

The Distribution of Wood Density along the Altitudinal Gradient of Pakistan

Sahar Suleman^{1*}, Shakeel Ahmad², Qafia Naz Aslam³, Ramiz Raja²

¹Department of Wildlife and Ecology, University of Veterinary and Animal Sciences, Lahore, Punjab, Pakistan.

²Bahauddin Zakariya University Multan, Punjab, Pakistan.

³Institute of Plant Breeding and Biotechnology, Muhammad Nawaz Sharif University of agriculture Multan

*Corresponding Author: saharSuleman59@gmail.com

Running Title: Wood density in Pakistan

Abstract: Understanding how plants adapt to extreme environments is central to ecology, and wood density serves as a primary indicator of these survival strategies. This study examines the variation in shrub wood density across a steep altitudinal gradient in Pakistan, spanning from 300 meters in the lowland plains to 2700 meters in the subalpine zones. We sampled 60 distinct shrub species across 12 ecological sites, representing six major forest ecosystems. Our analysis revealed a clear inverse relationship between altitude and wood density. The densest wood was found in the hot, arid tropical thorn forests (averaging 0.000734 g/cm³), while the lightest wood characterized the high-elevation subalpine stands (0.000544 g/cm³). Although broader comparisons among forest types did not yield a massive statistical divergence ($P = 0.424$), the variations among individual species coexisting within the exact same sites were highly significant ($P < 0.05$). These structural shifts demonstrate a fundamental ecological trade-off: lowland species prioritize rigid, cavitation-resistant wood to survive severe drought, whereas high-altitude plants invest in lighter, flexible wood to maximize rapid seasonal growth and withstand heavy snow loads. Beyond botanical adaptations, we highlight how this altitudinal shift in wood density directly shapes the broader ecosystem by dictating the structural integrity of avian nesting sites, the palatability of winter forage for mammalian herbivores, and the availability of deadwood microhabitats for invertebrate communities.

Key words: Wood density, altitudinal gradient, morphological adaptations, biomechanics, forest ecosystems, wildlife habitat

INTRODUCTION

Surviving in extreme environments requires highly specialized internal architecture, and for woody plants, wood density is one of the most critical functional traits. It serves as a master indicator of how a shrub or tree balances water management with mechanical strength. When a plant develops high-density wood, it is generally investing in thick, reinforced cell walls. This structural durability prevents the plant's internal water transport system from collapsing under severe drought or extreme heat (Hacke et al., 2001; Panshin & de Zeeuw, 1980). Conversely, species that produce lighter, less dense wood typically prioritize rapid volumetric growth and greater water storage, sacrificing some mechanical rigidity for the ability to expand quickly when conditions are favorable (Baker & Bunyavejchewin, 2006).

Mountainous regions offer a unique natural laboratory for observing these morphological shifts. As elevation increases, atmospheric pressure drops, temperatures plummet, and precipitation patterns alter dramatically. The geography of Pakistan is particularly well suited for this type of research, as the landscape transitions rapidly from arid sea-level scrublands to the towering, snow-covered peaks of the Himalayas (Champion et al., 1965).

While extensive floristic surveys have documented the types of vegetation present across South Asia, the functional and structural traits of these plants—specifically wood density—remain poorly quantified along continuous elevational gradients. Because shrubs form the foundational understory of these forests, their physical composition directly influences the structural complexity of the habitat. This study was designed to measure how wood density naturally shifts across a gradient from 300 to 2700 meters above sea level. We aim to document the extent of this variation both across

different climatic zones and among species sharing the same localized environment, ultimately linking these botanical traits to their broader impacts on forest ecology and wildlife habitat suitability.

MATERIALS AND METHODS

Study area and site selection

We established 12 sampling sites across a diverse altitudinal transect in Pakistan, capturing six distinct forest ecosystems. At the lowest elevation (300 m), the tropical thorn forest is characterized by hot, arid conditions with temperatures reaching 49 °C and minimal annual rainfall. Moving higher to 700 m, the dry temperate scrub features open canopies and a slightly cooler climate. Between 1200 m and 1250 m, subtropical chir pine forests dominate, supporting a robust understory layer. Mid-elevations ranging from 1450 m to 2285 m transition into dry temperate blue pine and deodar forests, where temperatures drop significantly and canopy cover increases. Finally, the highest sites between 2300 m and 2700 m consist of wet temperate and subalpine pine forests, which experience heavy precipitation and cool summer maxima.

Sampling protocols and laboratory analysis

Fieldwork was conducted during the active spring growing season, primarily between April and June. At each of the 12 elevation sites, we identified and selected five representative shrub species, resulting in a total sample pool of 60 species. We extracted uniform, healthy stem wood specimens measuring approximately 2.5 centimeters in length from mature individuals. These samples were immediately transported to the laboratory for processing.

To calculate accurate wood density metrics, we first determined the fresh volume of each sample using the water displacement method. The samples were then placed in a laboratory-drying oven at 80 °C for a full 48 hours to

eliminate all internal moisture. Once completely dried, the wood was weighed on a high-precision digital scale to obtain the dry mass. Wood density (g/cm^3) was calculated simply by dividing the dry mass by the fresh volume. The resulting data were subjected to a one-way Analysis of Variance (ANOVA) to determine the statistical significance of density variations across both the broad elevational gradient and within localized study sites.

RESULTS

Altitudinal trends in wood density

Our measurements revealed a distinct and consistent pattern across the elevational gradient. Among all the species sampled, wood density varied widely from a minimum of 0.000300 g/cm^3 to a maximum of 0.000960 g/cm^3 . The highest average wood density was recorded in the hot, low-altitude tropical thorn forests at 300 meters, coming in at 0.000734 g/cm^3 . As the elevation increased, the average density progressively declined. By the time the gradient reached the subalpine forests at 2700 meters, the average wood density had dropped to its lowest point of 0.000544 g/cm^3 .

When comparing the broad forest categories against one another, the ANOVA did not highlight a massive statistical divergence in the overall site averages ($F = 1.04$, $P = 0.424$). However, the analysis uncovered highly significant variations within the individual sites themselves. Across almost every elevation tested, the five species sharing the exact same habitat displayed profound differences in wood density ($P < 0.05$). For example, within the 300-meter site, *Prosopis* exhibited highly dense wood (0.000960 g/cm^3), while *Morus alba*, growing under the exact same climatic pressures, developed significantly lighter wood (0.000520 g/cm^3). This pattern of high intra-site variance was mirrored at the 700 m, 1450 m, 2250 m, and 2700 m locations, indicating that species rely on widely different evolutionary strategies even when faced with identical environmental challenges.

DISCUSSION

Environmental drivers of wood density

The progressive decline in wood density with increasing elevation aligns strongly with the physiological demands placed on plants by their physical environments. In arid lowland regions, summer temperatures regularly approach 49°C , creating a high-stress scenario where soil moisture is scarce. Shrubs growing in these conditions are forced to construct dense, durable wood just to survive. Without this heavy structural investment, the extreme tension required to pull sparse water from baked soil would cause their internal vascular systems to collapse entirely (Chave et al., 2009). The high density serves as a crucial mechanical reinforcement against drought-induced cavitation.

At higher elevations, the environmental pressures shift from heat and drought to cold and shortened growing seasons. In subalpine zones, plants must rapidly deploy leaves and expand their branches before the onset of freezing winter conditions. Constructing thick, heavy wood is a slow, energy-intensive process that simply does not fit within this narrow temporal window. Consequently, these plants favor the production of lighter, softer wood (Wiemann &

Williamson, 1989b). This softer wood also offers a distinct mechanical advantage: flexibility. When subjected to the immense weight of winter snowpacks or high-velocity mountain winds, flexible branches tend to bend and recover, whereas highly rigid, dense branches are prone to catastrophic snapping (Ennos, 1997).

Importantly, the pronounced intra-site variance we observed confirms that altitude is not the sole dictator of plant architecture. Even when rooted in the same soil and exposed to identical weather patterns, different shrub species pursue alternative survival pathways. Some opt for a conservative, high-density defense strategy, while others gamble on lower density to achieve rapid competitive growth.

Implications for habitat structure and wildlife

The physical density of the forest understory extends far beyond botanical survival; it actively shapes the living conditions for the entire local ecosystem. By altering the structural integrity of the habitat, wood density directly influences avian nesting behavior, mammalian foraging patterns, and the lifecycle of forest floor invertebrates.

In the hotter, lower elevations, shrubs characterized by high-density wood provide highly secure nesting microhabitats. Species producing this tough wood often form robust, thorny thickets that resist breakage and wind sway. These structures act as natural fortresses, offering small passerines and gamebirds—such as francolins—excellent protection from both the elements and terrestrial predators. The dense wood ensures that nests remain stable and secure throughout the breeding season.

Furthermore, wood density is intimately tied to the foraging ecology of local herbivores. Shrubs that invest heavily in dense wood structures generally possess higher levels of lignin and physical toughness, making them difficult to chew and digest. While wild ungulates like the markhor and Himalayan ibex may rely on these tough lowland shrubs during severe food shortages, browsing requires considerable energy expenditure (Coley, 1983). In contrast, the lighter, faster-growing wood of high-altitude shrubs provides softer, more pliable twigs and stems, offering a more accessible forage base for mammals enduring harsh alpine winters.

Finally, the initial density of the wood heavily dictates the timeline of decomposition and deadwood availability on the forest floor. In subalpine environments, the lighter wood of fallen branches decays relatively quickly, creating moist, nutrient-rich saproxylic habitats. These rotting logs are crucial breeding grounds for wood-boring insects, ants, and termites, which subsequently support populations of insectivorous birds like woodpeckers. Conversely, the incredibly dense wood found in arid lowland scrub degrades at a much slower rate. This recalcitrant deadwood provides long-lasting structural shelter, allowing small reptiles and rodents to escape the intense daytime heat.

CONCLUSION

The variation in wood density across Pakistan's altitudinal gradient demonstrates how shrubs physically remodel themselves to overcome extreme environmental challenges. Hot, arid lowlands necessitate the construction

of heavy, durable wood to maintain vascular integrity, while cooler, high-altitude zones favor lighter, flexible wood that facilitates rapid seasonal growth and resilience against snow accumulation. These structural adaptations do not occur in an ecological vacuum. The resulting shifts in understory architecture directly govern the availability of secure nesting sites, the quality of mammalian winter forage, and the persistence of deadwood microhabitats. Ultimately, the botanical trade-offs associated with wood density serve as a foundational driver of habitat quality and wildlife dynamics across these diverse mountain ecosystems.

REFERENCES

Baker, P. J., & Bunyavejchewin, S. (2006). Sapwood electivity and radial variations in wood density among trees of a seasonal tropical forest in Thailand. *Journal of Tropical Ecology*, 22(6), 633-641.

Champion, H. G., Seth, S. K., & Khattak, G. M. (1965). Forest types of Pakistan. Pakistan Forest Institute, Peshawar.

Chave, J., Coomes, D., Jansen, S., Lewis, S. L., Swenson, N. G., & Zanne, A. E. (2009). Towards a worldwide wood economics spectrum. *Ecology Letters*, 12(4), 351-366.

Coley, P. D. (1983). Herbivory and defensive characteristics of tree species in a lowland tropical forest. *Ecological Monographs*, 53(2), 209-233.

Ennos, A. R. (1997). Wind as an ecological factor. *Trends in Ecology & Evolution*, 12(3), 108-111.

Hacke, U. G., Sperry, J. S., Pockman, W. T., Davis, S. D., & McCulloh, K. A. (2001). Trends in wood density and structure are linked to prevention of xylem implosion by negative pressure. *Oecologia*, 126(4), 457-461.

Panshin, A. J., & de Zeeuw, C. (1980). Textbook of wood technology (4th ed.). McGraw-Hill.

Wiemann, M. C., & Williamson, G. B. (1989b). Wood specific gravity gradients in tropical dry and temperate dry trees. *American Journal of Botany*, 76(6), 924-928.

TABLES AND FIGURES

Table 1: Site attributes and localized wood density averages across the study gradient

Site	Forest Category	Altitude (m)	Rainfall (mm)	Max Temp (°C)	Average Density (g/cm³)	Significant Intra-site Variance?
A	Tropical Thorn	300	127	49	0.000734	Yes (P<0.05)
B	Dry Temperate Scrub	700	613	37	0.000694	Yes (P<0.05)
C	Chir Pine	1200	1200	40	0.000676	No
D	Chir Pine	1250	1200	40	0.000733	No
E	Dry Temp. Blue Pine	1450	1300	50	0.000580	Yes (P<0.05)
F	Dry Temp. Blue Pine	1500	1300	50	0.000622	No
G	Dry Temp. Blue Pine	1550	1300	50	0.000604	No
H	Deodar Forest	2200	1200	30	0.000607	Yes (P<0.05)
I	Deodar Forest	2250	1200	30	0.000570	Yes (P<0.05)
K	Deodar Forest	2285	1200	30	0.000712	Yes (P<0.05)
L	Wet Temp. Blue Pine	2300	2000	11	0.000686	No
M	Subalpine Pine	2700	1500	25	0.000544	Yes (P<0.05)

Table 2: ANOVA results comparing wood density among the distinct forest types

Trait	Comparison	Sum of Squares	df	Mean Square	F-Value	P-Value
Wood Density	Between Forest Types	0.0000003	11	0.000000027	1.04	0.424
	Error Margin	0.0000011	48	0.000000023		

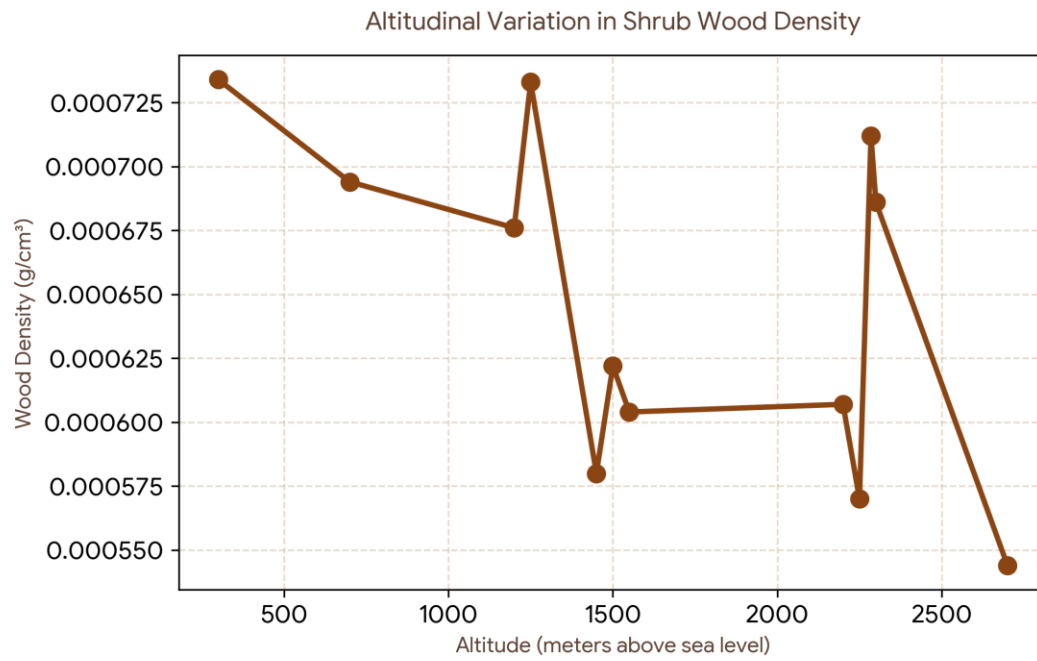


Figure 1: The distribution of average wood density across the altitudinal gradient. The general downward trend highlights the physiological shift from dense lowland woods to lighter subalpine woods.