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# ECOPHYSIOGRAPHIC INVENTORIZATION OF COFFEE GROWING SYSTEMS IN THE WESTERN HIMALAYAS

**Aashima Sharma[1], Vikas Kumar Sharma[2*], Yashasvi Thakur[3], Suman Lata[4], Udit Kumar[5]**

[1]Research Scholar, Department of Fruit Science, College of Horticulture and Forestry (Dr YSP UHF, Nauni), Neri, Hamirpur, 177001, Himachal Pradesh, India Email: aashimasharma979@gmail.com ORCID: 0009-0000-4133-4144
[2]* Senior Scientist, Department of Fruit Science, College of Horticulture and Forestry (Dr YSP UHF, Nauni), Neri, Hamirpur, 177001, Himachal Pradesh, India Email: vksdr2002@gmail.com ORCID: 0000-0002-0686-2061
[3]Assistant Professor, Department of Environment Science, College of Horticulture and Forestry (Dr YSP UHF, Nauni), Neri, Hamirpur, 177001, Himachal Pradesh, India, Email: yashasvi.thakur@gmail.com ORCID: 0000-0003-2137-9331
[4]Assistant Professor, Department of Fruit Science, College of Horticulture and Forestry (Dr YSP UHF, Nauni), Neri, Hamirpur, 177001, Himachal Pradesh, India Email: suman.india14@gmail.com ORCID: 0000-0002-6025-0947
[5]Research Scholar, Department of Fruit Science, College of Horticulture and Forestry (Dr YSP UHF, Nauni), Neri, Hamirpur, 177001, Himachal Pradesh, India, Email: udit.sharma.8348@gmail.com ORCID: 0009-0004-5443-5840

## ABSTRACT
Coffee cultivation is an emerging but promising diversification avenue in the subtropical low and mid-hill terrains of western Himalayas of Himachal Pradesh. The study focuses on GPS-GIS mapping of coffee plantations in the state and consists of an ecophysiographic inventory of 27 *Coffea arabica* plantation sites in the districts of Kangra, Bilaspur, Hamirpur, Una and Mandi. The study deals with elevation, slope, aspect, shade management and farmer adoption patterns. Geographic coordinates were recorded through field surveys and terrain attributes were derived from CartoSat-1 digital elevation models. Plantation level information on age, planting density, survival percentage and shade tree composition were obtained from systematic field surveys. The plantations were established between 445 and 1168 m amsl on gently to moderately sloping land. Survival at the district level ranged from 37.83 to 50.60 %, and at the site level from 5 to 87 %, indicating strong heterogeneity in establishment success. Shade management was identified as a major ecophysiographic modifier with orchard canopies dominated by *Mangifera indica* and substantially lower survival of inadequately shaded sites at similar elevations. The farmers' adoption patterns indicate that coffee is mainly incorporated as an understorey component within existing orchard systems. Results suggest that elevation bands, terrain exposure and shade-mediated microclimate have effect on Arabica establishment in these emerging systems and provide a spatially explicit framework for site-specific recommendations on coffee expansion in the western Himalayas.

**KEYWORDS**: *Coffea arabica*, ecophysiography, GPS–GIS, western Himalayas, shade management, survival percentage, crop diversification, Himachal Pradesh

## INTRODUCTION
Coffee is one of the most traded agricultural commodities worldwide and a key element of rural livelihoods in many tropical and subtropical countries. It provides income to millions of smallholders and contributes substantially to national export earnings (DaMatta et al. 2007; DaMatta et al. 2018). In world coffee production, *Coffea arabica* is the dominant species, due to its superior cup quality and sensory complexity, whereas *Coffea canephora* (robusta) supports a large part of the bulk and instant coffee market (DaMatta et al. 2007). Research into finding new acceptable habitats outside of the normal production landscapes has been spurred by the growing demand for distinctive, "origin-based," and high-altitude coffees (DaMatta et al. 2018).

Arabica coffee is usually grown in tropical highlands between 1000 and 1500 m amsl, where temperatures are moderate (15–25 °C), annual rainfall is high and there is partial shade. Robusta, on the other hand, is better adapted to lower elevations (500–1000 m amsl) and warmer temperatures (20–30 °C) (DaMatta et al. 2004). The suitability of coffee is expected to be strongly affected by changes in regional climate regimes, including warmer temperatures, changes in the seasonality of rainfall and the increased frequency of droughts (DaMatta et al. 2006; Craparo et al. 2015), due to its relatively narrow thermal and moisture requirements. Ecophysiological syntheses suggest that growth, photosynthesis and reproductive development can be impaired by supra-optimal temperatures, water deficits and excessive radiation, ultimately depressing yield and quality, although some of these stresses can be partially mitigated by elevated atmospheric CO2 (DaMatta et al. 2006, Martins et al., 2016).
Climate projections and distribution models already suggest that climatically suitable areas for coffee are decreasing in some traditional low latitudinal and low altitudinal areas. Therefore, new windows of suitability may open in cooler and higher altitude areas (Davis et al., 2012; DaMatta et al., 2018). Modelling approaches integrating climate, topography and soils have suggested that the Hindu Kush–Himalayan region could be one such emerging niche for the viability of *Coffea arabica* (Davis et al., 2012). At the same time, market narratives around "Himalayan specialty coffee" in countries such

as Nepal emphasize the distinctiveness of high-altitude environments and their potential for producing unique quality profiles (Ranjitkar et al., 2016).

In the western Himalayas, particularly in the mid-hills of Himachal Pradesh, elevation, slope, aspect, local thermal regimes, and monsoon rainfall combine to create fine-scale mosaics of microclimates that may be suitable for specialized coffee cultivation (Singh et al., 2023). However, the lack of a systematic ecophysiographic inventory of existing and potential coffee systems limits evidence-based site selection, variety choice and agroforestry design (Singh et al., 2023; Davis et al., 2012). Ecophysiographic characterization, which integrates relief, climate, land use and vegetation with crop performance indicators, has been successfully applied to typify coffee production environments elsewhere (Rodriguez et al., 2019; Rodriguez et al., 2017).

The western Himalayan region is a suitable environment to study the role of local ecophysiographic features in the establishment and sustainability of emerging coffee growing systems in this context. A systematic inventory of sites along gradients of elevation, slope, aspect, and microclimatic exposure can identify distinct ecophysiographic types of coffee environments, connect these site types with important indicators of establishment and production and produce evidence-based criteria for site selection and management under ongoing climate change. In order to support region-specific recommendations on coffee expansion, management, and policy support, the current study documents and examines the ecophysiographic features of coffee-growing systems in the western Himalayas, with a focus on the low and mid-hill landscapes of Himachal Pradesh.

## MATERIALS AND METHODS

### Study area

The present investigation was conducted during 2025-26 College of Horticulture and Forestry (CoH&F), Neri, Hamirpur, Himachal Pradesh, India. Field work was conducted in the subtropical coffee growing areas of the low to mid-hills of districts Hamirpur, Bilaspur, Una, Kangra and Mandi. These districts have a wide range of mean annual temperature of 20–27 °C and annual rainfall of around 1000–2000 mm, with complex topography and monsoon-dominated rainfall regimes.

### Selection of plantation sites and inventory

The ecophysiographic analysis was based on the 27 coffee plantation sites inventorized in a GPS based survey of coffee growing sites in Himachal Pradesh. Coffee plantations were identified from records of Department of Agriculture, Himachal Pradesh and Tea Board Regional Office, Palampur and supplemented by farmer networks, local extension officers and field reconnaissance surveys. All the sites were visited and the status of the plantation was visually checked.

### Acquisition of the GPS data and extraction of terrain features

A Garmin GPSMAP 64s receiver (WGS84 datum) was used to obtain the geographic coordinates (latitude, longitude and elevation) of all plantation sites. GPS data were imported into ArcGIS 10.8 and converted to point shapefiles. Slope (%) and aspect were derived from the CartoSat-1 digital elevation model (DEM) data (30 m spatial resolution) using the 3D Analyst extension. Prior to analysis and mapping, all spatial data were projected to UTM Zone 43N (WGS84).

### Percentage of survival estimation

Survival of coffee plants was determined by stratified random sampling in the 27 plantations. For each site, we counted the total number of planting positions, live plants (plants with green foliage and active growth) and dead or missing positions separately. The percentage of survival was calculated as:

Survival (%) = (Number of live plants / Total number of planted positions) * 100.

This metric was then used to compare establishment success between coffee growing sites and districts.

### Management of shade and microclimate observations

At each plantation, qualitative shade intensity, canopy configuration and shade tree species were documented. Farmers were interviewed using a semi-structured schedule to record perceived roles of shade, frost incidence, exposure to cold winds and heat stress and management interventions made in response.

### Ecophysiographic variables and site classification

The following ecophysiographic variables were collated for each site: elevation (m amsl), slope (%), aspect category (N, NE, E, SE, S, SW, W, NW), shade category, plantation age (years since establishment) and total number of plants planted. Sites were classified into elevation (low <600 m, mid-1: 600–800 m, mid-2: 800–950 m, high >950 m) and slope (gentle <5%, moderate 5–10%, moderately steep >10%) classes. The conceptual ecophysiographic typology was derived by integrating elevation band, slope class, aspect category and shade level together.

### Data analysis

Minimum, maximum and mean descriptive statistics were calculated for elevation, slope, survival percentage, plantation age and planted density at site and district levels. Survivorship classes were set as high (≥60%), moderate (30–59%) and low (<30%). Patterns of survival among elevation bands and shade categories were analyzed with cross-classification tables. This interpretation was based on strong patterns across many sites, not on individual outliers.

## RESULTS

### Elevation and spatial distribution of plantations

The 27 *Coffea arabica* plantations (Table 1) were spread over an elevation range of 445–1168 m amsl covering low-hill and mid-hill agro-ecosystems of Himachal Pradesh (Figure 1). The lowest plantation (K10, Kangra) was located at 445 m amsl and the highest (M1, Mandi) at 1168 m amsl. When clustered into elevation bands, most of the plantations were found in the 600-900 m amsl range, while relatively few sites were found below 500 m and above 1000 m (Figure 2).

In terms of location, Kangra district contributed maximum number of sites (n = 10) followed by Bilaspur (n = 9), Hamirpur (n = 4) and Una and Mandi with two sites each (n = 2). This uneven distribution is attributed to the early and concentrated adoption of coffee in Kangra and Bilaspur in response to pilot interventions and extension efforts from the Department of Agriculture and Tea Board. In Una and Mandi, plantations are less but extend the elevation envelope into mid-hill areas.

**Table 1: Geographical coordinates and site characteristics of the surveyed coffee plantations**

| S.No. | District | Code | Latitude ($^0$E) | Longitude ($^0$N) | Elevation (mamsl) | Slope (%) | Aspect |
|---|---|---|---|---|---|---|---|
| 1 | Kangra | K1 | 32.16297 | 76.28996 | 811.50 | 11.711 | SE |
| 2 | Kangra | K2 | 32.14297 | 76.29474 | 777.60 | 2.105 | SW |
| 3 | Kangra | K3 | 32.061099 | 76.361182 | 784 | 17.103 | S |
| 4 | Kangra | K4 | 32.07195 | 76.37931 | 915.62 | 5.607 | SE |
| 5 | Kangra | K5 | 32.072465 | 76.379313 | 886.968 | 13.268 | S |
| 6 | Kangra | K6 | 32.054049 | 76.607422 | 957 | 4.275 | NE |
| 7 | Kangra | K7 | 31.8945388 | 76.3398333 | 829 | 10.006 | NE |
| 8 | Kangra | K8 | 31.8521361 | 76.1812222 | 596 | 3.149 | NE |
| 9 | Kangra | K9 | 31.8782638 | 76.2217138 | 458 | 0.286 | W |
| 10 | Kangra | K10 | 31.9261138 | 75.9527138 | 445 | 6.629 | S |
| 11 | Hamirpur | H1 | 31.586681 | 76.552978 | 901.1 | 4.070 | SW |
| 12 | Hamirpur | H2 | 31.573601 | 76.561979 | 859.83 | 11.694 | W |
| 13 | Hamirpur | H3 | 31.585350 | 76.550857 | 831.90 | 1.917 | S |
| 14 | Hamirpur | H4 | 31.607737 | 76.609598 | 897.43 | 10.158 | S |
| 15 | Una | U1 | 31.821881 | 76.082746 | 869.47 | 9.372 | S |
| 16 | Una | U2 | 31.822256 | 76.081214 | 856.15 | 8.990 | NW |
| 17 | Mandi | M1 | 31.7067311 | 76.6975766 | 1168 | 10.936 | NE |
| 18 | Mandi | M2 | 31.7184388 | 76.9045888 | 1111 | 13.276 | W |
| 19 | Bilaspur | B1 | 31.5476 | 76.66792 | 841.04 | 14.299 | NE |
| 20 | Bilaspur | B2 | 31.54658 | 76.66644 | 829.41 | 7.080 | SE |
| 21 | Bilaspur | B3 | 31.55658 | 76.66544 | 827.52 | 6.281 | SE |
| 22 | Bilaspur | B4 | 31.55071 | 76.66793 | 861.55 | 6.114 | E |
| 23 | Bilaspur | B5 | 31.5515 | 76.67182 | 842.54 | 9.009 | E |
| 24 | Bilaspur | B6 | 31.55055 | 76.67203 | 833.86 | 2.200 | S |
| 25 | Bilaspur | B7 | 31.55125 | 76.67216 | 820.36 | 8.141 | NE |
| 26 | Bilaspur | B8 | 31.55108 | 76.66749 | 844.51 | 5.630 | NW |
| 27 | Bilaspur | B9 | 31.55494 | 76.65741 | 844.58 | 11.148 | E |

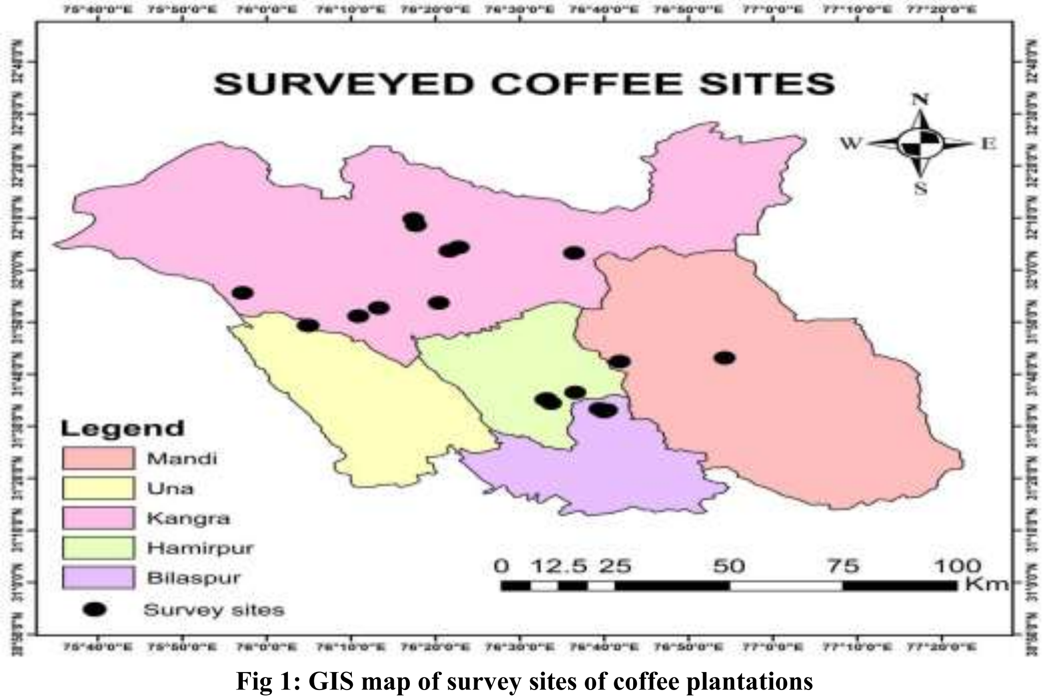


**Fig 1: GIS map of survey sites of coffee plantations**

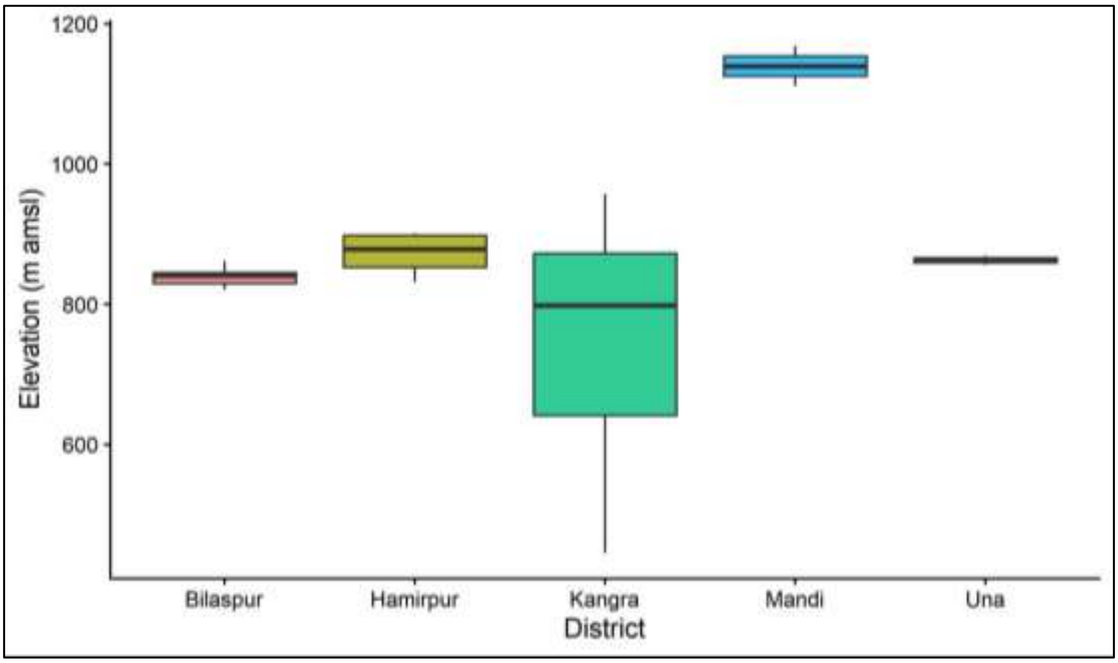


**Fig 2: Boxplot of elevation distribution of coffee sites across districts**

**Terrain features: slope and aspect**

The slopes of the plantation sites were mostly between about 0.3 and 17% (Figure 3). Therefore, most plantations were established on gentle to moderately sloping land. The pattern indicates that farmers have gravitated towards sites where topography facilitates management and soil conservation.

There were different aspects, including south, east and west exposures and north-east and north-west facing aspects (Figure 4). Frequent south and south-eastern exposures were noted in Kangra and Bilaspur, providing warmer winter conditions and higher radiation loads, while some sites in Una and Mandi were on north-westerly exposures with potential challenges from frost and reduced insolation. The differences in radiation reception and microclimate between aspects create a large ecophysiographic gradient in the study area.

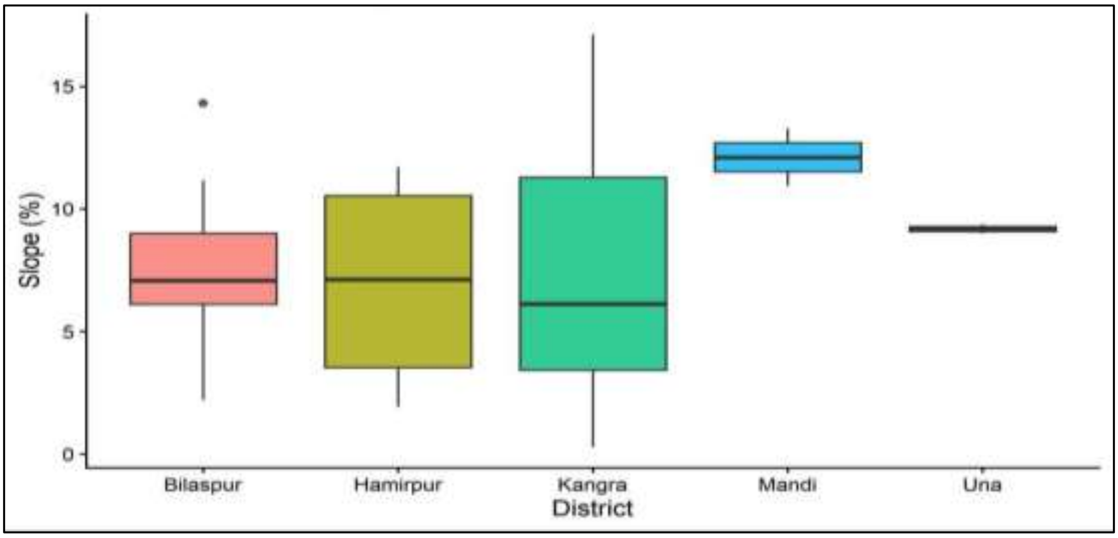


**Fig 3: Boxplot of slope distribution of coffee sites across districts**

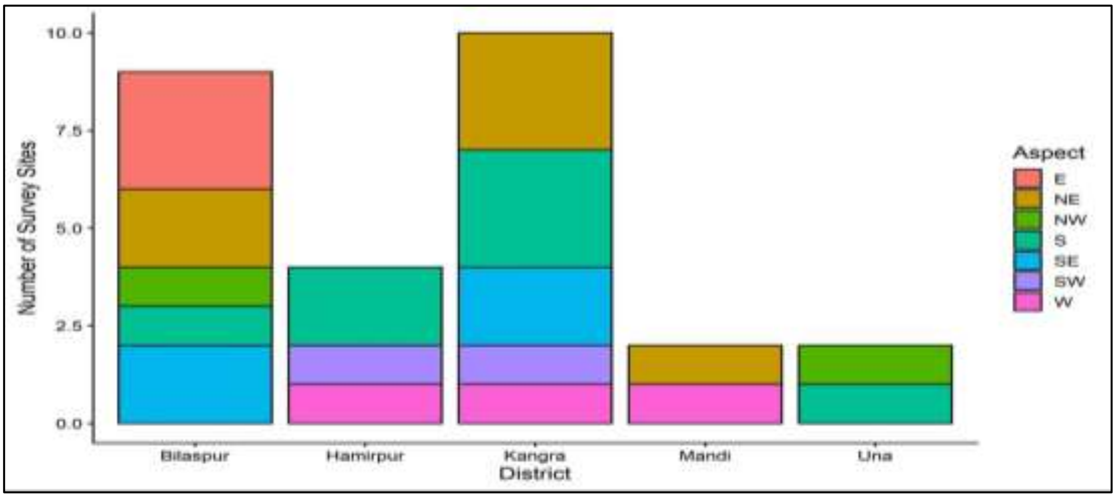


**Fig 4: Aspect distribution of coffee sites across districts**

**District wise status of plantation and survival**

The district wise summary reveals that 6504 coffee plants were established in the 27 plantations. Kangra and Bilaspur together accounted for more than two-third of total planted coffee, with 2,620 and 2,104 plants respectively. Hamirpur (680 plants), Una (500 plants) and Mandi (600 plants) had smaller planted populations (Table 2). This is matched by the greater intensity and duration of coffee promotion in Kangra and Bilaspur.

**Table 2: Survey details of coffee plantation sites with survival and shade tree information**

| S.No. | Code | Year of Plantation | Total No. of Plants Planted | Total No. of Plants Left | Survival Percentage | Fruit Bearing | Shade tree |
|---|---|---|---|---|---|---|---|
| 1 | K1 | 2014-15 | 400 | 300 | 75 | 300 | Mango |
| 2 | K2 | 2015<br>2018 | 200<br>100 | 10<br>40 | 5<br>40 | 50 | Mango |
| 3 | K3 | 2012-13 | 100 | 35 | 35 | 0 | Mango, silver oak |
| 4 | K4 | 2015-16<br>2018 | 200<br>500 | 100<br>410 | 50<br>82 | 300 | Mango, litchi |
| 5 | K5 | 2020<br>2021 | 100<br>200 | 30<br>20 | 30<br>10 | 0 | Mango |
| 6 | K6 | 2020 | 200 | 25 | 12.5 | 0 | Mango |
| 7 | K7 | 2019<br>2020 | 50<br>50 | 10<br>25 | 20<br>50 | 0 | Mango, khair |
| 8 | K8 | 2015-16<br>2019 | 200<br>20 | 90<br>13 | 45<br>65 | 3 | Mango |
| 9 | K9 | 2020 | 180 | 150 | 83.33 | 0 | Mango |
| 10 | K10 | 2020 | 120 | 50 | 41.67 | 0 | Mango |
| 11 | H1 | 2020 | 80 | 25 | 31.25 | 0 | Mango, no shade |
| 12 | H2 | 2017-18 | 200 | 30 | 15 | 25 | Mango, no shade |
| 13 | H3 | 2019 | 100 | 23 | 23 | 23 | Mango |
| 14 | H4 | 2020 | 300 | 190 | 63.33 | 0 | Mango |
| 15 | U1 | 2015-16 | 400 | 228 | 57 | 200 | Mango |
| 16 | U2 | 2019 | 100 | 25 | 25 | 23 | Mango |
| 17 | M1 | 2019 | 100 | 27 | 27 | | Mango |
| 18 | M2 | 2017 | 500 | 200 | 40 | 180 | Mango |
| 19 | B1 | 2014-15 | 200 | 50 | 25 | 40 | Mango |
| 20 | B2 | 2014-15 | 100 | 18 | 18 | 18 | Mango, citrus |
| 21 | B3 | 2014-15 | 136 | 35 | 25.74 | 25 | Mango |
| 22 | B4 | 2014-15 | 200 | 50 | 25 | 50 | Mango |
| 23 | B5 | 2014-15 | 500 | 310 | 62 | 250 | Mango, litchi |
| 24 | B6 | 2014-15 | 500 | 270 | 54 | 250 | Mango |
| 25 | B7 | 2014-15<br>2017-18 | 100<br>68 | 70<br>25 | 70 36.76 | 90 | Mango |
| 26 | B8 | 2014-15 | 100 | 20 | 20 | 20 | Mango, citrus |
| 27 | B9 | 2014-15 | 200 | 60 | 30 | 60 | Mango, citrus |

At district level average percentage of survival varied from 37.83% in Mandi to 50.60% in Una. Kangra registered 49.92%, Bilaspur 43.16% and Hamirpur 39.41% (Table 3). Thus even in the best performing districts, about half of the planting positions had failed, indicating the challenges involved with establishing a perennial crop in a non-traditional environment with variable microclimate and management. The relatively high survival in Una, with only two sites, suggest particularly favourable ecophysiographic or management conditions in those sites.

**Table 3: District-wise summary of surveyed sites, number of plants planted and survival percentage**

| District | Number of sites | Number of plants planted | Survival Percent |
|---|---|---|---|
| Kangra | 10 | 2620 | 49.92 |
| Hamirpur | 4 | 680 | 39.41 |
| Una | 2 | 500 | 50.6 |
| Mandi | 2 | 600 | 37.83 |
| Bilaspur | 9 | 2104 | 43.16 |

**Heterogeneity in survival and establishment at the site level**

At the site level, survival percentages varied from 5–12.5% in some young or poorly managed plantations to 83.33–87% in the most successful sites such as K9 ( Kangra) and U1 (Una) (Figure 5, 6). Using the thresholds we set, about a third of the plantations were in the high survival class (≥60%), with the rest divided between the moderate (30-59%) and low (<30%) survival classes (Figure 7).

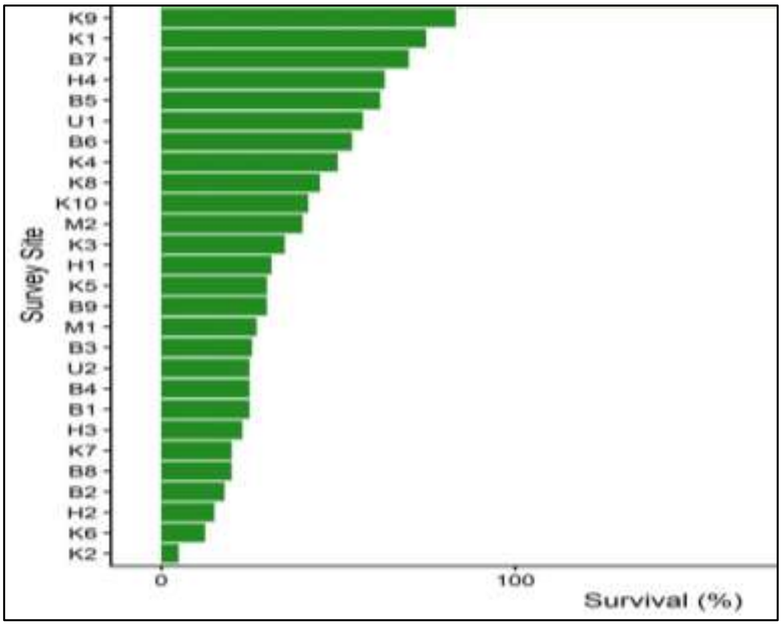


**Fig 5: Survival percentage by survey sites of coffee**

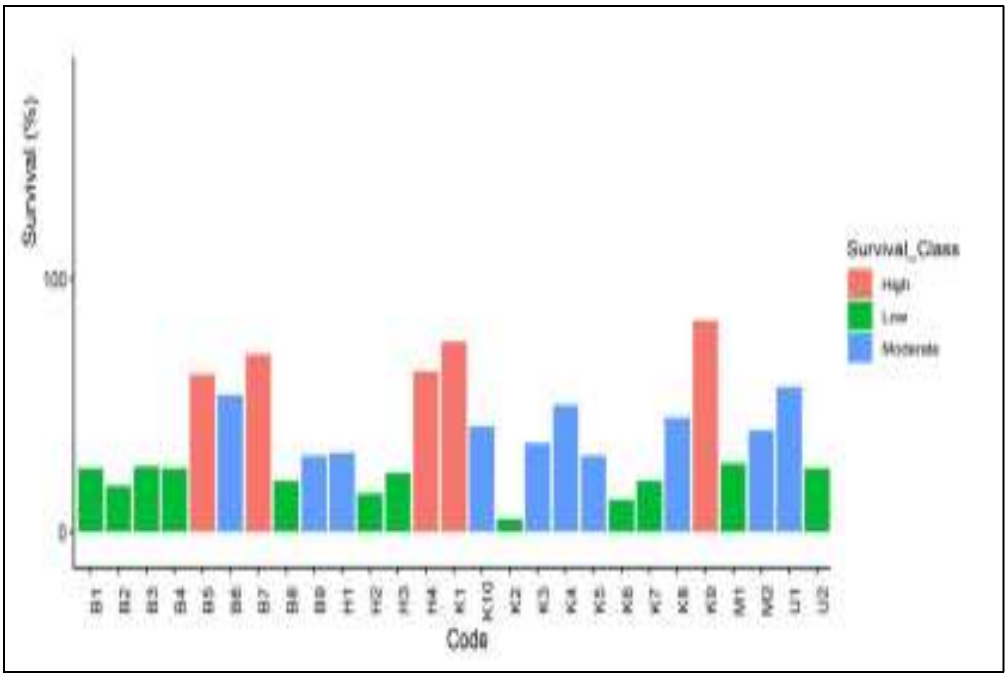


**Fig 6: Survival classes of survival percent at different locations**

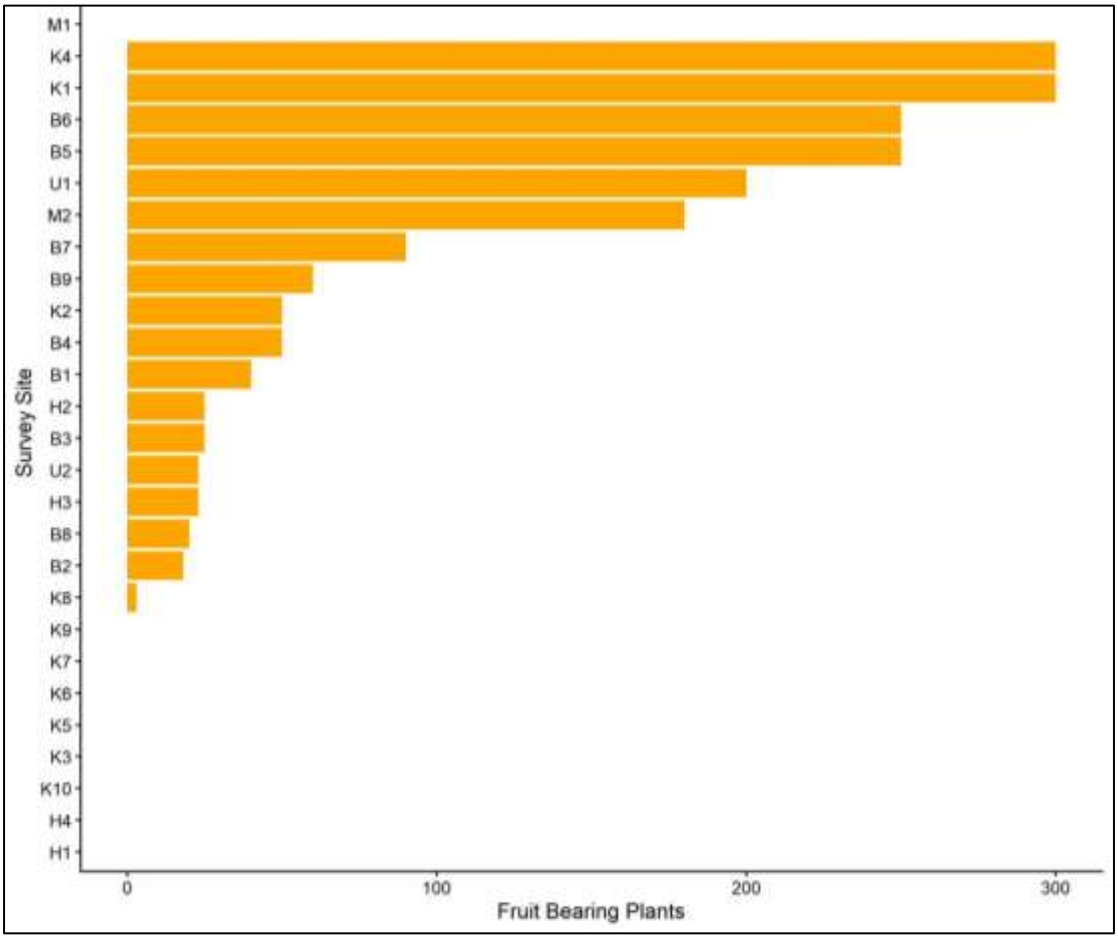


**Fig 7: Number of fruit bearing plants at different survey sites**

Older plantations like K1 (2014–15) and some Bilaspur sites had comparatively higher survival and higher number of bearing plants when compared to recently established sites, which shows that once coffee survives the initial establishment phase under suitable ecophysiographic conditions, stands can stabilize and enter into productive phases (Abdelzaher et al., 2025) (Figure 8, 9). In contrast, young plantings in frost-prone or poorly shaded sites such as parts of K2 and K6 had low survival and limited fruiting, demonstrating the sensitivity of Arabica to microclimatic stress during establishment.

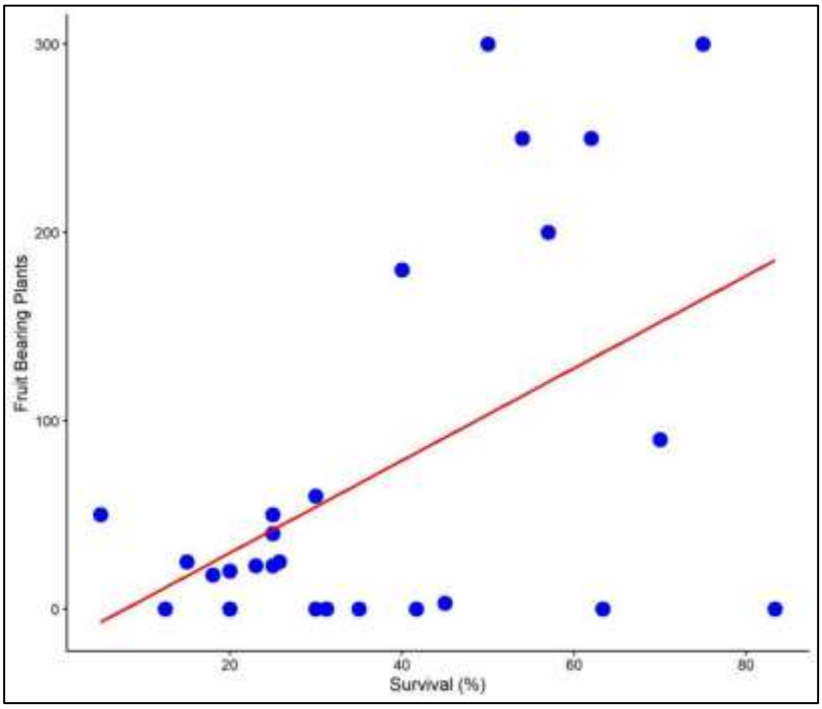


**Fig 8: Scatter plot presenting relationship between fruit bearing plants and survival percent**

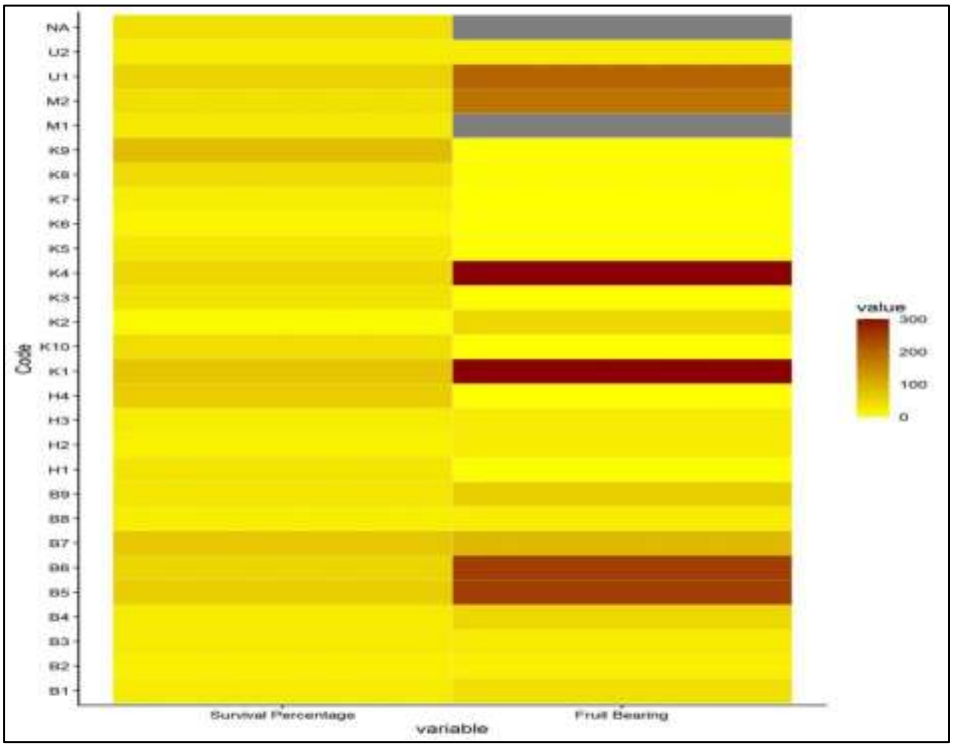


**Fig 9: Heatmap of survival percentage and number of fruit bearing plants at different locations**

**Patterns of shade management**

The regulation of shade was a common feature on most of the plantations. *Mangifera indica* (mango) was the dominant shade species either alone or in association with other trees such as *Grevillea robusta* (silver oak), *Litchi chinensis* (litchi), *Acacia catechu* (khair), *Cedrus deodara* (deodar) and *Citrus spp*. This reflects the existing dominance of fruit orchards in the region and the prevailing strategy of incorporating coffee as an understorey crop in orchard-based agroforestry systems. Survival and growth of coffee plants were generally higher in sites with moderate to dense shade than in sites with sparse or no shade at similar elevations. Farmers at shaded sites consistently identified reduced frost damage, reduced leaf scorch during hot spells and improved cherry development, whereas farmers at unshaded or exposed sites identified winter injury and moisture stress as major constraints. These results are consistent with other coffee growing regions where shade trees help buffer temperature extremes, reduce radiation stress and conserve soil moisture in coffee agroecosystems (Perfecto et al., 2019; Jha et al., 2014).

**Farmer adoption trajectories and plantation age**

Patterns of farmer adoption showed that coffee has been primarily introduced as a supplementary income generating crop incorporated into existing orchard or agroforestry systems, rather than as a stand-alone monoculture. The size of the plantations ranged generally from 50 to 500 plants per farm and the coffee seedlings were obtained from departmental programmes and exchanges between farmers.
The time profile of planting between 2012–13 and 2020–21 indicates a gradual diffusion process. The initial plantations in Bilaspur and Kangra by early adopters have now developed into more mature stands with better survival and fruiting. Later adopters are experimenting with smaller planting and still evaluating coffee performance under the local ecophysiographic and management conditions. The concentration of sites around early pilot villages and along road-accessible corridors also indicates the importance of demonstration effects and market access in driving adoption.

**Conceptual ecophysiographic types of site**
Four conceptual ecophysiographic site types were identified, based on information about elevation band, slope class, aspect and shade level:

Type I - Mid-elevation, gentle slopes, south-facing, moderate shade
On slopes between 600 and 900 m amsl, mostly with S or SE aspect and with shade of orchard dominated by mango. This type includes many of the high survival plantations of Kangra and Una.

Type II - Moderate slopes at mid elevation, mixed aspects, dense shade from orchard.
Similar elevation sites with slightly steeper slopes and dense mixed-species shade, common in older Bilaspur orchards. Survival is generally moderate to high, but sensitive to canopy management.

Type III - Low elevation, warm pockets, variable shade.
Sites below 600 m amsl in foothill and valley-bottom positions. These sites have higher summer temperatures and possible frost in winter; survival is largely determined by good shade and cold air drainage.

Type IV - Exposed slopes, cooler mid-hills, high altitude.
Sites above 950 m amsl in some parts of Mandi and upper Kangra with moderate slopes and varying aspects. Here coffee is more exposed to low winter temperatures and occasional frost; survival is usually moderate to low unless shelterbelts and adequate shade are provided.

This typology offers a management-oriented framework for discussing the role of terrain and microclimate on plantation performance without reference to soil or biochemical attributes.

## DISCUSSION

**Altitude Zones and Suitability of Arabica in Western Himalayas**
The elevation range where coffee has been established in Himachal Pradesh (445-1168 m amsl) overlaps with ranges identified as suitable for Arabica in other subtropical mountain settings (Ge et al., 2023; Davis et al., 2012). Classical recommendations usually locate Arabica in the tropical latitudes between 1000 and 1500 m amsl . At lower absolute elevations in the western Himalayas, similar thermal regimes exist, owing to cooler regional climates and local topographic effects.
The density of successful plantations within a range of 596-915 m amsl indicates that this band may be a particularly favourable ecophysiographic window where cold stress is less than at higher elevations and heat stress is less than that experienced in low-lying foothills. Model-based studies have shown that climate change will likely lead to shifts in Arabica suitability to higher altitudes in many regions (DaMatta et al., 2014), but in the Himalayan context, where land availability above 1500 m amsl is constrained and the risk of frost increases, the 600-900 m band might remain important for near-term expansion, particularly under well-managed shade.

**Terrain exposure, cold air drainage and microclimate**
Most coffee farms are located on gentle to moderate slopes for both practical and ecophysiographic reasons. Gentle slopes make planting, shading and harvesting easier, but still offer sufficient slope for cold air drainage and reduction of frost pockets. In contrast, flat valley bottoms are prone to trapping cold air on winter nights, increasing the risk of frost, while very steep slopes tend to increase erosion and limit management options.
The microclimate at a certain elevation varies also with the slope orientation. In the north hemisphere, south and south-eastern slopes are generally more exposed to solar radiation and warmer and drier and could therefore favor ripening but also increase evaporative demand, while north-facing slopes tend to be cooler and could increase the length of the bean development period (Perfecto et al., 2005; Jha et al., 2014). Viable plantations were found on both warm and cool aspects in the present study, suggesting that aspect effects can be partially buffered by shade and local topography. However, reports of increased winter damage from farmers on exposed north-westerly sites highlight the need to consider wind and cold-air movement in the choice of planting sites.

**Ecophysiological modifier: shade management**
Shade trees influence the radiation, temperature, and humidity regimes (Perfecto et al., 2005; Jha et al., 2014), thereby altering the ecophysiographic environment for coffee plants. The main source of shade in the study area was mango based orchard canopies, with some shade provided by silver oak, litchi, khair and deodar in some cases. Farmers reported

consistently less frost, less leaf scorching and better plant vigour in moderate to dense shade than in unshaded or sparsely shaded sites at similar elevations.

These results are in line with the broader agroforestry literature demonstrating that shade modifies the microclimate and leads to greater resilience of coffee to climate variability, especially in marginal or non-traditional settings (Jha et al., 2014; Perfecto et al., 2019). In the western Himalayas, winter temperatures sometimes approach or fall below the tolerance limit of young Arabica plants, so shade appears to be an essential management factor rather than a mere optional measure for improvement of quality. The task will be to calibrate shade intensity through pruning and species selection, to maintain microclimatic benefits without excessive suppression of light and productivity in mature stands.

**Farmer adoption practices**

The temporal and spatial patterns of adoption in the study area suggest a process of ecophysiographic learning. Early adopters in Bilaspur and Kangra where microclimate and existing orchard structure were found to be favourable experimented with coffee. These sites have the advantage of high survival and fruiting, which made these farmers local reference points to encourage neighboring farmers to plant coffee in similar ecophysiographic locations (Nugraha et al., 2021; Abdelzaher et al., 2025).

In contrast, poor survival at exposed or frost-prone sites has likely constrained expansion into less suitable ecophysiographic niches. This dynamism underscores the need for clear site-specific ecophysiographic guidance from extension to help farmers avoid repeated failures in marginal settings and focus investment in areas with demonstrably higher probabilities of establishment success.

**Implications for site selection and spatial planning**

The ecophysiographic patterns observed in the present study have practical implications for the expansion of Arabica coffee in Himachal Pradesh, indicating the priority zones to be the 600-900 m amsl band with gentle to moderately sloping land, especially where orchard-based shade is already available or can be easily established. Within this band, south and south-eastern aspects with good cold-air drainage and protection from prevailing cold winds appear to be particularly favourable as evidenced by several high survival plantations in Kangra and Una.

Sites at higher elevations, above ca 950 m amsl, may still be viable, but require more intensive microclimate management via shelterbelts and dense, well-designed shade canopies to buffer frost and cold winds. Summer can increase heat stress at low elevation sites (< 600 m amsl) and careful shade design and water management will be required. The conceptual ecophysiographic site types developed here can be combined with current suitability mapping and economic analyses (Nugraha et al., 2021; Rissatti et al., 2022; Rono and Mundia, 2016) to provide planners with a more nuanced, process-based rationale for zoning and targeting of future coffee development programmes.

## CONCLUSIONS

A study of the ecophysiology of 27 Coffee plantations in the western Himalayan state of Himachal Pradesh, focusing on elevation, terrain and shade rather than soil chemistry or bean quality, reveals clear patterns in the successful establishment of coffee. Plantations occur over a wide elevation range of 445-1168 m amsl but most high survival sites are found within the approximate range of 596-915 m amsl on gentle to moderately sloping land under shade of mango-based orchard.

Survival percentages vary greatly between plantations, ranging from 5-12.5% to 83-87%, showing that microclimatic and management factors are as important as the mere presence of coffee. Shade management is an especially powerful ecophysiographic modifier that can moderate the extremes of temperature and moisture stress that would otherwise limit Arabica establishment in the subtropical Himalayan environment. Farmer adoption patterns suggest that coffee is being added mostly into existing orchard systems, and future expansion is likely to be driven by diversification and intensification of these agroforestry mosaics, and not by large monoculture plantations.

Our study provides a site-specific ecophysiographic framework for understanding the combined effects of elevation, slope, aspect and shade on establishment success, and complements previous GPS-GIS surveys and suitability analyses in the region. These contributions can be used together by extension agencies, planners and farmers to guide coffee expansion into ecophysiographically favourable zones in the western Himalayas and also in designing management strategies to improve resilience and productivity under ongoing climate change.

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