

RESEARCH ARTICLE

Climate requirements for cultivated *Liberica* coffee (*Coffea liberica*) and consequences for its use and development as a crop species

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Societal Impact Statement

The global coffee industry, supporting 25 million smallholder farmers, is vulnerable to climate change. Diversifying the coffee species portfolio beyond Arabica and robusta is a promising intervention. *Liberica* coffee could provide adaptive capacity, although its climate parameters for cultivation are poorly known. This study pioneers climate niche analysis for cultivated *Liberica*, benchmarking it against its indigenous populations and Arabica coffee. Our analyses show that cultivated *Liberica* grows in warmer, wetter and less seasonal climates than its wild counterparts and exhibits distinct climate tolerances from Arabica. The results provide intelligence for integrating *Liberica* as a resource for a climate-resilient coffee portfolio.

Summary

- To secure the global coffee sector against climate change, diversification beyond the market-dominant Arabica (*C. arabica*) and robusta (*C. canephora*) could become a critical adaptation strategy for many farmers. This contribution provides the first comprehensive analysis of the cultivated (fundamental) niche of *Liberica* (*C. liberica*) to identify optimal climate parameters and suitable locations for cultivation.
- Environmental niche profiling was applied to a global dataset of wild (realised) and cultivated (fundamental) occurrences to quantify climate parameters for this species. This was supported by a species distribution model (SDM) for *Liberica* in Upper West Africa and an in-depth analysis of this coffee species in Malaysia, under current and future climate projections. Niche modelling for wild Arabica was used to provide a climate parameter benchmark for wild *Liberica*.
- Our research demonstrates that the cultivated climate niche of *Liberica* extends beyond its wild niche, enabling farming in warmer, wetter and less seasonal climates. Critically, the study reveals that some of the major cultivation areas, such as Sarawak (Malaysia), operate at the edge of the cultivated niche.

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- These findings expand our understanding of key climate parameters for Liberica, providing a data-driven guide for its integration into farming systems and breeding work. While confirming its promise as a climate-resilient crop species, realising the potential of Liberica will require targeted research and development to overcome its known agronomic and processing challenges.

KEYWORDS

Arabica coffee, *Coffea liberica*, climate change, climate profiling, climate resilience, Liberica coffee, niche modelling

1 | INTRODUCTION

Future-proofing global coffee supply is an international imperative that has yet to be adequately addressed, despite mounting evidence of systemic vulnerability to climate change (Kath et al., 2022). The coffee sector's overwhelming reliance on a duopoly of Arabica (*Coffea arabica*) and robusta (*C. canephora*), which comprise 63% and 37% of global production, respectively (ICO, 2025), has created an inherently precarious global supply chain (Davis et al., 2019). Both species exhibit marked climate sensitivity (Cabangbang-Jaranilla et al., 2025; Craparo et al., 2015; Davis et al., 2012, 2019, 2021; Kath et al., 2022; Tournebize et al., 2022), with projections forecasting sharp declines under future climate scenarios, including a potential Arabica yield reduction of up to 50% in key growing regions (Kath et al., 2022; Moat et al., 2017). The convergence of a changing climate (temperatures, precipitation and seasonality shifts), increased frequency and severity of extreme weather events and heightened pest and disease pressure (Alfonsi et al., 2019; Davis et al., 2021; Jaramillo et al., 2011), against a growing demand for coffee (2%–2.5% increase per year) (ICO, 2025), is driving global coffee stock shortfalls and unprecedented market volatility (ICO, 2023, 2025). This crisis represents a fundamental threat to both the economic stability of 25 million smallholder farmers, for which coffee is their primary source of income, and the vulnerability of the global coffee supply chain (Vega et al., 2003).

Species diversification has emerged as a promising pathway to enhance the adaptive capacity of the coffee sector under climate change (Bertrand et al., 2023; Davis et al., 2019, 2021, 2022). Liberica coffee (*C. liberica*) is one of several compelling, climate resilient candidates for this role (Davis et al., 2022). Recently, the taxonomic delimitation of Liberica has been redefined, considerably restricting the native range of this species to Upper West Africa (Sierra Leone, Liberia, Ivory Coast, Ghana and Nigeria) (Davis et al., 2025). Excelsa coffee, formerly considered a botanical variety of Liberica (as *C. liberica* var. *dewevrei*), has been recognised as a separate species (*C. dewevrei*), restricted mainly to central Africa (Davis et al., 2025). Hereafter, Liberica refers to *C. liberica*, as redefined by Davis et al. (2025). Unfortunately, only 19 wild populations of Liberica have been recorded to date (Davis et al., 2025), constraining our current understanding of its wild (realised) climate niche, that is, the full range of environmental conditions where the species can survive and reproduce. This is distinct from its cultivated (fundamental) niche, that is,

the actual range of climate conditions that this species is currently cultivated under rain-fed conditions. This distribution is heavily influenced by human intervention, in particular, due to historical and geopolitical factors.

During the later part of the 19th century, Liberica was distributed within 30 countries, due to its resistance to coffee leaf rust disease (*Hemileia vastatrix*) and adaptability to hot, and often wet (high precipitation), humid lowlands where Arabica failed, or could not be cultivated (Hooker, 1872, 1876, 1877, 1881, 1882). However, the promise of Liberica quickly unravelled due to multiple challenges, including processing difficulties that compromised flavour quality, economic pressure from low-cost Brazilian Arabica and the emergence and rapid uptake of robusta in the early 20th century as a high-performing crop species (Davis et al., 2022, 2025; McCook, 2014). By the early 1900s, Liberica had largely faded from commercial prominence, with its present-day global cultivated distribution subsequently presenting a misleading impression of where it can be farmed (McCook, 2014).

This contribution sets out to address four critical questions: (1) What is the cultivated niche of Liberica coffee, and how does it compare to that of the known wild niche? (2) What are the optimal climate limits for the cultivation of Liberica? (3) What regions possess suitable climatic conditions for the successful cultivation of Liberica? (4) What climate resilience advantages does Liberica offer compared to Arabica? We focus on Malaysia, which is noted as one of the world's largest producers of Liberica (also the Philippines and Indonesia) (Abdul Wahab & Mohammad Nor, 2016), and Upper West Africa, the native range of Liberica and historically the largest producer of Liberica (Sierra Leone, Ghana, Liberia; Davis et al., 2022). Substantial expansion is envisaged for Liberica cultivation in Malaysia, with new plantations, some of multiple thousand hectares, either planned or already in progress (K. Wee Ting Lee, pers. comm.). This expansion is expected to result in roughly 10,000 acres of Liberica in Malaysia (Department of Agriculture, Malaysia, 2023). It has been reported that Liberia is aiming to reinvigorate Liberica production (IITA, 2025). An accurate understanding of climate preferences for successfully cultivating Liberica is therefore a high priority for ensuring the effective allocation of investment.

We utilise a newly constructed, and refined, dataset of cultivated occurrences and wild occurrence data (Davis et al., 2025), undertake comparative analyses of climate parameters using the CHELSA BIOCLIM dataset (Karger et al., 2017) and employ a species distribution

model (SDM) for *Liberica* in Upper West Africa. This contribution assesses the climate suitability for farming *Liberica*, expanding our understanding from its well-defined (but data-scarce) wild niche, and identifies potential climate resilient characteristics.

2 | MATERIALS AND METHODS

2.1 | Occurrence data collection and processing

An initial dataset of over 2600 cultivated records was compiled from the Global Biodiversity Information Facility (GBIF.org, 2025a, 2025b), published literature (Ghawas, 2006; Mubarak et al., 2019; Panaligan et al., 2021; Wellman & Cramer, 1957) and herbarium records (held at: The Natural History Museum, London, UK [BM]; Meise Botanic Garden, Belgium [BR]; Royal Botanic Gardens, Kew UK [K]; Muséum National d'Histoire Naturelle, Paris, France [P], and Naturalis Biodiversity Center, Leiden, Netherlands [WAG]—abbreviations after Thiers, 2017). Cultivated records were defined as those under direct human management, intentionally planted or naturalised, or having escaped from cultivation. To prevent bias from artificially altered local conditions, records from sites known or assumed to be irrigated (e.g., botanical gardens, urban green spaces) were excluded. GBIF records were filtered to retain only those with verifiable imagery (photographs of living plants or herbarium specimens) and locality information. Using records without imagery would likely introduce errors, particularly given the historical taxonomic confusion surrounding this species (Davis et al., 2025). Each record was manually checked against the key identification features for *Liberica* (Davis et al., 2025) or independently verified by a taxonomic expert (A.P. Davis) or both. The resulting dataset of 116 occurrences was filtered to remove statistical outliers. This was necessary as the resolution of the CHELSA Bioclim data (1 km) (Karger et al., 2017) will not capture fine-scale microclimates characteristic of small islands and so forth. Therefore, to prevent the model from learning these artificial conditions, we removed statistical outliers. Occurrence points with environmental values falling beyond $\times 1.5$ the interquartile range were excluded. While this reduced the dataset size to 86 cultivated occurrences (Dataset S1), it ensured the SDM was trained on the species' core microclimate limits rather than spatial artifacts.

A separate verified dataset of 19 wild *Liberica* records, obtained from published research (Davis et al., 2025), was subject to the same filtering processes. Wild records were defined as those that occur naturally, independent of human management. Similarly, an *Arabica* dataset of wild occurrences was sourced from published data (Davis et al., 2021). Neither species had records associated with surface water bodies, or flooded landscapes, which would largely invalidate BIO12–BIO19 (Karger et al., 2017), due to excessive non-precipitation soil water availability.

To address spatial autocorrelation, the datasets were spatially thinned to a minimum distance of 1 km using the spThin package (Aiello-Lammens et al., 2015) and R software (R Core Team, 2021). This process yielded final datasets of 86 cultivated *Liberica*

(no occurrences removed), 13 wild *Liberica* (Dataset S2) and 193 wild *Arabica* occurrences (Davis et al., 2021). See Table S1 for an overview of the data cleaning process.

2.1.1 | Historical data collection

To contextualise the current range of *Liberica*, a historical analysis was conducted. Records detailing the global dissemination of *Liberica* during the late 19th century were compiled from literature (Cruwell, 1878; De Wildeman, 1906; Hooker, 1872, 1876, 1877, 1881, 1882; Royal Botanic Gardens, Kew, 1890; McCook, 2014) and archival sources (herbarium and other museum collections). These records refer specifically to *C. liberica*. Historical locations were compared against the present-day occurrence dataset to identify regions where cultivation has persisted over time.

2.2 | Environmental data

To model the climate niche, 19 Bioclim variables were acquired from the CHELSA V2.1 database at a global spatial resolution of approximately 1 km (30 arc-seconds) resolution (Karger et al., 2017). Elevation and soil data were acquired from the geodata package in R (Hijmans et al., 2024).

2.3 | Climatic niche comparisons

To quantify differences between the wild and cultivated niches of *Liberica*, values for all 19 variables were extracted for the cultivated and wild occurrences. The Shapiro–Wilk test was used to assess data normality. A *t*-test was applied to normally distributed variables ($p > 0.05$), while a non-parametric Wilcoxon rank-sum test was used for all other variables to identify significant differences. The same statistical analysis tests were run to compare wild *Liberica* and *Arabica*. To assess niche expansion in environmental space independent of geographic availability, we performed a principal component analysis (PCA) (Figures 1 and S1).

2.4 | Species distribution modelling for high suitability areas in Upper West Africa

To quantify potential suitability within the native range *C. liberica* (Davis et al., 2025), the model was restricted to Upper West Africa (Figure 2). This geographic focus ensures environmental relevance, avoiding biases associated with modelling across globally diverse, non-native environments (Soley-Guardia et al., 2024). The final training dataset consisted of 17 cultivated *C. liberica* occurrence records. To explicitly mitigate the risk of local overfitting inherent in small datasets, a strict spatial thinning protocol (1 km distance) was enforced on these records prior to modelling. These were paired with

300 pseudo-absences generated via spatially constrained random sampling, maintaining a minimum 1 km buffer from any presence record. This sample size was selected following sensitivity analyses

that evaluated pseudo-absence counts ranging from 100 to 1200 (in increments of 100) to determine which yielded the best model performance (see [Code S1](#)).

Prior to modelling, an initial screening based on predictive importance (area under curve; AUC) was performed on 19 bioclimatic variables, as well as soil and elevation data. Variables with low predictive power, including soil type and elevation, likely limited by the 1 km spatial resolution, were excluded. The remaining variables underwent multicollinearity analysis using Pearson's correlation matrix; for pairs with a correlation coefficient $|r| > 0.9$, the less biologically informative variable was removed. A lenient threshold was adopted to avoid premature information loss (Soley-Guardia et al., 2024), with model complexity instead managed through hyperparameter tuning.

A performance-weighted ensemble model was developed by stacking maximum entropy (MaxEnt) (Phillips et al., 2006), random forest (RF) (Breiman, 2001) and gradient boosting machine (GBM) (Friedman, 2001). Normalised weights were derived from the continuous Boyce Index (CBI), using the tidysdm framework (Leonardi et al., 2024). This ensemble approach was selected to maximise predictive power (Zhang et al., 2022) and robustness (Araújo & New, 2007), specifically to mitigate the overfitting risks associated with single algorithms and limited occurrence records (Breiner et al., 2015).

To validate model robustness, a stratified k-fold cross-validation ($k = 4$) was employed. While random cross-validation can theoretically inflate performance metrics due to spatial autocorrelation (Roberts et al., 2017), this approach was the only viable statistical method

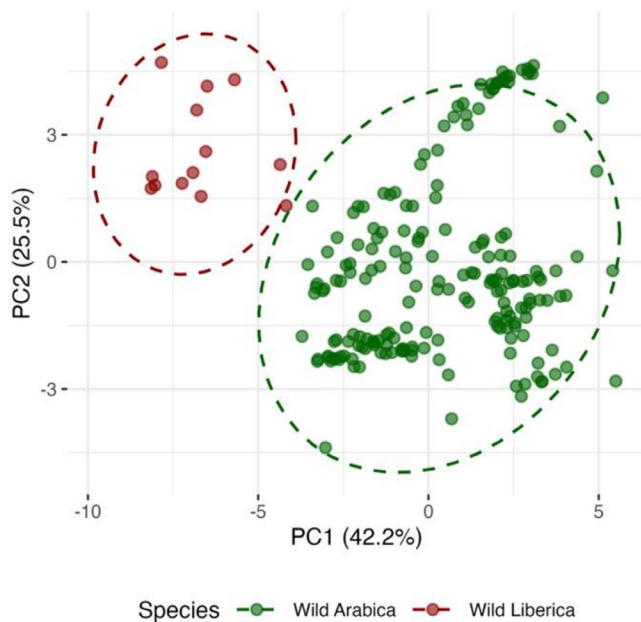


FIGURE 1 Principal component analysis (PCA) between wild Liberica and Arabica.

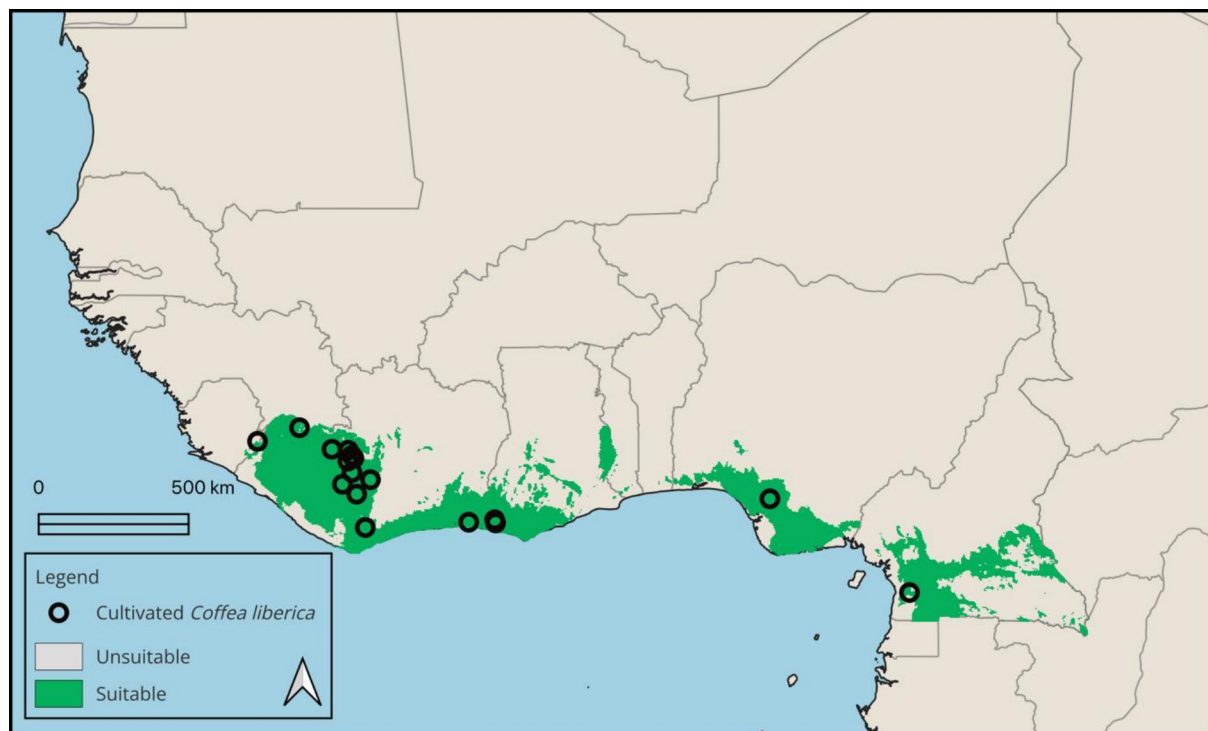


FIGURE 2 Predicted habitat suitability for wild Liberica in Upper West Africa. A map of predicted suitable (green) and unsuitable (grey) distribution for Liberica. The model is based on the cultivated occurrence data shown as black circles. See confidence variation in [Figure S2](#).

to maintain model stability given the data paucity ($n = 17$). To mitigate the potential for local overfitting and spatial autocorrelation associated with this method, a strict spatial thinning protocol was applied prior to modelling. The value of k was selected after evaluating model stability across a range (2–10) of fold numbers. Finally, an inclusive suitability threshold of 0.15 was applied to the ensemble map to produce a binary prediction of suitable versus unsuitable habitats. Both the True Skill Statistic (TSS: 0.26) and Lowest Presence Threshold (LPT: 0.48) were tested; however, given the small number of presence points, an inclusive threshold (0.15) was considered the best approach to maximise sensitivity and map the entire potential range, aligning with the exploratory objective of this SDM.

2.5 | Potential range estimation for Upper West Africa

We assessed the species ranges using Area of Occupancy (AOO), the measure of the area in which a species occurs (IUCN, 2012) via the SDM, as a comparator to that produced using recorded ground point data (Davis et al., 2025). The AOO was calculated as the total area of all cells, at a 2×2 km grid, classified as suitable from the binary output from the ensemble model, using terra (Hijmans, 2020). To interpret the predicted range, a confidence map (Figure S2) based on the standard deviation across algorithms was generated, distinguishing between high-consensus core areas and broader, lower consensus potential zones. High and low confidence was defined by Mean SD (0.36). The AOO value was compared against published figures derived from wild-only data (Davis et al., 2025) to quantify differences in the species' estimated range. Although the estimates in Davis et al. (2025) rely on presence-only data, rather than modelled distributions, and are therefore not directly comparable, they serve as a useful indicator of the minimum AOO.

3 | RESULTS

3.1 | Global distribution and climate niche of cultivated Liberica

The global distribution of cultivated Liberica is far greater than its wild distribution. Comparing the 34 documented introductions in the late 19th century to current evidence of occurrence, the species has persisted, to a greater or lesser extent, in 21 locations (e.g., countries, states and small island nations), a persistence rate of 61.8% (see Table S2 and Figure S3). The total known distribution of cultivated Liberica covers 52 countries and overseas territories (Figure 3).

Significant differences were observed across 13 of the 19 Bioclim variables (Karger et al., 2017, Table S3), confirming that cultivated Liberica occupies an environmental niche distinct from its wild origins (Table 1), confirmed by a PCA (Figure S1). The cultivated envelope is broadly characterised by a shift toward hydrological and temperature stability.

The most pronounced niche separation occurs in precipitation. While wild populations endure distinct seasonality, cultivated Liberica is predominantly grown in environments with consistent year-round rainfall (Figure 4). This is most evident during the driest quarter (BIO17), where cultivated locations receive a mean of 327 mm compared to just 80 mm in the wild, a fourfold increase in water availability. This preference for a seasonal, wet environment is reinforced by significantly lower precipitation seasonality (BIO15) in the cultivated niche (45 vs. 67).

3.2 | Global climate suitability analysis

3.2.1 | West African climate suitability potential and threats

The individual algorithms selected for the final ensemble model demonstrated strong predictive performance, achieving CBI scores of 0.858 (MaxEnt), 0.952 (RF) and 0.925 (GBM) (see Table S4 for all performance results). The model predicts a climatically suitable area that exceeds the species' currently known wild range (Davis et al., 2025). The Area of Occupancy (AOO) expands from recorded 52 km² to a predicted 388,892 km² (Figure 2). While this prediction identifies the full potential range, there was variation among the individual algorithms; random forest (7129 km²) and GBM (1943 km²) identified a restricted core, while MaxEnt (722,748 km²) predicted a broader area of suitability.

3.2.2 | Climate suitability for cultivating Liberica

The cultivated climate niche of Liberica is characterised by temperature and precipitation stability (Table 1). Unlike wild populations, cultivated Liberica occupies environments free from seasonal low temperatures, with substantial precipitation sustained during the driest quarters. See Table 1 for niche defining bioclimatic variables and Table S2 for the full results.

3.2.3 | Climate suitability for Liberica in Malaysia

Sites from the Malaysian states of Sabah and Sarawak consistently represent the wet extreme of the global cultivated niche (BIO12: 2653 and 3193 mm, respectively) (Table S5), exceeding the annual mean for wild populations (2215 mm), the annual mean for globally cultivated Liberica (2561 mm) and the annual mean for Peninsular Malaysia (2402 mm). These results correspond to rainfall data and models for Malaysia (Tan et al., 2015). Notably, the dry season is effectively absent in Malaysia, with the driest quarter receiving seven times that of the wild niche (BIO17, Table S5). Values for precipitation seasonality (BIO15) are extremely low for all Malaysian sites (mean of 26), falling well below the wild niche (mean of 67) and global value for cultivated Liberica (45).

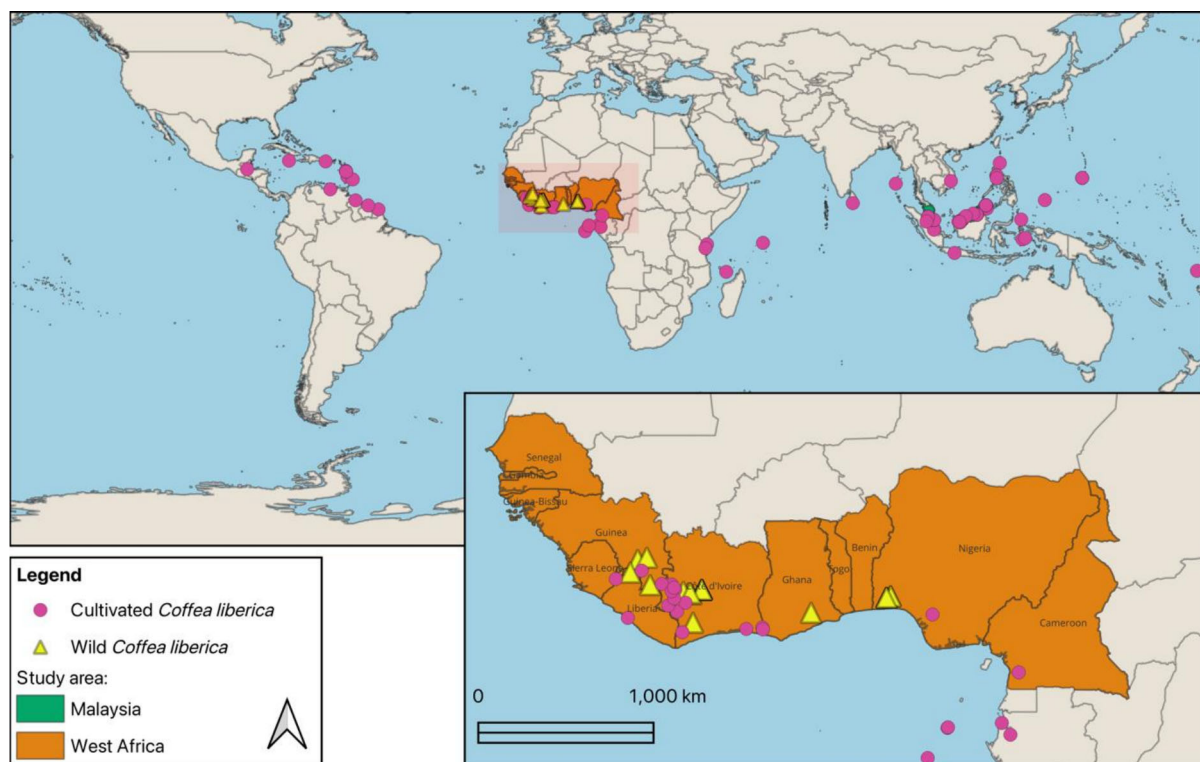


FIGURE 3 Distribution of cultivated and wild Liberica (1886–2023). Cultivated occurrence points shown as pink dots and wild occurrence points shown as yellow triangles. Both study areas are highlighted, Malaysia in green and West Africa in orange. An inset of West Africa is provided to see the distribution of wild and cultivated occurrences in more detail. Provenance and processing of occurrence data are described in Section 2.1. Map made in QGIS, base map from natural earth.

TABLE 1 Comparison of key Bioclim variables for the wild (realised) and cultivated (fundamental) niches of Liberica, with significance of differences (p value) between mean values.

Climate variable	Test used	p value	Significance	Wild mean $\pm$ SD	Cultivated mean $\pm$ SD
BIO1 (annual mean temperature)	Wilcoxon	0.000195	***	24.6 $\pm$ 0.9	25.7 $\pm$ 0.9
BIO4 (temperature seasonality)	Wilcoxon	9.79E–05	***	110.3 $\pm$ 21.8	70.5 $\pm$ 35.3
BIO5 (max temperature of warmest month)	t -test	6.83E–06	***	32.2 $\pm$ 1.2	29.9 $\pm$ 1.2
BIO6 (min temperature of coldest month)	t -test	0.000117	***	20.1 $\pm$ 1.4	22.2 $\pm$ 1.8
BIO7 (temperature annual range)	t -test	8.94E–09	***	12.1 $\pm$ 1.6	7.7 $\pm$ 3.0
BIO15 (precipitation seasonality)	Wilcoxon	0.000208	***	67 $\pm$ 11.0	45 $\pm$ 20.3
BIO17 (precipitation of driest quarter)	Wilcoxon	3.73E–05	***	80 $\pm$ 42.9	327 $\pm$ 222.7
BIO18 (precipitation of warmest quarter)	t -test	8.79E–11	***	312 $\pm$ 74	562 $\pm$ 203

Note: Standard deviation is marked as ($\pm$ SD). Non-significant results are marked 'ns'. See DatasetS3 for all Bioclims, also including quartile range, min and max values.

* $p < 0.05$. ** $p < 0.01$. *** $p < 0.001$.

The Malaysian mean annual temperature average for the sample sites (BIO1, 26.1°C) exceeds both the wild (24.6°C) and cultivated mean (25.7°C) (Tables 1 and S5). However, this figure is skewed by the higher mean temperatures in Peninsular Malaysia (26.7°C) and Sabah (26.4°C), whereas Sarawak (25.7°C) is more aligned to the cultivated mean (Table S5). For temperature seasonality, Malaysian sites are characterised by highly stable thermal conditions (BIO4), with mean values of 40.3 falling well below the wild (110.3) and cultivated

(70.5) niche mean. The most thermally stable conditions were found in Sarawak (mean 33.1), while Sabah had the highest regional seasonality (mean 49.3), and Peninsular Malaysia exhibited an intermediate value of (mean 45.2).

We had one high elevation record for Sarawak, from the Bario Highlands at 1072 m elevation (DatasetS4). This statistical outlier was removed during the thinning step (see Section 2.1). Bioclim data for this one locality (DatasetS4) shows that although the mean

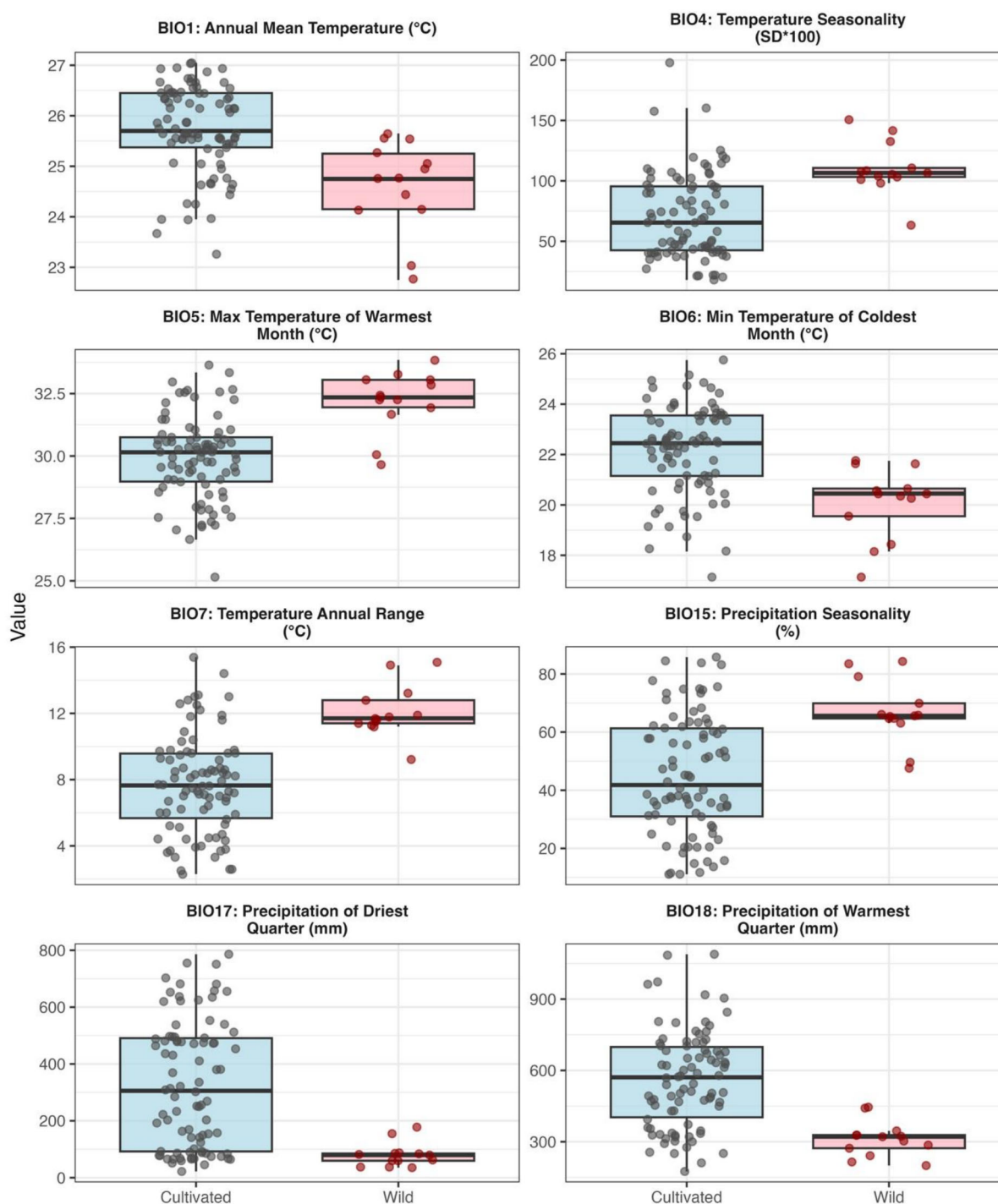


FIGURE 4 Comparison of key Bioclim variables for wild and cultivated Liberica populations. Box and whisker plots show climate parameters for cultivated (blue; left) and wild (red; right) populations across eight statistically significant Bioclims. Individual points are occurrence records. See Figure S5 for all 19 Bioclims and Table S3 for Bioclim variable definitions.

annual temperature (BIO1) is substantially lower (21°C) than the mean for Malaysia (26.1°C), most of the other key Bioclim precipitation variables are within the range of the other Sarawak samples. Even though mean annual precipitation (2656 mm) was lower than lowland Sarawak, precipitation seasonality was very low (BIO15 = 9.9).

3.3 | Climate variables of Liberica compared with Arabica

A comparison of the climatic niches of wild Liberica and wild Arabica revealed significant differences in 16 of the 19 Bioclim variables (Table 2).

TABLE 2 Comparison of Bioclim variables for the wild Arabica and wild Liberica niches, with significance of difference (*p* value).

Bioclim variable	Test used	<i>p</i> value	Significance	Wild Arabica mean ± SD	Wild Liberica mean ± SD
BIO1 (annual mean temperature)	Wilcoxon	6.82E−13	***	19.1 ± 1.7	24.6 ± 0.9
BIO2 (mean diurnal range)	Wilcoxon	1.09E−12	***	10.4 ± 1.0	7.9 ± 0.6
BIO3 (isothermality)	Wilcoxon	8.40E−10	***	0.73 ± 0.04	0.65 ± 0.05
BIO4 (temperature seasonality)	Wilcoxon	0.00382	**	97.7 ± 30.1	110.3 ± 21.8
BIO5 (max temperature of warmest month)	Wilcoxon	2.75E−12	***	27.1 ± 2.1	32.2 ± 1.2
BIO6 (min temperature of coldest month)	Wilcoxon	7.06E−13	***	12.9 ± 2.0	20.1 ± 1.4
BIO7 (temperature annual range)	Wilcoxon	6.05E−09	***	14.2 ± 1.0	12.1 ± 1.6
BIO8 (mean temperature of wettest quarter)	Wilcoxon	8.25E−13	***	18.3 ± 1.6	23.6 ± 1.0
BIO9 (mean temperature of driest quarter)	Wilcoxon	6.96E−13	***	19.7 ± 1.8	25.2 ± 1.0
BIO10 (mean temperature of warmest quarter)	Wilcoxon	6.86E−13	***	20.5 ± 1.9	26.2 ± 0.9
BIO11 (mean temperature of coldest quarter)	Wilcoxon	9.10E−13	***	18.1 ± 1.7	23.2 ± 0.9
BIO12 (annual precipitation)	Wilcoxon	0.704	ns	1982 ± 524.7	2215 ± 531.1
BIO13 (precipitation of wettest month)	Wilcoxon	0.0043	**	324 ± 155.9	377 ± 118.5
BIO14 (precipitation of driest month)	Wilcoxon	4.32E−10	***	41 ± 17.9	16 ± 10.4
BIO15 (precipitation seasonality)	Wilcoxon	0.0701	ns	56 ± 15.9	67 ± 11.0
BIO16 (precipitation of wettest quarter)	Wilcoxon	0.0122	*	813 ± 66.9	989 ± 331.5
BIO17 (precipitation of driest quarter)	Wilcoxon	3.43E−05	***	141 ± 58.9	80 ± 42.9
BIO18 (precipitation of warmest quarter)	Wilcoxon	0.515	ns	345 ± 144.2	312 ± 74
BIO19 (precipitation of coldest quarter)	Wilcoxon	0.000164	***	686 ± 186.3	962 ± 357

Note: Standard deviation is marked as (± SD). Non-significant results are marked 'ns'. See Figure S7 for all Bioclims visualised as box and whisker plots and Dataset S5 for quartile range, min and max values.

p* < 0.05. *p* < 0.01. ****p* < 0.001.

Liberica occupies a warmer thermal niche than Arabica. Its mean annual temperature (BIO1) is significantly higher at 24.7°C compared with 19.1°C for Arabica (a difference of 5.6°C). This pattern persists across all temperature metrics. Furthermore, Liberica demonstrates a greater tolerance for heat extremes, with a mean temperature of the warmest month (BIO5) of 32.2°C, well above the mean value for Arabica at 27.1°C (a difference of 5.1°C). A critical divergence is the minimum temperature of the coldest month (BIO6), where the threshold for Liberica is 20.1°C, a full 7.2°C warmer than that of Arabica (12.9°C).

Liberica inhabits locations with more rainfall during the wettest quarter and coldest quarter. Conversely, it also experiences a more pronounced dry season, receiving significantly less rainfall during the driest quarter (BIO17) than Arabica (mean 79 mm vs. 141 mm). A PCA confirms a clear separation between the niches of the two species, with 67.7% climatic variation (Figure 1).

4 | DISCUSSION

With a global-wide distribution spanning 52 countries and overseas territories, the cultivation of Liberica occupies an area that is much broader than its native range. A 61.8% persistence rate, that is, modern-day occurrence in 21 of 34 countries it was originally disseminated to in the late 19th century, underscores the adaptability of this species to exist in 'novel' environments (Table S2). While this

persistence may suggest a high level of suitable climates in these cultivated locations, it is also plausible that it reflects a high level of climate plasticity within the species, allowing original indigenous genotypes to survive under a wide range of environmental conditions. Adaptive processes may also be in play as Liberica is mainly propagated by seed and some introductions are over 150 years old. Whilst a minimum reproductive cycle, of less than 5 years, allows for numerous generations, adaptation may be limited by the long lifespan of individual trees (we estimate 30–60 years) and a likely restricted gene pool from limited original introductions, unless separate introductions were made from multiple gene pools, and whether there was mixing of genotype groups before or after dissemination. Crucially, the current cultivated distribution represents a realised niche heavily filtered by anthropogenic history and economic viability, rather than biological limits alone. Consequently, our model predictions likely underestimate the species' true potential range in regions where Liberica was never historically introduced or replaced by other crops, limiting the ecological inferences that can be drawn from presence-only data.

4.1 | Defining the optimal climate parameters for farming Liberica

Our analysis reveals an extended cultivated niche that is warmer and less seasonally variable in both precipitation and temperature than the

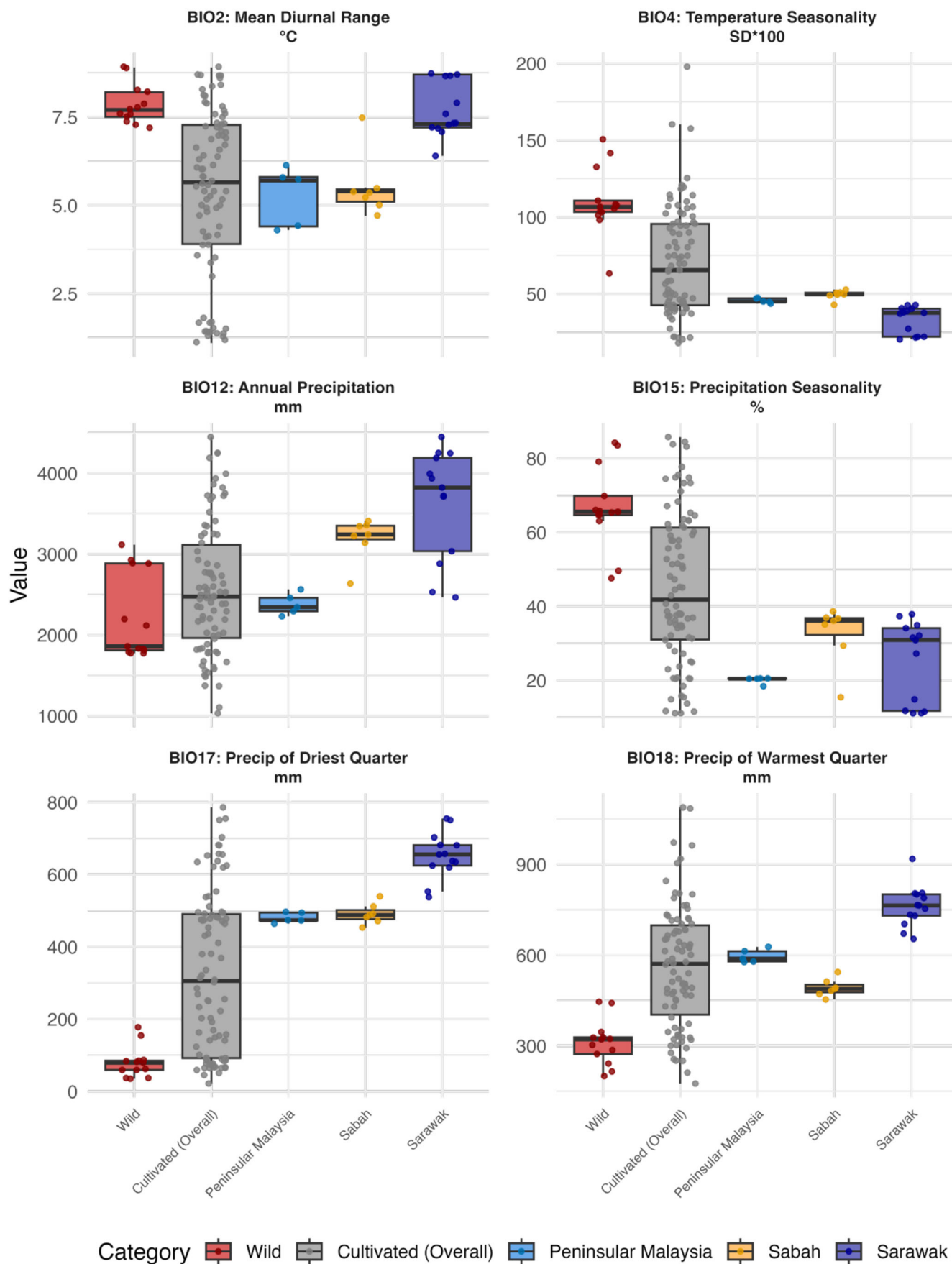


FIGURE 5 Legend on next page.

wild niche (Figure 4). Regarding precipitation, the critical divergence is not the total volume of rainfall, as evidenced by the similar mean annual precipitation values (Table 1) but rather the timing and intensity. Indeed, the wild climate niche of Liberica is defined by a distinct dry and wet season (Davis et al., 2025). A dry period often functions as a trigger for synchronous flowering and fruiting, a common phenomenon well-documented in other coffee species (Crisosto et al., 1992; Villers et al., 2009). This helps to standardise harvest times. Conversely, the cultivated niche has consistently high rainfall, leading in some cases to near-continuous, year-round flowering and fruiting. This complicates harvesting efforts due to the need to hand-pick throughout the year rather than in one distinct season. However, for smallholder farmers living in remote areas where labour resources are limited, this is not necessarily a disadvantage as it allows them to avoid sudden labour pressure that comes with a single concentrated harvest season. Instead, they can harvest and process gradually in small batches each month, making it feasible to operate with smaller scale equipment and lower infrastructure and labour costs. Other complications of year-round rainfall (low precipitation seasonality) include the extended post-harvest drying period, elevating the risk of fungal and bacterial growth during drying and storage, compromising the overall yield and green coffee quality (Jakkaew et al., 2024). There are also likely to be complications with plant health (see below). Therefore, although Liberica can survive in a broader cultivated niche, there are possible trade-offs in terms of yield, quality and processing techniques to consider.

A similar, though less pronounced, pattern of divergence emerges with temperature. Cultivated populations may experience hotter, year-round temperatures, while wild populations experience more pronounced monthly temperature extremes (Table 1). This demonstrates the adaptability of Liberica to be cultivated in locations with temporally less variable temperatures. However, a closer inspection of the upper temperature limits of the cultivated niche reveals a key overlap: the warmest quarter (BIO5) (Q3: 30.8°C) approaches the mean of the wild niche (32.2°C). This alignment suggests a potential for expanding cultivation into regions that balance the high-temperature tolerance observed in the wild with agricultural feasibility across various climates.

4.2 | Defining suitable regions for cultivating Liberica in Upper West Africa

Species distribution modelling (SDM) predicts highly suitable areas for Liberica cultivation across Liberia, Côte d'Ivoire, Nigeria and Cameroon. The Area of Occupancy (AOO) drastically increased from 52 km² for known wild locations based on known datapoints to

435,494 km² for potential climate suitability via modelling, suggesting that the opportunity for farming Liberica in Upper West Africa is considerable (Figure 2). Variation in model confidence (Figure S2) reflects the gradient between the realised niche (captured by RF/GBM) and broader climatic tolerance (MaxEnt), rather than prediction error. While the limited sample size ($n = 17$) constrains projections to observed conditions, likely underestimating the species' full tolerance, this approach identifies the most climatically secure zones, providing a robust, conservative baseline for agricultural planning aligned with growing commercial interest.

4.2.1 | Malaysia: assessing climatic suitability and long-term viability

As a leading producer of Liberica coffee, and one focused on upscaling the cultivation of this crop species, Malaysia is a high-priority case study for evaluating climate suitability. Malaysian Liberica cultivation areas are characterised by high temperatures, exceptionally high, year-round rainfall and extremely low (precipitation and temperature) seasonality, which deviate from the pronounced seasonal fluctuations the species experiences in the wild (Figure 5).

Regional disparities within Malaysia are evident. Peninsular Malaysia, despite having the highest mean annual temperature for cultivated Liberica (26.7°C), generally presents fewer extreme precipitation values than other Malaysian regions, with most locations falling within the interquartile range of both the cultivated and wild niches for precipitation (Figure S6). Farming locations in lowland Sarawak, however, exist on the upper limits of most climate parameters, having the highest rainfall (across BIO12–BIO19), lowest temperature seasonality, and lowest precipitation seasonality. High precipitation, such as that experienced in lowland Sarawak (e.g., around Kuching) can be detrimental to cultivation. Anthracnose (*Colletotrichum* spp.) is prevalent in Sarawak (A. Davis and K. Wee Ting Lee, pers. observ.) and correspond with the known expansion of this fungal disease under high temperatures and humidity (Gaitán et al., 2015). At the same time, the frequent and heavy rainfall reduces the effectiveness of protective sprays, such as copper based fungicides used to prevent anthracnose. Other issues include a high incidence of coffee berry borer (*Hypothenemus hampei*), a coffee pest causing losses of \$500 million annually, which thrives in high temperatures (Jaramillo et al., 2011) and high humidities (Vega et al., 2019). In Peninsular Malaysia, Anthracnose levels are low to negligible (K. Wee Ting Lee, pers. observ.), perhaps reflective of the region's less extreme precipitation patterns. Historically, coffee leaf rust (*Hemileia vastatrix*) was noted as a constraint for Liberica cultivation in SE Asia (Burkill, 1935; Cramer, 1957;

FIGURE 5 Bioclimatic comparison of wild versus cultivated Liberica populations with Malaysian subgroups. Box and whisker plots display six Bioclim variables (left to right) comparing wild (red), cultivated (grey); cultivated sites in peninsular Malaysia (green), Sabah (yellow) and Sarawak (blue) populations. Overlaid points indicate origins. See Figure S6 for all Bioclims with subdivided regions highlighted, Table S5 for values and Dataset S4 for individual occurrence values.

McCook, 2019) but is currently not a major disease of Liberica in Sarawak (A. Davis & K. Wee Ting Lee, pers. observ.).

The long-term suitability of the more climate-extreme Malaysian Liberica growing climates is questionable. Climate projections (World Bank Group, 2025) for Sarawak are incompatible with climate suitability for cultivated Liberica, driven mainly by reduced seasonality (during 2071–2100). Precipitation patterns are projected to flatten, with a wetter dry season and a drier wet season. This shift directly conflicts with the species' dry season requirement and concentrated wet season, leading to precipitation stressors like fungal outbreaks and physiological drought from waterlogging. Compounding this issue, a projected rise in year-round temperatures (T_{max} and T_{min}) and reduced temperature seasonality may push Liberica beyond its known thermal limits, possibly further compromising phenology (flowering and fruiting times), physiology, and disease tolerance (DaMatta & Cochicho Ramalho, 2006).

While further climate scenario research and ground truthing is required (e.g., using a broader spatial resolution beyond weather stations and modelled climate data, and multi-location trials), this analysis unequivocally places lowland Sarawak at the edge of the cultivated niche and far beyond the parameters of the wild niche. While the plasticity limits for Liberica remain unknown, Sarawak's production potential could be highly vulnerable to future climate shifts. This finding should be a key consideration for farmers and investors looking to scale Liberica production in Malaysia, and to plant breeders concerned with futureproofing Liberica. Conversely, it is notable that Sarawak is currently producing high quality Liberica, which is profitable across the value chain, under what are extreme conditions for coffee cultivation.

4.3 | Climate resilience advantages of wild Liberica compared with wild Arabica

Wild Liberica and wild Arabica, that is, the indigenous populations of these species, inhabit distinct climate niches (Figure 1). Liberica has a higher heat tolerance and experiences significantly higher mean maximum temperatures than Arabica (Table 2). For Arabica, continuous exposure to temperatures as high as 30°C induces stress, reduces growth and causes abnormalities like leaf yellowing (DaMatta & Cochicho Ramalho, 2006). Heat tolerance in Liberica is therefore a valuable attribute in an era of rising global temperatures (Shukla et al., 2023) and increasing vapour pressure deficit (VPD), a critical measure of atmospheric dryness (Kath et al., 2022). Even a modest 0.1 kPa increase in VPD beyond the suitability threshold can drastically reduce Arabica yields by up to 50%, a threshold that many Arabica-producing nations are projected to cross under a 2°C warming scenario (Kath et al., 2022; Shukla et al., 2023).

Another key advantage of Liberica lies in its dual capacity to tolerate both intense wet seasons and pronounced dry spells (Table 2). With projected increases in prolonged droughts and intensified rainfall events (Shukla et al., 2023), a tolerance for extremes becomes increasingly valuable.

4.4 | Recommendations for farmers, breeders and policy makers

Countries in Upper West Africa could leverage their climatic suitability for the expansion of Liberica and take advantage of the indigenous coffee genetic resources located in their native forests (e.g., Sierra Leone, Liberia, Ivory Coast, Ghana and Nigeria). In the numerous other countries across the world's tropical belt that possess climate suitability, Liberica could be used to diversify and enhance coffee crop portfolios. Unfortunately, Liberica does not possess many of the key attributes required for complete agronomic success and efficient post-harvest processing, as required of a mainstream coffee crop species. Development would be needed to increase yields and outturns (ratio of fresh fruit to clean coffee) via increases in the number of flowers/fruits per node, and reductions in the thickness of the fruit pulp (exocarp and mesocarp) and parchment (endocarp), and possibly seed size (Davis et al., 2022, 2025). This might be possible to achieve via interspecies hybridisation with species of the Liberica species alliance (Davis et al., 2025), as a means of introducing required traits.

For those countries at the upper limits for successful Liberica cultivation, due mainly to excessive precipitation and low precipitation seasonality in combination with high temperatures (particularly Sarawak), breeding programs should focus on fungal resistance to diseases such as Anthracnose and other key constraints associated with these extreme cultivation conditions. This may require hybridisation with other *Coffea* species: A good starting point would be species of the Liberica species alliance (Davis et al., 2025) that are indigenous to areas of high precipitation and low precipitation seasonality. The behaviour of Liberica in Malaysia in cooler climates at higher elevations (e.g., above 1000 m) but with low precipitation seasonality, such as that found in the Bario Highlands (see above), should be carefully monitored.

In countries with a long history of Liberica cultivation and use, such as Liberia, Malaysia, Indonesia and the Philippines, where there is a strong cultural association with this species, retention of the traditional variants is likely to be paramount. In all cases, good agronomic practices (GAPs) and integrated pest and disease management systems are vital.

4.5 | Concluding remarks

This contribution reveals that the climate niche of Liberica is considerably broader than the wild climate niche (Davis et al., 2025), enabling it to thrive in warmer, wetter and less seasonal conditions than its wild counterparts. This extended niche highlights new cultivation opportunities, particularly in its native region of Upper West Africa, but also in many other tropical areas, including those at low elevations. Current commercial zones, such as Malaysia and particularly Sarawak, occupy the climatic upper limits of the cultivated niche. This position warrants caution to the cultivation of Liberica in lowland Malaysia (mainly lowland Sarawak), especially since the long-term climate viability of this

region for the cultivation of this species is likely to deteriorate as the climate changes. Despite this, the species demonstrates remarkable tolerance to specific climate parameters, providing farmers in Malaysia with a stable and profitable income under seemingly extreme conditions. Liberica also demonstrates potential for extending cultivation beyond that of Arabica and robusta, and perhaps also excelsa, due to its unique combination of climate parameters. Liberica does not, however, possess all the agronomic and processing attributes of a successful mainstream coffee crop species, compared with Arabica, robusta and excelsa (Davis et al., 2022, 2025). Its success as a crop species at scale will therefore likely depend on further development via plant breeding methods.

Modelling studies require ground truthing and verification, and we would suggest multilocation field trials monitored using research-grade climate recording equipment, as a means of substantiating our findings. Increasing the sampling of ground points, particularly for key regions of interest for the cultivation of Liberica, is also recommended. Regardless of these caveats, we demonstrate the climate flexibility of Liberica and its potential for farming across a range of climates and consider this species to represent a vital resource for developing climate resilient coffee crop variants.

AUTHOR CONTRIBUTIONS

Aaron P. Davis, Isobel M. J. Wild and Justin Moat conceptualised the research; Isobel M. J. Wild, Aaron P. Davis and Kenny Wee Ting Lee collected occurrence data; Isobel M. J. Wild and Aaron P. Davis performed data analysis and interpretation; Isobel M. J. Wild prepared the maps and manuscript; Aaron P. Davis and Justin Moat reviewed and edited the text.

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CONFLICT OF INTEREST STATEMENT

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

DATA AVAILABILITY STATEMENT

All data obtained in this study area are available in the [Supporting Information](#). However, geocoordinates for Malaysia and Vietnam have been excluded, as these data relate to private farms, and they have requested that their locations are not shared publicly. Accompanying code is available from GitHub: https://github.com/isobelmjwild/liberica_climate_requirements.git.

ETHICS STATEMENT

This research is based on species distribution modelling using secondary occurrence data derived from public databases, herbarium specimens and literature. As the study did not involve human participants, live animals or sensitive personal data, formal ethical approval and informed consent were not required.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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