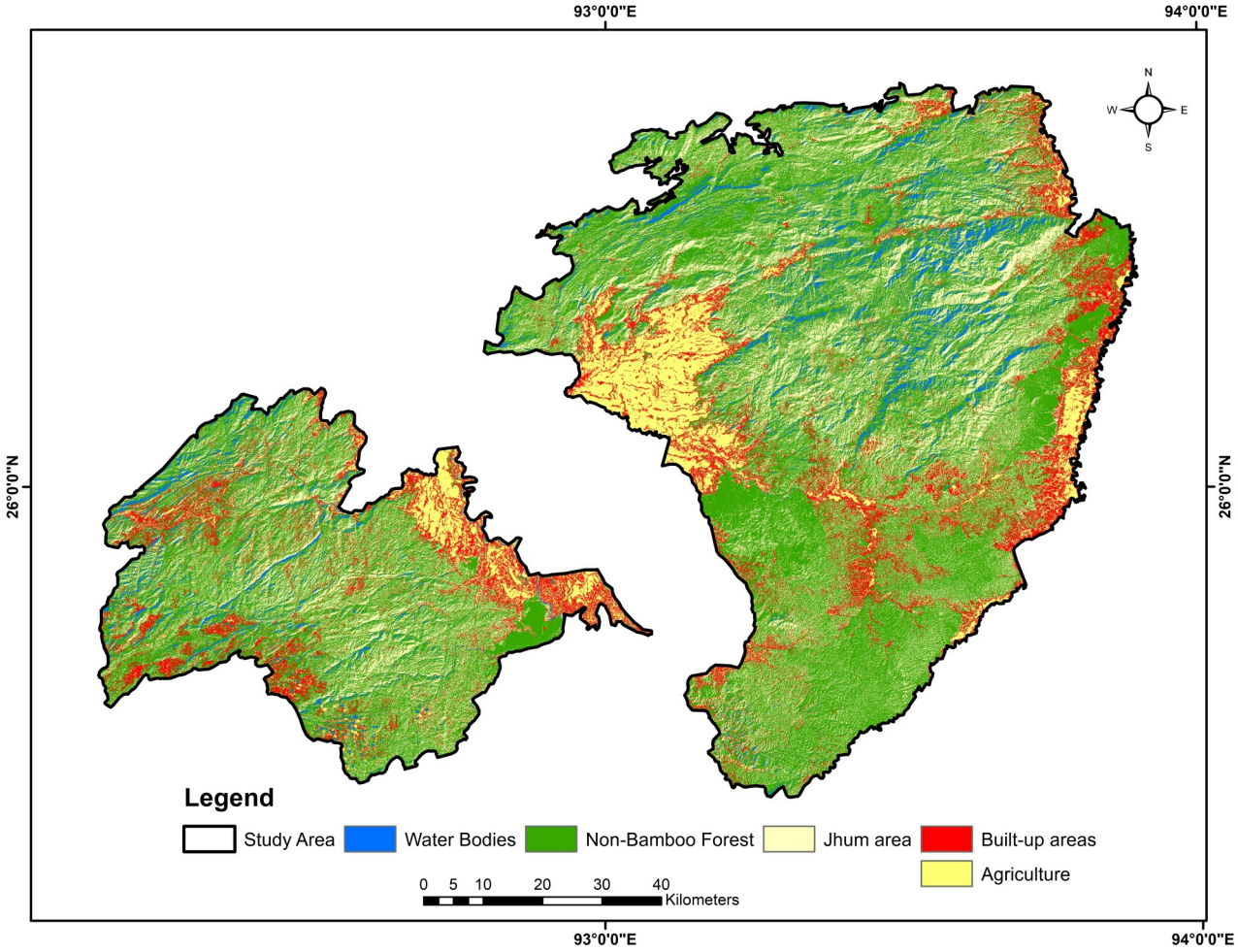

Fig 4. Land use and Land cover pattern of the study area, 1993

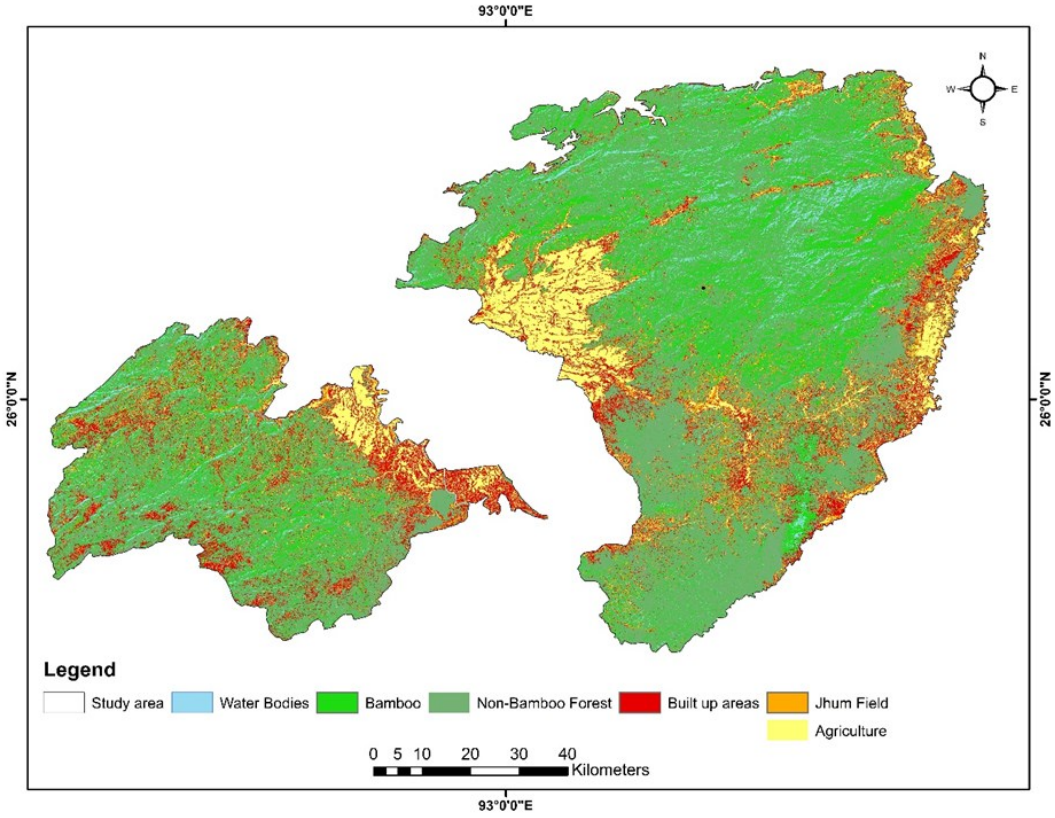

Fig 5. Land use and Land cover pattern of the study area, 2014

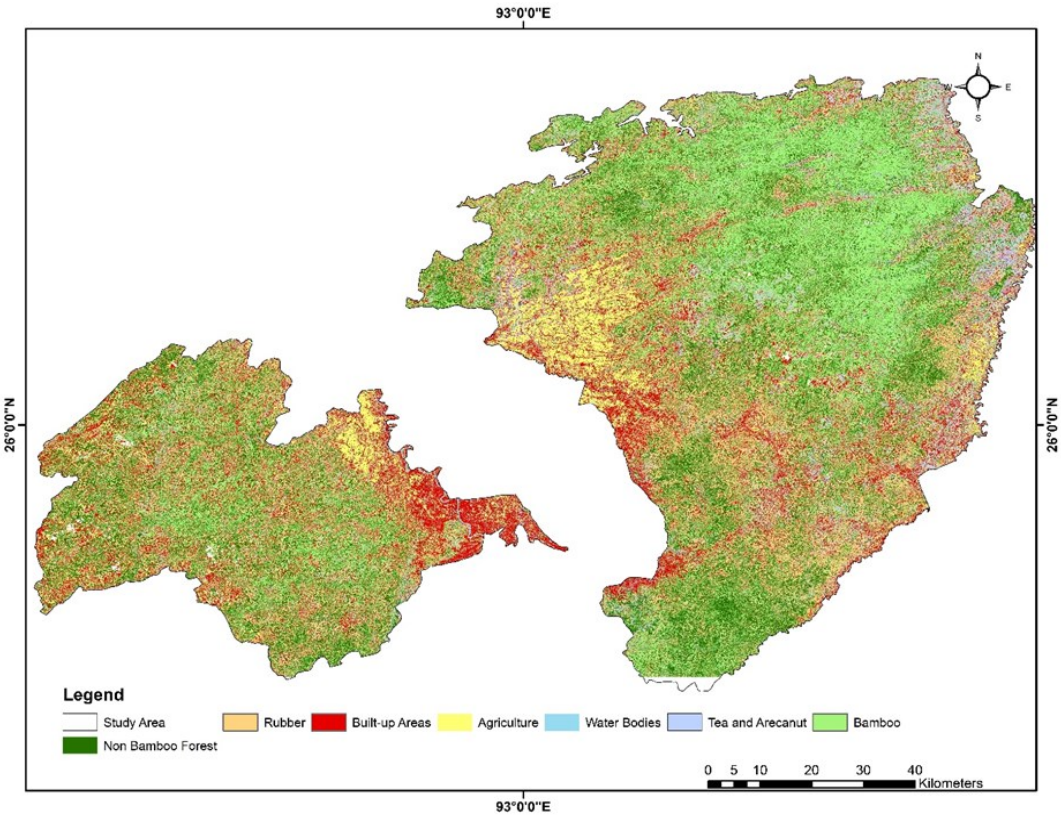

Fig 6. Land use and Land cover pattern of the study area, 2024

Table 6. Land Use/Land Cover of Karbi Anglong, 1993-2024 (Area in hectares)

Category	1993		2014		2024	
	Area (ha)	%	Area (ha)	%	Area (ha)	%
Water Bodies	49319.1	4.73	47,739.60	4.58	6,790.00	0.65
Non-bamboo forest	510688	49.02	4,52,025.00	43.38	2,81,438.00	26.97
Jhum area	2,70,777.00	25.99	75,980.30	7.29	—	—
Built-up areas	1,22,058.50	11.72	1,28,161.40	12.3	1,50,561.00	14.42
Agriculture	89,051.40	8.55	80,033.10	7.68	1,08,095.00	10.36
Bamboo	—		2,57,954.60	24.76	2,58,243.00	24.75
Rubber	—				1,38,940.00	13.31
Tea and Arecanut	—				99,361.10	9.52

Note: The wide spatial distribution among the various land-use strata was included in the bamboo assessment of stocks (Table 7). The dominant share of bamboo area (26.06%) and culm stock (44.27%) is on private land. The state reserve forests (SRF) occupy a large area of bamboo (63.15%) and have a very high culm density, accounting for over 42 per cent of the total bamboo stock. Homestead bamboo, on the other hand, which covers a smaller land area of 4.81 per cent of the total bamboo land, exhibits the greatest culm density (67,805 culms/ha).

The LULC category are classified in the following way:

Water Bodies: Areas that are covered by surface water as rivers, streams, ponds, and reservoir.

Forest: Areas covered by tree species. This category of 1993 has bamboo and in 2014 and 2024 classification, it represents non-bamboo forest.

Jhum area: fallows and active stage of shifting cultivation practices that are slash and burn.

Built-up areas: Settlement and infrastructures such as roads, and other human-made construction.

Agriculture: Crop land area which consists of seasonal and permanent farmlands.

Bamboo: Regions characterized by the presence of bamboo species which are either naturally present or planted.

Rubber: Plantation areas are primarily consisting of rubber trees

Tea and arecanut: Plantation areas dominated by tea and arecanut (betel nut) cultivation

The environmental sustainability results show that Bamboo Stock and Regeneration (4.0), Soil Fertility and Productivity (3.7), and Water Availability Functions (3.9) received high ratings for bamboo use (Table 8). These scores underscore the significant role of bamboo in activities such as erosion management, soil conservation, and the control of hydrological processes. Carbon sequestration achieved an average score (3.5), indicating that bamboo has

significant potential for storing carbon, but its use in the context of a larger landscape is not fully utilised. Of all the indicators, forest cover and land use change (2.5) and species diversity and integrity (2.8) got the lowest values. Such lower scores indicate rising ecological pressure linked to deforestation, land conversion, and the expansion of monoculture plantations.

Table 7. Bamboo Stock in Karbi Anglong by Stratum

Strata	Total Area (ha)	Bamboo Area (ha)	Culm Density (culms/ha)	Estimated Stock (culms)	Bamboo Area (%)	Stock Contribution (%)
SRF	83,554	52,760	15,607	823,450,000	63.15	42.26
DCRF	27,184	8,229	11,831	97,366,547	30.27	5.00
Homestead	50,701	2,437	67,805	165,279,693	4.81	8.48
Private	736,672	191,996	4,493	862,635,628	26.06	44.27
Total	898,111	255,424	—	1,948,731,868	28.43	100

Table 8. Environmental Sustainability Scores of Bamboo Utilisation in Karbi Anglong

Indicator	Mean Score	Interpretation
Bamboo Stock and Regeneration	4.0	Sustainable - good regeneration capacity
Forest Cover and Land Use Change	2.5	Unsustainable - declining natural forest
Species Diversity and Integrity	2.8	Fairly sustainable - reduced under monocultures
Soil Fertility and Productivity	3.7	Sustainable - supports erosion control
Water Availability Functions	3.9	Sustainable - regulates springs and streams
Carbon Sequestration	3.5	Fairly sustainable - strong potential but underused

Economic Sustainability Scores

The results of Economic sustainability indicate moderate. Bamboo continues to play a role in household security and resilience in livelihood with a score of 3.5-3.8 (Table 9). Its role as a reliable and stable source of income, however, seems to have been undermined, as indicated in the low scores between 2.3 and 3.0. The results indicate that bamboo remains a small yet additional source of income for most households through handicrafts, edible bamboo shoots (fresh and fermented), and

small-scale trade. Nevertheless, with the closure of the Jagiroad/Nagaon Paper Mill in 2017, industrial demand for bamboo dropped significantly, thereby affecting market accessibility and price stability. The jobs associated with bamboo have now been reduced to seasonal harvesting and informal handicraft production. The availability of value addition is also limited due to the lack of proper infrastructure for processing and marketing in the area. Alongside this, the proliferation of rubber, tea and arecanut plantations has minimised households' reliance on bamboo as the primary economic source.

Table 9. Economic Sustainability Scores of Bamboo Utilization in Karbi Anglong

Indicator	Mean Score	Interpretation
Household Income from Bamboo	3.0	Fairly sustainable, supplementary, but declining share
Market Access and Price Stability	2.5	Unsustainable, unstable demand post-mill closure
Employment and Labour Opportunities	2.8	Fairly sustainable, seasonal/part-time only
Value Addition and Processing	2.3	Unsustainable, limited infrastructure for processing
Economic Diversification	3.8	Sustainable, alternative cash crops reducing vulnerability
Livelihood Resilience	3.5	Fairly sustainable, bamboo as fallback during shocks

Social Sustainability Scores

The social sustainability score ranged from 3.0 to 4.5, indicating a moderate to high level of sustainability across the selected indicators (Table 10). The social sustainability aspect measures how bamboo supports cultural identity, community resilience, equitable access, and the transfer of traditional knowledge. According to respondents in the household survey, bamboo is closely tied to the lives of local communities. A large number of respondents observed that bamboo continued to play a significant role in social and cultural uses (rituals, festivals), temporary buildings (rice grains, stores), and emergency utilisation. There are also high ratings on equity of access, as bamboo resources can continue to be made available to poorer and wealthier households in the area. Among all the indicators, social, knowledge, and skills transmission received the lowest scores, indicating that the younger generation is not keen on learning and adopting bamboo-based skills.

Sustainability Index for Bamboo Utilization (SIB)

The total SIB score of 3.4 indicates that the overall use of bamboo in Karbi Anglong is quite sustainable. It revealed that the social aspect of bamboo sustainability is stronger compared to the environmental and economic aspects (Table 11).

The level of environmental sustainability shows moderate performance scores due to bamboo's ecological advantages, such as erosion prevention and water management, while also considering the pressures associated with deforestation and biodiversity loss. Conversely, its economic sustainability is the weakest dimension, indicating susceptibility to dwindling industrial demand and the diversification of bamboo markets. These data suggest that future management strategies should emphasise reinforcing the economic value of bamboo and safeguarding its ecological processes and social significance in the area (Fig 7).

The radar chart shows the relative performance of three sustainability dimensions, including environmental, economic and social. Social sustainability scored highest (3.9), followed closely by environmental sustainability (3.4) and, lastly, by economic sustainability (2.9).

Table 10. Social Sustainability Scores of Bamboo Utilization in Karbi Anglong

Indicator	Mean Score	Interpretation
Cultural Identity and Practices	4.5	Highly sustainable, strong role in rituals/festivals
Housing and Shelter Security	4.2	Sustainable, widely used for housing and storage
Equity and Access to Resources	4.0	Sustainable, accessible to all households
Community Resilience	3.8	Sustainable, fallback material in crises
Knowledge and Skills Transmission	3.0	Fairly sustainable, younger generations disengaging
Social Cohesion and Cooperation	3.2	Fairly sustainable, declining collective management

Table 11. Composite Bamboo Sustainability Index (SIB) in Karbi Anglong

Dimension	Mean Score	Interpretation
Environmental	3.4	Fairly sustainable - benefits offset by forest loss
Economic	2.9	Fairly unsustainable - weakened after mill closure
Social	3.9	Sustainable - strong cultural and social role
Composite SIB	3.4	Fairly sustainable overall

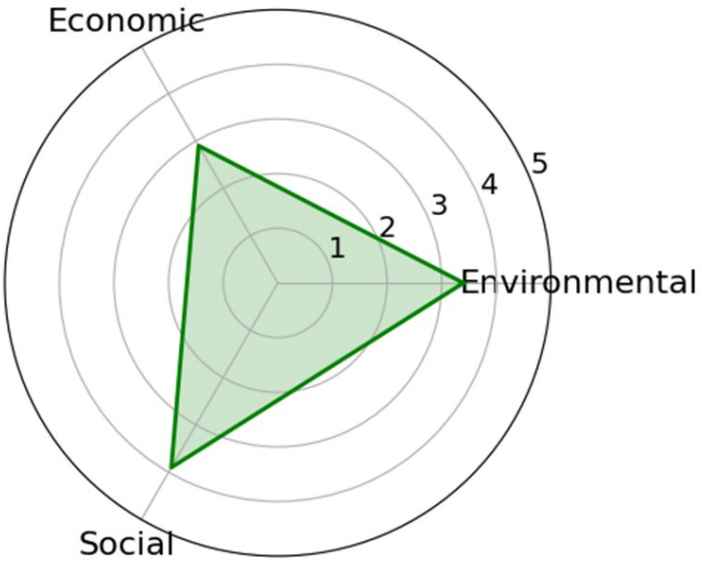

Fig 7. Radar chart of the environmental, economic, and social aspects of the Bamboo Sustainability Index (SIB) in Karbi Anglong

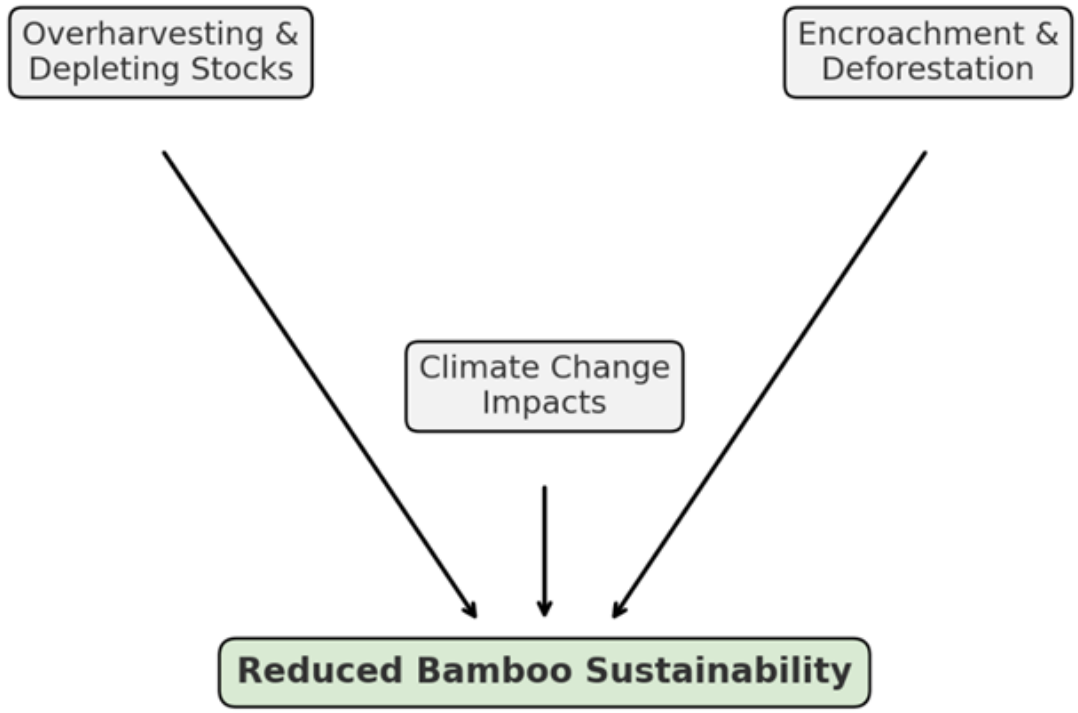

Fig 8. Conceptual diagram showing the major challenges affecting bamboo sustainability in Karbi-Anglong

Discussion

Despite bamboo's ecological resilience and strong cultural presence in Karbi Anglong, it faces long-term sustainability challenges that are both persistent and emerging. The outcomes of the Sustainability Index of Bamboo (SIB), along with the latest land-use change forecast of 2023-24, show observable disproportions at the ecological, economic, and social levels. The bamboo still remains socially and culturally significant to the local communities. This is, however, under pressure from overharvesting, deforestation, and climate change, which are beginning to strain its long-term sustainability.

Overharvesting

Among the various pressures identified, overharvesting is one of the greatest threats to bamboo sustainability in Karbi Anglong (Fig 8). The traditional practices of Jhum cultivation by local communities allowed to ensure a balance between the use and regeneration of resources. This began to shift in the middle of the 1980s, as the industrial needs for bamboo began to grow. The creation of the Jagiroad/Nagoan Paper Mill, which relies heavily on bamboo from Karbi Anglong, spurred the large-scale extraction of natural forests and community lands (NDTV, 2021). Simultaneously, the government-assisted expansion of bamboo plantations stimulated monoculture growth, without adequate focus on sustainable harvesting practices.

By the beginning of the 2000s, bamboo-rich areas that had been readily available had long since begun to decline at rates higher than those of natural regeneration. Younger culms were usually cut before they reached maturity, thereby reducing stand productivity and influencing long-term growth potential. Unsustainable harvesting persists even after the paper mill's shutdown, especially for supplying materials for house construction, handicraft production, and small-scale trade.

The SIB results show these pressures, with lower environmental scores for biodiversity and regeneration in areas with lots of plantations. The closer a village was to market hubs, the worse its ecological sustainability was as cutting was more serious. Unless management practices such as rotational harvesting, controlled cutting periods,

and culm maturity are addressed, overharvesting will continue to damage bamboo stocks (Lobovikov *et al*., 2007; Nath *et al*., 2009).

Encroachment and Land-Use Change

The other major issue is the intrusion into forests where bamboo is found, which is directly linked to population growth, settlement expansion, and agricultural adjustments. According to the analysis of land-use changes, forest cover declined drastically from 1993 to 2023/24. Meanwhile, jhum fields were cleared and replaced by rubber, tea, and arecanut fields, which developed in a short time. These developments indicate that communities are changing to embrace new economic opportunities, but it also implies that bamboo -rich habitats are gradually being eliminated.

Shifting cultivation is often the first step in forest encroachment. Once new patches are made into temporary use, the land is eventually settled, and after the mill period, it is increasingly converted into cash-crop plantations. In some cases, private ownership of community bamboo lands has occurred, indicating shifts in land tenure and a decline in communal ownership and management. The peri-urban landscape is further disrupted by built-up areas such as roads, schools and market centres, which replace bamboo forests and further fragment the landscape.

The environmental costs of such deforestation are quite high. These land changes not only have a direct negative impact on bamboo stocks but also damage ecological services such as soil fertility, soil erosion, and hydrology. The mixed-bamboo-forest ecosystems that previously sustained a greater variety of species are being replaced by monoculture plantations, which is detrimental to biodiversity. The SIB's environmental indicators were lowest in areas with extensive encroachment, indicating that unsustainable land-use change is a major cause of ecological vulnerability. This has also occurred in other regions of Northeast India in terms of land use and forest loss (FAO 2010; Nath *et al*., 2018; van der Lugt and King, 2019). The sustainability of bamboo as an ecological entity will continue to suffer unless the forest rules are tightened and the management of the communities is rejuvenated.

Climate Change

In Karbi Anglong, climate change is a novel yet increasingly evident threat to bamboo sustainability. Widespread concerns were revealed through field observations: villagers reported decreased water retention in bamboo landscapes compared with previous decades, altered rainfall timing, and reduced streamflow. Bamboo flowering events, which are frequently associated with stress conditions, have been observed to occur irregularly in some areas, impacting both regeneration and culm quality.

Bamboo is extremely vulnerable to drought stress and low soil moisture, which can result in defoliation, physiological damage, and reduced hydraulic and photosynthetic efficiency, especially when soil water content is below 0.17 m3/m3 (Zhang *et al*., 2019).

Periods of water scarcity can affect hydraulic conductivity and photosynthesis, as shown by experimental studies (Wu *et al*., 2019; Zhang *et al*., 2023). This could worsen the long-term development of bamboo plantations due to a possible decline in the water table in parts of Karbi Anglong (such as Tengkeralangso). With rising temperatures and changing weather patterns, young culms are more prone to pests and fungal attacks.

The effects of climate change on bamboo habitats could be overall unsuitable, leading to shifts in their distribution to new microclimates or elevations and reducing their availability in already growing regions. These developments pose severe threats to communities that depend on bamboo for strength, housing, celebrations, stores, and emergency facilities. Bamboo's increasing susceptibility to ecological stress is already indicated by the SIB results, which produced mid-range environmental scores for hydrological and carbon functions. These results are in line with international evaluations that point to climate change as a significant new threat to bamboo-based economies (van der Lugt and King, 2019).

Conclusion

Bamboo usage in the study area is found to be fairly sustainable with an SIB score of 3.4. The social dimension tops the three pillars due to its roots in culture, housing, and daily life. Environmental indicators are moderate, especially for soil protection

and water flow, but raise concerns about deforestation and species loss. The weakest of the three is economic sustainability, due to its poor market, low value, and limited industrial demand. It can be concluded that, given the current landscape, there is a need for sustainable planning in collaboration with the local community and a stronger focus on the bamboo market.

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References

Breiman, L. 2001. Random forests. Machine Learning 45 (1): 5–32. https://doi.org/10.1023/A:1010933404324

Cochran, W.G. 1977. Sampling techniques. New York: John Wiley and Sons.

Congalton, R.G. 1991. A review of assessing the accuracy of classifications of remotely sensed data. Remote Sensing of Environment 37(1): 35–46. https://doi.org/10.1016/0034-4257(91)90048-b

FAO 2010. Global forest resources assessment 2010: main report. FAO Forestry Paper 163. Rome: Food and Agriculture Organization of the United Nations.

Karbi Anglong District n.d. District profile. Government of Assam. Available at: https://karbianglong.gov.in/information-services/district-profile (accessed 1 December 2022).

Landis, R.J. and Koch, G.G. 1977. The measurement of observer agreement for categorical data. Biometrics 33(1): 159–174. https://doi.org/10.2307/2529310

Likert, R. 1932. A technique for the measurement of attitudes. Archives of Psychology 140: 1–55.

Lobovikov, M., Ball, L. and Guardia, M. 2007. World bamboo resources: a thematic study prepared in the framework of the global forest resources assessment 2005. FAO Forestry Paper 149. Rome: FAO.

Mayer, A.L. 2008. Strengths and weaknesses of common sustainability indices for multidimensional systems. Environment International 34(2): 277–291. https://doi.org/10.1016/j.envint.2007.09.004

Nath, A.J., Brahma, B., Sileshi, G.W. and Das, A.K. 2018. Impact of land use changes on the storage of soil organic carbon in active and recalcitrant pools in a humid tropical region of India. Science of the Total Environment 624: 908–917. https://doi.org/10.1016/j.scitotenv.2017.12.199

Nath, A.J., Das, G. and Das, A.K. 2009. Above-ground standing biomass and carbon storage in village bamboos in North-East India. Biomass and Bioenergy 33(9): 1188–1196. https://doi.org/10.1016/j.biombioe.2009.05.020

NDTV 2021. 2 more paper mill employees die in Assam; toll rises to 95. 23 September. Available at: https://www.ndtv.com (accessed 2 August 2022).

OECD 2008. Handbook on constructing composite indicators: methodology and user guide. Paris: OECD Publishing. https://doi.org/10.1787/9789264043466-en

Olofsson, P., Foody, G.M., Herold, M., Stehman, S.V., Woodcock, C.E. and Wulder, M.A. 2014. Good practices for estimating area and assessing accuracy of land change. Remote Sensing of Environment 148: 42–57. https://doi.org/10.1016/j.rse.2014.02.015

Rigby, D., Woodhouse, P., Young, T. and Burton, M. 2001. Constructing a farm-level indicator of sustainable agricultural practice. Ecological Economics 39(3): 463–478. https://doi.org/10.1016/S0921-8009(01)00245-2

Rouse, J.W., Haas, R.H., Schell, J.A. and Deering, D.W. 1973. Monitoring vegetation systems in the Great Plains with ERTS. In: Third ERTS Symposium, NASA SP-351, Vol. 1: 309–317.

Singh, R.K., Murty, H.R., Gupta, S.K. and Dikshit, A.K. 2012. An overview of sustainability assessment methodologies. Ecological Indicators 15(1): 281–299. https://doi.org/10.1016/j.ecolind.2011.01.007

Singnar, P. 2019. Comparative study on the carbon storage and sequestration rate in forest bamboo species in Karbi Anglong district of Assam. PhD thesis. Assam University, India. Available at: http://hdl.handle.net/10603/259677 (accessed 29 Nov 2022)

Singnar, P., Nath, P.C., Nath, A.J. and Das, A.K. 2023. Bamboo resources in Karbi Anglong district of Assam and their role in soil carbon management. In: Soil carbon dynamics in Indian Himalayan region. Singapore: Springer: 205–215. https://doi.org/10.1007/978-981-99-3303-7_11

Sullivan, G.M. and Artino, A.R. 2013. Analyzing and interpreting data from Likert-type scales. Journal of Graduate Medical Education 5(4): 541–542. https://doi.org/10.4300/JGME-5-4-18

van der Lugt, P. and King, C. 2019. Bamboo in the circular economy: the potential of bamboo in a zero-waste, low-carbon future. Beijing: INBAR.

Wu, X.P., Liu, S., Luan, J., Wang, Y. and Cai, C. 2019. Responses of water use in Moso bamboo culms of different developmental stages to manipulative drought. Forest Ecosystems 6(1): 31. https://doi.org/10.1186/s40663-019-0189-8

Zhang, M., Chen, S., Jiang, H., Lin, Y., Zhang, J., Song, X. and Zhou, G. 2019. Water-use characteristics and physiological response of Moso bamboo to flash droughts. International Journal of Environmental Research and Public Health 16(12): 2174. https://doi.org/10.3390/ijerph16122174

Zhang, X., Tong, C., Fang, D., Mei, T. and Li, Y. 2023. Different hydraulic and photosynthetic responses to summer drought between newly sprouted and established Moso bamboo culms. Frontiers in Plant Science 14: 1252862. https://doi.org/10.3389/fpls.2023.1252862

Questionnaire

a. Name of the respondent:

b. Age:

c. Gender:

d. Occupation of Head of Household: Farmer/Service/cultivator

e. Religion: Hindu/Christian/Animism Community:

f. Total members of the house:

Sl. no	Age	Sex	Occupation	Education
1				
2				
3				
4				
5				
6				
7				

g. Utilization Pattern of Bamboo (Source of bamboo a. Natural Forest (SRF, DCRF, homestead, private plantation (Own)

Species	Local name	Uses	Sources of bamboo	Price of bamboo culm

h. **Socio-economic background**

(Livelihood Capitals: Natural, Physical, Financial, Human, Social)

Land owned & Livestock (Natural Capital)

Category	Area (Hector)
Rice field	
House plot	
Jhum field	
Bamboo forest	

Rubber garden	
Arecanut Garden	
Livestock	Nos
Pig	
Chicken	
Cow & buffalo	
Goat	

Patterns of Physical Capital

Assets	Type	Proportion
Transport		
House		
Water (pond)		
Energy (hydro and solar)		
Agriculture tools		
Television		
Radio		
Cycle		
Bamboo house		
Bamboo utensils		
Bamboo furniture		
Bamboo agriculture implements		

Annual Household Income (Financial Capital)

Sl. no	Income Sector	Per month/year (Rs)
1	Service	
2	Paddy	
3	Domesticated animals	
4	Bettle nut	
5	Bamboo	
6	Ginger	
7	Broom	
8	Others (specify)	

Human Capital

Category	Proportion	Male/ female	Age	Specify
Service				
Farmer				
Daily Wage Labor				
Contractor				
Business				
Working in Bamboo based related				
Cultivator				
Other works related with bamboo handicrafts				

Patterns of Social & Cultural Capital

Type	Frequency of participation
Participation in Community based organization	
Political participation	
Festival of harvesting bamboo	
Others bamboo related	

Environmental Indicators for bamboo utilization

1. Do you observe sufficient bamboo availability in your area? □ Yes □ No
2. Compared to the past (10–15 years), bamboo stock is: □ Increasing □ Decreasing □ Same
3. How well does bamboo regenerate after harvesting? □ Very good □ Good □ Poor □ Very poor
4. Are there any efforts for bamboo plantation/replanting? □ Yes □ No
5. Has bamboo forest area changed over time? □ Increased □ Decreased □ No change
6. What has replaced bamboo areas (if decreased)? □ Agriculture □ Rubber plantation □ Tea plantation □ Settlement □ Other: _____
7. How would you describe current land use in bamboo areas? □ Mostly Forest □ Mixed use □ Mostly converted

Indicator	Score (1-5)				
Bamboo Stock and Regeneration	1	2	3	4	5
Forest Cover and Land Use Change	1	2	3	4	5
Species Diversity and Integrity	1	2	3	4	5
Soil Fertility and Productivity	1	2	3	4	5
Water Availability Functions	1	2	3	4	5
Carbon Sequestration	1	2	3	4	5

Economic Indicators in bamboo utilization

Annual Income	Proportion	Per month/year (Rs)
Bamboo culm		
Bamboo handicrafts		
Bamboo shoots		
Pickles		
Fermented bamboos		
Furniture		
Others (specify)		

Market Access and Price stability	Response Option
Selling location	Local/nearby market/towns/middlemen/direct buyers
Distance to market	<5/5-10/>10
Price stability	Very stable/moderate/fluctuation/unstable
Change after mill closer	Increased/Decreased/No change/Don’t know

Please rank, the following indicators based on their sustainability and importance in your livelihood using a scale from 1-5

Score	Meaning
1	Highly unsustainable
2	Unsustainable
3	Fairly Sustainable
4	Sustainable
5	Highly sustainable

Indicator	Score (1-5)				
Household Income	1	2	3	4	5
Market Access	1	2	3	4	5
Employment	1	2	3	4	5
Value Addition	1	2	3	4	5
Economic Diversification	1	2	3	4	5
Livelihood Resilience	1	2	3	4	5

Social Indicators for bamboo utilization

1. Does your household use bamboo for construction (house, fencing, storage)? ☐ Yes ☐ No

If yes, in which structures? (tick all) □ House walls □ Roofing □ Fencing □ Grain storage

2. Approximately how much of your household structure uses bamboo? □ Less than 25% □ 25–50% □ 50–75% □ More than 75%

3. Can all households in your village easily access bamboo resources? □ Yes □ No

4. Do you consume bamboo shoots? □ Yes □ No

5. How often do you consume bamboo shoots? □ Regularly (weekly) □ Occasionally □ Rarely

6. Does your household use bamboo for handicrafts? □ Yes □ No

7. If yes, for what purpose? □ Household use □ Selling □ Both

8. What proportion of bamboo is used for handicrafts? □ Less than 25% □ 25–50% □ 50–75% □ More than 75%

9. Is bamboo used in religious rituals in your household/community? □ Yes □ No

10. How often is bamboo used in such rituals? □ Always □ Often □ Sometimes □ Rarely

11. Is bamboo used during festivals? □ Yes □ No

12. How is bamboo used? □ Decoration □ Structure (temporary sheds, gates) ☐ Tools/items ☐ All

13. How important is bamboo in festivals? □ Very important □ Important □ Moderately important □ Less important

14. Do you think bamboo use in your culture is: ☐ Increasing ☐ Decreasing ☐ Same

15. How important is bamboo in maintaining your cultural identity? □1 □2 □3 □4 □5

16. Do younger generations continue using bamboo traditions? □ Yes □ No □ Not sure

17. Are bamboo-related skills (craft, construction) passed to younger generations? □ Yes □ No

18. Do you use bamboo during difficult times (floods, crop failure)? □ Yes □ No

19. Do people in your village cooperate in bamboo harvesting or use? □ Yes □ No

20. Please rank, the following indicators based on importance of bamboo in your life and community using a scale from 1-5.

Score	Meaning
1	Not importance at all
2	Slightly important
3	Moderately important
4	Important
5	Very Important

Indicator	Score (1-5)				
Cultural Identity	1	2	3	4	5
Housing and Shelter Security	1	2	3	4	5
Equity and Access to Resources	1	2	3	4	5
Community Resilience	1	2	3	4	5
Knowledge and Skills Transmission	1	2	3	4	5
Social Cohesion and Cooperation	1	2	3	4	5

Survey questionnaire (community level)

Focus group discussion (from community elders and craftsmen/craftswomen)

1. Changes in bamboo resource situation over the last 5-10 years (historical mapping)

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2. What are the problems with regards to bamboo production, collection and processing?

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3. Suggestions/recommendation to develop bamboo resources production, collection and processing

Processing----------

Management----------

Harvesting----------

Collection systems----------
