ISSN (Online): 2349-1183; ISSN (Print): 2349-9265
TROPICAL PLANT RESEARCH
The Journal of the Society for Tropical Plant Research

12(1): 1–11, 2025
DOI: 10.22271/tpr.2025.v12.i1.001

Research article

A rapid field-based non-destructive estimation of wood density and tree growth characteristics of *Pinus roxburghii* Sarg. in the mid-hill region of Nepal

Sarala Adhikari[1]*, Anjana Giri[1], Deepa Shree Rawal[2], Rikita Bhandari[2], Mahendra Prasad Uprety[3], and Sarala Budhathoki Chhetri[2]

[1]Biological Resource Unit (BRU), Faculty of Science,
Nepal Academy of Science & Technology (NAST), Lalitpur, Nepal
[2]Environment Research Laboratory, Faculty of Science,
Nepal Academy of Science & Technology (NAST), Lalitpur, Nepal
[3]Central Department of Environmental Science, Tribhuvan University, Kathmandu, Nepal

*Corresponding Author: adhi.sarala2055@gmail.com [Accepted: 25 January 2025]

Abstract: The present study assessed the wood density and tree slenderness coefficient (TSC) of *Pinus roxburghii* in Jalpa Devi Community forest, Bhaktapur, Nepal. A total of 72 increment cores were collected using Haglof increment borer (5.15 mm). The ρk was calculated as the ratio of wood dry mass (dm) obtained by the core method to core volume (v), while TSC was determined by dividing the total tree height (TH) to diameter at breast height (DBH) outside the bark. The average wood density was measured 533. 37 kg m^{-3}, while the corresponding tree slenderness coefficient was found 48.72. Majority of *Pinus roxburghii* (95.83%) in the study sites was found with a low slenderness coefficient (TSC<70). Relationships between different tree growth variables revealed a significant positive correlation of TSC with tree height and a significant negative correlation (P <0.05) with DBH, while wood density showed a positive correlation with all tree growth variables except TSC and tree height. Among all the regression models, the exponential model was observed as the best-fit model for *Pinus roxburghii*. The present study not only enhances our understanding of the growth characteristics of *Pinus roxburghii* but also opens avenues for further exploration and innovation in the field of forest ecology. Future studies could use a combination of methodologies, to validate the results and investigate the broader ecological implications of wood density measurements.

Keywords: Age - Growth Model - *Pinus roxburghii* - Tree Slenderness Coefficient - Wood Density.

[Cite as: Adhikari S, Giri A, Rawal DS, Bhandari R, Uprety MP & Chhetri SB (2025) A rapid field-based non-destructive estimation of wood density and tree growth characteristics of *Pinus roxburghii* Sarg. in the mid-hill region of Nepal. *Tropical Plant Research* 12(1): 1–11]

INTRODUCTION

Pinus roxburghii Sarg. (Local name - Khote Salla, Common name - Chir pine) is an evergreen tree species belonging to the family Pinaceae that is indigenous to the Himalayas and has a distribution range in Nepal, Bhutan, India, and Pakistan (Rajbhandari *et al*. 2020). Around 105 species of pines are found worldwide among which only three species (*Pinus roxburghii* Sarg., *Pinus wallichiana* A.B.Jacks., and *Pinus wallichiana* var. *manangensis* H.Ohba & M.Suzuki are found in Nepal (Press *et al*. 2000). The two species, *Pinus roxburghii* and *Pinus wallichiana*, are one of the most important tree species for the local people for their livelihoods and subsistence in mid-hills of Nepal (Springate-Baginski & Dev 2003, DFRS 2015). *Pinus roxburghii* grows mainly between 900 m and 1,950 m above mean sea level and it is one of the most widely planted species in Nepal (Jackson 1994). This species holds significant commercial value in the Himalayas, being utilized for timber, turpentine, and various medicinal and cultural purposes (Tiwari 1994, Siddique *et al*. 2009). Various

Received: 10 September 2024 Published: 30 April 2025
https://doi.org/10.22271/tpr.2025.v12.i1.001

studies have been carried out to study the age structure, disturbance history, tree growth performance, and tree ring structure of *P. roxburghii* with the changing climate (Bhattacharya *et al*. 1992, Bhuju & Gaire 2012, Speer *et al*. 2012, Tiwari *et al*. 2020), allometric relationships for biomass prediction (Sharma & Pukkala 1990), and basal area growth model (Gyawali *et al*. 2015). However, studies on wood density and tree slenderness coefficient (TSC) with reference to its relationship with the tree growth characteristics are scare in Nepal. Understanding these relationships is crucial because it can provide valuable insights into the health, productivity, and resilience of forests.

Tree slenderness coefficient (TSC) is a significant quantitative measurements, technically defined as the ratio of total tree height (THT) to diameter outside bark at 1.3 m or 4.5 ft above the ground level, when both DBH and height measured in the same unit (Wang *et al*. 1998, Harja *et al*. 2012, Oyebade *et al*. 2015). The tree slenderness ratio provides an excellent indication of their long-term exposure to wind before harvesting (Rudnicki *et al*. 2001). According to Navtatil (1996) biological factors which deal with the species characteristic and physical factors which are directly connected to wind components determine the stability of a forest stand. Wang *et al*. (1998) also mentioned that the susceptibility of a stand to wind throw is influenced by a combination of the tree's physical growth characteristics, the stand condition as well as the site soil and quality. Navrtatil *et al.* (1994) have categorized tree slenderness coefficient into three different classes as low slenderness coefficient (SC< 70), moderate slenderness coefficient (70–99) and high slenderness coefficient (SC> 99). Several studies have been carried out on slenderness coefficient and stand stability potential in many parts of the world (Wang *et al*. 1998, Liu *et al*. 2003, Rudnicki *et al*. 2004, Műnzer *et al*. 2023). However, in Nepal research on tree slenderness coefficient (TSC) is rare compared to other related studies. Information on the slenderness coefficient is very important in the face of changing climate and ecosystem management as they provide valuable information about the forest stability and continued existence, while providing insight into the susceptibility of species to wind-related damages. This knowledge gap in the present context demands dedicated studies on TSC in Nepal to enhance our understanding of forest structure, growth patterns, and responses to environmental stressors.

The determination of basic wood density is a functional parameter for forest inventories, reporting forest biomass, carbon stocks and climate financing (Brown *et al*. 1989, Morel *et al*. 2018). According to Chave *et al*. (2005) after DBH, wood density measurements are the second most important parameter in predicting the biomass of a tree and have an appreciable influence on many solid wood properties. The density of wood is highly variable and it can vary within and between individual trees in forests (Gao *et al*. 2017). In particular within-tree variation constitutes a major part of the overall variability where wood density varies considerably from pith to bark, especially in tropical trees (Hietz *et al*. 2013, Bastin *et al*. 2015). The mass and amount of carbon are significant variables in carbon inventories which also depend on wood density (UNFCCC 2008). The methods for the determination of wood density are often scare due to costs involved, techniques and instruments in use (Olale *et al*. 2019). The conventional method for determining volume and mass of standing trees involves taking increment cores and processing them in a laboratory. The term non-destructive is used in comparison with sampling methods that require felling of trees. X-ray densitometry, X-ray diffractometry and image analysis is another method for wood density measurements which also uses increment cores (Cown & Clement 1983, Eberhardt & Samuelson 2015). In the meantime, different non-destructive methods and field instruments have been widely used to determine the wood density without using increment borers. Examples of such techniques include the torsiometer, Pilodyn wood tester, nail withdrawal and resistance drilling tools (Gao *et al*. 2017). In Nepal, volume equations and biomass prediction have been addressed by Sharma & Pukkala (1990), which includes volume tables for twenty important tree species and two species groups as miscellaneous species in the Terai and Hills. Their study was the first step that convert the volume tables into equations and metric systems. This study provides a baseline for rough estimates of the biomass of stem, branches and foliage. However, in the method they have adopted, they have also taken air-dry densities of several Nepalese tree species from the Master Plan for the Forestry Sector, 1988. Given the advancements since then, updated research is needed to enhance the accuracy of these estimates in the context of changing climate and environmental degradation to inform conservation and management strategies about enhancing carbon sequestration potential.

Therefore, for the purpose of achieving rapid, reliable, and economical wood density measurements, the present study determined the wood density using a nondestructive conventional increment core method. This is the first study attempting to assess the wood density of conifer species using dimensional method. Furthermore, the objective of this study is to assess and develop the best fit model for slenderness coefficient of *P. roxburghii* in Jalpa Devi Community Forest, Telkot, Bhaktapur, which could also serve as baseline means of assessing the stability of tree to wind throw. The results of the study would provide a significant gateway for similar kinds of study in different research areas. This would also pave paths that would lead to more research in various ecological sectors that could benefit from the dimensional method.

MATERIALS AND METHODS

Study area and climate

The study was carried out in a planted *Pinus roxburghii* forest stand in Jalpa Devi Community Forest, Telkot, Bhaktapur (Fig. 1). The community forest was established in 2057 B.S., covering an area of 34.64 ha. The community forest lies in ward no. 9, Challing of Bhaktapur District which is located at 1500 m from msl. The community around this forest has been protecting the forest by forming a conservation committee for 2 years before it was formally transferred and taken as a community forest in 2058/059. The forest area extends across North-South aspects, harboring a diverse array of reproductive species in a mixed composition, such as *Pinus roxburghii*, *Pinus wallichiana*, *Schima wallichii* (DC.) Korth., *Castanea sativa* Mill., *Myrica esculenta* Buch.-Ham. ex D.Don, *Myrsine capitellata* Wall., *Myrsine semiserrata* Wall., *Quercus glauca* Bürger ex Blume, and *Rhododendron arboretum*. The community forest currently has 266 household consumers from Chaling ward no. 9 and Nagarkot ward no. 1, 2 and 3. According to the available meteorological data of Changunaryan station (27.71° N, 85.42° E, 1502 m) from 2011–2023 AD, which is nearby the study sites, an average monthly temperature generally ranges from 4°C to 28°C. June and August are the hottest month in the Bhaktapur. Whereas January is the coldest month of the year with an average low of 3°C and high of 21°C temperature. Monthly rainfall in Bhaktapur changes across the seasons. July and August receive the highest amount of rainfall, whereas the minimal rainfall period in Bhaktapur lasts for about 6 months extending from November to April (Fig. 2).

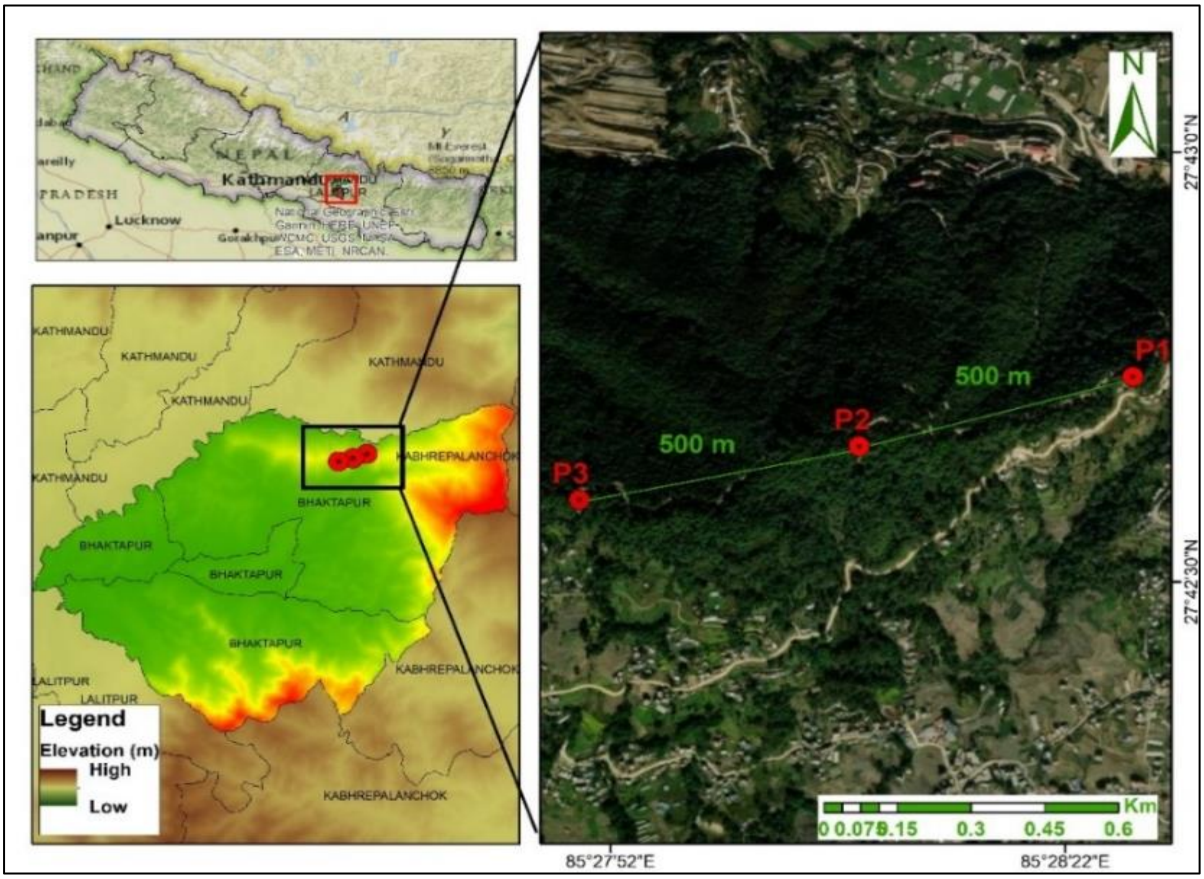

Figure 1. Location of the study area showing sampling sites of *Pinus roxburghii* Sarg. in Jalpa Devi Community Forest, Telkot Bhaktapur.

Data collection

The sampling sites of the present study lie in mid- hill regions of Nepal with an altitudinal range of 1500 m from msl. Single-line transects of 1Km were delineated for the collection of samples (Fig. 1). Three 0.0625 ha (25 m × 25 m) (Oladoye *et al*. 2020) plots were laid along the transect at 500 m distance, excluding the northern part of the forest due to the absence of pine trees. Therefore, sampling was exclusively done across the southern part of the forest. All the *Pinus roxburghii*, that encountered within plots were measured for DBH and height. The *Pinus roxburghii* in the community forest was planted, therefore the majority of tree are found with more than 30 cm girth at breast height. Hence, for wood density measurement, a total of 72 increment cores were collected using Haglof increment borer (5.15 mm) following commonly used techniques (Fritts 1965, 1976). After the collection of tree core samples, the samples were well preserved in handmade straws, and the samples were analyzed in the Dendro laboratory of Nepal Academy of Science and Technology (NAST). To determine the age of a particular tree the total rings were measured to the nearest 0.01 mm with a LINTAB^{TM5} measuring system attached to a PC running time-series analysis package for Windows (TSAP-win software) (Rinn 2003).

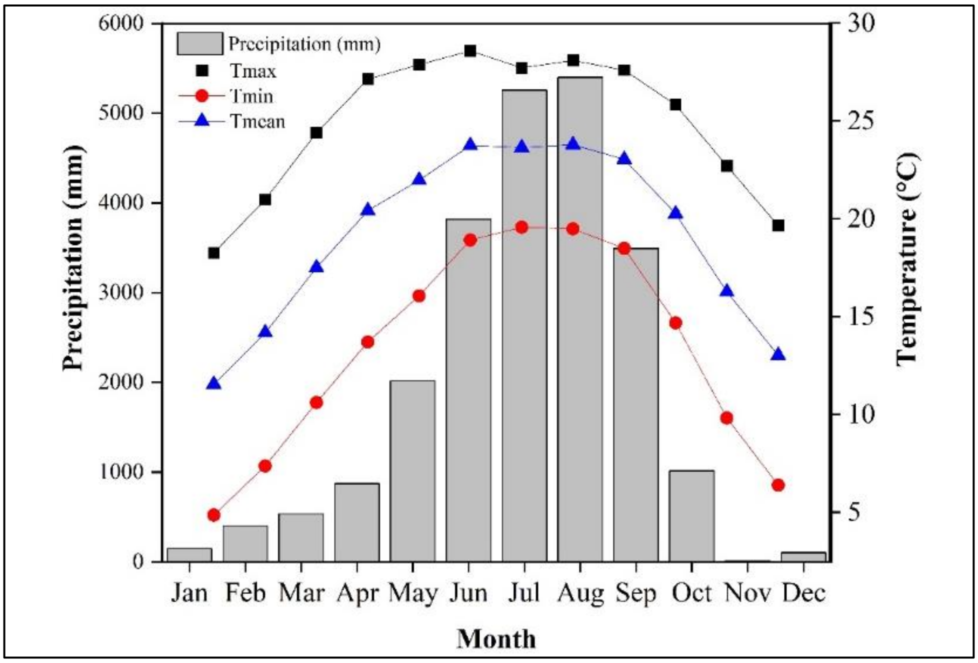

Figure 1. Climograph showing monthly sum of precipitation and average minimum maximum and mean temperature (2011–2023 AD) recorded in Changunaryan meteorological station.

Laboratory measurements

The wood density (ρk) refers to the mass of oven-dry wood per unit volume of green wood (Nogueira *et al*. 2008). For the measurements, only those samples that have both bark and pitch were used. The green volume of each individual tree core was measured using a non-destructive dimensional method. In the dimensional method, the volume of a tree core was calculated assuming a regular cylindrical shape (Olale *et al*. 2019).

$$V = \frac{\pi d^2}{4} \times l \qquad 1$$

Where, d is the core diameter (0.00515 m) and l is the total length of the core in m. The total length of the core samples was measured with a caliper. To determine the weight of an individual core at oven-dry moisture content, the cores were oven-dried at 105°C for 48 hours (Černý *et al*. 2019; Dirnberger *et al*. 2017) until constant weight was obtained. The ρk was then calculated as the ratio of wood dry mass (dm) obtained by the core method to core green volume (v).

$$\mathrm{Wd} = \frac{\mathrm{dm}}{\mathrm{v}} \qquad 2$$

Where, dm is wood dry mass (kg) and v is core green volume (m^3)

The tree slenderness coefficient (TSC) as a dimensionless value was calculated per tree (Adeyemi & Adesoye 2016; Liepiņš & Rieksts-Riekstiņš 2013; Oyebade *et al*. 2015) using:

$$\mathrm{TSC} = \frac{\mathrm{H}}{\mathrm{DBH}} \qquad 3$$

Where TSC is tree slenderness coefficient, H is tree height (m) and DBH is diameter at breast height (m).

Basal area, the sum of cross-sectional area measured at breast height (1.3 m) for individual trees within each plot was estimated using equation (Husch *et al*. 2003).

$$BA = \frac{\pi D^2}{4} \quad 4$$

Where, BA = Basal Area (m^2), π = 3.142 (constant), D = diameter at breast height (m)

Data analysis

Descriptive statistics, correlation analysis and regression models (Linear, exponential, logarithmic, power and polynomial) were used to analyze the relationships between TSC and the independent variables (tree height and DBH). DBH and tree height were used as predictor variables as these variables can be easily measured in the field with better accuracy (Ige 2017). The evaluation of the fitted models was based on the numerical analysis of the residuals with the least values of the standard error of estimate (SEE) and the highest values of coefficient of determination (R^2) (Ige 2017, Oladoye *et al*. 2020). The correlation among the tree stand growth variables was evaluated using Karl Pearson's correlation coefficient at a significance level of $\alpha = 0.05$.

RESULTS

Summary statistics of tree growth variables for Pinus roxburghii

All together 72 trees were measured, the summary statistics of the measured data used in the present study is summarized in table 1. The average height measured for all trees in the study sites was 22.51 m with a standard deviation of 1.71. The DBH and BA value ranges from 0.32 m to 0.59 m and 0.08 to 0.27, respectively. The TSC and wood density (with bark and pitch) have a mean value of 48.72 and 533.37 kg m^{-3}. This dataset has the broadest range of wood densities from 401.94 kg m^{-3} to 670.3 kg m^{-3}. A greater variability in basal area among the trees was observed with Cov of 28.11, followed by TSC, age, core length, DBH, wood density and tree height (Table 1). The result of TSC categorization for the measured data in the study area revealed that the majority of *Pinus roxburghii* (95.83%) had low slenderness coefficient (TSC < 70) (Fig. 3). Only 4.16% of the trees had moderate slenderness category (70–99) (Fig. 3). The wood density values across age classes showed an increasing trend with tree age. The average wood density value was highest for age class 40-50 (542.65 kg m^{-3}) followed by 30-40 (532.78 kg m^{-3}) and 20-30 (507.76 kg m^{-3}) (Fig. 4A). In a similar way wood density follows the increasing trend with increased DBH of the tree. Among three classes, DBH class 50–60 had the highest wood density of 554.21 kg m^{-3} (Fig. 4B).

Table 1. Statistical summary of tree growth variables of *Pinus roxburghii* Sarg. in Jalpa Devi Community Forest, Bhaktapur.

Tree Growth Variables	Mean	SD	Cov	Minimum	Median	Maximum
DBH (m)	0.47±0.008	0.072	15.05	0.32	0.49	0.59
Tree Height (m)	22.51±0.20	1.710	7.55	16.50	22.50	27.50
Core Length (m)	0.23±0.004	0.040	17.09	0.16	0.23	0.33
TSC	48.72±1.06	9.080	18.62	34.73	45.99	73.43
Wood density (kg m^{-3})	533.37±7.49	63.630	11.92	401.94	529.62	670.30
BA (m^2)	0.180±0.005	0.050	28.11	0.08	0.19	0.27
Age	38.72±0.79	6.730	17.38	25.00	39.50	51.00

Note: SD - Standard Deviation, Cov - Coefficient of Variation, DBH - Diameter at Breast, WD - Wood Density, Height, BA - Basal Area, TSC - Tree Slenderness Coefficient.

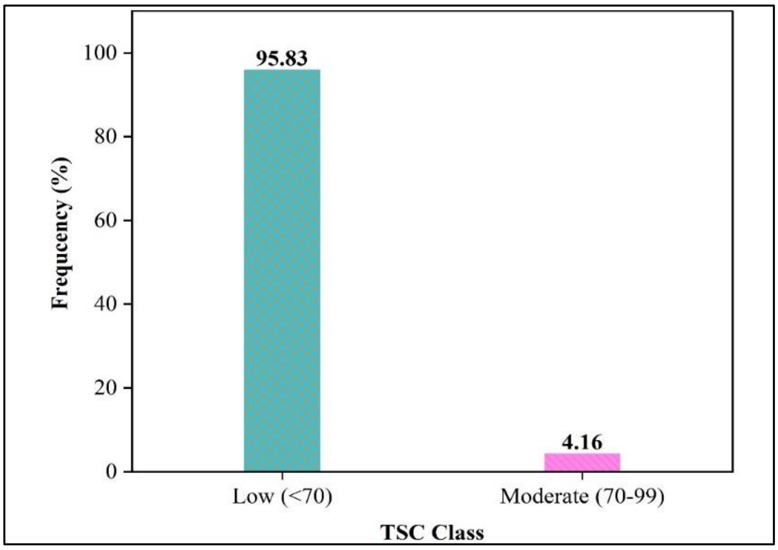

Figure 2. Frequency distribution of *Pinus roxburghii* Sarg. by TSC class.

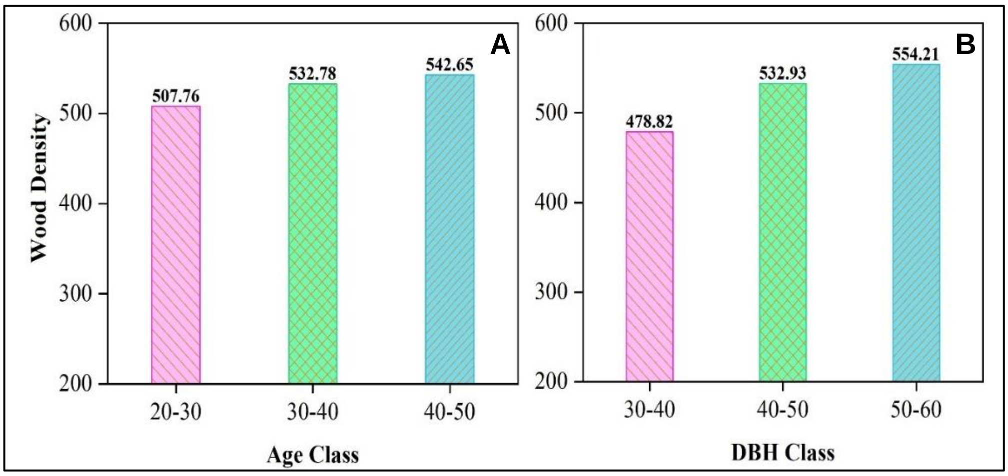

Figure 3. Average wood density value: **A**, age class; and **B**, DBH class.

Correlation analysis and tree slenderness coefficient (TSC) models

To determine the relationship between different tree growth variables such as DBH, tree height, TSC, core length, wood density, BA and age a triangular heatmap was made to visualize relationships in a symmetric matrix. Most of the tree growth variables had a significant positive correlation with each other with fewer variables having weak and negative correlations. There was a significant and positive correlation between DBH and core length, wood density, BA and age. Tree height showed a significant positive correlation with TSC and age. In addition to this BA also had a significant positive correlation with core length and wood density with correlation coefficients (r- values) of 0.29 and 0.36, respectively (Fig. 5). The categorization of the best fit model was based on high R^2 value and lowest value of standard error. Based on these criteria, among the five regression models, the exponential model demonstrated the best fit, with a high R^2 (0.821) and the lowest standard error (0.561), followed by the polynomial, linear, logarithmic, and power models (Table 2).

Table 2. Tree slenderness coefficient models for *Pinus roxburghii* Sarg.

Models	Equations	R^2	SEE
Linear	TSC= -0.007*DBH+ 0.8124	0.783	0.347
	TSC = 0.0568*TH + 19.748	0.091	4.88
Exponential	TSC = $1.0306e^{-0.016DBH}$	0.821	0.561
	TSC= $19.689e^{0.0027TH}$	0.097	2.28
Logarithmic	TSC = -0.363LN(DBH) + 1.8778	0.769	1.70
	TSC = 3.358LN(TH) + 9.5156	0.115	8.79
Power	TSC= $12.119DBH^{-0.841}$	0.796	23.28
	TSC= $12.119TH^{0.1592}$	0.123	3.03
Polynomial	TSC = $-2E\text{-}05DBH^2$ - 0.0051DBH + 0.7631	0.783	0.29
	TSC = $-0.0069TH^2$ + 0.8006TH+ 0.3464	0.226	7.82

Note: DBH-diameter at breast height, TH-tree height, SEE-standard error of estimation, R^2-coefficient of determination.

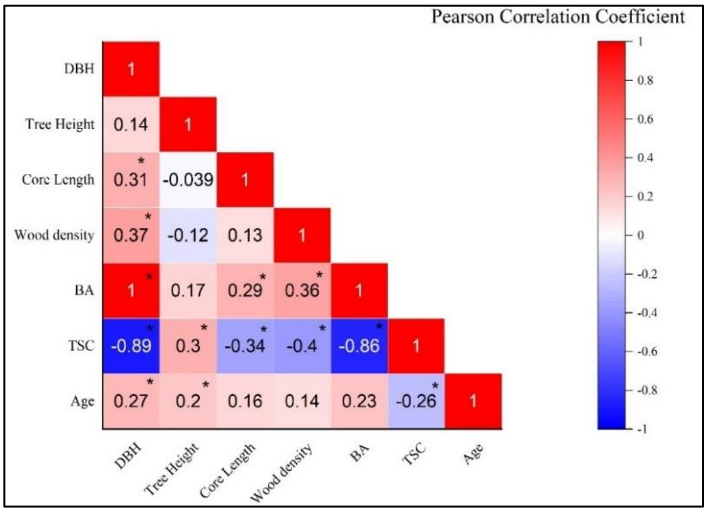

Figure 4. Triangular heat map showing the pairwise Pearson correlation coefficients (R) of the tree growth variables. The significance levels (*) for positive and negative correlations were calculated at 95% confidence level.

DISCUSSION

Summary statistics of tree growth variables for Pinus roxburghii

The majority of *Pinus roxburghii* (95.83%) in the study area have a low slenderness coefficient (TSC<70). This suggests a high level of stability, particularly during periods of high wind velocity. Conversely, only a small proportion (4.16%) of the trees falls into the moderate slenderness category (70–90), indicating a comparatively lesser degree of stability under similar wind conditions. A low slenderness coefficient generally reflects trees with longer crowns, a lower center of gravity, and a well-developed root system, contributing to greater stability. In contrast, trees with values exceeding the threshold of 80 are more likely to experience wind-throw or wind-induced breakage, as they tend to be taller, narrower, and structurally less stable (Vollsinger *et al.* 2005). In general, the values of TSC above 100 indicate low stability and trees are prone to wind damage because their root is not well developed and the tree are often characterized with shorter crown and lower center of gravity (Oladoye *et al*. 2020). Thus, the results obtained in the present study highlights that the majority of *Pinus roxburghii* trees in the area are well adapted to withstand high wind velocities, while a minor portion may be at greater risk due to their moderate slenderness. Tree in the study sites are mostly dominated by *Pinus roxburghii*, therefore, planting a mix type of tree species, including those known for better wind resistance, would be a better option to increase forest resilience to high wind events. Furthermore, training should be provided to local forest managers and communities on best practices for managing windthrow risk and maintaining forest health. Encouragement should be given for further research on the wind resistance of different tree species and the factors influencing tree stability, as this can provide valuable insights for improving forest management practices.

The use of increment cores for wood density determination is one of the most widely used traditional methods in standing trees. Since this method is rapid, reliable, and economic compared to other methods, its applications have become increasingly important for various researchers. To avoid the complete fell down of the trees, the present study used a nondestructive, increment cores for wood density measurements using a dimensional method. The mean wood density value in the present study was 533.37 kg m^{-3} ranging from 401.94 kg m^{-3} to 670.3 kg m^{-3}. Wood density increased with increasing DBH and age, with the highest densities being recorded in the largest diameter and age classes indicating older and larger trees have higher wood density which play a crucial role in carbon sequestration, contributing effectively to climate change mitigation. The wood density value of *P. roxburghii* in the present study is comparatively low as compared to the value obtained by (Sharma & Pukkala 1990) which is 650 kg m^{-3}. Variation in wood density value for the same species may be due to methods used in estimation, and locations of study sites as most of the pine species depends on the location where they grows (Zobel Talbert 1984). Local environmental variables such as soil granulometry, precipitation and wind conditions, including the genetic makeup of individual trees, and their mechanical and physical characteristics also play an important role in determining the wood density of tree (Kollmann & Côté 1968). In addition to this, abiotic factors such as temperature and elevation might have affected the density of the wood (Patino *et al*. 2009). Gryc *et al*. (2011) reported an average wood density value of Pine (*Pinus sylvestris* L.) of 551.89 kg m^{-3} with 28.03 standard deviation and 5.08 % of Cov. Bunn (1981) found density of *Pinus sylvestris* L. close to the pith was 340 kg m^{-3} while the density immediately below the bark was 450 kg m^{-3}. Based on the results of previous studies, it can be inferred that our result (533.37 kg m^{-3}) is within the range reported in literature for pine species. Panshin & Zeeuw (1982) found a considerable variation in wood density and further explained that wood density may vary uniformly followed by either increase or decrease over the lifetime of the tree or even value decrease during the juvenile period and then increase as the tree gets old. Although, we observed variation across the three DBH classes, our results showed a trend of increasing wood density as the tree developed, which points towards an increase in the strength of the tree (Adedeji *et al.* 2013). The measurements obtained by coring method accurately represent the whole tree, due to this simplicity the coring method is well suited for acquiring wood density from standing trees both in the forest area and outside the forest area. The resistance drilling an alternative method for coring has considerable advantages over other methods such as torsiometer, nail withdrawal, and Pilodyn. It causes less damage to trees, operates more quickly, and provides a more sensitive measurement scale (Gao *et al*. 2017). On the other hand, the use of Pilodyn for wood density measurements has been criticized. However, this method is also less time consuming, easy to use and suitable for preliminary classification of a large population having diverse genetic materials (Wei & Borralho 1997, Fukatsu *et al*. 2011). Conventional feeling down of trees for basic wood density measurements is considered to be accurate. While accurate, this approach is highly destructive, labor-intensive, time-consuming, costly, and tedious. Moreover, it may not be feasible in areas where tree cutting is restricted

(Kuyah *et al*. 2016). Previously a caparison study was done by Olale *et al*. (2019) using both destructive (Cutting trees) and non-destructive methods (increment cores) and found that wood density values derived from the two methods produced no significant difference for some species, *Mangifera indica* and *Grevillea robusta* pointing towards coring or auger method is also a reliable satisfactory method. Paul and Baudendistel (1956) also revealed that the increment core method was almost similar in accuracy to standard methods of determining specific gravity in wood specimens. However, taking samples at 1.30 m (breast height) may cause sampling bias, due to the difference in tree heights, and DBH of individual trees growing at particular areas leading to different values of wood density for the same species. Lack of precision in coring, unequal sample core, hard to get complete bark to pitch sample in large tress and difficulty in taking samples in dense wood are some drawbacks of coring method (Robert & Maeglin 1979, Josza 1988).

Correlation analysis and tree slenderness coefficient (TSC) models

Relationships of TSC exhibited a significant positive correlation with tree height and a significant negative correlation (P <0.05) with DBH. This implies that tree size is responsible for low tree slenderness instead of height. The largest slenderness coefficient values occur for the trees with small DBH and relatively greater height, suggesting that taller trees are more likely to be slender while trees with greater thickness (larger DBH) are generally less slender. Similarly, the correlation coefficients between TSC and DBH were higher than those between TSC and all other tree characteristics, indicating that DBH is a better predictor of tree slenderness compared to the other variables. The TSC have a negative correlation with BA and DBH suggesting that the trees with larger basal areas tend to have lower slenderness coefficients. As the tree with low TSC are less prone to wind-throw or damage, the possibility of wind damage in the study area is likely to decrease with an increase in basal area. This results corresponds with the findings of (Wang *et al*. 1998, Ige 2017, Oladoye *et al*. 2020). Onilude & Adesoye (2007) suggested that one possible reason for this could be the inherent height-diameter relationship, which varies across different species and over time. However, this study was carried out in planted community forest thus, the results may vary in natural or other planted *pinus* forest stands. A combination of environmental, genetic, and physiological factors significantly influences the potential of a forest tree species for seed quality, survival, and long-term growth (Daniels & Veblen 2003). The positive correlation between TSC and tree height in the present study aligns with the study of (Onilude & Adesoye 2007). Such a positive relationship is an indication of high competition among the tree stands for sunlight and other limited resources within the plantations in the study area (Shamaki 2013). The present study introduces a new gateway to assess the wood density value and it also provides a reference for comparative analysis with other methods. Although, this study used a limited number of samples from small areas, future research can expand in the same orother geographical regions to identify most suitable method for wood density determination. Additionally, several other factors that influence the wood density such as state of ecosystems disturbances, topography and soil fertility, should be considered in future studies for the improvement of wood density estimation. Among the five regression models used to estimate the relationships between TSC values in the study area, the exponential model was considered the best model based on the least values of standard error of estimate (SEE) but highest values of R^2 (R^2=0.821, and SEE=0.561 for DBH). This suggests that as DBH increases, the slenderness coefficient changes at an exponential rate, rather than a linear one. The exponential model's superior fit implies that the relationship involves rapid increase or gradual decrease in slenderness with respect to changes in DBH.

CONCLUSION

In the present study, the mean wood density value of *Pinus roxburghii* was found 533.37 kg m^{-3}, increased with increasing DBH and age, indicating older and larger trees have higher wood density. Majority of *Pinus roxburghii* trees within the study sites found with low slenderness coefficient (TSC<70). Only a small percentage of trees fall into the moderate slenderness category (70–90). The findings further highlight that tree size is a stronger factor for tree stability than tree height. Wood density shows a positive relationship with all tree growth variables except tree height and TSC. Similarly, TSC exhibited a significant positive correlation with tree height and a significant negative correlation (P <0.05) with DBH. Based on five regression models, the exponential model was observed as the best fit model for *Pinus roxburghii* with the highest R^2, and least value of SEE. Although this study introduces new wood density values for *Pinus roxburghii*, a comprehensive study is needed to validate the results. In future, comparative research can be done with large sample sizes from different geographical regions.

ACKNOWLEDGEMENTS

The authors express sincere gratitude to the Ministry of Forests and Environment, Directorate of Forests, Division Forest Office, Sano Thimi Bhaktapur and Jalpa Devi Community Forest for granting permission to conduct this research work. The authors acknowledge the Department of Hydrology and Meteorology, for meteorological data. Special thanks to Mr. Yuv Raj Dahal, Mr. Ramesh Gautam, Mr. Suman Poudel, and Mr. Arjun Regmi for their kind support during field work.

REFERENCES

Adedeji GA, Ogunsanwo OY & John J (2013) Density Variations in Red Mangrove (*Rhizophora racemose GFW Meyer*) in Onne, River State, Nigeria. *International Journal of Science and Nature* 4: 165–168.

Bastin JF, Fayolle A, Tarelkin Y, Van Den Bulcke J, De Haulleville T, Mortier F, Beeckman H, Van Acker J, Serckx A, Bogaert J & De Cannière C (2015) Wood specific gravity variations and biomass of central African tree species: The simple choice of the outer wood. *PLoS ONE* 11: 1–16.

Bhuju DR & Gaire NP (2012) Plantation History and Growth of Old Pine Stands in Kathmandu Valley: a Dendrochronological Approach. *FUUAST Journal of Biology* 2: 13–17.

Bunn EH (1981) The nature of the resource. *New Zealand Journal of Forestry* 26: 162–169.

Bhattacharya A, La Marche VC & Hughes MK (1992) Tree-ring chronologies from Nepal. *Tree Ring Bulletin* 52: 59–66.

Brown S, Gillespie AJR & Lugo AE (1989) Biomass estimation methods for tropical forests with applications to forest inventory data. *Forest Science* 35: 881–902.

Černý J, Pokorný R, Haninec P & Bednář P (2019) Leaf area index estimation using three distinct methods in pure deciduous stands. *Journal of Visualized Experiments* 150: 10.3791/59757.

Chave J, Andalo C, Brown S, Cairns MA, Chambers JQ, Eamus, D, Fölster, H, Fromard F, Higuchi N, Kira T, Lescure JP, Nelson BW, Ogawa H, Puig H, Riéra B & Yamakura T (2005) Tree allometry and improved estimation of carbon stocks and balance in tropical forests. *Oecologia* 145: 87–99.

Cown DJ & Clement BC (1983) A wood densitometer using direct scanning with X-rays. *Wood Science and Technology* 17: 91–99.

Daniels LD & Veblen TT (2003) Altitudinal tree lines of the southern Andes near 40°S. *Forestry Chronicle* 79: 237–241.

DFRS (2015) *State of Nepal's Forests*. Forest Resource Assessment (FRA) Nepal, Department of Forest Research and Survey (DFRS), Kathmandu, Nepal.

Eberhardt TL & Samuelson LJ (2015) Collection of wood quality data by X-ray densitometry: a case study with three southern pines. *Wood Science and Technology* 49: 739–753.

Fritts HC (1976) *Tree rings and climate*. Cambridge University Press, Cambridge.

Fritts HC, Smith DG, Cardis JW & Budelsky CA (1965) Tree-ring characteristics along a vegetation gradient in northern Arizona. *Ecology* 46: 393–401.

Fukatsu E, Tamura A, Takahashi M, Fukuda Y, Nakada R, Kubota M & Kurinobu S (2011) Efficiency of the indirect selection and the evaluation of the genotype by environment interaction using Pilodyn for the genetic improvement of wood density in *Cryptomeria japonica*. *Journal of Forest Research* 16: 128–135.

Gao S, Wang X, Wiemann MC, Brashaw BK, Ross RJ & Wang L (2017) A critical analysis of methods for rapid and nondestructive determination of wood density in standing trees. *Annals of Forest Science* 74: 1–13.

Gryc V, Vavrčík H & Horn K (2011) Density of juvenile and mature wood of selected coniferous species. *Journal of Forest Science* 57: 123–130.

Gyawali A, Sharma RP & Bhandari SK (2015) Individual tree basal area growth models for Chir pine (*Pinus roxberghii* Sarg.) in western Nepal. *Journal of Forest Science* 12: 535–543.

Harja D, Vincent G, Mulia R & Van Noordwijk M (2012) Tree shape plasticity in relation to crown exposure. *Trees - Structure and Function* 26: 1275–1285.

Hietz P, Valencia R & Joseph Wright S (2013) Strong radial variation in wood density follows a uniform pattern in two neotropical rain forests. *Functional Ecology* 27: 684–692.

Husch B, Beers TW & Kershaw JA (2003) *Forest mensuration, 4th edition*. Wiley, 443 p.

Ige PO & Komolafe OO (2022) Tree Slenderness Coefficient Models for Biodiversity Conservation in International Institute of Tropical Agriculture Forest Ibadan, Nigeria. *Tanzania Journal of Forestry and Nature Conservation* 91: 20–31.

Jackson JK (1994) *Manual of Afforestation in Nepal*. Kathmandu, Forest Research and Survey Centre, Ministry of Forest and Soil Conservation. 824 p.

Josza L (1988) *Increment Core Sampling Techniques for High Quality Cores*. Wood Science Dept. Laboratoire

Vancouver Laboratory. Special Pub. No. SP-30, pp 34.

Kollmann FFP & Côté WA (1968) *Principles of wood science and technology I: solid wood*. Springer, Berlin.

Liepiņš K & Rieksts-Riekstiņš J (2013) Stem wood density of juvenile silver birch trees (*Betula pendula* Roth) from plantations on former farmlands. *Baltic Forestry* 19: 179–186.

Liu X, Silins U, Lieffers VJ & Man R (2003) Stem hydraulic properties and growth in lodgepole pine stands following thinning and sway treatment. *Canadian Journal of Forest Research* 33: 1295–1303.

Navratil S (1996) Silvicultural systems for managing deciduous and mixed wood stands with white spruce understory. In: *Silvicultural of temperate and boreal broadleaf-conifer mixture*. Springer, pp 35–46.

Navratil S, Brace LG, Sauder EA & Lux S (1994) *Silvicultural and harvesting options to favor immature white spruce and aspen regeneration in boreal mixed woods*. Canadian Forest Service, Northwest Region, Northern Forestry Centre, Edmonton, Alberta, pp. 337.

Nogueira EM, Fearnside PM, Nelson BW, Barbosa RI & Keizer EWH (2008) Estimates of forest biomass in the Brazilian Amazon: New allometric equations and adjustments to biomass from wood-volume inventories. *Forest Ecology and Management* 256: 1853–1867.

Olesen PO (1971) *The water displacement method*. The Royal Veterinary and Agricultural University of Copenhagen, pp 18.

Onilude QA & Adesoye PO (2007) Relationships between tree slenderness coefficient and tree growth characteristics for *Triplochiton scleroxylon* (k. schum) stands in Ibadan Metropolis, Nigeria. *Obeche Journal* 25: 16–24.

Oladoye AO, Ige PO, Onilude QA & Animashaun ZT (2020) Slenderness coefficient models for tree species in Omo biosphere reserve, South-western Nigeria. *Tropical Plant Research* 7: 609–618.

Olale K, Yenesew A, Jamnadass R, Sila A & Shepherd K (2019) *A simple field-based method for rapid wood density estimation for selected tree species in Western Kenya*. Scientific African.

Oyebade BA, Eguakun FS & Egberibin A (2015) Tree Slenderness Coefficient (TSC) and tree Growth Characteristics (TGCS) for *Pinus caribaea* in Omo Forest Reserve, Nigeria. *IOSR Journal of Environmental Science* 9: 2319–2399.

Panshin AJ & Zeeuw C (1982) *Textbook of wood technology*. New York.

Patino S, Lloyd J, Paiva R, Baker TR, Quesada CA, Mercado LM, Schmerler J, Schwarz M, Santos AJB, Aguilar A, Czimczik CI, Gallo J, Horna V, Hoyos EJ, Jimenez EM, Palomino W, Peacock J, Pena-Cruz A, Sarmiento C & Phillips OL (2009) Branch xylem density variations across the Amazon Basin. *Biogeosciences* 6: 545–568.

Paul BH & Baudendistel ME (1956) *A field method of determining specific gravity by use of increment cores or auger chips*. Forest Products Laboratory Report No. 1587. pp. 8.

Press, JR, Shrestha KK & Sutton DA (2000) *Annotated checklist of the flowering plants of Nepal*. The Natural History Museum, London.

Rajbhandari K R, Joshi L, Chhetri R & Khatri S (2020) *A handbook of the Gymnosperms of Nepal*. National Herbarium and Plant Laboratories.

Rinn, F (2003) *TSAP-Win: time series analysis and presentation for dendrochronology and related applications*. Heidelberg, Germany.

Maeglin RR (1979) *Increment cores - how to collect, handle, and use them. U.S.D.A*. Forest Service General Technical Report FPL-25. 18 pp.

Rudnicki M, Silins U, Lieffers VJ & Josi G (2001) Measure of simultaneous tree sways and estimation of crown interactions among a group of trees. *Trees - Structure and Function* 15: 83–90.

Shamaki SB & Akindele SO (2013) Volume estimation models from stump diameter for teak (*Tectona grandis* Linn f.) plantation in Nimbia forest reserve, Nigeria. *Journal of Environmental Science and Water Resources* 2: 89–94.

Sharma ER & Pukkala T (1990) *Volume equations and biomass prediction of forest trees of Nepal*. Publication No. 47. Forest Survey and Statistics Division, Ministry of Forests and Soil Conservation, Babarmahal, Kathmandu, Nepal.

Siddiqui MH, Ahmed M, Wahav M, Khan S, Khan MU, Nazim K & Hussain SS (2009) Phytosociology of *Pinus roxburghii* Sargent. (Chir pine) in lesser Himalayan and Hindukush range of Pakistan. *Pakistan Journal of Botany* 41: 2357–2369.

Springate-Baginski O & Dev O (2003) Community forest management in the middle hills of Nepal: the changing context. *Journal of Forest and Livelihood* 3: 5–20.

Kuyah S, Mbow C, Sileshi GW, van Noordwijk M, Tully KL & Rosenstock TS (2016) *Quantifying tree biomass carbon stocks and fluxes in agricultural landscapes*. Methods for measuring greenhouse gas balances and evaluating mitigation options in smallholder agriculture. pp. 119–34.

Speer JH, Brauning A, Zhang QB, Pourtahmasi K, Gaire NP, Dawadi B, Rana P, Dhakal YR, Acharya RH, Adhikari DL, Adhikari S, Aryal PC, Bagale D, Baniya B, Bhandari S, Dahal N, Dahal S, Ganbaatar N, Giri A, Gurung DB, Khandu Y, Maharjan B, Maharjan R, Malik RA, Nath CD, Nepal B, Ngoma J, Pant R, Pathak ML, Paudel H, Sharma B, Hossain MS, Soronzonbold B, Swe T, Thapa I & Tiwari A (2016) *Pinus roxburghiist* and dynamics at a heavily impacted site in Nepal: Research through an educational fieldweek. *Dendrochronologia* 41: 2–9.

Speer JH, Bräuning A, Zhang QB, Pourtahmasi K, Gaire NP, Dawadi B, Rana P, Dhakal YR, Acharya RH, Adhikari DL & Adhikari S (2017) *Pinus roxburghii* stand dynamics at a heavily impacted site in Nepal: Research through an educational field week. *Dendrochronologia* 41: 2–9.

Tiwari A, Thapa N, Aryal S, Rana P & Adhikari S (2020) Growth performance of planted population of *Pinus roxburghii* in central Nepal. *Journal of Ecology and Environment* 44: 1–1.

Tiwari DN (1994) *A monograph on Chir pine (Pinus roxburghii Sarg)*. Indian Council of Forestry Research and Education, Dehradun.

UNFCCC (2008) *Proceedings of the Conference of the Parties on its Thirteenth Session*. United Nations Framework Convention on Climate Change, Bonn, Germany, 2008 Bali, 3–15 December 2007. Addendum, Part 2. Document FCCC/CP/2007/6/Add.1.

Vollsinger S, Mitchell SJ, Byrne KE, Novak MD & Rudnicki M (2005) Wind tunnel measurements of crown streamlining and drag relationships for several hardwood species. *Canadian Journal of Forest Research* 35: 1238–1249.

Wang Y, Titus SJ & LeMay VM (1998) Relationships between tree slenderness coefficients and tree or stand characteristics for major species in boreal mixedwood forests. *Canadian Journal of Forest Research* 28: 1171–1183.

Wei X & Borralho NMG (1997) Genetic control of wood basic density and bark thickness and their relationships with growth traits of eucalyptus urophylla in south east China. *Silvae Genetica* 46: 245–250.

Zobel BJ & Talbert J (1984) *Applied Forest Tree Improvement*. New York, Wiley.