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Influence of Physical and Environmental Factors on Yield Prediction Variability in Sri Lankan *Pinus* Plantations

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Abstract. This study investigates the influence of slope and agro-ecological regions on the growth and timber volume of *Pinus* plantations in the wet and intermediate zones of Sri Lanka. Annually, the Forest Department of Sri Lanka releases approximately 1,000 hectares of *Pinus* plantations for thinning and clear felling to the State Timber Corporation, which estimates timber yield using enumeration data. Notable discrepancies between estimated and actual timber volumes prompted a detailed analysis of the physical and environmental factors affecting plantation growth. The study covered 48 coupes from 11 plantations across three districts Nuwara Eliya, Matara, and Ratnapura selected based on regional representation. Data collected included actual timber volumes extracted in 2020 and 2021, slope measurements, standing tree counts, and agro-ecological region classifications. Statistical analysis focused on identifying correlations between slope, agro-ecological regions, and recorded timber volume. Results indicated a predominantly negative correlation between slope and timber volume, with volumes decreasing progressively from up-country to low-country regions. Steeper slopes were consistently associated with reduced timber yields, while agro-ecological zone significantly influenced overall plantation productivity across all sampled sites. These findings highlight the importance of incorporating topographical and ecological factors into timber yield forecasting models. Improved integration of such variables would reduce estimation discrepancies, support more accurate harvest planning, and contribute to the long-term sustainable management of forest plantation resources across Sri Lanka.

Keywords: pine, *Pinus*, Pinus growth, slope impact on wood increment, agro-ecological regions, timber volume, Sri Lankan plantations

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Научная статья

Влияние физических и экологических факторов на изменчивость прогнозируемой урожайности на сосновых плантациях Шри-Ланки

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Аннотация. Изучено влияние уклона местности и отнесенности территории к агроэкологическому региону на рост и объем древесины сосновых плантаций во влажных и переходных зонах Шри-Ланки. Департамент лесного хозяйства Шри-Ланки ежегодно выделяет Государственной лесопромышленной корпорации около 1000 га сосновых плантаций для проведения рубок ухода и сплошных рубок. На основе данных лесной таксации корпорация рассчитывает выход древесины. В связи со значительными расхождениями между расчетными и фактическими объемами древесины был проведен анализ физических и экологических факторов, влияющих на рост насаждений. Исследование охватило 48 участков на 11 плантациях в 3 районах Шри-Ланки: Нувара-Элия, Матара и Ратнапура, – выбранных на основе региональной репрезентативности. Полученные данные включали фактические объемы заготовленной древесины в 2020 и 2021 гг., результаты измерений угла склона местности, сведения о количестве живых деревьев и классификацию агроэкологических регионов. Методом статистического анализа была установлена корреляция между уклоном, отнесенностью территории к агроэкологическому региону и учтенным объемом древесины. Отмечена преимущественно отрицательная корреляция уклона склона и выхода древесины, причем выход древесины постепенно уменьшался по мере перехода от горных районов к равнинным. Более крутые склоны всегда обусловливали снижение выхода древесины, в то время как агроклиматическая зона оказывала существенное влияние на общую продуктивность насаждений на всех исследованных участках. Полученные данные подчеркивают важность топографических и экологических факторов в моделях прогнозирования выхода древесины. Более полный учет этих факторов позволит сократить погрешности в расчетах, обеспечит более точное планирование лесозаготовок и будет способствовать долгосрочному рациональному лесопользованию в Шри-Ланке.

Ключевые слова: сосна, *Pinus*, рост сосны, влияние склонов на прирост древесины, агроэкологические регионы, объем древесины, плантации Шри-Ланки

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Introduction

Pinus trees were first introduced to Sri Lanka in 1870, with plantations beginning around 1920. Initially, *Pinus patula* was cultivated in mountainous regions above 1,600 meters but on a limited scale. By the early 1950s, *Pinus caribaea* was introduced and cultivated in areas above 900 meters [1, 6]. The 1960s saw a rapid expansion of *Pinus* plantations in the mountainous regions, reaching approximately 2,300 hectares by 1983. Globally, there are about 122 species of *Pinus*, and this conifer native to Central America now covers around 15,000 hectares of cultivated land in Sri Lanka [12].

The Forest Department of Sri Lanka currently manages about 93,000 hectares of forest plantations, of which 75,000 hectares are harvestable. Among these, 21,000 hectares consist of mature *Pinus* plantations established around 1970. The demand for *Pinus* construction timber is high, reaching 1.6 million cubic meters in 2018, driven partly by the tree's relatively uniform shape which enhances its market appeal [14].

The Forestry Sector Master Plan (1995–2020) was developed to guide sustainable forest management in Sri Lanka, ensuring continued ecosystem services [15, 18]. *Pinus caribaea* wood is particularly suitable for producing sawn wood, laminations, plywood, particleboard, and MDF. Finger jointing, a woodworking technique used to minimize timber waste, is often applied to softwoods like *Pinus*, which has gained popularity in furniture manufacturing due to its fresh appearance and environmental benefits [11, 16, 19].

Pinus wood contains significant amounts of turpentine due to resin tissues, which can reinforce the wood structure internally but may reduce bonding strength and paint adhesion. Therefore, the physical and structural properties of *Pinus* must be carefully considered in furniture design and production to optimize aesthetics and functionality.

A survey by the State Timber Corporation identified Teak, Mahogany, and Satin as the main timber species used for furniture in Sri Lanka, with no notable use of *Pinus* timber in this sector. This study aims to investigate the influence of terrain slope and agro-ecological zonation on the volume of *Pinus* trees and to provide recommendations for improving volume estimation methods for *Pinus* plantations in Sri Lanka.

Research Objects and Methods

Study Area. This study examines the relationship between the growth and yield of *Pinus* trees and the slope of the land within three key districts of Sri Lanka, Nuwara Eliya, Matara, and Ratnapura representing wet and intermediate agro-ecological zones. Plantations released in previous years, with similar ages, were selected to ensure consistency in the analysis. Forest block sizes were determined based on the extent of *Pinus* plantations in these districts during 2020 and 2021. This regional focus allows for an in-depth assessment of how topographical variations influence timber volume and growth patterns specific to these diverse ecological and climatic conditions (Fig. 1 and Table 1).

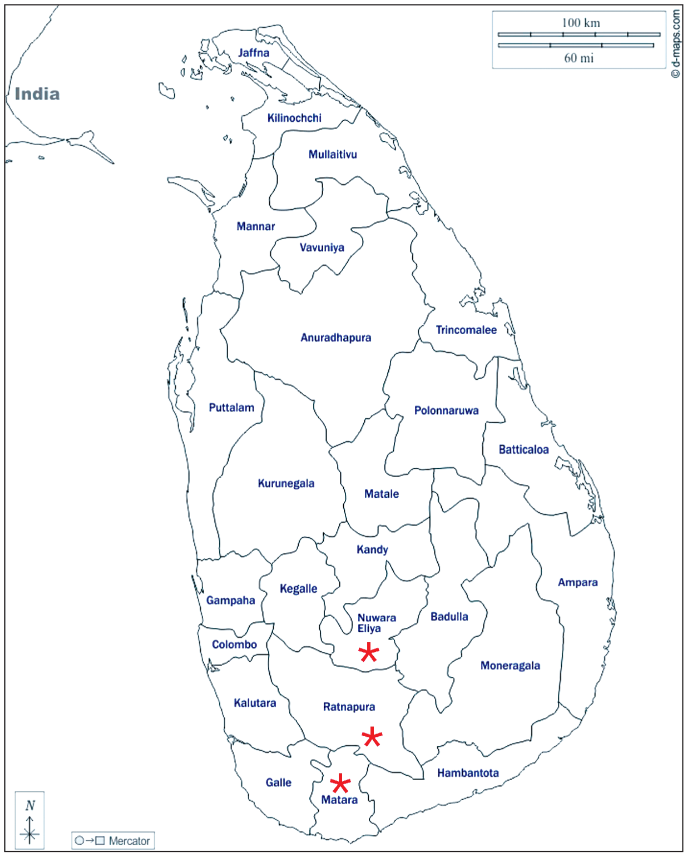

Fig. 1. Study Locations

Table 1

Allotments of the Forest Department in each of the selected districts

Region	Division	Range	Block
Nuwara Eliya	Nuwara Eliya	Halgranoya	Hanguranketha 02/002A
			Hanguranketha 02/003
		Hatton	Moragahahena 02/001
		Nuawara Eliya	Watawala
Matara	Matara	Kamburupitiya	Athuraliya 03/002A
		Deniyaya	Pasgoda 01/001
	Hambantota	Walasmulla	Kunumuldeniya 01/007
	Matara	Kamburupitiya	Lenabatuwa 01/001
Rathnapura	Kaluthara	Ingiriya	Hadapangoda 01/013
			Hadapangoda 01/010

Data Collection. Data for this study were gathered using both primary and secondary sources. Primary data included measurements of slope, GPS coordinates, and sampling conducted during field visits. Secondary data comprised enumerated tree volume records, plantation maps, and comprehensive tree inventories from the selected plantations.

Used Formula. The following equation is used to calculate the volume of the *Pinus* stand tree:

$$V = 0.000075 \cdot DBH^{(1.87185)} \cdot \text{Height}^{(0.91418)} \cdot (-4,275) \cdot DBH^{(-2.83174)},$$

where, V – volume of a tree; DBH – diameter at breast height.

Data Collection and Analysis. Data from each plantation were systematically collected and presented in tabular form for clarity. Data were compiled and visualized through graphs to highlight trends. The average tree volume for each coupe was calculated, and slope measurements between coupes were taken using a clinometer. These values were organized into tables to support further analysis. Graphs illustrating the relationship between average tree volume and slope were produced. Statistical analysis was performed to assess the correlation between slope and average tree volume, with the correlation coefficient calculated accordingly. All data processing and analysis were carried out using Microsoft Office 2007 to ensure precision and clarity in presentation.

Results and Discussion

Analysis of 48 coupes across the Nuwara Eliya, Matara, and Ratnapura districts showed a clear negative relationship between slope gradient and average tree wood volume in *Pinus* plantations. In most locations (90.9 %), steeper slopes were linked to lower wood productivity. This trend was especially strong in Walasmulla and Hadapangoda, where the correlation coefficient was nearly perfect at $r = –0.997$, indicating that slope is a highly reliable predictor of tree volume under the specific conditions found there.

An exception to this pattern was found in Aberdeen, where the slope and tree volume showed a positive correlation ($r = 0.44$, $R^2 = 0.92$), suggesting different site dynamics in that area. Despite the moderate correlation coefficient, the high coefficient of determination ($R^2 = 0.92$) indicates that 92 % of the variance in tree volume could be explained by slope in this location, suggesting a genuine site-specific relationship rather than random variation. This anomalous pattern warrants further investigation to identify the underlying environmental, edaphic, or management factors that may differentiate Aberdeen from other study locations.

The relationship between slope and tree wood volume exhibited considerable variation across the three study districts, reflecting the influence of distinct agro-ecological conditions on *Pinus* plantation productivity (Table 2).

Table 2

District-wise summary

District	Locations	Avg. correlation	Range	Dominant trend
Nuwara Eliya	5	–0.445	[–0.988, 0.443]	Negative
Matara/Hambantota	4	–0.845	[–0.997, –0.40]	Strong negative
Ratnapura/Kaluthara	2	–0.994	[–0.997, –0.99]	

In the Nuwara Eliya district, representing the up-country wet zone, five locations were studied, showing an average correlation coefficient of $r = –0.445$. The correlation values varied widely, from $r = –0.988$ to 0.443, highlighting considerable spatial variation in how slope relates to tree volume. This suggests that other factors, such as microclimate, soil depth, or elevation-driven temperature differences, may have a stronger influence on tree productivity in this high-altitude region.

By contrast, the Matara and Hambantota districts, which fall within the low-country wet and intermediate zones, showed a more consistent and stronger negative correlation. Analysis across four locations revealed an average correlation of r = –0.845, with values ranging between r = –0.997 and r = –0.40. This stronger and more uniform relationship implies that slope plays a more decisive role in determining tree volume in these lower-elevation areas, potentially due to greater erosion risks from higher rainfall or variations in soil properties.

The Ratnapura and Kaluthara districts, also part of the low-country wet zone, exhibited the strongest and most consistent negative correlations between slope and tree volume. From two study locations, the average correlation was r = –0.994, with a narrow range from r = –0.997 to r = –0.99. This near-perfect negative correlation indicates that slope is a highly reliable predictor of tree productivity here, likely because the combination of steep terrain, heavy rainfall, and vulnerable soils makes slope the primary limiting factor for *Pinus* growth and wood accumulation.

The study covered six distinct agro-ecological regions as classified by Sri Lanka's Department of Agriculture, representing a range of climatic and soil conditions across montane and lowland zones where commercial *Pinus* plantations are established. These regions were selected to reflect the environmental diversity shaped by Sri Lanka's varied topography and rainfall patterns, both of which strongly affect forest plantation productivity. Timber volume productivity at the stand level, measured in cubic meters per hectare (m³/ha), was calculated for all plantations within each agro-ecological zone using coupe harvest records (Table 3).

Table 3

Six agro-ecological regions

<table>
<tr><th>Agro-ecological region</th><th>Region</th><th>Block name</th><th>Volume of timber, m³/ha</th></tr>
<tr><td>WU1</td><td rowspan="5">Nuwara Eliya</td><td>Kiriammadeniya</td><td>459</td></tr>
<tr><td rowspan="3">WU2</td><td rowspan="2">Hanguranketha 02/002</td><td>511</td></tr>
<tr><td>317</td></tr>
<tr><td>Hanguranketha 02/003</td><td>316</td></tr>
<tr><td>WM1</td><td>Aberdeen 02/001</td><td>214</td></tr>
<tr><td rowspan="3">WL1</td><td>Matara</td><td>Puwakgahahena 01/001</td><td>310</td></tr>
<tr><td rowspan="2">Rathnapura</td><td>Handapangoda 01/013</td><td>157</td></tr>
<tr><td>Handapangoda 01/010</td><td>123</td></tr>
<tr><td rowspan="2">WL2</td><td rowspan="3">Matara</td><td>Athuraliya 03/002</td><td>155</td></tr>
<tr><td>Lenabatuwa 01/001</td><td>170</td></tr>
<tr><td>I(L1-L3)</td><td>Kunumuldeniya 01/007</td><td>289</td></tr>
</table>

This spatial distribution of study sites across multiple agro-ecological regions enabled the examination of how macro-scale environmental factors including mean annual rainfall, temperature regimes, potential evapotranspiration, and soil moisture availability interact with topographic variables to influence *Pinus* growth dynamics. The agro-ecological classification system integrates climatic parameters (particularly rainfall seasonality and intensity), elevation zones (up-country Nuwara Eliya, mid-country Ratnapura, and low-country Matara), and moisture regime categories (wet, intermediate, and dry zones), providing a comprehensive framework for interpreting regional variation in plantation performance. By stratifying the analysis across these ecologically meaningful units, it becomes possible to distinguish between site-specific effects attributable to local topography (such as slope gradient) and broader regional patterns driven by climatic and physiographic factors that operate at the landscape scale (Fig. 2).

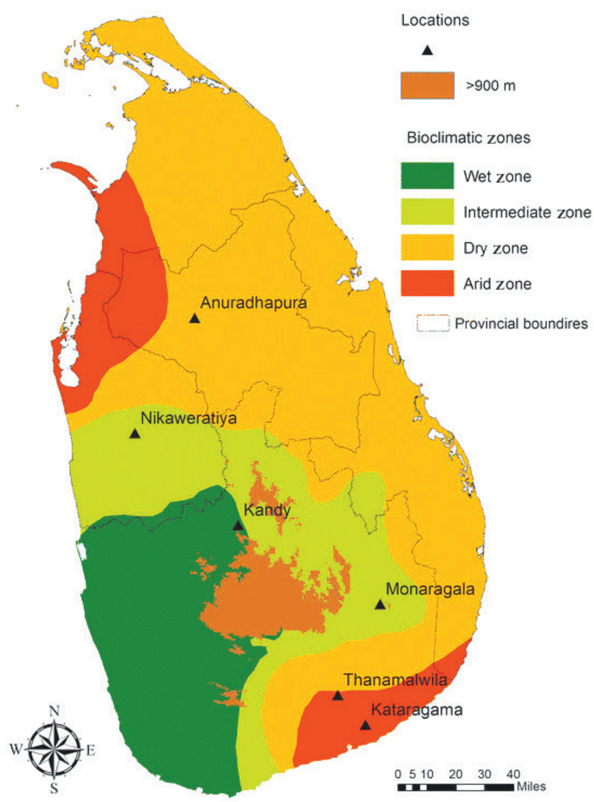

Fig. 2. Divisions of agro-ecological regions in Sri Lanka

A total of 54 sites derived from 48 harvested coupes were stratified across six agro-ecological regions based on the classification system of Hearath et al. 2023 [5], with the following spatial distribution: WM1 (Mid-country Wet zone, n=5), WU1 (Up-country Wet zone 1, n = 3), WU2 (Up-country Wet zone 2, n = 29), I(L1-L3) (Low-country Intermediate zone, n = 2), WL1 (Low-country Wet zone 1, n = 9), and WL2 (Low-country Wet zone 2, n = 6). Linear regression analysis revealed zone-specific relationships between slope gradient and average individual tree volume. In the up-country wet zones, negative correlations dominated: WU1 showed a strong inverse relationship with an R^2 close to 1 ($p < 0.05$), while WU2 displayed a weaker but consistent negative trend with R^2 below 0.7. Similarly, WM1 had a robust negative correlation with high explanatory power ($R^2 \approx 1$). The intermediate zone I(L1-L3) exhibited a moderate negative correlation, though with lower predictive strength. In contrast, the low-country wet zones (WL1 and WL2) showed positive correlations between slope and tree volume. WL1 demonstrated a strong positive relationship ($R^2 > 0.9$), and WL2 maintained a weaker but steady positive trend ($R^2 < 0.7$). This divergence in slope-volume relationships between highland and lowland zones suggests fundamental differences in limiting factors governing *Pinus* productivity, with moisture availability, soil depth distribution along slope gradients, and erosion susceptibility potentially varying systematically with elevation and rainfall regime, thereby altering the functional impact of topographic position on stand-level biomass accumulation (Fig. 3).

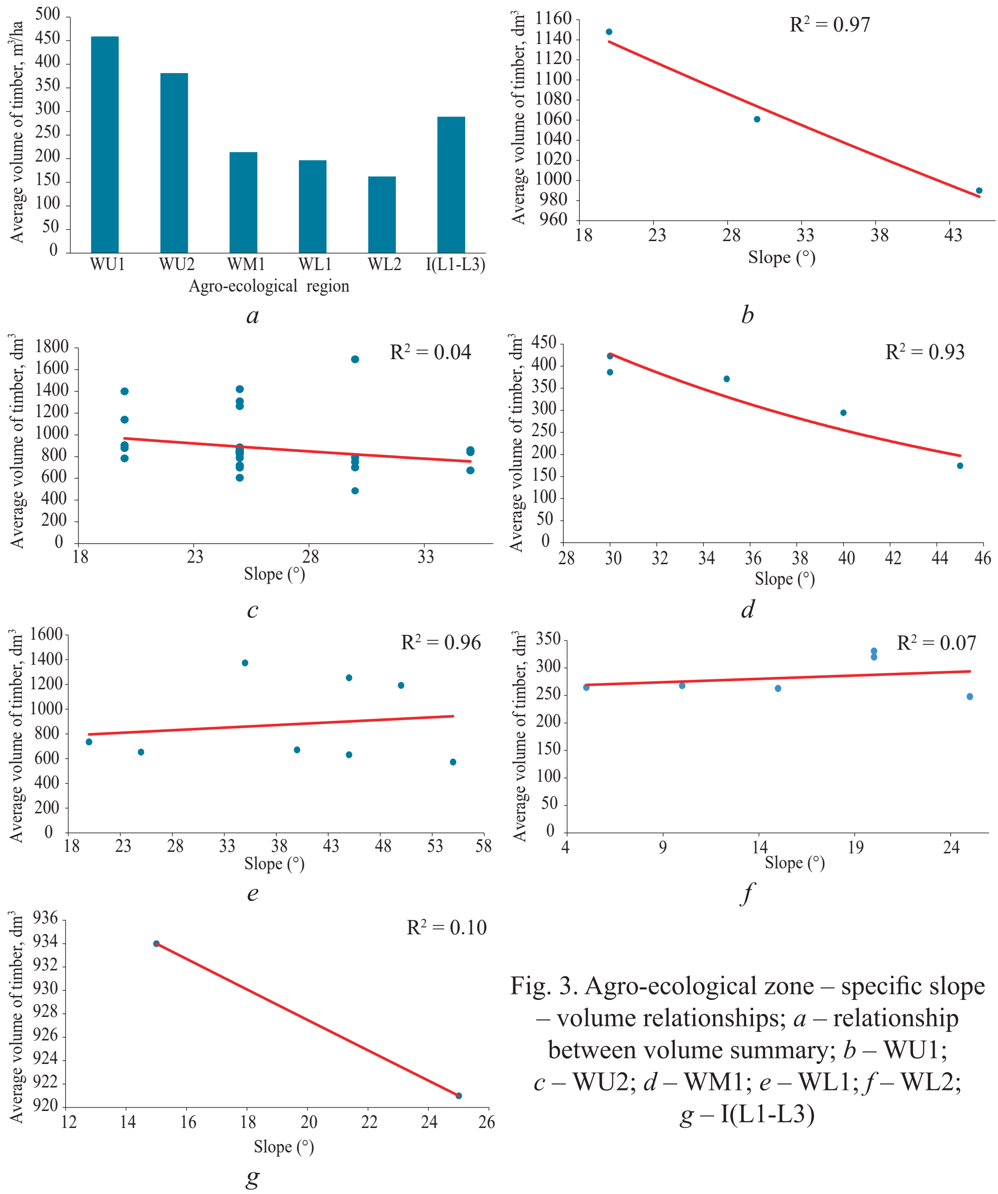

Fig. 3. Agro-ecological zone – specific slope – volume relationships; *a* – relationship between volume summary; *b* – WU1; *c* – WU2; *d* – WM1; *e* – WL1; *f* – WL2; *g* – I(L1-L3)

The analysis of 48 coupes across the Nuwara Eliya, Matara, and Ratnapura districts demonstrates a predominantly negative association between slope gradient and average tree wood volume in *Pinus* plantations, with 90.9 % of locations displaying this inverse relationship. This finding aligns with ecological and silvicultural research indicating that steeper slopes often present more challenging conditions for tree growth due to factors such as shallow soil depth, increased erosion, reduced nutrient availability, and difficulty in water retention [9, 20]. These limitations can restrict root expansion and resource uptake, ultimately reducing tree biomass accumulation and wood volume. The near-perfect negative correlation observed in Walasmulla and Hadapangoda (r = –0.997) underscores the critical influence of slope on productivity where these site-specific conditions are amplified.

Such strong slope-volume relationships have been reported in other mountainous forest ecosystems, where the slope acts as an abiotic stressor adversely affecting tree growth [13, 17]. The impact of slope-related stresses plays a crucial role in forest management, highlighting the need to incorporate topographical data into yield prediction models to optimize wood production in plantation forestry.

In contrast, the positive correlation found in Aberdeen ($r = 0.44$, $R^2 = 0.92$) challenges this general trend, suggesting that local conditions may alter or even reverse the usual negative effects of slope on growth. The strong explanatory power of slope in this area points to specific environmental or management factors, such as soil characteristics, microclimate, slope orientation, or forestry practices like thinning, species choice, or soil treatments, that could improve productivity on steeper slopes.

This anomalous pattern in Aberdeen is consistent with findings in some forestry research where positive growth responses are attributed to improved drainage on slopes, better sunlight exposure depending on aspect, or adaptive silvicultural interventions [8]. Hence, further detailed investigation incorporating soil physicochemical properties, microclimatic data, and management history is necessary to disentangle the drivers of this relationship and to refine silvicultural recommendations tailored to local conditions [2].

The relationship between slope and tree wood volume shows marked variability across the three districts studied (Nuwara Eliya, Matara-Hambantota, and Ratnapura-Kaluthara) reflecting the diverse agro-ecological settings and their impact on *Pinus* plantation productivity. Within the up-country wet zone of Nuwara Eliya, the wide range of correlation values from strongly negative ($r = –0.988$) to moderately positive ($r = 0.443$) indicates that slope alone does not fully account for variations in tree volume. This aligns with ecological research emphasizing the complex influences on tree growth in high-elevation ecosystems, where microclimatic variables like temperature fluctuations, soil depth, and moisture availability significantly affect outcomes. Elevation-related temperature gradients may also impact physiological processes such as photosynthesis and respiration, influencing biomass accumulation independently of slope.

In contrast, the lowland districts of Matara and Hambantota exhibit a more pronounced and consistent negative relationship between slope and wood volume. The stronger average correlation ($r = –0.845$) with less spatial variability points to the dominant role of slope-induced erosion and soil degradation exacerbated by higher rainfall intensity typical of these agro-ecological zones [7]. Soil erosion on steep slopes reduces nutrient availability and rooting volume, constrained further by soil texture and organic matter content representatives of these low-country wet and intermediate zones [4]. The findings are consistent with regional forestry reports emphasizing slope as a critical factor limiting plantation productivity due to accelerated surface runoff and sediment loss in these areas [3].

The Ratnapura and Kaluthara districts, with their robust and narrowly ranged strong negative correlations (average $r = –0.994$), affirm that topographic gradients represent the principal limiting factor for *Pinus* growth under the combined influence of steep terrain, high rainfall, and susceptible soil conditions [10]. This corroborates landscape-scale studies from tropical wet zone forests pointing to the amplification of slope effects where geophysical attributes and climatic variables synergize to hinder tree volumetric growth. In such contexts, slope not only impacts soil moisture dynamics and nutrient cycling but also physical stability, making it the most reliable predictor of plantation productivity.

Conclusion

The study confirms that slope gradient significantly impacts the growth and volume of *Pinus* trees, with an evident inverse relationship between slope steepness and tree volume. While the basal area per hectare and stump surface area remains relatively constant across slopes, the reduction in tree height on steeper slopes primarily drives decreased wood volume. This height reduction is likely influenced by diminishing sunlight availability on steeper slopes, which restricts photosynthetic capacity and subsequently growth. Furthermore, regional agro-ecological differences shape *Pinus* productivity, with higher volumes typically seen in the Wet Zone Upcountry compared to the Intermediate Zone. This pattern reflects the combined effects of climatic factors like rainfall and temperature alongside topographical influences.

Limitations of the Study. Limitations of the study include potential inaccuracies in timber volume estimates due to variability in tree age and height, despite the characteristic sigmoidal growth pattern of *Pinus* species. Additionally, the relatively small sample area restricts the ability to generalize findings across all *Pinus* plantations in Sri Lanka. Furthermore, the study focused primarily on slope and agro-ecological region effects, leaving out other influential biotic and abiotic factors such as soil texture, nutrient availability, and silvicultural management practices which may significantly affect tree volume outcomes.

Future Research Directions. Future studies should broaden spatial coverage to include all major *Pinus* growing districts in Sri Lanka to capture wider agro-ecological diversity. Comprehensive analyses incorporating additional growth determinants such as soil properties, microclimate variations, nutrient status, and specific management regimes are essential to develop more robust growth and volume prediction models. Such research will enable finer-scale adaptation of plantation management to optimize wood productivity under varying environmental constraints.

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