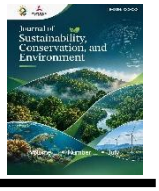
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Spatial Identification of Coffee-Based Agroforestry Potential in Meghalaya for Community Livelihoods and Sustainable Development

Arun Pratap Mishra [a*] Ankit Rawata [b], Shiv Narayan Yadava [c]

[a,b,c] *Department of Forestry and Remote Sensing, Earthtree Data Services Private Limited, Shillong, 793006, Meghalaya, INDIA*

[*]*Corresponding author:* Arun Pratap Mishra. *E-mail address:* arunpratap7371@gmail.com

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a b s t r a c t

Background: A coffee-based agroforestry system is one such practice that has been recognized as a significant tool for facilitating sustainable livelihoods, biodiversity conservation, and climate-resilient land management practices in the tropics. Despite its potential, there have been very few assessments to map out the spatial zones of suitability for Coffea arabica and Coffea canephora (Robusta) cultivation in Meghalaya that have diverse agroclimatic zones suited for plantations.
Aims: The current research focused on identifying and mapping spatial zones for the cultivation of Arabica coffee and Robusta coffee under coffee-based agroforestry systems in Meghalaya through geospatial modelling approaches.
Methods: Multi-Criteria Decision Analysis (MCDA) has been carried out in Google Earth Engine using parameters like elevation, temperature, precipitation, slope, aspect, and soil pH. Weighted overlay has been done for both types of coffee, viz., Arabica and Robusta.
Results: Arabica coffee suitability was found to be concentrated mostly in the high-elevation zones of East Jaintia Hills, West Jaintia Hills, Ri Bhoi, and East Khasi Hills. Robusta coffee had wider spatial distribution, with suitability being found for warmer and low-elevation areas, including the Garo Hills region. Blocks like Saipung, Thaadlaskein, Khliehriat, Laskein, Umsning, and Umling were highly suitable for coffee agroforestry development.
Conclusions: It is evident from the research that there is considerable potential for developing coffee-based agroforestry practices in Meghalaya to facilitate sustainable rural livelihoods, biodiversity conservation, and climate-resilient agricultural practices.

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1. Introduction

Sustainable land-use planning in mountainous and high-rainfall areas calls for strategies that are able to address both ecology and livelihood security at the same time (Sati, 2014). Landscapes in such areas should avoid following any form of agricultural intensification that could pose serious risks to the environment in the future (Pretty, 2018). The solution lies in employing perennial and tree-based production strategies that integrate sustainability into the equation (Reed et al., 2017). Agroforestry emerges as not only a means of land management

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but also as a development strategy that enables the combination of conservation objectives and sustainable livelihoods (Plieninger et al., 2020). Meghalaya is one such landscape where the need for balancing livelihood needs and ecological sustainability poses a challenge (Sarma, 2026). An area characterized by undulating landform features, varied microclimatic zones, high annual rainfall, and community-managed land tenure systems, is highly dependent on land-related activities (De, 2011). Conventional farming practices in the region face several challenges, such as soil erosion, transitioning from shifting cultivation to other forms of land use, lack of crop diversity, and changes in climate (Altieri & Nicholls, 2017). This situation has resulted in the need for new crops to stabilize income without jeopardizing sustainability (Dong, 2021).

One such alternative is coffee cultivation, particularly through agroforestry practices that involve shading (Nasiro, 2024). Globally, agroforestry with coffee has proven successful for soil conservation, climate regulation, carbon sequestration, maintenance of biodiversity, and provision of sustainable economic benefits to smallholder farmers (Tazebew et al., 2025). In the case of Meghalaya, where monoculture plantation crops would not be suitable due to ecological conditions as well as social considerations of current land tenure systems, coffee represents a less environmentally impactful alternative that may be grown in conjunction with trees and mixed cropping practices (Erni, 2009; Erni, 2015). While there is a rich tradition of coffee cultivation in the state, the total geographical spread is still relatively constrained (Majaw, 2025). Commercial cultivation of coffee was initiated in sites including Umling (Ri-Bhoi), Lumshnong (East Jaintia Hills), and Tura (West Garo Hills) as early as 1954. However, cultivation did not become ubiquitous across the state thereafter. Contemporary data show some resurgence in interest along with continued expansion of the area under coffee farming. NER Databank (n.d.) reports that, during 2022-23, coffee farming was undertaken on a total area of 336 ha, with Ri-Bhoi being the dominant district with 109 ha, followed by West Garo Hills (63 ha) and South Garo Hills (45 ha), among others.

Long-term changes further emphasize the slow and gradual expansion. Specifically, the area of coffee cultivation expanded from 248 ha in 2013-14 to 416 ha in 2016-17, with the Ri-Bhoi district recording its cultivation area from 86 ha in 2013-14 to 145 ha in 2016-17 (NER Databank, n.d.). According to more recent data, the current state of coffee cultivation in Meghalaya is such that about 1,275 ha is currently under coffee farming, with the breakdown showing about 267 ha of Arabica and 1,008 ha of Robusta, while there are 2,588 growers who are cultivating 388 ha actively (NER Databank, n.d.). The estimated area under coffee cultivation for 2024-25 stands at 452 ha, and the state government has promised to increase this area by 248 ha (India Today NE, 2025). Moreover, the geographical spread of the coffee production area is expanding, with the crop now present in up to 11 districts, including Ri-Bhoi, East and West Khasi Hills, Jaintia Hills, and Garo Hills, among others (MBDA, 2023; Meghalaya Monitor, 2025). Notably, Ri-Bhoi remains the central area for coffee production, while Garo Hills' contribution to coffee production has also become significant recently (MBDA, 2023; Meghalaya Monitor, 2025). Nevertheless, the expanding area of coffee production in Meghalaya highlights the lack of any strategic geographic information regarding the suitability of various areas for coffee production.

Taking an agroecological perspective, the heterogeneity in Meghalaya poses an opportunity and challenges (Mylliemngap, 2021). The variations in elevation, temperature,

rainfall, and soil conditions within small distances make each region suitable for various crops (Nagashree et al., 2025). Specifically, when considering coffee plantations, it is important to understand that Commercially grown *Coffea* species differ in their ecological requirements (Liere et al., 2012): higher, cooler sites with stable precipitation favor Arabica, whereas lower and warmer ground favors Robusta (Hameed et al., 2020). State agencies have recognized these differences in general terms; the Meghalaya Basin Development Authority notes the suitability of the Khasi Hills and parts of the Garo Hills for Arabica and a broader suitability for Robusta (MBDA, 2023), but such assessments remain administrative and descriptive. The available information on coffee in the state comes almost entirely from government databases, development reports, and extension records, which document planted area and production without spatial or analytical treatment, while national bodies such as the Coffee Board of India and NRSC report only generalized estimates for Northeast India.

The absence of species-specific spatial guidance carries real costs. Without it, expansion is driven by administrative convenience or short-term opportunity and can be directed to unsuitable land, producing poor yields, heightened exposure to climate stress, and financial insecurity for smallholders, while public expenditure on saplings, capacity building, and infrastructure is misallocated. In the fragile hill ecosystems of Meghalaya, unplanned expansion also risks degrading marginal land and depleting natural resources. Geospatial analysis of the relevant environmental variables offers a direct remedy: mapping climate, terrain, and soil conditions identifies where a crop can be promoted with minimum ecological risk and maximum socio-economic return. Framing that exercise within agroforestry is appropriate, since it is the integration of the crop with tree cover that delivers ecological benefit alongside income. The present study responds to that need, and its novelty lies in its species-specificity, treating the distinct ecological requirements of both commercially significant *Coffea* species separately throughout.

To make the research gap explicit rather than descriptive, **Table 1** synthesizes the principal earlier studies on coffee suitability and site selection, the scale and setting in which each was conducted, the analytical method employed, and the specific limitation each carries with respect to Meghalaya. The synthesis confirms that no peer-reviewed study has so far produced a species-specific, block-level spatial suitability assessment for coffee in Meghalaya and that the small body of available regional literature is administrative and statistical rather than analytical. This scarcity of prior work is itself a feature of the research context, and Section 5.4 revisits this scarcity of prior work, which is a defining characteristic of the research context. in Section 5.4.

Table 1. Synthesis of previous coffee suitability studies and the research gap addressed by the present study.

Previous study	Location / scale	Method	Limitation with respect to Meghalaya
Davis et al. (2012)	Ethiopia (indigenous Arabica)	Bioclimatic niche modelling	Addresses wild Arabica populations; not oriented to plantation or agroforestry siting

Previous study	Location / scale	Method	Limitation with respect to Meghalaya
Bunn et al. (2015)	Global	Climate-envelope modelling of Arabica and Robusta	Coarse global grid; no district or block-level resolution; soil and terrain excluded
Kath et al. (2020)	Global Robusta belt	Statistical yield–temperature response analysis	Yield-focused; produces no spatial suitability surface and omits edaphic and topographic criteria
Sharma (2023)	Nagaland and Manipur, NE India	Machine-learning hot-spot prediction	Unpublished MSc thesis; no species differentiation; Meghalaya not covered
Fekadu & Andarege (2025)	North Shewa, Ethiopia	GIS-based parametric zonation	Single species (Arabica) in a different agro-ecological and tenure setting
Akafu et al. (2025)	Western Ethiopia	MaxEnt under climate-change scenarios	Arabica only; Ethiopian highland context not transferable to the Meghalaya plateau
Nagashree et al. (2025)	India (southern coffee belt)	Earth-observation based site suitability	Concentrated on the established Karnataka–Kerala–Tamil Nadu belt; North East India not assessed
MBDA (2023); NER Databank (n.d.); Majaw (2025)	Meghalaya	Administrative reporting of area, production and grower statistics	Descriptive and non-spatial; no biophysical modelling, no suitability surface, no species zoning
Present study	Meghalaya; state-wide, block level	GIS-based MCDA with AHP weighting in Google Earth Engine	First species-specific, block-level spatial suitability assessment for Arabica and Robusta in Meghalaya

The need to balance livelihood needs and ecological sustainability poses a challenge (Sarma). Despite the growing interest in coffee cultivation in Meghalaya, existing studies and government reports are largely descriptive and primarily focus on cultivation areas and production statistics. To date, no study has comprehensively mapped the species-specific spatial suitability of *Coffea arabica* and *Coffea canephora* using a GIS-based Multi-Criteria Decision Analysis (MCDA) framework by integrating climatic, topographic, and edaphic factors. Therefore, this study aims to identify and map the spatial suitability of Arabica and Robusta coffee cultivation under agroforestry systems in Meghalaya using a GIS-based MCDA framework. The generated suitability maps are expected to support scientific land-use planning, sustainable coffee expansion, and evidence-based decision-making for enhancing rural livelihoods and ecological sustainability.

Study Area

The study covers the state of Meghalaya in Northeast India (**Figure 1**). The landscape is ecologically diverse, shaped by strong interactions between relief, climate, and land use. Plateau surfaces and hill ranges with steep elevational gradients dominate, generating pronounced

microclimatic variation over short distances, a condition of direct relevance to perennial plantation crops such as coffee, which respond sharply to temperature and moisture. The climate is humid monsoonal with very high, strong orographic rainfall that varies considerably across the state with topography. High rainfall suits tree-based perennial production, although at the wettest locations excess moisture constrains productivity and plantation management. Soils are largely deeply weathered and acidic as a consequence of prolonged heavy rainfall; these conditions restrict conventional arable farming but are generally acceptable for shade-grown perennials. Agroforestry and continuous vegetative cover with established root systems help stabilize soil and regulate moisture on slopes. Land use is governed largely by community-based tenure and customary management, producing a mosaic of forest, agroforestry, shifting cultivation, plantation, and mixed cropping. In this socio-ecological setting, spatial assessment of suitability is central to reconciling ecological conservation with rural livelihoods.



Figure 1. Geographic location and district boundaries of the study area, Meghalaya, northeastern India

2. Methods

2.1 Study framework and analytical approach

A spatial Multi-Criteria Decision Analysis (MCDA) was used to assess the potential suitability of coffee cultivation in Meghalaya, with particular reference to coffee-based agroforestry. The analysis was implemented on the Google Earth Engine (GEE) cloud platform, which supports reproducible processing of large environmental datasets (Gorelick et al., 2017). MCDA is well established for land suitability assessment because it allows multiple environmental parameters of differing influence to be combined within a single evaluation (Malczewski, 2006), and comparable geospatial approaches are now widely applied to

agroforestry siting and plantation planning in tropical and mountainous settings, including Northeast India (Sharma, 2023). The workflow comprised data acquisition, preprocessing, criterion standardization, weighted overlay, and suitability mapping (**Figure 2**). Separate models were run for *Coffea arabica* and *Coffea canephora* (Robusta), whose ecological requirements differ appreciably, with thresholds for elevation, temperature, precipitation, slope, aspect, and soil pH set independently for each species from the published literature (DaMatta & Ramalho, 2006; Bunn et al., 2015).

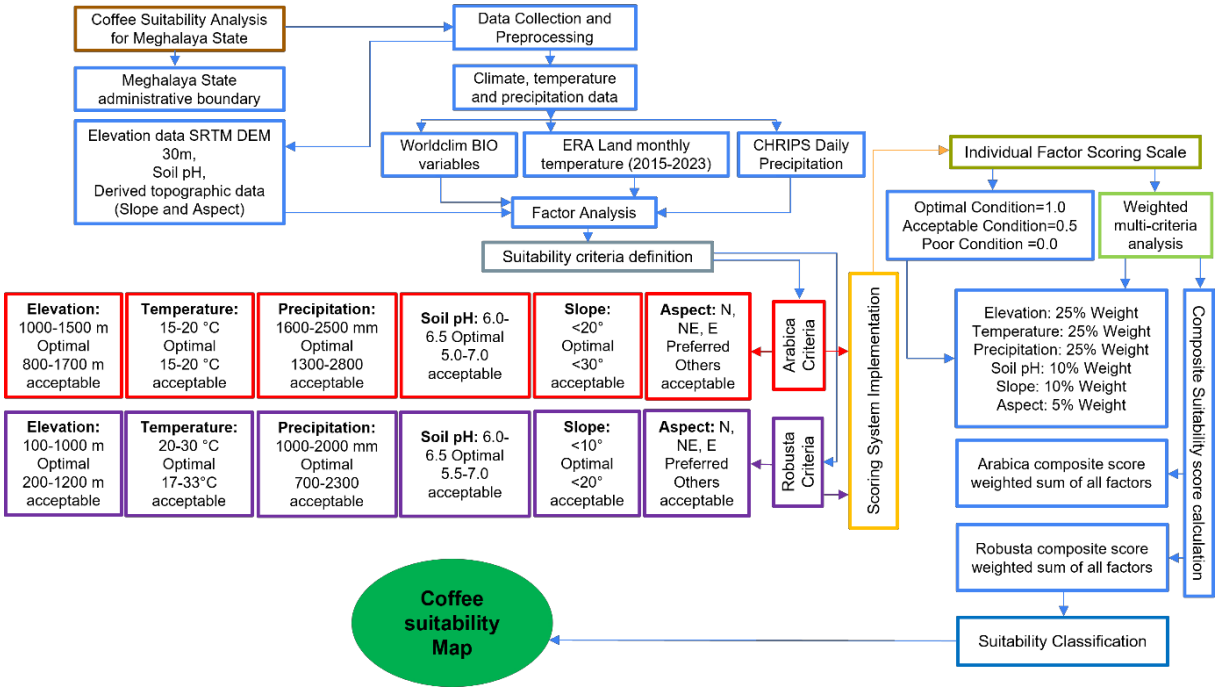


Figure 2. The overall workflow adopted for coffee suitability assessment in Meghalaya.

2.2 Geospatial datasets and pre-processing

Several sets of geospatial data pertaining to climatic, topographic, and edaphic features were used in the suitability assessment (Table 2). Geographical elevation data came from SRTM. Digital Elevation Model at the spatial resolution of 30 m (Farr et al., 2007). The slope and aspect were computed from DEM with the use of tools of digital terrain analysis available in Google Earth Engine. For the description of climatic characteristics, such variables as annual mean temperature (BIO1) and annual precipitation (BIO12) were selected among WorldClim version 1 data at a spatial resolution of approximately 1 km (Hijmans et al., 2005). To consider the changes in climatic conditions in recent years, the monthly dataset on temperature and dew point temperature from ERA5-Land was obtained from ECMWF (Muñoz-Sabater et al., 2021). In addition to that, rainfalls have been assessed by means of Climate Hazards Group InfraRed Precipitation with Station Data (CHIRPS), which provides highly accurate rainfall estimation at small spatial resolution for climatic studies (Funk et al., 2015).

Soil pH was obtained from the OpenLandMap soil datasets at 250 m resolution (Hengl et al., 2017) and supplemented with regional data from the North Eastern Space Applications Centre (NESAC). Administrative boundaries from the Survey of India (SOI) were used to clip all layers to the state. Geospatial datasets of this kind are increasingly relied upon for

agroforestry and crop suitability mapping across the Northeastern states, where terrain is complex, holdings are fragmented, and climate is heterogeneous (Dagar et al., 2014; Gogoi, 2015; Raj et al., 2024). All raster layers were reprojected to a common coordinate system and resampled to 100 m, or about one hectare per pixel. This makes up for the different native resolutions of the inputs and strikes a balance between spatial detail and processing efficiency, as well as the needs native resolutions of the inputs and balances spatial detail against processing efficiency and the requirements of district and block-level planning.

Table 2. Geospatial datasets and biophysical variables used for coffee suitability assessment in Meghalaya

No.	Dataset name	Variable / band	Spatial resolution	Data source	Used for
1.	USGS SRTM DEM 30 m	Elevation	30 m	NASA/USGS	Elevation criteria; slope and aspect calculation
2.	WorldClim BIO v1	Bio01 (annual mean temperature)	~1 km (30 arc-sec)	WorldClim	Temperature suitability
.	WorldClim BIO v1	Bio12 (annual precipitation)	~1 km (30 arc-sec)	WorldClim	Precipitation suitability
4.	ERA5-Land Monthly	Temperature (2 m)	~11 km (0.1°)	ECMWF / Copernicus	Recent temperature analysis
5.	ERA5-Land Monthly	Dewpoint temperature (2 m)	~11 km (0.1°)	ECMWF / Copernicus	Humidity calculation
6.	CHIRPS Daily	Precipitation	~5 km (0.05°)	UCSB-CHG	Recent precipitation analysis
7.	OpenLandMap soil pH and NESAC data	B0 (0–5 cm depth)	250 m	OpenLandMap / North Eastern Space Applications Centre	Soil pH suitability
8.	SOI	Administrative boundaries	Vector polygons	Survey of India	State and block area boundaries

2.3 Selection of suitability criteria

Six biophysical factors were selected based on their documented influence on coffee physiology, survival, and productivity: elevation, temperature, precipitation, soil pH, slope, and aspect. These variables collectively represent climatic, edaphic, and topographic controls on coffee cultivation (Getachew et al., 2022). Elevation was included as a proxy for temperature regime and orographic effects, particularly relevant in mountainous regions (Dwivedi et al., 2025). Temperature and precipitation were considered primary climatic drivers governing flowering, fruit development, and overall plant viability (Bacelar et al., 2024). Soil pH was selected to reflect nutrient availability and root-zone suitability, while

slope was used to account for erosion risk and management constraints (Priori et al., 2020). Aspect was included to capture variations in solar exposure and microclimate, which can influence moisture retention and plant stress (Dwivedi et al., 2025).

Each of the six criteria was reclassified into four ordinal suitability classes before the overlay was performed. The class breakpoints, which were defined separately for the two species, are reported in full in **Table 3**. The thresholds were compiled from the published agronomic and eco-physiological literature on coffee (DaMatta & Ramalho, 2006; Bunn et al., 2015; Hameed et al., 2020; Kath et al., 2020; Getachew et al., 2022) and were organized following the four-class structure of the FAO (1976) land-evaluation framework. Each class was assigned a standardized score of 4 (highly suitable, S1), 3 (moderately suitable, S2), 2 (marginally suitable, S3), or 1 (not suitable, N), so that all criteria entered the weighted overlay on a common dimensionless scale.

Table 3. Species-specific reclassification matrix of biophysical criteria used in the weighted overlay for *Coffea arabica* and *Coffea canephora* (Robusta)

Criterion (unit)	Species	Highly suitable, S1 (score 4)	Moderately suitable, S2 (score 3)	Marginally suitable, S3 (score 2)	Not suitable, N (score 1)
Elevation (m a.s.l.)	*C. arabica*	900-1,600	600-900; 1,600-1,800	400-600	<400; >1,800
	C. canephora	100-800	800-1,000	1,000-1,200	<100; >1,200
Mean annual temperature (°C)	*C. arabica*	18-22	15-18; 22-24	13-15; 24-26	<13; >26
	C. canephora	22-26	20-22; 26-28	18-20; 28-30	<18; >30
Annual precipitation (mm)	*C. arabica*	1,500-2,500	1,200-1,500; 2,500-3,000	1,000-1,200; 3,000-4,000	<1,000; >4,000
	C. canephora	2,000-3,000	1,500-2,000; 3,000-3,500	1,200-1,500; 3,500-4,500	<1,200; >4,500
Soil pH (0–5 cm)	*C. arabica*	5.5-6.5	5.0-5.5; 6.5-7.0	4.5-5.0; 7.0-7.5	<4.5; >7.5
	C. canephora	5.0-6.5	4.5-5.0; 6.5-7.0	4.0-4.5; 7.0-7.5	<4.0; >7.5
Slope (%)	Both species	0-15	15-25	25-35	>35
Aspect (compass direction)	*C. arabica*	N, NE	E, NW	SE, W	S, SW
	C. canephora	S, SE	E, SW	NE, W	N, NW

Note: class scores are dimensionless. Aspect classes reflect Arabica's preference for cooler, lower-insolation northern and north-eastern slopes and Robusta's tolerance of warmer southern and south-eastern slopes. Slope thresholds consider erosion risk and the practical limits of terracing and harvesting in Meghalaya (Priori et al., 2020).

2.4 Weighted overlay and suitability index computation

All the suitability layers were combined into a weighted linear combination (WLC) to generate a composite suitability index (Malczewski, 2006). Weights were assigned based on the relative ecological importance of each variable for coffee cultivation, which was derived from agronomic literature and ecological reasons (Bunn et al., 2015; Kath et al., 2020). The climatic variables (elevation, temperature, and precipitation) were aggregated and given a weighting of 75%, with each variable 25%. This weighting is based primarily on the power of climate in determining the spatial distribution, productivity, and survival of coffee. Previous research has shown that while local soil and topographic conditions may be suitable for cultivating coffee, inappropriate temperature and precipitation can significantly limit or even eliminate the potential to grow it (DaMatta & Ramalho, 2006; Bunn et al., 2015). The physical variables (soil pH and soil slope) received 10% of the total weight for each variable. The major variables affecting growth performance, nutrient availability, plantation management, and productivity are less about crop survival. Moderate limitations due to soil conditions or slope may decrease yield potential, but soil conditions or slope may impose moderate limitations that decrease yield potential, but agronomic interventions and soil management practices can partly mitigate these effects. Agronomic interventions and soil management practices can partly mitigate these effects. The remaining 5% was allocated to topographic aspect, a secondary influence on the microclimatic variability. While climatic and edaphic factors have a more restrictive influence on coffee suitability than topographic aspects, certain aspects of the topography can still affect solar radiation exposure, evapotranspiration, and regional moisture conditions.

The overall suitability index (SI) was calculated as:

$$SI = \Sigma\ (Wi \times Xi),\ \text{for } i = 1 \text{ to } \underline{n} \quad (1)$$

where Wi is the weight assigned to criterion i, Xi is the standardized suitability score of that criterion, and n is the number of criteria (n = 6).

The continuous composite index produced by Equation 1 was reclassified into four final suitability classes using equal-interval breakpoints across the theoretical range of the index (1.00-4.00), as set out in **Table 4**. Equal intervals were preferred over distribution-based breaks so that the classification remains directly comparable between the two species and reproducible for any future re-run of the model. Each class therefore spans an interval of 0.75 index units, a figure that is used again in the sensitivity analysis reported in Section 3.6.

Table 4. Reclassification of the composite suitability index into final suitability classes

Final class	Composite suitability index (SI)	Interpretation for planning
S1-Highly suitable	3.25-4.00	No or only minor biophysical constraints; priority zones for plantation establishment and nursery investment
S2-Moderately suitable	2.50-3.24	Moderate constraints in one or more criteria; viable with shade management, soil amendment or terracing
S3-Marginally suitable	1.75-2.49	Severe constraints; expansion economically risky and recommended only on a trial basis
N-Not suitable	1.00-1.74	Limiting conditions in one or more climatic criteria; expansion not advised

2.5 Rationale for weight assignment

The continuous composite index produced by Equation 1 was reclassified into four final suitability classes using equal-interval breakpoints across the theoretical range of the index (1.00-4.00), as set out in **Table 4**. Equal intervals were preferred over distribution-based breaks so that the classification remains directly comparable between the two species and reproducible for any future rerun of the model. Each class therefore spans an interval of 0.75 index units, a figure that is used again in the sensitivity analysis reported in Section 3.6. The weighting structure follows from an established asymmetry in coffee ecology. Climatic variables explain the majority of the spatial variation in coffee distribution at regional and global scales, and a deficiency in temperature or precipitation can cause outright crop failure, whereas soil and topographic constraints principally affect yield level and management intensity rather than absolute feasibility. The guiding principle of the model is therefore that climate determines whether coffee can grow, while soil and topography determine how well it grows, and the weights were set to reflect that hierarchy. To move the weighting scheme beyond a purely qualitative judgement, the relative importance of the six criteria was formalized through Saaty's Analytic Hierarchy Process (Saaty, 2008). Pairwise comparisons were made on the standard 1-9 fundamental scale, with the judgements derived from the published eco-physiological evidence summarized above: the three climatic criteria were treated as equally important to one another; each climatic criterion was rated moderately more important (3) than soil pH and slope; and soil pH and slope were each rated slightly more important (2) than aspect. The resulting pairwise comparison matrix and the priority vector obtained from its principal eigenvector are presented in **Table 5**.

Table 5. Analytic Hierarchy Process pairwise comparison matrix and derived criterion weights

Criterion	Elev.	Temp.	Precip.	Soil pH	Slope	Aspect	AHP priority	Weight applied
Elevation	1	1	1	3	3	5	0.258	0.25
Temperature	1	1	1	3	3	5	0.258	0.25
Precipitation	1	1	1	3	3	5	0.258	0.25
Soil pH	1/3	1/3	1/3	1	1	2	0.089	0.10
Slope	1/3	1/3	1/3	1	1	2	0.089	0.10

Criterion	Elev.	Temp.	Precip.	Soil pH	Slope	Aspect	AHP priority	Weight applied
Aspect	1/5	1/5	1/5	1/2	1/2	1	0.049	0.05

Note: λmax = 6.006, CI = 0.001, RI = 1.24 (n = 6), and CR = 0.001. The CR is below the 0.10 threshold, indicating consistent pairwise judgements (Saaty, 2008). For Google Earth Engine implementation, AHP priorities were rounded to 0.25, 0.25, 0.25, 0.10, 0.10, and 0.05, with a maximum deviation of <0.011 from the eigenvector values and no change in criterion ranking.

2.6 Sensitivity of the suitability index to the weighting scheme

Because the outcome of any weighted linear combination depends on the weight vector, the sensitivity of the composite index to that vector was examined analytically. Consider a one-at-a-time perturbation in which the weight of criterion i is changed by a proportion p, so that $\delta = p \cdot wi$, and the difference is redistributed proportionally across the remaining five criteria so that the weights continue to sum to unity. Substituting into Equation 1, the resulting change in the composite index reduces to

$$\Delta SI = \delta (Xi - Mi), \text{ where } Mi = (SI - wi\ Xi) / (1 - wi)$$

in which Xi is the standardized score of the perturbed criterion and Mi is the weighted mean score of the remaining criteria. Because every standardized score lies in the interval (1, 4), the term (Xi-Mi) is bounded by 3 in absolute value, and therefore the maximum possible displacement of the composite index under any perturbation of magnitude δ is 3δ. This bound is attained only in the extreme case where the perturbed criterion scores 4 while every other criterion scores 1, or the reverse; in practice the displacement is smaller. **Table 6** evaluates the bound for perturbations of ±10% and ±20% applied to each criterion in turn and expresses it relative to the 0.75 unit width of a suitability class.

Table 6. Analytical bounds on the displacement of the composite suitability index under one-at-a-time perturbation of each criterion weight

Criterion	Baseline weight	δ at ±10%	Maximum |ΔSI| at ±10%	δ at ±20%	Maximum |ΔSI| at ±20%	Maximum shift as % of one class interval (±20%)
Elevation	0.25	0.025	0.075	0.050	0.150	20.0
Temperature	0.25	0.025	0.075	0.050	0.150	20.0
Precipitation	0.25	0.025	0.075	0.050	0.150	20.0
Soil pH	0.10	0.010	0.030	0.020	0.060	8.0
Slope	0.10	0.010	0.030	0.020	0.060	8.0
Aspect	0.05	0.005	0.015	0.010	0.030	4.0

Three conclusions follow. First, the three climatic criteria are the most sensitive to a change in weight and the least in aspect, in direct proportion to their AHP priorities. Second, the largest displacement obtainable anywhere in the state is 0.150 index units, produced by a ±20% change in a climatic weight; this displacement is one-fifth of the 0.75-unit width of a

suitability class, and the corresponding figure for aspect is 0.030 units, or 4% of a class interval. Third, a pixel can therefore change class only if its baseline index already lies within 0.150 units of a class boundary, so the broad spatial pattern reported in Section 4, Arabica restricted to the eastern uplands and Robusta extending into the Garo Hills, cannot be an artifact of the particular weights chosen. The bound is analytical and conservative and holds for every pixel; a full empirical re-run over a grid of perturbed weight vectors would tighten it and is recommended as an extension of this work.

2.7 Species-specific suitability mapping

Separate models were built for Arabica and Robusta, since the two species differ in climatic requirements and habitat. Thresholds for every environmental variable were therefore set independently for each species before the overlay was performed. This separation matters particularly in Meghalaya and the wider Northeast, where large altitudinal range and microclimatic contrast create distinct ecological niches for perennial plantation crops (Dagar et al., 2014), and where earlier agroforestry work has emphasized site-specific planning for livelihood, biodiversity, and sustainability objectives (Gogoi, 2015; Raj et al., 2024). The resulting classified surfaces support differentiated planning for Arabica and Robusta across the state.

2.8 Methodological Strengths and Reproducibility

The approach adopted here is transparent and reproducible. All inputs are open datasets, and the entire workflow runs in Google Earth Engine, so the analysis can be re-executed, audited, or extended by other groups without licensing cost. Comparable cloud-based geospatial workflows are increasingly used for agroforestry and land-suitability planning in the ecologically sensitive parts of Northeast India (Behera et al., 2025). The same framework can be rerun with higher-resolution climate surfaces or with socio-economic layers as these become available for the state.

3. Results

3.1 Spatial distribution of suitable areas for arabica coffee

The suitability surface for *Coffea arabica* is concentrated in the eastern and central uplands of Meghalaya (**Figure 3**). Contiguous suitable tracts occur in East Jaintia Hills, West Jaintia Hills, Ri-Bhoi, and parts of East Khasi Hills and coincide with the higher-elevation, cooler, and reliably wet portions of the plateau. Within this belt the largest tracts fall in the Thaadlaskein, Saipung, and Khliehriat blocks, with smaller extents in Laskein, Mawryngkneng, Mawphlang, and Umsning; the corresponding areas are reported in **Table 7** and are not repeated here. Suitable land is largely absent from the western and southern parts of the state, where elevation falls below the Arabica threshold and mean annual temperature rises above it.

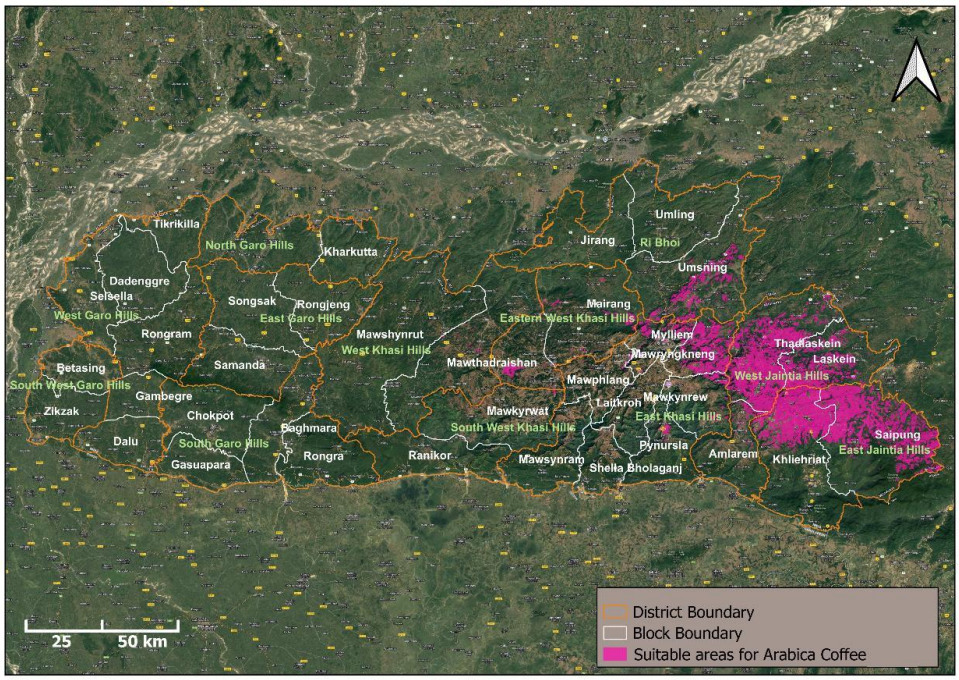


Figure 3. Spatial distribution of suitable areas for cultivation of *Coffea arabica* in Meghalaya

3.2 Block-wise distribution of suitable areas for arabica coffee

Suitable land is unevenly distributed between blocks (Figure 4). The distribution is strongly right-skewed: three blocks account for roughly three quarters of the suitable area, seven blocks contain almost all of it, and the remainder is fragmented into small pockets. Below the seven blocks listed in **Table 7**, Myllem, Mairang and Mawthadraishan retain intermediate extents of 400-600 ha, whereas Mawkyrwat, Mawshynrut, Nongstoin and Pynursla fall below 50 ha and are treated as negligible for planning purposes. The skew follows directly from the narrow elevation and temperature window for Arabica: only blocks whose terrain lies substantially within that window accumulate appreciable area.

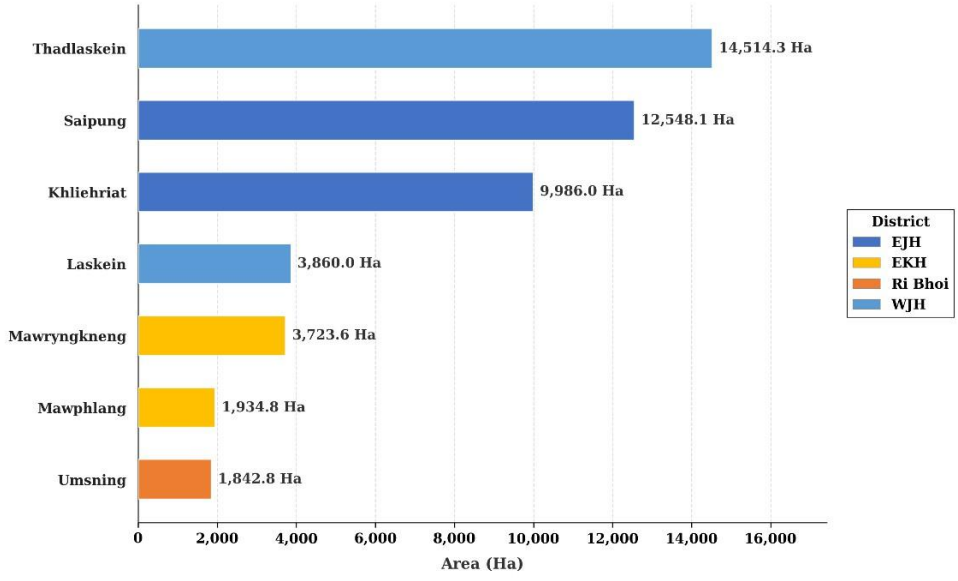


Figure 4. Block-wise distribution of potentially eligible areas suitable for cultivation of *Coffea arabica* in Meghalaya

3.3 Spatial distribution of suitable areas for robusta coffee

The suitability surface for *Coffea canephora* (Robusta) is wider and more evenly distributed than that for Arabica (**Figure 5**). Suitable land occurs in both the eastern and the western halves of the state, following the warmer, lower-lying, and humid parts of the landscape. The eastern tracts lie in Saipung, Thaadlaskein, Umsning, Umling, Laskein, and Khliehriat, and the western tracts in the Garo Hills, principally Zikzak and Resubelpara; block areas are given in **Table 7**. The presence of suitable land in the Garo Hills, where Arabica has none, is the principal spatial contrast between the two species.

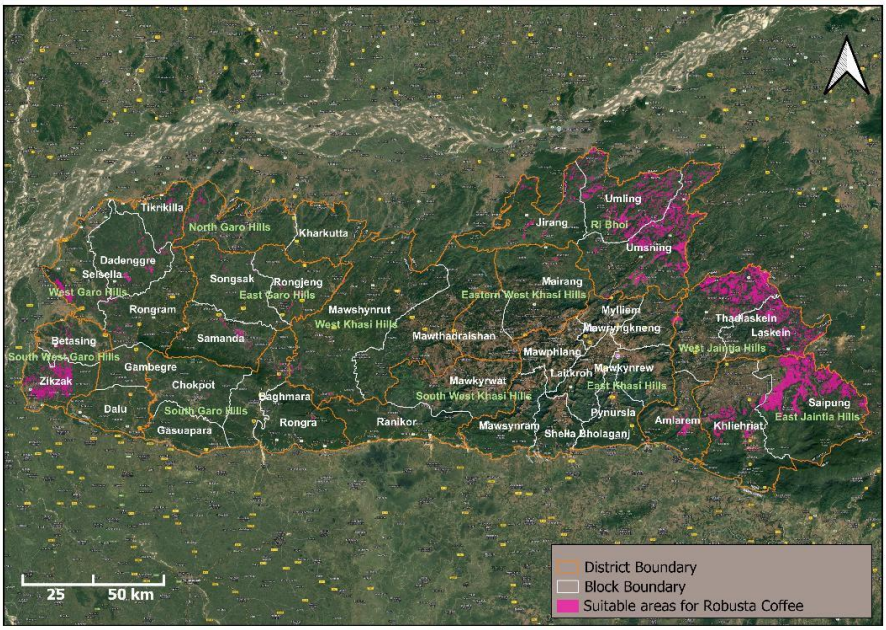


Figure 5. Spatial distribution of suitable areas for cultivation of *Coffea canephora* (Robusta coffee) in Meghalaya

3.4 Block-wise distribution of suitable areas for robusta coffee

The block-wise distribution for Robusta is also skewed, but less sharply than for Arabica (**Figure 6**). Four blocks, Saipung, Thaadlaskein, Umsning, and Umling, carry the majority of the area, with Laskein and Zikzak forming a second tier and Khliehriat, Resubelpara, and Tikrikilla retaining moderate extents. Chokpot, Rongram, Gambegre, Dalu, and Rongjeng return only small and fragmented patches. Robusta therefore occupies a broader ecological range within the state than Arabica, but its area is divided among a larger number of blocks in smaller units.

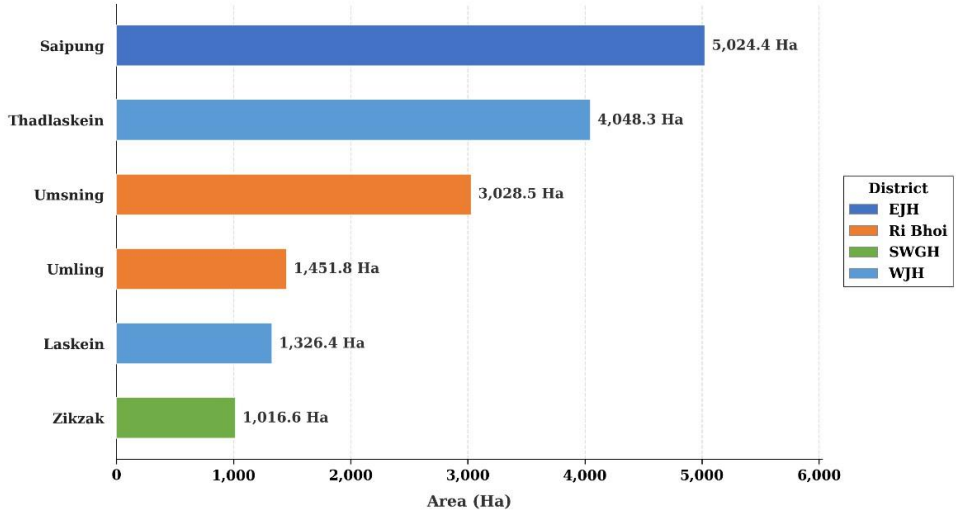


Figure 6. Block-wise distribution of potentially eligible areas suitable for cultivation of *Coffea canephora* (Robusta coffee) in Meghalaya

3.5 Comparative distribution of arabica and robusta suitability

Separate models were built for Arabica and Robusta, since the two species differ in climatic requirements and habitat. Thresholds for every environmental variable were therefore set independently for each species before the overlay was performed. This separation matters particularly in Meghalaya and the wider Northeast, where large altitudinal range and microclimatic contrast create distinct ecological niches for perennial plantation crops (Dagar et al., 2014), and where earlier agroforestry work has emphasized site-specific planning for livelihood, biodiversity, and sustainability objectives (Gogoi, 2015; Raj et al., 2024). The resulting classified surfaces support differentiated planning for Arabica and Robusta across the state.

The two species occupy largely separate parts of the state. Arabica suitability is confined to the eastern high-altitude districts of East Jaintia Hills, West Jaintia Hills, Ri-Bhoi, and East Khasi Hills, whereas Robusta suitability extends westward into the Garo Hills, and the two surfaces overlap in only five blocks. Existing community plantations in the Garo Hills confirm that coffee can be established under agroforestry conditions in the western districts (MBDA, 2023). The maps therefore provide a spatial basis for allocating each species to the part of the state that suits it, rather than treating the two as alternatives to be chosen on market grounds alone.

3.6 Quantitative summary of suitable areas

Table 7 summarizes the block-level results presented in Sections 4.1 to 4.4 and reports each block as a percentage of the total suitable area reported for each block tabulated for each species. The above-described contrast is quantified in the comparison. Three blocks of Arabica, namely Thaadlaskein, Saipung, and Khliehriat, contribute 76.5% of the suitable area tabulated, and this shows good concentration of Arabica potential in the Jaintia hills in Meghalaya. As for concentration, Robusta is less, but more importantly, it extends into blocks of the Garo Hills, which have zero Arabica potential. The total suitable area tabulated for Arabica (48,409.6 ha)

is about 2.9 times the total suitable area tabulated for Robusta (16,706.2 ha), while the latter is spread over a larger number of districts and elevation bands.

Table 7. Block-wise suitable area for Arabica and Robusta coffee and the share of each block in the tabulated total.

Block	District	Arabica area (ha)	Share of Arabica total (%)	Robusta area (ha)	Share of Robusta total (%)
Thaadlaskein	West Jaintia Hills	14,514.3	30.0	4,048.3	24.2
Saipung	East Jaintia Hills	12,548.1	25.9	5,024.4	30.1
Khliehriat	East Jaintia Hills	9,986.0	20.6	475.7	2.8
Laskein	West Jaintia Hills	3,860.0	8.0	1,326.4	7.9
Mawryngknen g	East Khasi Hills	3,723.6	7.7	–	–
Mawphlang	East Khasi Hills	1,934.8	4.0	–	–
Umsning	Ri-Bhoi	1,842.8	3.8	3,028.5	18.1
Umling	Ri-Bhoi	–	–	1,451.8	8.7
Zikzak	South West Garo Hills	–	–	1,016.6	6.1
Resubelpara	North Garo Hills	–	–	334.5	2.0
Total		48,409.6	100.0	16,706.2	99.9

Note: Percentages are each block's share of the tabulated total, not of state or block area. A dash indicates no reportable suitable area for that species. Blocks under 50 ha are omitted as negligible. Robusta shares sum to 99.9 owing to rounding.

The numbers are aggregated to the district level, and the results are compared with the geographical area of Meghalaya (2,242,900 hectares, or 22,429 km²) to make the results proportionate (Table 8). The selected range of suitable areas for Arabica is 2.16%, and for Robusta 0.74% of the land area of the state, which is less than 3% in total. The percentage is a small fraction, but it is deliberately so: the criteria and thresholds used in Table 3 are relatively conservative, and the goal of the assessment is to identify where coffee agroforestry is a good fit, not where it is possible. The same figures are large when set against current cultivation, however. The suitable area (65,115.8 ha) is about 144 times the estimated coffee in 2024-25 (452 ha) and 51 times the cumulative area established until date (1,275 ha), suggesting that the biophysical resource is not the limiting factor to the expansion in Meghalaya

Table 8. District-level aggregation of suitable area and its share of the geographical area of Meghalaya.

District	Arabica suitable area (ha)	Share of Arabica total (%)	Robusta suitable area (ha)	Share of Robusta total (%)	Combined area (ha)	Combined as % of state area
East Jaintia Hills	22,534.1	46.5	5,500.1	32.9	28,034.2	1.250
West Jaintia Hills	18,374.3	38.0	5,374.7	32.2	23,749.0	1.059

District	Arabica suitable area (ha)	Share of Arabica total (%)	Robusta suitable area (ha)	Share of Robusta total (%)	Combined area (ha)	Combined as % of state area
East Khasi Hills	5,658.4	11.7	–	–	5,658.4	0.252
Ri-Bhoi	1,842.8	3.8	4,480.3	26.8	6,323.1	0.282
South West Garo Hills	–	–	1,016.6	6.1	1,016.6	0.045
North Garo Hills	–	–	334.5	2.0	334.5	0.015
Total	48,409.6	100.0	16,706.2	100.0	65,115.8	2.903

Note: Percentages of state area are computed against Meghalaya's geographical area of 22,429 km² (2,242,900 ha): Arabica 2.158%, Robusta 0.745%. The combined column is additive and slightly overstates the aggregate where the two envelopes overlap, chiefly in Saipung, Thaadlaskein, Khliehriat, Laskein and Umsning, the blocks identified in Section 5.2 for elevation-stratified planting. Arabica is strongly concentrated, with 84.5% in the two Jaintia Hills districts, whereas Robusta is more evenly spread (26.8% in Ri-Bhoi, 8.1% in the Garo Hills).

4. Discussion

4.1 Species-specific suitability patterns

The separation between the two species mapped here is not a local peculiarity but the spatial expression of a well-documented physiological difference. *Coffea arabica* has a narrow thermal optimum near 18-22°C and suffers accelerated respiration, floral abortion, and impaired bean filling above approximately 24°C, whereas *Coffea canephora* sustains net carbon gain several degrees higher (DaMatta & Ramalho, 2006). In a landscape whose relief spans some 1,800 m over short horizontal distances, that physiological difference is converted directly into geography: elevation acts as a proxy for temperature, and the boundary between the two species follows the contour at which mean annual temperature crosses the Arabica threshold. The eastern Jaintia and Khasi uplands lie above that contour, and the western plateau and Garo lowlands are below it. The same mechanism has been inferred from global envelope models (Bunn et al., 2015) and from Ethiopian and Central American suitability studies (Fekadu & Andarege, 2025; Akafu et al., 2025); its reproduction here from independent regional data provides a measure of external consistency in the absence of any local precedent.

Two features of the Meghalaya case qualify that general picture. First, the state is among the wettest inhabited regions on earth, so precipitation is rarely the variable that excludes coffee; more often it constrains cultivation from above, since sustained excess rainfall on the southern escarpment impedes drying, favors berry disease, and complicates harvest. Rainfall therefore behaves asymmetrically between the two species, sitting closer to the optimum for Robusta across much of the plateau and closer to the upper tolerance limit for Arabica on the wettest slopes. Second, because Arabica's suitability here is bounded above by the elevation ceiling of the plateau and below by temperature, its envelope has no room to migrate upslope. Warming of the magnitude projected by Bunn et al. (2015) and Davis et al. (2012) would compress that envelope rather than displace it, and the area reported in Section 4.6 should accordingly be read as a present-day maximum. Robusta faces no equivalent ceiling within the state, although Kath et al. (2020) caution that its thermal tolerance has been overstated in the planning literature.

The heterogeneity between adjacent blocks carries a practical implication that the district-level figures obscure. Because suitability responds to elevation, slope, and aspect at scales finer than administrative units, blocks with similar mean conditions can differ severalfold in suitable area, and neighboring blocks within the same district can fall on opposite sides of a class boundary. Extension effort and planting material allocated on a district basis will therefore be misdirected in a predictable way, over-supplying blocks whose terrain lies mostly outside the envelope and under-supplying those whose terrain lies mostly inside it. Block-level targeting is not a refinement of district-level planning in this landscape; it is a precondition for it. This approach matters more for coffee than for an annual crop program, because a planting decision commits land for two to three decades, so the cost of a siting error is carried forward over the productive life of the stand rather than corrected in the following season.

All these patterns suggest that the constraint organization differs in kind and amount between the two species. The suitability of Arabica in Meghalaya is constrained by the high elevation on the upper limit and the temperature on the lower limit, which is limited to a narrow zone of elevation in the eastern districts, where it is the more climate-sensitive of the two species. Excessive rainfall and the upper elevation limit are the primary constraints on Robusta suitability; however, these limitations are more evenly distributed throughout the plateau, resulting in a wider but shallower suitable area. The above asymmetry, not the ranking of the total suitable area, is the most obvious finding with the best implications for planning and is elaborated upon in the comparative assessment.

4.2 Comparative assessment of arabica and robusta suitability

The two species are frequently treated in regional planning documents as interchangeable options to be selected on market grounds. The present results indicate that they are not interchangeable in Meghalaya, because the environmental envelopes that define them barely overlap. **Table 9** sets the two side by side across the ecological, spatial, and management dimensions that emerge from this analysis.

Table 9. Comparative ecological, spatial and management characteristics of Arabica and Robusta suitability in Meghalaya

Attribute	*Coffea arabica*	*Coffea canephora* (Robusta)
Optimal elevation band	900-1,600 m a.s.l.	100-800 m a.s.l.
Optimal mean annual temperature	18-22 °C	22-26 °C
Optimal annual rainfall	1,500-2,500 mm	2,000-3,000 mm
Core suitable districts	East and West Jaintia Hills, East Khasi Hills, Ri-Bhoi	East and West Jaintia Hills, Ri-Bhoi, plus North and South West Garo Hills
Spatial pattern	Concentrated; 84.5% of the suitable area in the two Jaintia Hills districts	Dispersed; 26.8% in Ri-Bhoi and 8.1% in the Garo Hills
Suitable area identified	48,409.6 ha (2.16% of the state)	16,706.2 ha (0.74% of the state)
Principal limiting factor in Meghalaya	Upper temperature limit and restricted high-elevation area	Excess rainfall on the wettest southern slopes and the upper elevation limit

Attribute	*Coffea arabica*	*Coffea canephora* (Robusta)
Exposure to warming	High; the suitable band shifts upslope and contracts as temperature rises	Lower; the species tolerates the warmer end of the observed range
Shade and agroforestry requirement	Obligate in practice; shade buffers heat and improves bean quality	Beneficial for erosion control and microclimate, but less critical for survival
Recommended deployment	Quality-led specialty production in cool upland blocks	Volume-led and climate-buffered production in warmer, lower blocks including the Garo Hills

There are three planning consequences from this comparison. Firstly, the narrow range of the Arabica envelope highlights the fact that the area of the Arabica envelope reported here is an upper bound that is likely to shrink with warming as observed by Bunn et al. (2015) and warned by Davis et al. (2012); expansion of the Arabica envelope should be aimed at the upper side of this envelope rather than at its warm edge. Second, Robusta should not be considered as the second choice. Despite the findings of Kath et al. (2020), showing that Robusta is more sensitive to temperature than it is often believed to be, its potential for geographical livelihood diversification is more widespread than coffee, due to its more widely distributed suitable area, particularly in the Garo Hills. Thirdly, the natural zones for elevation-stratified planting are the blocks where the two envelopes overlap (Saipung, Thaadlaskein, Laskein, Khliehriat, and Umsning), with Arabica planted on the upper slopes and Robusta planted on the lower slopes of the same catchment, thus distributing climatic risk within the same administrative area and making extension easier to deliver.

4.3 Coffee-based agroforestry as a nature-based solution and its contribution to the sustainable development goals

Nature-based solutions (NbS) are defined by IUCN as actions to protect, sustainably manage, and restore natural or modified ecosystems that address societal challenges while delivering benefits for human well-being and biodiversity (Cohen-Shacham et al., 2016). Coffee-based agroforestry fits that definition closely: a perennial crop established beneath a retained or planted canopy, addressing rural income insecurity, land degradation, and climate vulnerability through ecosystem function rather than engineered substitutes. Shade-coffee systems conserve more biodiversity than open plantations, stabilize soil on steep slopes, moderate microclimate, and accumulate carbon in biomass and soil (Jose, 2009; Jha et al., 2014; Sahoo et al., 2022). The framing matters in Meghalaya, where short-cycle shifting cultivation is under pressure and where policy must restore ecological function on land that remains under community management, rather than pursue land-sparing models that separate communities from the land they manage.

The effectiveness of any NbS depends on where it is placed. Poorly sited interventions lead to maladaptation, ecosystem damage, and wasted investment (Seddon et al., 2020; Chausson et al., 2020), which is precisely the gap a spatial suitability assessment fills. By mapping the biophysical preconditions at the block level and separately for each species, the present analysis converts a policy aspiration into a spatially explicit plan that can be applied

before sapling, nursery, and extension resources are committed. Section 4.6 sharpens the point: land is not the constraint, since the suitable area is roughly 144 times that currently cultivated; the question is which land.

The contribution of coffee-based agroforestry in Meghalaya to the 2030 Agenda (United Nations, 2015) is correspondingly broad, and **Table 10** maps the principal pathways together with the specific role of the present analysis in each.

Table 10. Pathways through which coffee-based agroforestry in Meghalaya contributes to the Sustainable Development Goals, and the role of the present spatial assessment.

Sustainable Development Goal	Pathway through coffee-based agroforestry in Meghalaya	Specific contribution of this study
SDG 1-No Poverty (1.4, 1.5)	Perennial cash income diversifies household earnings and reduces dependence on short-cycle shifting cultivation and wage migration	Delineates 65,115.8 ha across six districts where such income can be established on sound agro-ecological grounds, allowing poverty-targeted schemes to be spatially prioritized
SDG 2-Zero Hunger (2.3, 2.4)	Multi-strata systems intercrop coffee with fruit, spice, timber and food species, sustaining food production while raising land productivity	Species-specific siting lowers the risk of establishment failure that would otherwise displace food production without replacing the income
SDG 8-Decent Work and Economic Growth (8.3)	Nursery, harvesting, pulping, drying, roasting and marketing generate on-farm and off-farm employment, particularly for women in post-harvest processing	Concentrates processing and aggregation infrastructure in the blocks with sufficient contiguous suitable area to sustain it
SDG 12-Responsible Consumption and Production (12.2)	Shade-grown coffee under community tenure supports origin, organic and biodiversity-friendly certification	Provides the spatial evidence base underpinning origin and sustainability claims for Meghalaya specialty coffee
SDG 13-Climate Action (13.1, 13.2)	Canopy and soil carbon accumulation contribute to the tree-cover carbon sink; shade buffers heat and moisture extremes for the understorey crop	Maps climatically appropriate zones and so reduces the risk of maladaptive planting; supplies a spatial baseline for carbon accounting and climate finance
SDG 15-Life on Land (15.1, 15.3, 15.9)	Retained canopy conserves biodiversity relative to open cultivation, controls erosion on steep slopes and restores degraded fallow land	Excludes slopes above 35% and ecologically unsuitable terrain from the recommended expansion area, integrating biodiversity values into land-use planning
SDG 17-Partnerships for the Goals (17.16, 17.17)	Delivery depends on partnership between state agencies, Autonomous District Councils, village institutions, research bodies and buyers	Uses open datasets and a reproducible Google Earth Engine workflow that partner institutions can re-run, audit and extend without licensing cost

These pathways also connect the study to the current national commitments. India had the first National Agroforestry Policy (Government of India, 2014), and trees outside forests contribute to the additional carbon sink India has committed to through the expansion of forest and tree cover. Coffee agroforestry on community land in Meghalaya is a direct tool for this commitment, and suitability surfaces can be used to identify suitable implementation areas without ecological costs. The wider value of the work lies in what the surfaces make possible. They supply the spatial stratification needed to design a defensible carbon and biodiversity monitoring network so that nature-based solution claims for coffee agroforestry can be measured rather than asserted. Because the model is parameterized on climate, it can be rerun with downscaled projections to identify which Arabica patches are likely to become marginal and where a transition to different shade systems or species should begin now. The delineated zones also give carbon finance, biodiversity credits, and green investment a credible basis for reaching communities whose land is genuinely suitable, a long-standing difficulty in smallholder-scale financing. Finally, the framework transfers readily to other perennial crops of the Northeastern Himalaya, such as large cardamom, black pepper, areca, and cocoa, for which comparable spatial evidence is equally absent. The study is therefore offered less as a settled account of coffee than as a replicable model for evidence-based planning in an under-researched region.

5. Limitations

These results should be interpreted with some caveats. No field sampling or accuracy checking is done; thus, these maps are indicative of potential suitability, not actual suitability, the most important next step being stratified field sampling with a confusion matrix against surveyed plantations. Analytical rather than empirical sensitivity was evaluated, and a conservative bound was derived, but not the area reclassified under each perturbed weight vector. Climatic inputs were coarser than the analysis grid (WorldClim ~1 km, ERA5-Land ~11 km, resampled to 100 m), and results are intended to be read at the block and district level, rather than plot level. The climatology is fixed, and the Arabica region is the maximum possible today. There is no land-use or tenure masking, and the biophysical envelope of 65,115.8 ha in Table 8 will be reduced materially under community tenure. The socio-economic factors for adoption and biotic and management factors, such as leaf rust, stem borer, shade-tree composition, planting density, and cultivar choice, are excluded from the model. The weights are subjective and not elicited as such, and the thresholds are not continuous but rather discrete divisions separating ecologically and continuously graded transitions. Last but not least, there was no prior study from Meghalaya, and therefore only cross-validation was possible with Ethiopian, Central American, and southern Indian work, the results of which are thus a first spatial baseline, but not a settled account.

6. Conclusion

This study mapped the species-specific spatial suitability of *Coffea arabica* and *Coffea canephora* across Meghalaya using a GIS-based multi-criteria framework implemented in Google Earth Engine. The two species were found to occupy largely separate parts of the state: Arabica in the cooler, higher-elevation eastern districts, and Robusta across warmer and lower-lying areas extending into the Garo Hills. The difference between them is one of constraint

structure rather than of extent alone, which is why the two cannot be substituted for one another on market grounds. Together the two envelopes cover 65,115.8 ha, about 2.9% of the state and roughly 144 times the area presently under coffee, indicating that the binding constraint on expansion is the absence of siting guidance rather than the availability of biophysically suitable land. Because the assessment rests on a static climatology and has not yet been validated in the field, the surfaces should be treated as a first spatial baseline for prioritizing survey, pilot planting, and extension effort rather than as a substitute for either. On that basis they offer policymakers, planners, and development agencies a reproducible starting point for coffee-based agroforestry in Meghalaya.

Author Contributions

Arun Pratap Mishra conceived and designed the study, conducted the analysis, and wrote the original manuscript draft. Ankit Rawat supervised the research work, provided technical inputs, and contributed to writing and revising the manuscript. Shiv Narayan Yadav contributed to revising the manuscript. All authors have read, reviewed, and approved the final version of the manuscript.

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References

Akafu, T., Korecha, D., Garedew, W., & Amare, A. (2025). Modeling the current land suitability and future dynamics for coffee (*Coffea arabica* L.) cultivation under climate change scenarios in Western Ethiopia with MaxEnt model. *Earth Systems and Environment*, 1–18. https://doi.org/10.1007/s41748-025-00689-w

Altieri, M. A., & Nicholls, C. I. (2017). The adaptation and mitigation potential of traditional agriculture in a changing climate. *Climatic Change*, *140*(1), 33–45. https://doi.org/10.1007/s10584-013-0909-y

Bacelar, E., Pinto, T., Anjos, R., Morais, M. C., Oliveira, I., Vilela, A., & Cosme, F. (2024). Impacts of climate change and mitigation strategies for some abiotic and biotic constraints influencing fruit growth and quality. *Plants*, *13*(14), 1942. https://doi.org/10.3390/plants13141942

Behera, M. D., Behera, S. K., Barik, S. K., Mohapatra, M., & Mohapatra, T. (2025). Inter-linkage among climate, terrestrial and marine systems: Sustainable development perspectives. In M. D. Behera, S. K. Behera, S. K. Barik, M. Mohapatra, & T. Mohapatra

(Eds.), Sustainable development perspectives in earth observation (pp. 1–6). *Elsevier*. https://doi.org/10.1016/B978-0-443-14072-3.00024-1

Bunn, C., Läderach, P., Ovalle Rivera, O., & Kirschke, D. (2015). A bitter cup: Climate change profile of global production of Arabica and Robusta coffee. *Climatic Change*, *129*(1), 89–101. https://doi.org/10.1007/s10584-014-1306-x

Chausson, A., Turner, B., Seddon, D., Chabaneix, N., Girardin, C. A. J., Kapos, V., Key, I., Roe, D., Smith, A., Woroniecki, S., & Seddon, N. (2020). Mapping the effectiveness of nature-based solutions for climate change adaptation. *Global Change Biology*, *26*(11), 6134–6155. https://doi.org/10.1111/gcb.15310

Cohen-Shacham, E., Walters, G., Janzen, C., & Maginnis, S. (Eds.). (2016). Nature-based solutions to address global societal challenges. IUCN. https://doi.org/10.2305/IUCN.CH.2016.13.en

Dagar, J. C., Singh, A. K., & Arunachalam, A. (Eds.). (2014). Agroforestry systems in India: Livelihood security & ecosystem services (Vol. 10). Springer India. https://doi.org/10.1007/978-81-322-1662-9

DaMatta, F. M., & Ramalho, J. D. C. (2006). Impacts of drought and temperature stress on coffee physiology and production: A review. *Brazilian Journal of Plant Physiology*, *18*(1), 55–81. https://doi.org/10.1590/S1677-04202006000100006

Davis, A. P., Gole, T. W., Baena, S., & Moat, J. (2012). The impact of climate change on indigenous Arabica coffee (Coffea arabica): Predicting future trends and identifying priorities. *PLOS ONE*, *7*(11), e47981. https://doi.org/10.1371/journal.pone.0047981

De, U. K. (2011). Livelihood pattern, dependence on forest and causes of degradation in Meghalaya (SSRN Scholarly Paper). SSRN. https://doi.org/10.2139/ssrn.1810440

Dong, L. (2021). Toward resilient agriculture value chains: Challenges and opportunities. *Production and Operations Management*, *30*(3), 666–675. https://doi.org/10.1111/poms.13308

Dwivedi, S. K., Chandra, N., Mishra, A. P., Bahuguna, S., Srivastava, A., Arya, D., Singh, G., Đurin, B., Kranjčić, N., & Singh, R. (2025). Assessing the role of Alnus nepalensis D. Don in stabilizing landslide and its potential distribution: A case study from Uttarakhand, Western Himalaya. *Integrated Environmental Assessment and Management*, *21*(1), 105–116. https://doi.org/10.1093/inteam/vjae002

Erni, C. (2009, August 27–29). Shifting the blame: Southeast Asia's indigenous peoples and shifting cultivation in the age of climate change [Paper presentation]. Seminar on Adivasi/ST Communities in India: Development and Change, Delhi, India.

Erni, C. (Ed.). (2015). Shifting cultivation, livelihood and food security: New and old challenges for indigenous peoples in Asia. Food and Agriculture Organization of the United Nations, International Work Group for Indigenous Affairs, & Asia Indigenous Peoples Pact. http://www.fao.org/3/a-i4580e.pdf

Farr, T. G., Rosen, P. A., Caro, E., Crippen, R., Duren, R., Hensley, S., Kobrick, M., Paller, M., Rodriguez, E., Roth, L., Seal, D., Shaffer, S., Shimada, J., Umland, J., Werner, M., Oskin, M., Burbank, D., & Alsdorf, D. (2007). The shuttle radar topography mission. *Reviews of Geophysics*, *45*(2), RG2004. https://doi.org/10.1029/2005RG000183

Fekadu, A., & Andarege, B. (2025). GIS and parametric based coffee site suitability zonation in North Shewa zone of Oromia region, central Ethiopia. *Environmental and Sustainability Indicators*, *26*, 100674. https://doi.org/10.1016/j.indic.2025.100674

Food and Agriculture Organization of the United Nations. (1976). A framework for land evaluation (FAO Soils Bulletin No. 32). FAO.

Funk, C., Peterson, P., Landsfeld, M., Pedreros, D., Verdin, J., Shukla, S., Husak, G., Rowland, J., Harrison, L., Hoell, A., & Michaelsen, J. (2015). The climate hazards infrared precipitation with stations—A new environmental record for monitoring extremes. *Scientific Data*, *2*(1), 150066. https://doi.org/10.1038/sdata.2015.66

Getachew, M., Tolassa, K., De Frenne, P., Verheyen, K., Tack, A. J. M., Hylander, K., Ayalew, B., & Boeckx, P. (2022). The relationship between elevation, soil temperatures, soil chemical characteristics, and green coffee bean quality and biochemistry in southwest Ethiopia. *Agronomy for Sustainable Development*, *42*(4), 61. https://doi.org/10.1007/s13593-022-00801-8

Gogoi, B. (2015). Soil productivity management and socio-economic development through agroforestry in north-east India. *Asian Journal of Science and Technology*, *6*, 2048–2053.

Gold, M. A., & Garrett, H. E. (2021). Agroforestry nomenclature, concepts and practices. In H. E. Garrett, S. Jose, & M. A. Gold (Eds.), North American agroforestry (3rd ed., pp. 27–41). American Society of Agronomy, Crop Science Society of America, and Soil Science Society of America. https://doi.org/10.1002/9780891183785.ch2

Government of India. (2014). *National Agroforestry Policy 2014*. Department of Agriculture and Cooperation, Ministry of Agriculture.

Gorelick, N., Hancher, M., Dixon, M., Ilyushchenko, S., Thau, D., & Moore, R. (2017). Google Earth Engine: Planetary-scale geospatial analysis for everyone. *Remote Sensing of Environment*, *202*, 18–27. https://doi.org/10.1016/j.rse.2017.06.031

Hameed, A., Hussain, S. A., & Suleria, H. A. R. (2020). "Coffee bean-related" agroecological factors affecting the coffee. In J.-M. Mérillon & K. G. Ramawat (Eds.), Co-evolution of secondary metabolites (pp. 641–705). *Springer International Publishing.* https://doi.org/10.1007/978-3-319-96397-6_21

Hengl, T., Mendes de Jesus, J., Heuvelink, G. B. M., Ruiperez Gonzalez, M., Kilibarda, M., Blagotić, A., Shangguan, W., Wright, M. N., Geng, X., Bauer-Marschallinger, B., Guevara, M. A., Vargas, R., MacMillan, R. A., Batjes, N. H., Leenaars, J. G. B., Ribeiro, E., Wheeler, I., Mantel, S., & Kempen, B. (2017). SoilGrids250m: Global gridded soil information based on machine learning. *PLOS ONE*, *12*(2), e0169748. https://doi.org/10.1371/journal.pone.0169748

Hijmans, R. J., Cameron, S. E., Parra, J. L., Jones, P. G., & Jarvis, A. (2005). Very high-resolution interpolated climate surfaces for global land areas. *International Journal of Climatology*, *25*(15), 1965–1978. https://doi.org/10.1002/joc.1276

India Today NE. (2025, August 14). Meghalaya targets doubling coffee production as specialty crop gains momentum. https://www.indiatodayne.in/meghalaya/story/meghalaya-targets-doubling-coffee-production-as-specialty-crop-gains-momentum-1261193-2025-08-14

Jha, S., Bacon, C. M., Philpott, S. M., Méndez, V. E., Läderach, P., & Rice, R. A. (2014). Shade coffee: Update on a disappearing refuge for biodiversity. *BioScience, 64*(5), 416–428. https://doi.org/10.1093/biosci/biu038

Jose, S. (2009). Agroforestry for ecosystem services and environmental benefits: An overview. *Agroforestry Systems, 76*(1), 1–10. https://doi.org/10.1007/s10457-009-9229-7

Kath, J., Byrareddy, V. M., Craparo, A., Nguyen-Huy, T., Mushtaq, S., Cao, L., & Bossolasco, L. (2020). Not so robust: Robusta coffee production is highly sensitive to temperature. *Global Change Biology, 26*(6), 3677–3688. https://doi.org/10.1111/gcb.15097

Liere, H., Jackson, D., & Vandermeer, J. (2012). Ecological complexity in a coffee agroecosystem: Spatial heterogeneity, population persistence and biological control. *PLOS ONE, 7*(9), e45508. https://doi.org/10.1371/journal.pone.0045508

Majaw, I. (2025). From bean to brew: Cultural, environmental, and economic benefits of coffee cultivation in Meghalaya and its impact on indigenous livelihoods [Research report]. Chief Minister's Research Grant, Government of Meghalaya. https://cmrgmeghalaya.org/wp-content/uploads/2025/12/From-Bean-to-Brew-4th-revision-1.pdf

Malczewski, J. (2006). GIS-based multicriteria decision analysis: A survey of the literature. *International Journal of Geographical Information Science, 20* (7), 703–726. https://doi.org/10.1080/13658810600661508

Meghalaya Basin Development Authority. (2023). Smoky Falls Tribe coffee: Taking Meghalaya's indigenous coffee to the world. Government of Meghalaya. https://be.dev.mbda.mbma.org.in/smoky-falls-tribe-coffee-taking-meghalaya%E2%80%99s-high-quality-indigenous-coffee-world

Meghalaya Monitor. (2025, May 16). Govt explores coffee and cocoa plantations. https://meghalayamonitor.com/govt-explores-coffee-and-cocoa-plantations/

Muñoz-Sabater, J., Dutra, E., Agustí-Panareda, A., Albergel, C., Arduini, G., Balsamo, G., Boussetta, S., Choulga, M., Harrigan, S., Hersbach, H., Martens, B., Miralles, D. G., Piles, M., Rodríguez-Fernández, N. J., Zsoter, E., Buontempo, C., & Thépaut, J.-N. (2021). ERA5-Land: A state-of-the-art global reanalysis dataset for land applications. *Earth System Science Data, 13*(9), 4349–4383. https://doi.org/10.5194/essd-13-4349-2021

Mylliemngap, W. (2021). Agrobiodiversity and natural resource management in traditional agricultural systems of Northeast India. *Agrobiodiversity & Agroecology, 1*(1), 1–23. https://doi.org/10.33002/aa010101

Nagashree, M. K., Trivedi, S., Mukharib, D. S., Hebbar, R., Srivastav, S. K., & Chauhan, P. (2025). Earth observation-based mapping and site-suitability analysis of coffee agro-ecosystem in the face of climate change. In M. D. Behera, S. K. Behera, S. K. Barik, M. Mohapatra, & T. Mohapatra (Eds.), Sustainable development perspectives in earth observation (pp. 269–285). *Elsevier*. https://doi.org/10.1016/B978-0-443-14072-3.00011-3

Nasiro, K. (2024). The benefits of agroforestry coffee production systems: A review. *World Journal of Food Science and Technology, 8*(4), 86–105. https://doi.org/10.11648/j.wjfst.20240804.13

NER Databank. (n.d.). Coffee plantation. North Eastern Development Finance Corporation Ltd. Retrieved May 22, 2026, from https://databank.nedfi.com/ne-agriculture/coffee- plantation

North Eastern Spatial Data Repository. (n.d.). NESDR portal. Retrieved May 22, 2026, from https://www.nesdr.gov.in/

Plieninger, T., Muñoz-Rojas, J., Buck, L. E., & Scherr, S. J. (2020). Agroforestry for sustainable landscape management. Sustainability Science, 15(5), 1255–1266. https://doi.org/10.1007/s11625-020-00836-4

Pretty, J. (2018). Intensification for redesigned and sustainable agricultural systems. *Science, 362*(6417), eaav0294. https://doi.org/10.1126/science.aav0294

Priori, S., Pellegrini, S., Vignozzi, N., & Costantini, E. A. C. (2020). Soil physical-hydrological degradation in the root-zone of tree crops: Problems and solutions. *Agronomy*, *11*(1), 68. https://doi.org/10.3390/agronomy11010068

Raj, A., Jhariya, M. K., Banerjee, A., Jha, R. K., & Singh, K. P. (Eds.). (2024). *Agroforestry*. John Wiley & Sons.

Reed, J., Van Vianen, J., Foli, S., Clendenning, J., Yang, K., MacDonald, M., Petrokofsky, G., Padoch, C., & Sunderland, T. (2017). Trees for life: The ecosystem service contribution of trees to food production and livelihoods in the tropics. *Forest Policy and Economics*, *84*, 62–71. https://doi.org/10.1016/j.forpol.2017.01.012

Saaty, T. L. (2008). Decision making with the analytic hierarchy process. *International Journal of Services Sciences, 1*(1), 83-98. https://doi.org/10.1504/IJSSCI.2008.017590

Sahoo, G., Swamy, S. L., Wani, A. M., & Mishra, A. (2022). *Agroforestry systems for carbon sequestration and food security: Implications for climate change mitigation*. In P. K. Shit, P. P. Adhikary, G. S. Bhunia, & D. Sengupta (Eds.), Soil health and environmental sustainability: Application of geospatial technology (pp. 503–528). Springer International Publishing. https://doi.org/10.1007/978-3-031-09270-1_22

Sarma, K. K. (2026). *North East Himalayan ecosystem: Issues, challenges and need for technology interventions.* In S. P. Aggarwal, S. S. Kundu, & B. K. Handique (Eds.), Remote sensing of the North Eastern Himalayan ecosystem (pp. 1–20). Springer. https://doi.org/10.1007/978-981-95-3221-6_1

Sati, V. P. (2014). Towards sustainable livelihoods and ecosystems in mountain regions. Springer International Publishing. https://doi.org/10.1007/978-3-319-03533-8

Seddon, N., Chausson, A., Berry, P., Girardin, C. A. J., Smith, A., & Turner, B. (2020). Understanding the value and limits of nature-based solutions to climate change and other global challenges. *Philosophical Transactions of the Royal Society B*, 375(1794), 20190120. https://doi.org/10.1098/rstb.2019.0120

Sharma, N. (2023). Potential coffee production hot-spots using machine learning techniques: Nagaland and Manipur, India [Master's thesis, National College of Ireland]. NORMA Institutional Repository. https://norma.ncirl.ie/6661/

Survey of India. (n.d.). Digital products. Retrieved May 22, 2026, from https://onlinemaps.surveyofindia.gov.in/Digital_Product_Show.aspx

Tazebew, E., Tiruneh, F., & Anbes, Y. (2025). Ecological and socio-economic contributions of coffee-based agroforestry systems in Ethiopia: A systematic review. *Science Research, 13*(6), 148–158. https://doi.org/10.11648/j.sr.20251306.11

United Nations. (2015). Transforming our world: The 2030 Agenda for Sustainable Development (A/RES/70/1). United Nations General Assembly.