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Forest Structure and Composition under Contrasting Precipitation Regimes in the High Mountains, Western Nepal

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Abstract: The high mountains stretch over 20.4% of Nepal's land surface with diverse climatic conditions and associated vegetation types. An understanding of tree species and forest structural pattern variations across different climatic regions is crucial for mountain ecology. This study strived to carry out a comparative evaluation of species diversity, main stand variables, and canopy cover of forests with contrasting precipitation conditions in the Annapurna range. Firstly, climate data provided by CHELSA version 1.2, were used to identify distinct precipitation regimes. Lamjung and Mustang were selected as two contrasting precipitation regions, and have average annual precipitation of 2965 mm and 723 mm, respectively. Stratified random sampling was used to study 16 plots, each measuring 500 m^2 and near the tree line at an elevation range of 3000 to 4000 m across different precipitation conditions. In total, 870 trees were identified and measured. Five hemispherical photos using a fisheye lens were taken in each plot for recording and analyzing canopy cover. Margalef's index was used to measure species richness, while two diversity indices: the Shannon–Wiener Index and Simpson Index were used for species diversity. Dominant tree species in both study regions were identified through the Important Value Index (IVI). The Wilcoxon rank-sum test was employed to determine the differences in forest structure and composition variables between the two precipitation regimes. In total, 13 species were recorded with broadleaved species predominating in the high precipitation region and coniferous species in the low precipitation region. Higher species richness and species diversity were recorded in the low precipitation region, whereas the main stand variables: basal area and stem density were found to be higher in the high precipitation region. Overall, an inverse J-shaped diameter distribution was found in both precipitation regions signifying uneven-aged forest. A higher proportion of leaning and buttressed trees were recorded in the high precipitation region. However, similar forest canopy cover conditions (>90%) were observed in both study regions. The findings of this research provide a comprehensive narrative of tree species and forest structure across distinct precipitation regimes, which can be crucial to administrators and local people for the sustainable management of resources in this complex region.

Keywords: precipitation; diversity; mountain; Annapurna

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1. Introduction

Forest structure, composition, and diversity patterns are crucial ecological features that correlate significantly with prevailing environmental and anthropogenic components [1–3].

Stand structure and species composition are essential for forest biodiversity, and an understanding of these is the basis of sustainable forest management [4]. Forest structure and composition also have a vital role in the global carbon budget as they act as huge C-pools [5]. Tropical forests are hotspots of biodiversity, and their geographical variation depends on their evolutionary history and climatic conditions [6,7]. Comparisons in tropical forests have illustrated that mountain forests are usually shorter and less diverse than forests in the lowlands [8,9]. In addition to altitudinal gradient, regional climate plays a major role in influencing forest structure. It is usually inferred that forests in higher precipitation and temperature regions have taller trees and more biomass [10,11]. Furthermore, precipitation has been demonstrated to have a positive effect on tree diameter and the basal area of forests [12,13]. The shaping and configuration of forests are thus largely affected by changes in climate variables [14]. Over the past decades, upward shifts in tree species and tree lines have been documented owing to rises in temperature [6,15].

The relationship between species diversity and climatic effects has been analyzed in recent studies [16,17]. Field et al. [16] developed a model that describes the relationship between climate and plant richness, while Francis and Currie [17] developed a model for angiosperms. Higher species richness has been recorded with increasing temperatures up to a certain point, where richness diminishes due to water deficiency [16,18]. While Goldie et al. [19] found that in arid regions, water availability plays an important role in the evolutionary processes of woody plants and these processes are diminished by persistent drought, around 63% of global variability in angiosperm richness and 68% in woody plant family richness, explained by precipitation [16,17,20]. Similarly, a positive relationship was established between species richness and precipitation up to 4000 m in a neotropical region [21]. However, the relationship between species richness and temperature is found to be negative under limited water availability [18].

Due to the complex and diverse topographies and rain-shadow effects of high mountains, the Himalayan region of Nepal is characterized by significant local variations in climate [22]. The orographic effect of the Himalayan range plays an important role in determining the distribution of precipitation in this area. At a large scale, precipitation has been vital for determining species richness [23], composition [24], and distribution [25–28]. Vegetation monitoring allows in-depth analyses of components like moisture and temperature, and delivers knowledge on subtle monsoon variations for the Himalayas [29]. Likewise, species–environmental interactions can be applied as indicators of environmental conditions, and the diversity and forest patterns can be used to explain ecological phytogeography [12,30]. The fragile ecology of Himalayan forests is well-known [31]. However, fundamental knowledge of the structure and composition of Himalayan forests is limited in many regions [32]. Moreover, an understanding of how forest structure and diversity vary between different precipitation regimes is still lacking [33–36].

The high mountain region of Nepal has the highest forest proportion with forests covering 37.81% of the total land area [37]. Moreover, this region has been characterized by strong contrasts in precipitation regimes and forests, which are influenced by the effects of climate and land-use change. A better understanding of environmental factors influencing the distribution, abundance, and co-existence of tree species is crucial in forest ecology. Therefore, in this study, we examined the species diversity, species distribution, and stand structure of forests in contrasting precipitation regimes of the high mountain. The study aims to provide a better understanding of phytogeography in this complex region. This study may provide better insights on composition and structure in the mountain forests and would be highly applicable to several mountainous countries for the sustainable management of forest resources. The main objective of our study is to assess the forest structure and composition of high mountain forests in two contrasting precipitation conditions. To achieve the main objective of this study, we strived to address two main questions: (1) Are there any variations on forest composition and structure across contrasting precipitation conditions? (2) If so, how do the forest composition and structure vary with contrasting precipitation conditions?

2. Materials and Methods

2.1. Study Area

The high mountains area stretches from longitudes of 80°30′4″ to 88°07′04″ E and latitudes of 26°59′15″ to 30°06′47″ N, covering approximately 20.4% of the total land area of Nepal [37]. This study was carried out in the Annapurna Mountain range of Nepal. The Annapurna range or Annapurna massif (Figure 1) lies in the north-central part of Nepal and covers several peaks, including Annapurna (8091 m), the tenth highest mountain in the world [38]. The range covers five districts of Nepal, namely: Kaski, Lamjung, Manang, Mustang and Myagdi. It covers a total area of around 11,930 km^2 with 36% forest cover (see Appendix A) [39].

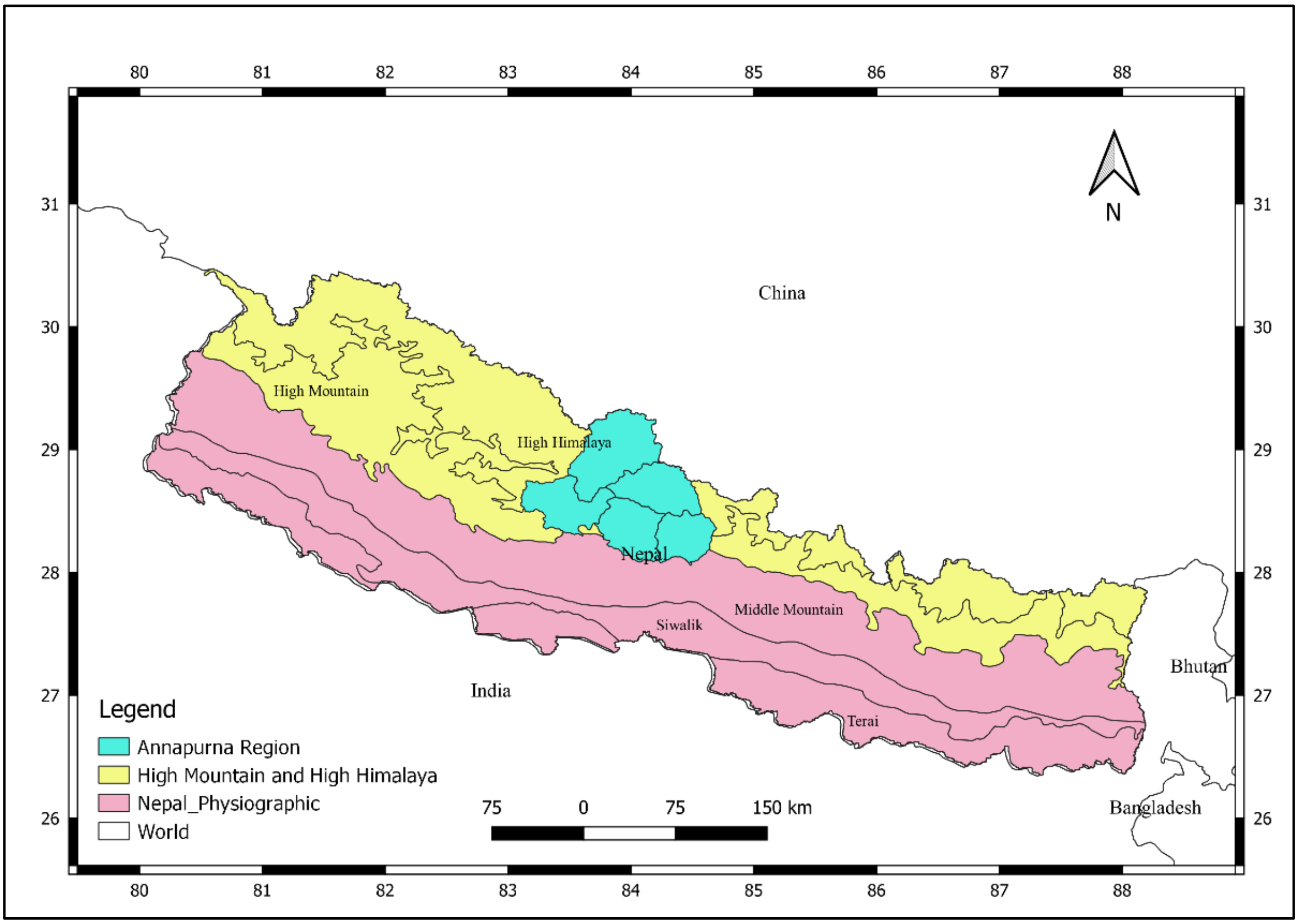


Figure 1. Physiographic zones of Nepal and the Annapurna region.

The region is bounded by the Marshyangdi valley in the east, the Kali Gandaki river in the west, the dry alpine desert of Mustang in the north, and the valleys and foothills of Pokhara in the south [40]. The presence of the Annapurna massif has created strong variations in climate across the region. Spanning 120 km with altitudes of below 1000 m up to 8000 m, it has two distinct climatic regions [40]. The southern belt of this range—the Pokhara region—receives the highest precipitation, while the northern belt—the trans-Himalayan region—receives the lowest precipitation in Nepal [41]. Nepal's largest conservation area, the Annapurna Conservation Area (ACA), covers most of this range and is situated between 83°34′ to 84°25′ E and 28°15′ to 28°50′ N, covering an area of 7629 km^2. ACA is rich in biodiversity, harbors 29 ecosystem types [42,43] and has a wide range of habitats, from *Shorea robusta* to perennial snow forests, harboring 22 different forest types. *Schimwa wallichi*, *Castanopsis indica*, *Alnus nepalensis*, *Pinus wallichiana* and *Betula utilis* are the region's major tree species [44]. The primary type of disturbances in this region are grazing, timber cutting, firewood collection, leaflitter collection and collection of other non-timber forest products [40].

As this study strives to compare forest composition and structure between two different climatic conditions, intensive study sites were selected by analyzing precipitation conditions over the ACA region using the CHELSA (Climatologies at high resolution for the Earth's land surface areas) version 1.2 global climate dataset [45] (http://chelsa-climate.org/, (accessed on 21 September 2020)). The dataset provides monthly and annual precipitation and temperature patterns for the period from 1979 to 2013. Other climate analysis studies in Nepal, e.g., [41,46–49] were also used as references for study area selection. Two intensive study sites (Table 1, Figure 2) were selected for the contrasting precipitation regimes, caused by the strong orographic effects of Annapurna massif. Bhujung, Lamjung lies on the windward side, while Kobang, Mustang is on the leeward side of the Annapurna range. Climatic conditions in the intensive study sites are presented in Section 2.2.

Table 1. Descriptions of intensive study sites in the Annapurna range differentiated by contrasting precipitation regimes.

Precipitation Regime	Study Site	Location
High/Humid	Bhujung, Lamjung (here after "Lamjung")	28°22′47″ N, 84°15′27″ E
Low/Dry	Kobang, Mustang (here after "Mustang")	28°40′29″ N, 83°35′04″ E

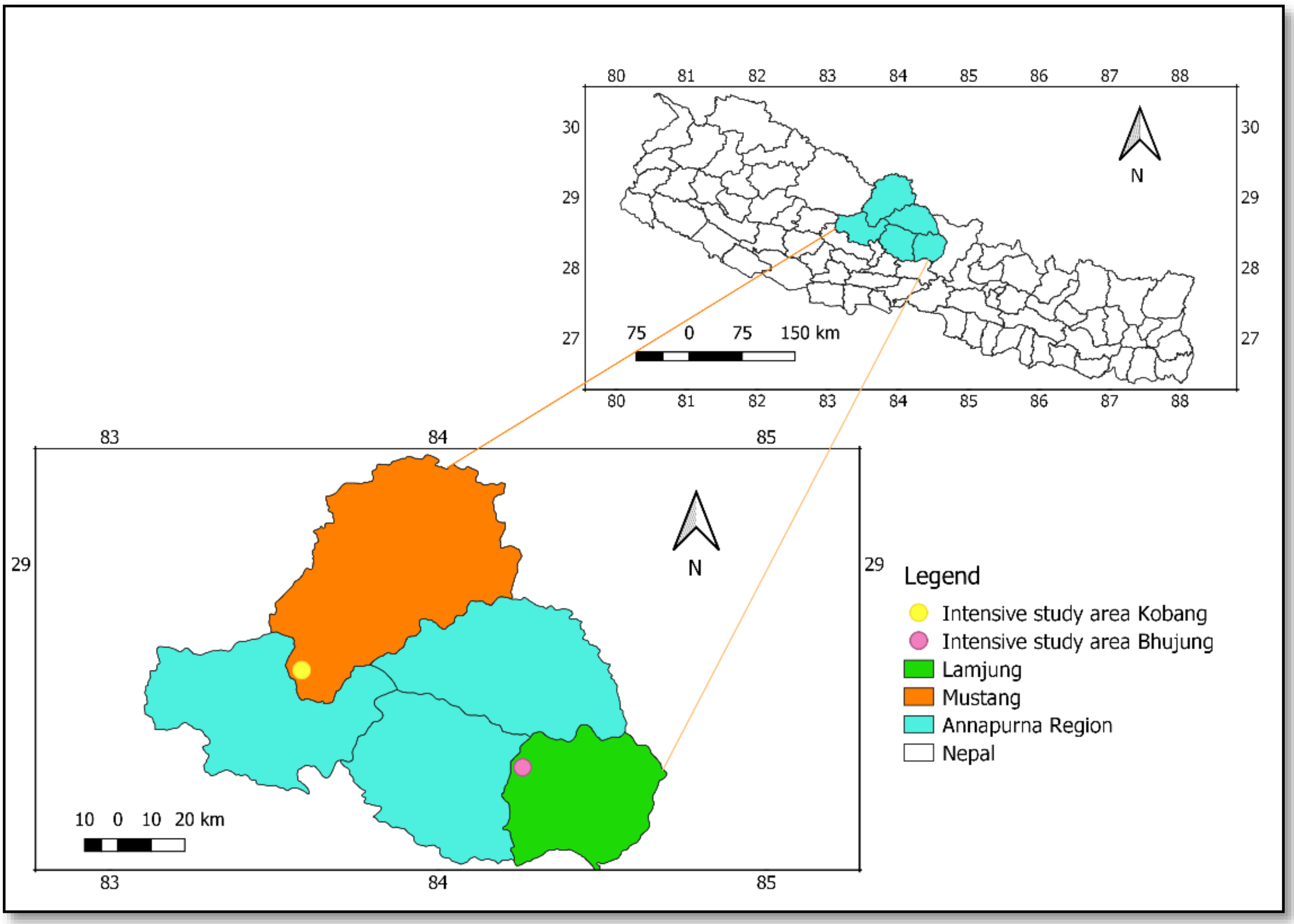
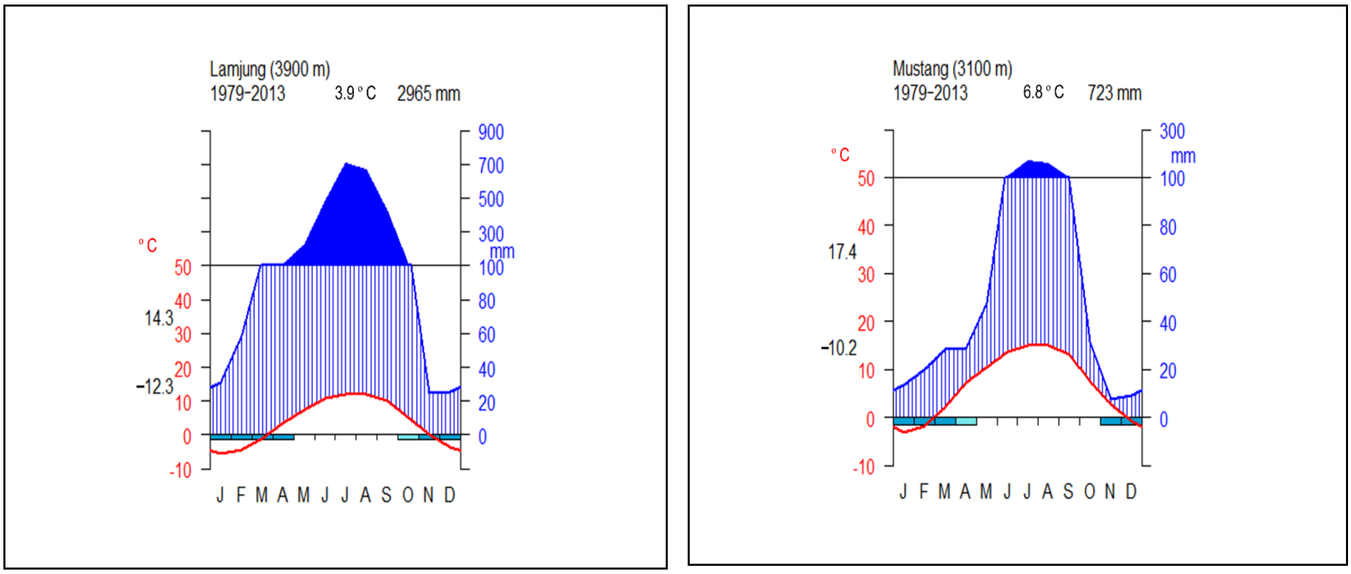


Figure 2. Map showing the intensive study sites: Lamjung and Mustang.

2.2. Climatic Conditions in the Intensive Study Sites

Average annual precipitation in the high precipitation region (Lamjung) is 2965 mm, as depicted through the climate diagram [50] (Figure 3a). The average temperature in Lamjung is 3.9 °C, with a maximum average temperature of 14.3 °C in July and a minimum of −12.3 °C in January. The region receives higher precipitation from June to September, with an average of more than 500 mm.



(**a**) (**b**)

Figure 3. Climate diagrams based on CHELSA data (1979–2013) for both study sites prepared using the *Climatol* package [51] in R-studio [52]. (**a**) Climate diagram for Lamjung where the light blue box for October signifies probable frost condition while definite frost conditions for six months from November to April are represented by dark blue boxes (**b**) Climate diagram for Mustang where the definite frost conditions for five months from November to March are indicated by the dark blue boxes while likely frost conditions in April is indicated by the light blue box. Letters in the x-axis of both (**a**) and (**b**) denote months.

The climate diagram for the low precipitation region (Mustang) (Figure 3b) shows average annual precipitation of around 723 mm and an average temperature of 6.8 °C. In Mustang, the maximum average temperature is 17.4 °C in July with a minimum of −10.2 °C in January. The four months from June to September receive the highest precipitation with averages above 100 mm.

Seasonal analyses of precipitation for both study sites were carried out based on the four seasons prevalent in Nepal: pre-monsoon (March–May), monsoon (June–September), post-monsoon (October–December) and winter (January–February) [48]. In both study sites, around 75% of precipitation occurred during the monsoon season (June–September) (see Table 2). Winter precipitation contributes more to total annual rainfall in the drier Mustang region. The greatest variation in precipitation for both study sites was in the post-monsoon season (coefficient of variation-CV: 74.1% for Lamjung, and 69.29% for Mustang).

Table 2. Average seasonal and annual precipitation and CV based on CHELSA data (1979–2013). Values in brackets are CV percentages.

Study Site	Winter (January–February) (mm)	Pre-Monsoon (March–May) (mm)	Monsoon (June–September) (mm)	Post-Monsoon (October–December) (mm)	Annual (mm)
Lamjung	89.41 (64.80)	441.37 (33.30)	2273.94 (15.10)	160.74 (74.19)	2965.40 (13.00)
Mustang	32.25 (58.10)	105.08 (31.49)	535.82 (14.67)	48.54 (69.29)	723.00 (12.00)

2.3. Geology and Soil in the Intensive Study Area

Our study sites: Lamjung and Mustang lie in two upper most tectonic plates namely Greater Himalayan Sequence (GHS) and Tethyan Himalayan Sequence (THS) respectively [53]. The underlying rocks in both study sites are mainly Gneisses, migmatite and some parts with limestone, shales, and sandstone in northern Mustang [54,55]. The soil sample (0–15 cm deep) from the center of each plot was collected to determine the physical and chemical properties. Both study sites were characterized by acidic soil conditions and high level of soil nutrients, whereas medium range of soil organic matter (Table 3). The method used to test the soil properties and the ranking chart used by the Soil Management Directorate Nepal [56] is presented in Appendix B.

Table 3. Physical and chemical properties of soil for both study sites.

Study Site	Soil Texture	Average Soil pH	Average Soil Organic Matter (%)	Soil Nutrients *		
				Average N (%)	Average P_2O_5 (Kg ha^{-1})	Average K_2O (Kg ha^{-1})
Lamjung	Loam	4.75	4.70	0.23	159.73	561.00
Mustang	Loam	6.20	5.15	0.26	154.43	561.30

* Soil Nutrients: N- Nitrogen, P_2O_5- Phosphorus pentoxide, K_2O- Potassium oxide

2.4. Data Collection

Forest inventories for 16 plots (8 plots at each study site) were employed to acquire information on forest composition and structure and assess them under different climatic conditions. Systematic random sampling was employed for this study. The first plot was established randomly and remaining plots in a tentative straight line in the same direction with 100 m distances between plots. Rectangular sampling plots, each with an area of 500 m^2 (25 m × 20 m) were established at each study site based on Nepal's National Inventory Guideline [57]. Slope correction was carried out for plots on slopes with gradients of >10%, as slope correction is mainly applied for slopes exceeding 10% [58]. Slope angle was measured using a clinometer. The true horizontal distance was calculated using the formula:

$$L = Ls \times \cos S \tag{1}$$

where 'L' is the true horizontal distance, 'Ls' is the measured distance along the slope, and 'S' is the slope in degrees.

The area was then calculated using the true horizontal distance, and adjustments to plot area were made during analysis. Sampling plots were established near the tree line to determine tree line species in the Annapurna range. Total enumeration was done during forest inventory as most trees in higher elevations were dwarf trees. The brief research design framework is illustrated in Figure 4. In Lamjung, the sample plots lay at elevations of 3700 to 4000 m in southern aspect with average steepness of 38° while in Mustang they were at 3000 to 3100 m in northern aspect with average steepness of 42° near the tree line. Tree lines in the Annapurna region lie between 3600 and 3700 m on southern slopes, while tree line elevation increases considerably, entering high mountain massifs, i.e., 4000 to 4100 m [59,60]. With an increment in distance from Annapurna, the timberline elevation decreases again [60]. In the southwestern part of Mustang, tree lines dominated by *Abies spectabilis* and *Pinus wallichiana* can be found at elevations from 2900 to 3500 m [61].

All trees (stems) inside the research plots were measured other than seedlings. In total, 870 trees were measured in the two study sites: 549 in Lamjung and 321 in Mustang. Species name, DBH (diameter at breast height) and total height were recorded for each tree. Diameter tape was used for DBH measurement and a Suunto height meter for height measurement with measurement accuracy of 0.1 cm and 0.1 m, respectively. To analyze mountain forest canopy cover, hemispherical photographs were taken of each plot. In total, 80 hemispherical photographs (five for each plot) were recorded. In each plot, one photograph was taken at the center of the plot, and the remaining four were taken 5 m inside each border, at a 5 m distance from plot corners (Figure 5). A DSLR (Digital Single Lens Reflex) camera (Nikon, Model-D5300) and fisheye lens (Sigma Circular Fisheye 4.5 mm 1:2:8 lens with a view angle of 180°) were used for this purpose. The hemispherical photographs were taken according to the Beckschäfer method [62] at a height of 1.5 m during windless weather and standard overcast condition [63]. In addition, to assess the variability of mountain forest leaf sizes in two distinct precipitation conditions, 50 leaves/leaflets were collected for each species (a total of 650 leaves/leaflets) maintaining a representation of all three layers of crown: lower, middle, and top. For coniferous species, the size of a single needle was measured, considering the leaflet. The areas of around 576 leaves/leaflets were measured: 400 in Mustang and 176 in Lamjung. The remaining samples were deemed unacceptable due to shape distortion. The Leaf Byte app [64] iOS (iPhone Operating System) version was used for measuring leaf area.

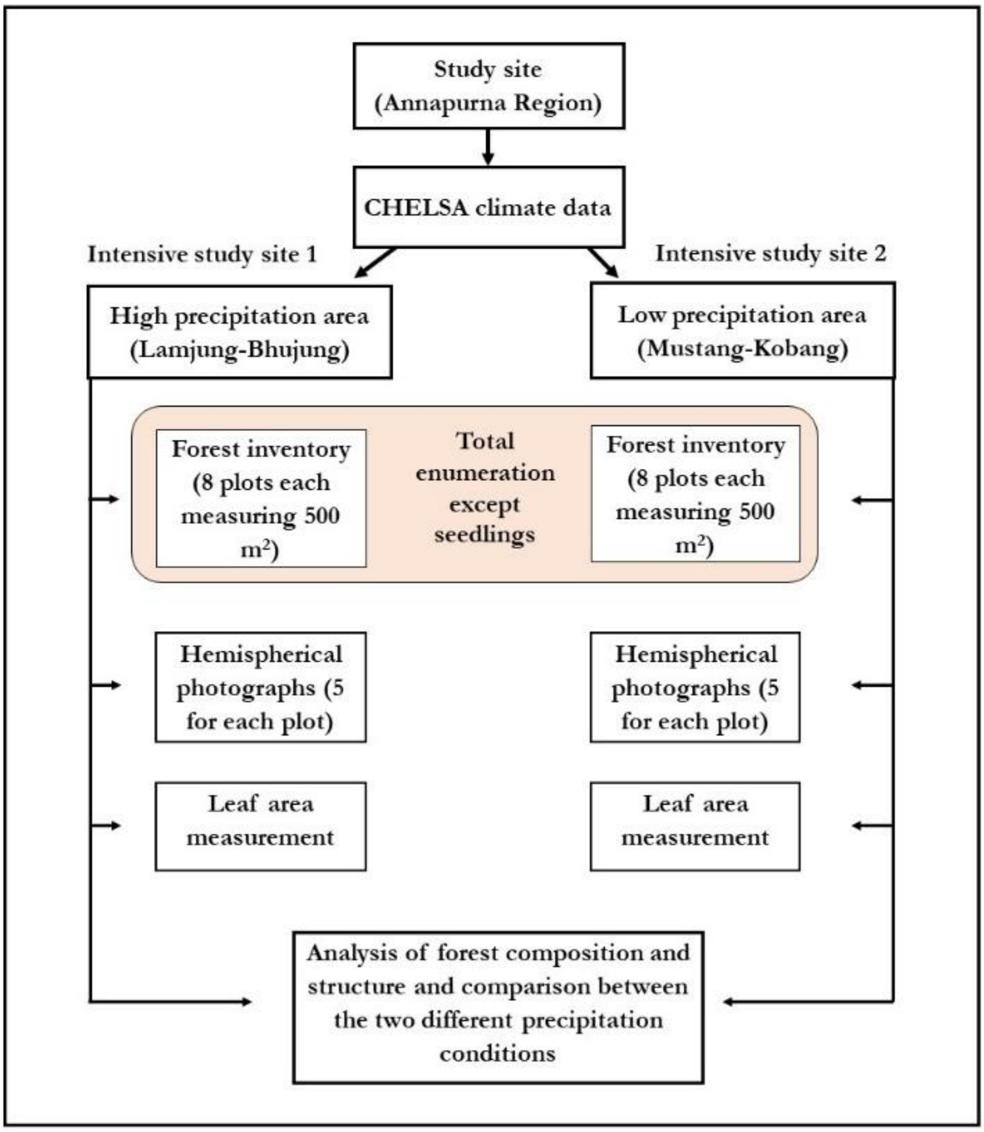


Figure 4. Research design.

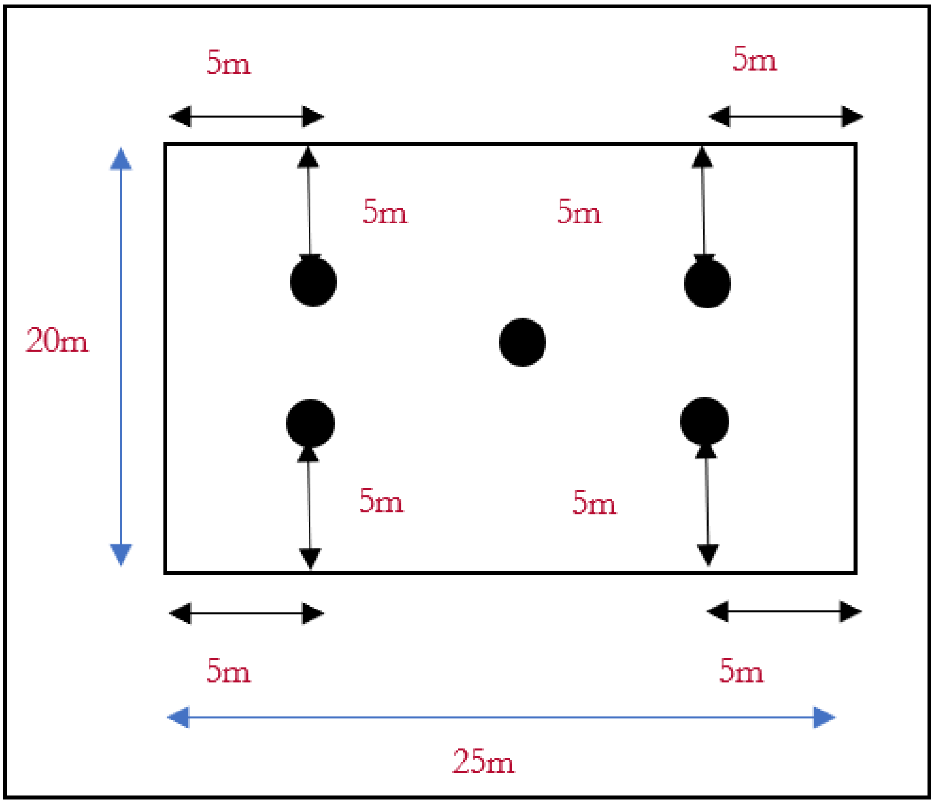


Figure 5. Research design for capturing hemispherical photographs in each study plot.

2.5. Data Analysis

Firstly, a list of tree species recorded in both study sites was developed. The Shapiro–Wilk test [65] was used to assess the normality assumption which showed the collected field data were not normally distributed. General stand variables, such as basal area (m^2 ha^{-1}), quadratic mean diameter (cm), stem density (stems ha^{-1}), mean canopy height (m), volume (m^3 ha^{-1}) were calculated using descriptive statistics. Species diversity, species richness [66], and species evenness [67] were generated using the *vegan* [68] package in R-studio [52]. Species diversity was measured using two indices: the Shannon–Wiener Index [69] and Simpson′s Index [70]. Additionally, a boxplot in R-studio [52] was used to visualize diversity indices, species richness, and species evenness. A tree diameter distribution graph was prepared using the inventory data for both study sites, which were crucial for describing forest structures and functions [71]. In simple terms, the histograms of frequencies of individual stems per hectare divided into diameter classes determined the tree distribution patterns in stands [72]. The R-studio [52], *tidyverse* [73] and *ggplot2* [74] packages were used to visualize diameter frequency distribution. Important Value Index (IVI) was calculated for each species in both study sites to get an overview of important (dominant) species. The IVI was calculated by quantifying three components of each species: relative density, relative dominance, and relative frequency.

$$\text{IVI} = \text{relative density} + \text{relative dominance} + \text{relative frequency} \tag{2}$$

where: density = number of individuals per ha, dominance = basal area per ha, and frequency = occurrence of certain species in respective sample plots:

Similarly:

$$\text{relative density} = \frac{\text{Number of individuals of the species}}{\text{total number of individuals of all species}} \times 100\%$$

$$\text{relative dominance} = \frac{\text{Total basal area of the species}}{\text{Total basal area of all species}} \times 100\%$$

$$\text{relative frequency} = \frac{\text{percent of sample plots occupied by the species}}{\text{percent of the occurence of all species}} \times 100\%$$

Each of these values is expressed as a percentage ranging from 0% to 100%. The IVI is the sum of these three components and can range from 0 to 300 (Adapted from [75]). The hemispherical photos were analyzed in ImageJ [76] using the Beckschäfer method [77]. At first, the hemispherical photos were converted to binary pictures and the pixel values of gap fraction and canopy cover were recorded. The pixel values of the canopy divided by the total pixel value provided the percentage of canopy cover. The Wilcoxon rank-sum test, also called the Mann–Whitney U test [78], was used for the statistical analysis in this study. In R-studio [52], the *wilcox.test* was used to examine the statistical significance of differences observed in inventory analysis findings between the study sites.

3. Results

3.1. Forest Composition

3.1.1. Species Recorded and Their Main Features

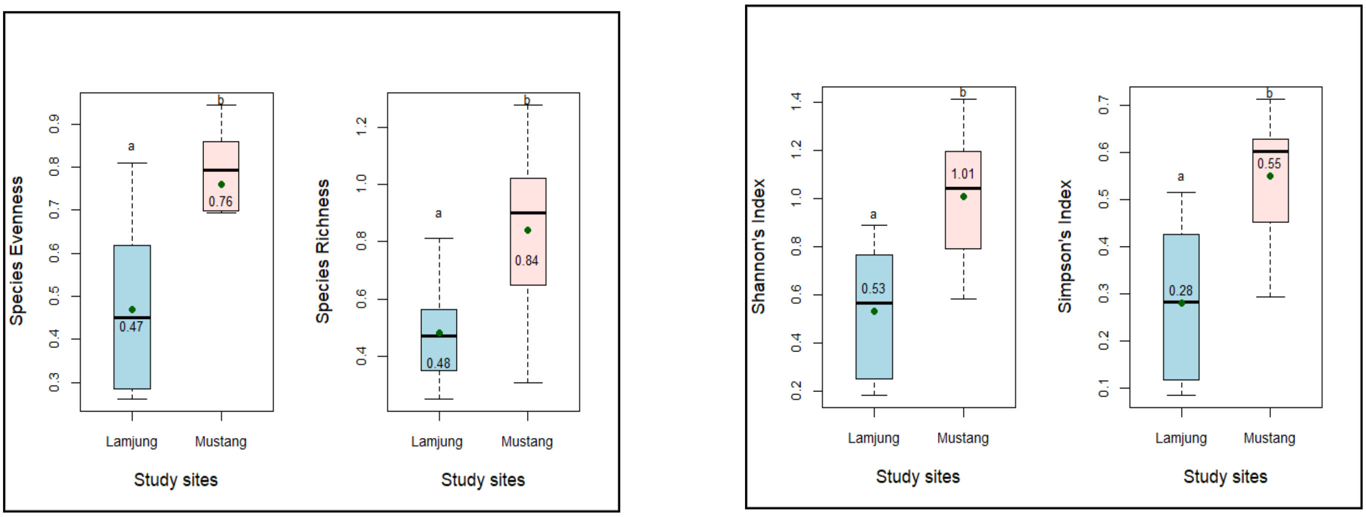
In total, 13 species were recorded near the tree lines during the field studies (Table 4). In Lamjung, five species: *Betula utilis*, *Juniperus indica*, *Rhododendron campanulatum*, *Salix nepalensis* and *Sorbus microphylla* were recorded, while in Mustang eight species: *Abies spectabilis*, *Acer campbellii*, *Cotoneaster microphyllus*, *Elaeagnus parviflora*, *Ilex dipyrena*, *Pinus wallichiana*, *Rhododendron arboreum*, and *Taxus wallichiana* were recorded.

Table 4. Species recorded in both study sites along with elevations and main features.

Study Site	Species Name, Recorded Range (Meter above Mean Sea Level)	Number of Trees Inventoried	Main Features
Lamjung	*Betula utilis* 3700–4000 m	21	The only broadleaved species that dominates extensive areas in sub-alpine altitudes [79] and forms tree line vegetation in the Himalayas [80].
	Juniperus indica 3900–4000 m	17	Found in upper montane woodlands in pure stands or with *Abies*, *Pinus*, or in *Betula* woodland or alpine heath and grassland, these were also reported in the sunny slopes of Mustang [81].
	Rhododendron campanulatum 3700–4000 m	440	The major understory component of sub-alpine forest and forms pure stands above the tree line in the Himalayas of Nepal [82].
	Salix nepalensis 3700–4000 m	26	*Salix* spp. colonizes open soil patches after disturbance, and cattle trampling promotes *Salix* cover. It mainly occurs with alpine dwarf thickets such as *Rhododendron* [81].
	Sorbus microphylla 3700–4000 m	45	This is also called small leaf rowan and its berries are mainly consumed by the red panda (*Ailurus fulgens)* [83]. It commonly occurs with *Betula utilis* [81].
Mustang	*Abies spectabilis* 3100 m	65	The dominant tree in the western and central Himalayas, it grows better in cool and moist north-facing slopes [84]. It occurs as a canopy dominant species along with different species of *Rhododendron* and *Betula utilis* [85].
	Acer campbellii 3100 m	65	The lower Mustang region has mixed forest of *Acer*, *Pinus wallichiana*, and *Rhododendron* spp. [86]. This is one of the less dominant species of the Annapurna region [87]. It forms good habitat for the red panda (*Ailurus fulgens*) [88] but evidence of red panda presence is unreported from Mustang district [89].
	Cotoneaster microphyllus 3000–3100 m	11	In the rain-shadow valley of the Himalayas, this species occurs along with the distribution range of *Abies* spp. between 2000 and 3500 m [81]. It is a shrub (0–5 m) and small tree (up to 15 m), acts as a good soil stabilizer [81] and is used for fuelwood, fencing, making tools, and for medicinal purposes in the Mustang region [90].
	Elaeagnus parviflora 3000–3100 m	11	This species commonly occurs with *Ilex* spp. [81], is reported at elevations of 2800–3000 m in Mustang and is mainly used for food [91].
	Ilex dipyrena 3100 m	3	An evergreen tree that occurs in sub-humid to sub-arid conditions. This species mainly occurs intermixed with *Rhododendron arboreum* and *Taxus wallichiana* [92] in [81].
	Pinus wallichiana 3000 m	96	Found in temperate to sub-alpine zones, typically in mountain screes and glacier forelands. It forms the tree line in relatively dry regions such as Manang [22].
	Rhododendron arboreum 3000–3100 m	85	It has the widest distribution range among all Himalayan species [93]. It mainly occurs on sunny slopes. It also occurs at the understory of *Abies spectabilis* and forms the second layer in mountains [81].
	Taxus wallichiana 3100 m	21	Like most conifers, it is an evergreen species belonging to *Taxaceae*. Also known as Himalayan Yew, it is slow-growing species and a major source of Taxol. This species occurs in the Annapurna range [94].

3.1.2. Species Evenness, Richness, and Diversity

Before assessing the species diversity indices of our study sites, species evenness and richness were analyzed (Figure 6a). Mustang had higher species evenness (0.76 ± 0.03) and species richness (0.84 ± 0.06) than Lamjung (evenness- 0.47 ± 0.03 and richness- 0.48 ± 0.02). Similarly, statistically significant differences were observed between the two study sites in terms of species evenness (W = 7, *p*-value: 0.006) and species richness (W = 9, *p*-value: 0.014). The higher Shannon index and Simpson index values for forests in Mustang indicate higher species diversity in comparison to Lamjung. A significant difference was observed between the two study sites for species diversity based on the two diversity indices (W = 8, *p*-value: 0.01). Shannon index values varied from 0.53 ± 0.01 to 1.01 ± 0.03 between Lamjung and Mustang. Similarly, the Simpson index value was 0.28 ± 0.01 for Lamjung and 0.55 ± 0.06 for Mustang (Figure 6b).



(**a**) (**b**)

Figure 6. (**a**) Comparison of species evenness and species richness; (**b**) Comparison of species diversity, between the study sites. The different letters (**a**,**b**) denote significant differences between mean values.

3.1.3. Species Distribution

In Lamjung, *Rhododendron campanulatum* was found to be the dominant species (Table 5). It had an abundance of 1100 stems ha^{-1}, a basal area of 16.4 m^2 ha^{-1}, and a frequency of 100%. The least dominant tree species was *Juniperus indica* with an abundance of 43 stems ha^{-1}, and a frequency of only 13% in the study site. This study site was dominated by broadleaved species with few undergrowth of coniferous species. In Mustang, *Abies spectabilis* was the most dominant species (Table 6). It had an abundance of 163 stems ha^{-1}, a basal area of 13.4 m^2 ha^{-1}, and a frequency of 50%. *Ilex dipyrena* was the least dominant species in Mustang with a stem density of 8 stems ha^{-1} and a frequency of only 13%. The study site in Mustang was found to be dominated by two coniferous species: *Abies* and *Pinus* in addition to the broadleaved species *Rhododoendron arboreum,* which had a frequency of 100%, signifying its presence in all research plots.

3.2. Forest Structure

3.2.1. Diameter Frequency Distribution

The diameter frequency distributions of all species in the total study area and in the precipitation, conditions differentiated study sites signifies the presence of natural forest in the region (Figure 7). Except for trees below 10 cm diameter, both study sites showed an inverse J-shaped curve, indicating that numbers of trees decrease as diameters increase. The highest proportion of trees belonged to the 10–20 cm diameter class (around 51% in Lamjung and 37% in Mustang). The >80 cm diameter class accounted for only 0.18% of trees in Lamjung and 0.37% in Mustang. The inverse J-shaped curve was more pronounced for Lamjung. Diameters of measured trees varied from 3.9 to 96 cm in Lamjung, and 2.1 to 84 cm in Mustang.

Table 5. IVI analysis of tree species for the study site in Lamjung.

Species Name	Abundance [n ha^{-1}]	Basal Area [m^2 ha^{-1}]	Frequency [%]	IVI
Rhododendron campanulatum	1100	16.4	100	171.9
Sorbus microphylla	112	5.3	88	56.1
Betula utilis	53	5.6	63	44.5
Salix nepalensis	65	0.6	38	19.5
Juniperus indica	43	0.2	13	8.0
Total	1373	28.0		300

Table 6. IVI analysis of tree species for the study site in Mustang.

Species Name	Abundance [n ha^{-1}]	Basal Area [m^2 ha^{-1}]	Frequency [%]	IVI
Abies spectabilis	163	13.4	50	85.9
Pinus wallichiana	240	7.7	63	76.0
Rhododendron arboreum	213	2.3	100	60.7
Acer campbellii	73	0.6	38	20.6
Cotoneaster microphyllus	28	0.2	63	19.7
Taxus wallichiana	53	0.9	25	16.5
Elaeagnus parviflora	28	0.1	50	16.4
Ilex dipyrena	8	0.1	13	4.2
Total	806	25.2		300

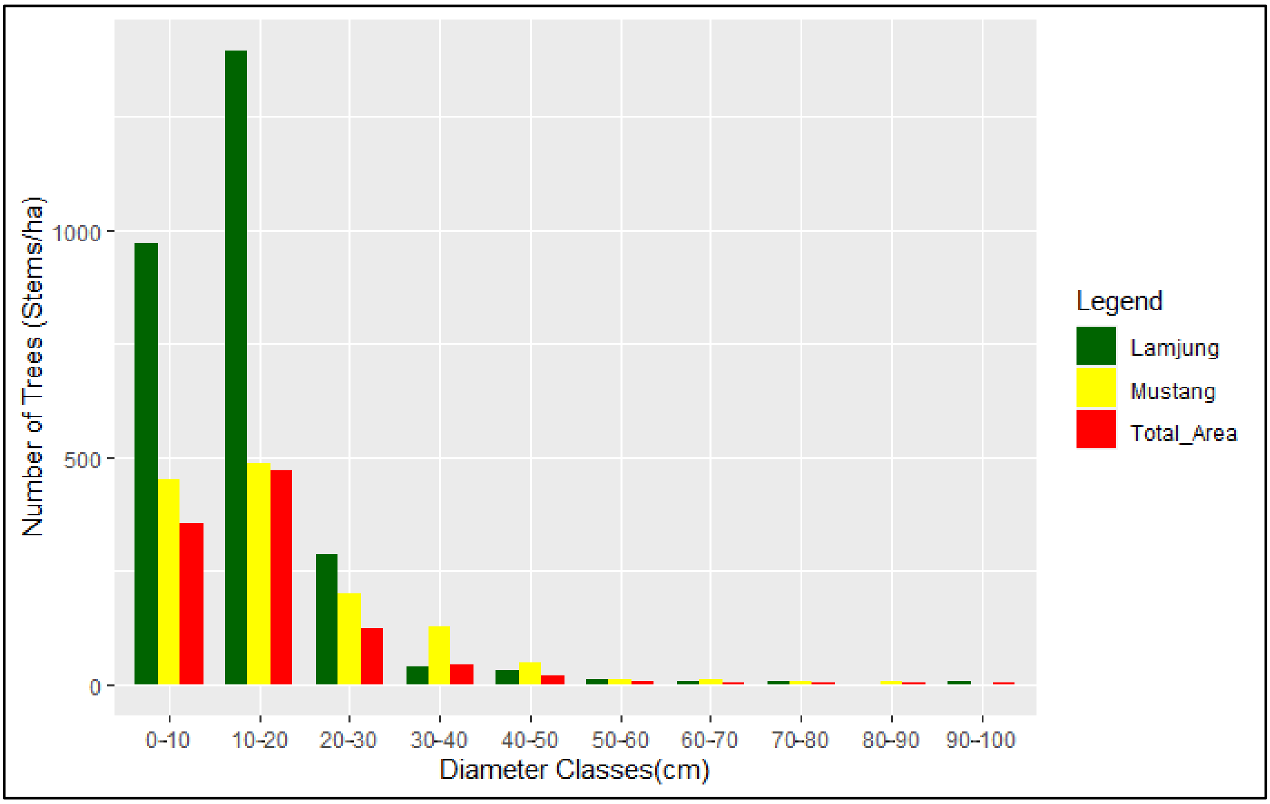


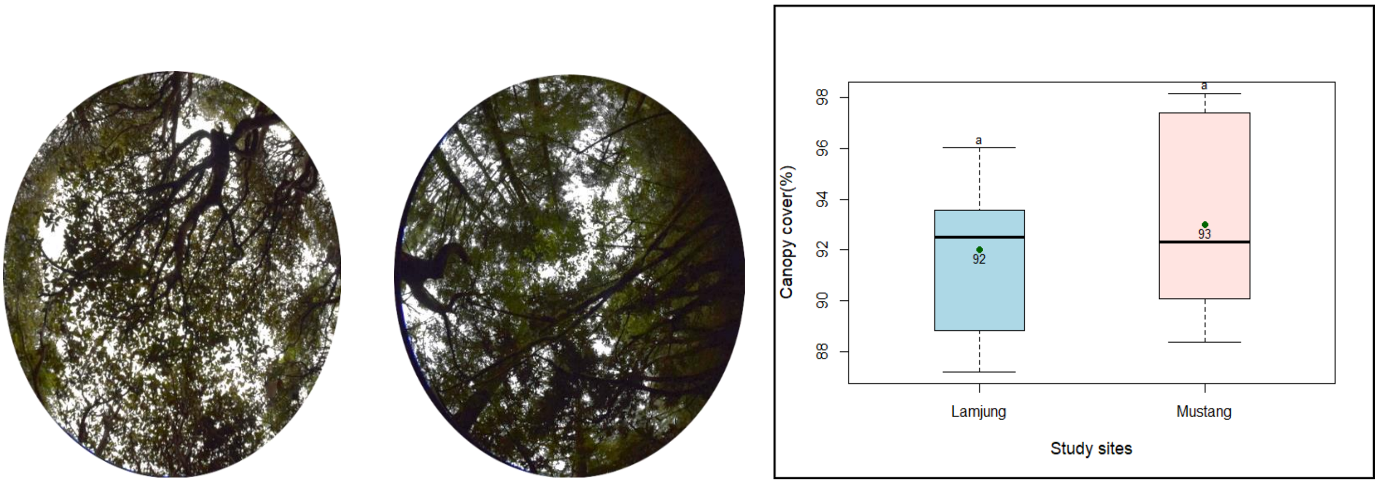
Figure 7. Diameter frequency distribution for both study sites.

3.2.2. Main Stand Variables and Health Attributes of Trees

Both horizontal and vertical stand variables were derived in this study. The main stand variables, such as basal area, quadratic mean diameter (QMD), stem density, mean tree height, and tree volume were generated for both study sites (Table 7). The forest in Lamjung had a higher basal area and stem density than forest in Mustang. Average basal area was approximately 28 m^2 ha^{-1} for forest in Lamjung, and 25 m^2 ha^{-1} for Mustang with no significant difference between mean values. There was significant difference in stem density between the two study sites, where Lamjung and Mustang had stem densities of 1373 stems ha^{-1} and 806 stems ha^{-1}, respectively. QMD values were 16.12 cm for the forest in Lamjung, and 21.53 cm for Mustang, with no statistically significant difference between the two study sites. Average tree height was roughly double in Mustang (10.2 m) compared to Lamjung (5.2 m), with a statistically significant difference. Stem volume ranged from 102.68 m^3 ha^{-1} in Lamjung to 282.47 m^3 ha^{-1} in Mustang. The higher volume in Mustang might be due to the higher QMD and mean tree height values in the area, though no statistically significant difference was observed in mean values for volumes between the study sites. Moreover, analyzing the hemispherical photographs (Figure 8a,b) of both study sites showed similar canopy cover, i.e., > 90% (Figure 8c) with no statistically significant difference (W = 24, *p*-value: 0.43).

Table 7. Main stand variables for both study sites generated from forest inventory data.

Stand Variable	Lamjung	Mustang	Wilcoxon Test Statistics (W)	*p*-Value
Basal Area (m^2 ha^{-1})	28.03	25.19	40	0.44
Stem density (stems ha^{-1})	1373	806	52	0.037
Quadratic mean diameter (cm)	16.12	21.53	20	0.23
Mean tree height (m)	5.2	10.2	1	0.0003
Volume (m^3 ha^{-1})	102.68	282.47	17	0.13



(**a**) (**b**) (**c**)

Figure 8. Sample hemispherical photographs captured in Lamjung (**a**) and Mustang (**b**), and canopy cover of forests in Lamjung and Mustang (**c**) where a denotes non-significant difference between the mean values.

Comparisons of five health and morphological attributes, namely: dead/dying trees, the presence of buttresses, leaning trees, crooked trees, and trees with broken crowns, were made between the two study sites (Figure 9). Lamjung had higher proportions of leaning (>60%) and buttressed trees (39%) in comparison to Mustang. The forest in Lamjung had the highest values for all attributes except for broken crowns, while crooked trees were absent from the forest in Mustang.

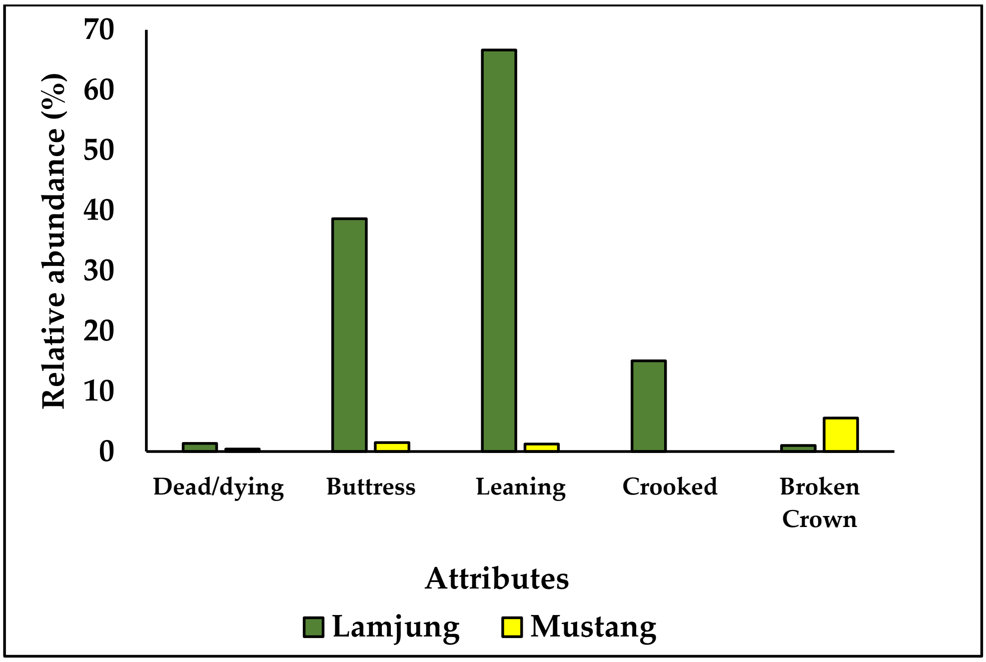


Figure 9. Relative abundance of tree health and morphological attributes in both study sites.

3.2.3. Leaf Sizes of Mountainous Tree Species

Leaf sizes of the species recorded during the study differed significantly between the forests with different precipitation conditions (Table 8). In the high precipitation region, the dominant species, *Rhododendron campanulatum*, had the biggest leaf size at 40.94 ± 2.30 cm^2, while *Sorbus microphylla* had the smallest leaf size at 2.48 ± 0.15 cm^2. The only recorded coniferous species: *Juniperus indica* in Lamjung had the needle/leaflet size at 0.44 ± 0.03 cm^2. The sparsely recorded broadleaved species in Mustang i.e., *Rhododendron arboreum*, was found to have the largest leaf size at 31.29 ± 1.80 cm^2. Among the coniferous species recorded in Mustang, *Pinus wallichiana* had the largest needle/leaflet size at 0.65 ± 0.02 cm^2.

Table 8. Average leaf areas of species recorded in the study sites.

Study Site	Species Name	Average Leaf Area ± se (cm^2)	Species Type
Lamjung	*Betula utilis*	31.70 ± 2.95	Broadleaved
	Juniperus indica	0.44 ± 0.03	Coniferous
	Rhododendron campanulatum	40.94 ± 2.30	Broadleaved
	Salix nepalensis	11.00 ± 0.70	Broadleaved
	Sorbus microphylla	2.48 ± 0.15	Broadleaved
Mustang	*Abies spectabilis*	0.47 ± 0.12	Coniferous
	Acer cambellii	21.11 ± 2.40	Broadleaved
	Cotoneaster microphyllus	8.90 ± 0.76	Broadleaved
	Elaeagnus parviflora	26.42 ± 2.99	Broadleaved
	Pinus wallichiana	0.65 ± 0.02	Coniferous
	Ilex dipyrena	25.27 ± 2.40	Broadleaved
	Rhododendron arboreum	31.29 ± 1.80	Broadleaved
	Taxus wallichiana	0.53 ± 0.03	Coniferous

4. Discussion

Climate variables, especially precipitation, strongly influence vegetation distribution and composition through impacts on water availability and local weather conditions [95,96]. The spatiotemporal patterns of vegetation at upper tree lines in mountains are largely determined by soil moisture [97,98] and patterns differ between slopes due to differences in the presence of permafrost [99,100]. The two study sites varied only in terms of slope direction and precipitation while all other factors slope inclination, type of soil were almost similar. The most common species recorded near the tree line in Nepal are *Abies spectabilis, Rhododendron campanulatum, Pinus wallichiana* [84], *Betula utilis* [101], *Sorbus microphylla, Salix* spp. and *Juniperus* spp. [102], which supports our findings on the species encountered during this study. Dense *Rhododendron campanulatum* forest in the Lamjung site has also been documented in the Annapurna range by Schickhoff's study [59] on the timberline of the Hindu-Kush Himalayas. In this study, broadleaf forest with *Rhododendron campanulatum* and *Betula utilis* was found in the higher precipitation zone, whereas needle-leaved forest with *Abies spectabilis* and *Pinus wallichiana* was found in the lower precipitation zone. The predominance of *Rhododendron campanulatum*, *Sorbus* spp. in mesic sites has been documented by Singh and Singh [103]. The evergreen species and large shrubs of *Rhododendron* spp. in areas dominated by monsoon precipitation have also been reported by Schickhoff [59]. The dominance of *Pinus wallichiana* in south-facing dry slopes, and *Abies spectabilis* and *Rhododendron campanulatum* in mesic slopes in the Himalayas of Nepal have been reported by many studies [22,59,104,105]. However, the presence of *Abies spectabilis* in a dry area like Mustang contradicts many studies [61,81]. The area near Kobang (Lete region) is estimated to receive more precipitation and therefore has a wider distribution of this species [106].

Many studies, e.g., [107–109] have mentioned climate variables, mainly precipitation and temperature, and their interactions as the main factors for variation in species richness. Species richness and species diversity were higher in Mustang than in Lamjung, which depicts the negative correlation between precipitation and diversity. The higher species richness and diversity in Mustang than Lamjung could be due to the differences in study plot aspects. The higher diversity recorded on the north-facing slopes of Mustang than the south-facing forest of Lamjung in this study concurs with other findings in Nepal [110,111] and other parts of the globe [112,113]. In the northern hemisphere, south-facing slopes are usually warmer due to their higher levels of irradiance, which support drought-resistant vegetation and restrict tree growth, while north-facing slopes are cold and humid with higher soil moisture, which support a larger number of species [111]. Another reason for the higher number of species recorded in Mustang might be due to the higher precipitation in our study area (Kobang/Lete region) at 723 mm compared to the average of 200 mm for the Mustang region [48]. Increases in precipitation have been found to enhance species richness and plant diversity markedly by promoting soil moisture variability, especially in semi-arid and arid regions [114–116]. The difference in species richness and diversity between Mustang and Lamjung could be also due to the different elevations of the study sites, as species richness is believed to decrease with increases in elevation [117,118]. Though this is open to debate with other studies showing a hump-shaped relationship in the Himalayas [104,119].

The vague relationship between species richness and precipitation has been determined by different studies. A study in Eastern Himalaya in Bhutan showed the nil effect of precipitation on species richness. However, in different moisture regimes, temperature had a significant effect on species richness [120]. The non-significant effect of precipitation on species diversity is also reported by Stan and Sanchez-Azofeifa [121]. In contrast, the study by Kushwaha and Nandy [122] recorded lower species richness in dry forest than moist forests, stating that moisture availability affects the regeneration of tree species. In lower-elevation tropical forests, higher species diversity and richness were recorded in high precipitation regions than dry regions in Myanmar by Khaine et al. [123], and in mangrove forest [124] and sub-Saharan Africa [125] as well. Regarding forest structure, most studies [1,32,126–128] have focused on Himalayan vegetation patterns along altitudinal gradients, though few have mentioned the importance of climate variables in predicting forest stand structure [21,129,130]. Considering forest structure varies with water availability [131], and environmental and biological factors control forest structure at higher elevations [132,133], this study tried to assess differences in forest structure along a precipitation gradient in the Annapurna range. The higher stem density and basal area in Lamjung than Mustang signified a positive relationship between precipitation and forest structure. Similar to our findings, Khaine et al. [123] reported the strong influence of precipitation on forest structure in Myanmar. They found increases in basal area and stem density with precipitation increasing from 843 to 2035 mm. Muñoz Mazón et al. [131] also found an increase in basal area with increasing precipitation and decreasing temperature along the Atlantic slope of Talamanca Mountain. Higher basal area and stem density were observed in humid versus dry areas of forest in Brazil, and were attributed to precipitation seasonality [134]. Moreover, a strong relationship between climate variables and forest structure was observed in the Eastern Himalayan of India [135]. Restricted tree growth due to low water availability during long dry seasons is documented by Hiltner et al. [136]. Structural changes owing to changes in precipitation were also forecast by Hiltner et al. [136]. Similarly, Kushwaha and Nandy [122] discovered a strong relationship between precipitation and forest structure in West Bengal, India. The influence of annual precipitation on forest structure in tropical regions has also been documented by Beard [137]. A study by Duchesne and Ouimet [138] mentions the significant effects of precipitation on the structural development of forests over time. Basal area and density increased from younger to medium age stands, then decreased in older stands in sites with higher precipitation, whereas basal area showed a linear relationship with stand age in sites with lower precipitation [138]. According to Hiltner et al. [136], precipitation affects forest structure through its impact on moisture availability and therefore drought-tolerant species would show no significant change.

Furthermore, the inverse J-shaped pattern documented for overall size class distribution in this study is similar to the findings of Bhutia et al. [32] who found the highest number of individuals in the smallest DBH class of 3 to 13 cm and least in the highest class in Eastern Himalayan, India. This pattern is further supported by the findings of Shrestha et al. [139], Dar et al. [140], Pandey et al. [127], and Schwab [141]. More than 90% of trees were found in lower diameter classes in the Himalayan forest of India [140]. Pandey et al. [127] recorded maximum percentages of trees in the DBH range of 10 to 29.9 cm in the trans-Himalayan region of Nepal. Most tree species in the Krummholz tree line of Rolwaling Himal, Nepal in the lower DBH range i.e., 0–14 cm were *Abies spectabilis*, *Betula utilis*, *Sorbus microphylla* and *Rhododendron campanulatum* [141]. This type of diameter distribution suggests an uneven-aged forest with enough young recruitment to replenish mature forest stands [142]. Although canopy cover analysis of mountain forests using fisheye lenses are rarely documented, the percentage of canopy cover recorded by this study is higher than observations made by Uniyal et al. [143] in the Garhwal Himalayan forest in India, and by Måren and Sharma [144] in the Langtang area of Nepal. The canopy cover of high-elevation forest was recorded at >60% in Garhwal, India [143] and around 65 to 77% in protected and government forest in the mountains of Nepal [144]. Woody life forms such as buttresses are common features of tropical forest communities [145] but may also be present in sub-tropical and higher elevation forests [146,147]. The presence of different woody life forms has been documented in lower proportions at higher elevations [148,149], which supports our findings on different health and morphological attributes in the study sites. Although there is no satisfactory theory to describe life form development, it might be due to the influence of the humid environment on root tension [145]. However, quantitative studies of forest structure, including life forms, are rarely documented in higher elevation forests [150].

The size of leaves varied according to the species. Since the species in two study sites were completely different, it was difficult to compare leaf size to the precipitation. However, the Rhododendron species in high precipitation region had larger leaves than low precipitation region. The larger leaf sizes in cold and wet climates were also recorded by Peppe et al. [151]. A reduction in leaf size along lower soil phosphorus and rainfall was also recorded by McDonald et al. [152]. In our study, soil properties were uniform in both areas, therefore, the change in leaf size could be associated with precipitation. The study of other morphological traits in leaves along different precipitation region is recommended. This study is based on a small number of sample plots as the number of sample plots is determined by topographical and climatic factors as well as time constraints [153]. Roughly 21–108 trees were recorded per plot, which included almost all types and species of trees available in the area. Even though this study is based on few plots, this gives reliable information about structure and composition of mountain forest along contrasting precipitation conditions. In small forest area, the smaller sample size and resulting higher level of sampling error is usually accepted [154]. However, research on large-scale forest monitoring certainly requires the larger sample size for an appropriate precision level [154].

5. Conclusions

This study analyzed the variation in the forest structure specially stand variables and forest composition that include species richness, evenness, and diversity in two sites with similar topographic and edaphic factors but different precipitation conditions. The mountain forest in the high precipitation region is dominated by broadleaved forest, whereas in the low precipitation region, coniferous forest is dominant. The mountain forest was characterized by the uneven-aged stand and uneven diameter distribution signifying natural forest condition. The precipitation had a positive impact on forest structure, but had a negative impact on species diversity. However, precipitation had no effect on canopy cover, whereas the leaf area depended on the nature of plant species. Conclusively, precipitation is an important parameter in defining the structure and composition of the forest stand. Although the findings of this study were based on a smaller sample size, they give a clear indication of the importance of this research in understanding species composition and forest structure on two contrasting sides of the mountain range. Although it would be desirable to validate and quantify the findings of this study with more research in this area, it may nevertheless prove very useful in understanding high-elevation forest and in implementing a sustainable management approach.

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Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Table A1. Land cover pattern in the Annapurna range (Source: EU-Copernicus, 2020).

Land Cover	Area (km^2)	Percentage
Forest	4300.70	36.05
Sparse vegetation	3095.07	25.94
Herbaceous vegetation	2781.35	23.32
Snow/Ice	1486.45	12.46
Cropland	99.43	0.83
Shrubland	90.45	0.76
Built up area	49.92	0.42
Permanent inland water	18.93	0.16
Herbaceous wetland	7.08	0.06
Total	11,929.37	100.00

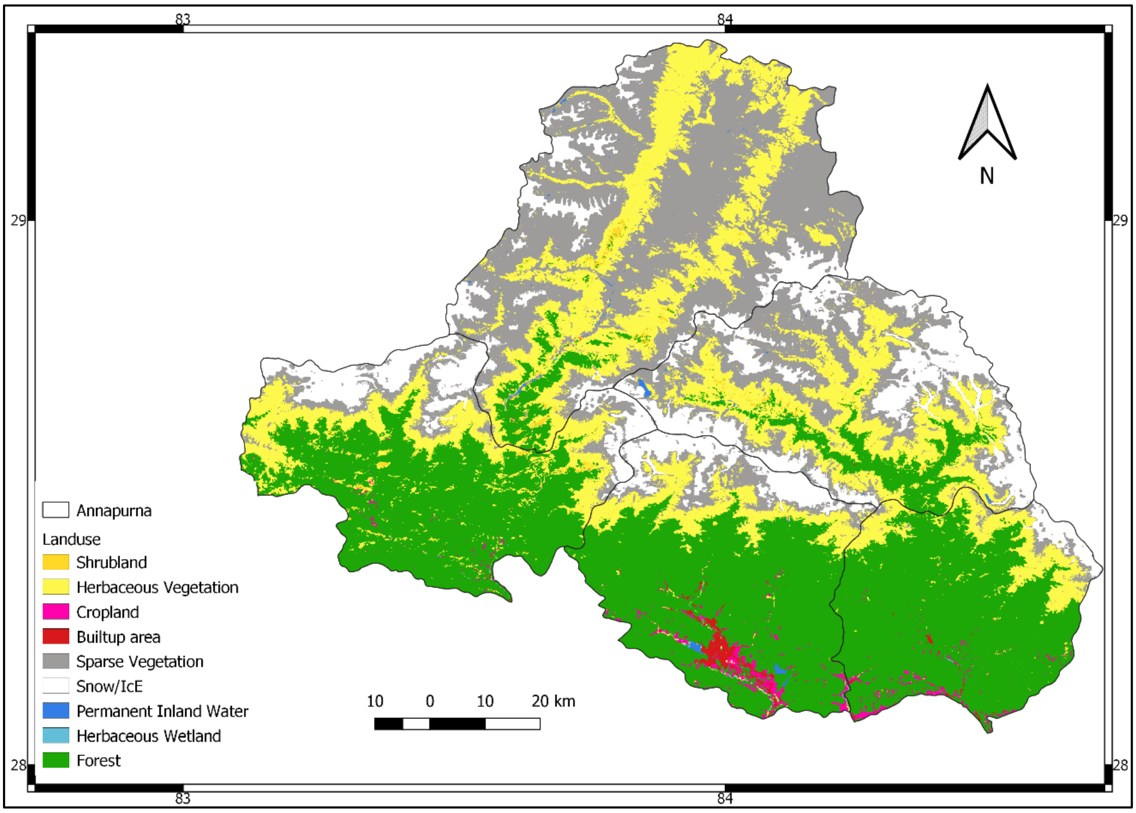

Figure A1. Land cover map of the Annapurna range prepared based on information provided by the European Union Copernicus Land Monitoring Service, 2020.

Appendix B

Table A2. Method used for testing of soil's physical chemical properties at Soil lab in Nepal.

Test	Method
Soil Texture	Hydrometer method [155]
pH	1:2 soil water suspension [156]
Organic matter content (OM, %)	Walkely and Black [157]
Total Nitrogen content (N, %)	Kjeldahl method [158]
Available Phosphorus (P_20_5, kg ha^{-1})	Olsen's bicarbonate [159]
Available Potassium (K_20, kg ha^{-1})	Flame photometry [160]

Table A3. Rating of soil chemical properties provided by Soil Management Directorate Nepal.

Properties	Rating
pH	IF > 7.5, "Alkaline", IF > 6.4, "Neutral", "Acidic"
O.M.	IF > 5, "High", IF > 2.4, "Medium", "Low"
N.	IF > 0.2, "High", IF > 0.1, "Medium", "Low"
P_2O_5	IF > 55, "High", IF > 31, "Medium", "Low"
K_2O	IF > 280, "High", IF> 110, "Medium", "Low"

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