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Comparison of Planted *Pine* versus Natural Mix Forests in Nepal

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Abstract: This study aimed to compare the socio-environmental benefits of one of the most widely planted forest species, i.e., *Pinus roxburghii* (Sarg., hereafter 'Pine' or '*Pinus*') with naturally regenerated mixed forests in two community forests of Nepal. By analyzing tree rings, we estimate biomass production, carbon accumulation, and growth enhancement in both forest types using regression models, offering insights into sustainable forest management. *Pinus* forests exhibit instant social benefits through direct economic conversion and a higher rate of carbon sequestration. However, the lack of perpetuated production, due to unimodal stand structures, necessitates anthropogenic interventions for long-term sustainability. Challenges such as the absence of natural regeneration, frequent fires, limited undergrowth, limited species diversity, and likely soil erosion hinder long-term sustainability in *Pinus* forests. In contrast, natural regenerated mixed forests offer slow carbon sequestration with less opportunity for immediate economic conversion, yet they maintain a proportional age-class distribution and experience minimal fire incidence, abundant regeneration, higher biodiversity, and lower regeneration costs. Although no abrupt environmental disasters were observed through the dendrochronological assessment, a significant positive correlation ($p < 0.05$) was found between age and girth at breast height, biomass, and volume of the forests. This study underscores the crucial role of human intervention beyond conventional management focusing on the protection motive to production-oriented forests in optimizing the socio-economic and environmental benefits of both forest types in the changing socio-environmental challenges through informed management planning.

Keywords: age gradation; biomass production; forest ecosystem; scenario planning; socio-environmental benefits

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1. Introduction

Almost one-quarter of the total land area is covered by forests globally [1]. This constitutes both natural forests and artificially regenerated forests. Realizing the fact that forest vegetation and forest soils are viable sinks of atmospheric carbon and can significantly mitigate global climate change [2–5], regardless of their mode of regeneration, the concern of global communities regarding forest ecosystems has increased. Additionally, these terrestrial ecosystems offer numerous benefits, such as improving soil fertility, ecosystems, and biodiversity, which in turn lead to a series of other positive outcomes [3,5–7] benefitting people and the planet. A large chunk of global forests are natural; however, their conversion to arable land and other types of land uses has resulted in the shrinkage of these areas day by day [1,8]. In response, humans started to regenerate forests through artificial approaches, for example, plantation forests. The global area of planted forests surged from 167.5 million hectares to 277.9 million hectares between 1990 and 2015, with Pine species predominantly utilized, especially in temperate and boreal zones [9,10]. Despite constituting diverse physiographic and climatic variation associated with social and environmental benefits, constituting approximately 8.45% of the total forested area, 16.2% of stem density, and 3.8% of trees with an 11.62 m^3 ha^{-1} stem volume [11], the potential benefits from this single species compared with adjacent natural forests have not been properly illustrated in the changing world from social and environmental perspectives.

Following global trends, Nepal's forest cover was estimated at 5.96 million hectares in the latest assessment—almost 45% of the country's land mass, marking a significant increase from the past record [12]. Plantation forests have played a key role in this expansion, with around 370,000 hectares established since the 1980s, largely dominated by Pine species [13]. Among all the forest cover including planted forests, over one-third of Nepal's forests are managed by local communities, with 97% being naturally regenerated and the remaining 3% planted as community forests (CFs) [14]. Local communities, with the support of the government and donors, were devoted to planting Pine, especially *Pinus roxburghii*, across the Mid Hills area due to its multiple benefits and wide range of distribution. These benefits include but are not limited to a wide range of adaptability in the new environment for forest restoration and the control of soil erosion [15], a wide range of distributions beyond Nepal from Bhutan, Myanmar, Sikkim, and Tibet from the east to Nepal, India, Pakistan, and Afghanistan on the west along the Hindu-Kush Himalayas foothills, and one of the largest elevation ranges from 450 m to 2700 m, mostly in south-facing dry areas [15]. The species forms 1 of the 12 ecoregions in Nepal [16,17] and is a major forest type in subtropical regions [11]. After the energy crisis of the 1970s in Nepal, following the Theory of the Himalayas' Environmental Degradation [18], plenty of plantation work started and it became the most widely planted species during the 1980s and subsequent decades in Nepal [15]. This plantation effort supplemented the demand for construction timber for house-building, wood fuel demands, and bedding materials for livestock to harness social needs [13,15]. Recently, resin extracted from Pine has a growing market, offering high economic returns to forest owners and the government through revenue generation in subtropical countries like Nepal and India [19]. As a result, a recent national forest assessment report highlighted several important production and conversion assets concerning *P. roxburghii* regarding harnessing societal needs as well as meeting environmental challenges like carbon offsetting [17]. To realize these benefits, it is crucial to assess the time-based biomass estimation and optimize the economic, social, and environmental benefits. Yet, it is uncertain whether these benefits will be perpetual for any type of forest, including planted Pine. This can be achieved by analyzing and comparing forest structures at the existing stage to plan scenarios for both types of forests, regenerated naturally or planted, to inform future planning and optimize the social and environmental benefits for sustainability. For this, as a proxy measure, above-ground biomass is useful for comparing the structural and functional attributes of forest ecosystems across a wide range of environmental setups [20].

Several studies have employed different methodologies to determine the age of standing trees and subsequent interrelationships. Some of these studies used a ring count via destructive sampling techniques [21], coring using Pressler's borer [22,23], a radiometric scanner [24], or tomography [25,26]. If a forest is dominated by *Pinus*, the approximate age of the stands can be found by counting the whorls of branches [15]. However, this technique is not scientific since the pure *Pinus* stand, in most cases, performs self-pruning of its branches, which hinders the whorls for accurate counting [27]. Furthermore, destructive techniques, radiometric scanners, or tomography are, of course, more accurate than the conventional whorls counting method. However, these tools and techniques are relatively demanding regarding time, effort, technology, and resources [28]. Coring is one of the established techniques that readily facilitates the determination of the age of standing trees without causing significant damage to trees regarding their future growth. Also, radial growth and wood density are important traits in assessing wood quality [29], which can be obtained from coring samples. Coring samples allow for the determination of the mentioned quality and growth components among many other aspects of the environment [28]. Despite having several high-tech infrared and radio wave-based tools and techniques in place to identify the age and quality assurance of wood in trees using software and a flatbed scanner [30], there are limitations of tools and techniques in Nepal due to the limited coverage of many types of research in many areas and ecological data management [31]. Past research also highlighted time-based production, especially for Pine species across the Himalayas regions [32], providing an effective strategy using the dendrochronological technique in species [24,28] like *P. roxburghii* for estimating biomass and carbon storage in forests for management planning [32]. Realizing the benefits and minimizing the negative consequences, we utilize coring tools to estimate the age (time-based production) to assess the quality of wood production in addition to determining the rotation and productivity of the forests [33] and measuring other physical dimensions of the standing Pine trees in this study. However, estimating the age of natural forests is challenging, so we performed our estimations by interpolating the diameter at breast height (DBH) with the total tree height, as suggested by Jackson (1994) [15].

Numerous studies worldwide have addressed biomass and carbon estimation, as well as monitoring and assessment issues concerning forest ecosystems. These include the estimation of biomass in Australian Eucalyptus forests [34] and Indian humid tropical forests [35], environmental assessment using tree rings in France [33], the growth response to climate change in Chinese forests [36], and carbon concerning REDD+ in Latin American countries [37]. Similarly, in Nepal, studies cover a wide range of aspects such as ecosystem services [31], carbon-to-soil properties, and REDD+ concerns [38,39]. However, there is a lack of research comparing planted and natural forests regarding ecological sustainability and biomass production potential. Further, forest sustainability largely depends on regeneration conditions, plant density, age or size (or class) gradation, biomass accumulation, forest conditions that optimize biomass production, biodiversity management, and incentives from carbon financing mechanisms or other means, which are yet to assess the most widely planted Pine versus natural mixed forests in a contagious landscape under a similar management system (i.e., in CFs).

In this study, we endeavor to comprehend the social and environmental benefits of planted Pine forests and natural mixed forests from sustainability perspectives. Specifically, the study aims to compare the community structure and characteristics of mixed forests and planted Pine forests in the same environment by utilizing several variables of production potential frontiers to harness societal needs and environmental sustainability in the contemporary changing world. The results of this research will contribute to the comparative ecological knowledge of Pine plantations and natural forests. This study offers crucial insights into ensuring ecological sustainability, addressing climate change, and promoting sustainable forest management. The findings have global applicability, informing forest management decisions for both plantation and natural forests in the face of increasing socio-economic demands and environmental challenges.

2. Materials and Methods

2.1. Study Area

This study was conducted in the Gorkha district, which extends between 27°15′ and 28°45′ N latitude and 84°27′ and 84°58′ E longitude, in the middle hills and high mountains of the Gandaki Province of Nepal (Figure 1). This district covers an area of 3614.70 km^2, bounded by Tibet (China) to the north, Dhading district to the east, Manang and Lamjung districts to the west, and Tanahun and Chitwan districts to the south, with an elevation range of 228 m asl at the bank of Trisuli river to 8163 m asl at the top of Mount Manaslu [40]. Gorkha district possesses five distinct types of forest ecology according to the altitudinal range—tropical, subtropical, temperate, sub-alpine, and alpine—which offer a wide array of vegetation, in which the sub-tropical region is dominated by *Pinus roxburghii* and *Schima-Castanopsis* forests.

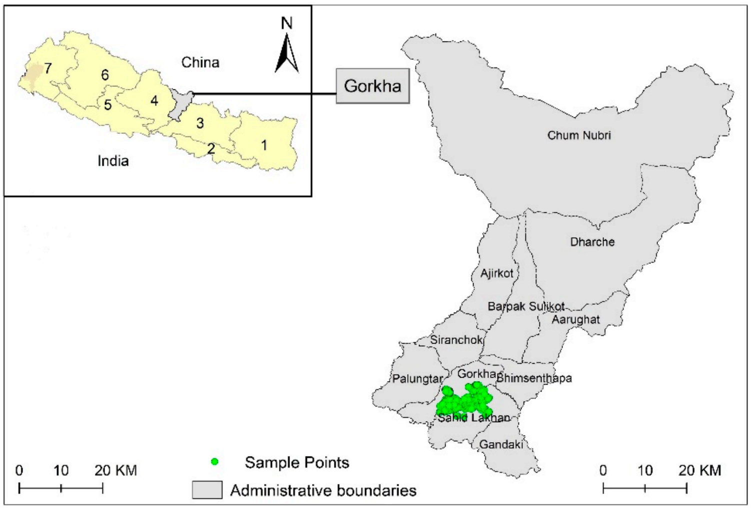

Figure 1. Maps showing study area. The digits in Nepal's map indicate the names of provinces of Nepal, i.e., 1 = Koshi Province, 2 = Madhesh Province, 3 = Bagmati Province, 4 = Gandaki Province, 5 = Lumbini Province, 6 = Karnali Province, and 7 = Sudurpachhim Province.

The study area lies in the Ludikhola sub-watershed area of Gorkha district, located at 27°55′02.85″–27°59′43.88″ N and 84°40′41.87″–84°33′23.13″ E; the altitude ranges from 318 to 1714 m asl; and the mean annual temperature is 23.1 °C [41]. For this study, the Ludi Damgade Community Forest (LDCF) and Ghaledanda Ranakhola Community Forests (GRCFs) were used, which constitute both natural mixed forests and planted Pine across the contagious landscape.

Plantation Forest: There were two patches of plantation forests, each covering approximately 20 hectares, with *Pinus roxburghii*. Ten hectares of each forest belonged to GRCF and LDCF within the mixed forests of the Ludi Khola watershed area. These forests were mostly east-facing, with some sample plots facing southeast and northeast. The forest was in a gently sloping area with approximately two-thirds of crown cover and an elevation ranging from 700 to 1000 m asl.

Natural Mixed Forest: The natural forests were primarily covered by three species—*Shorea robusta* (Gaertn.), *Schima wallichii* (DC.), and *Castanopsis indica* (Roxb.)—as naturally regenerating broad-leaved forests. Commonly associated species include *Cleistocalyx operculatus* (Roxb.), *Syzygium cumini* (L.), *Lyonia ovalifolia* (Wall.), *Wendlandia coriacea* (Wall.), *Pinus roxburghii,* and *Engelhardia spicata* (Lesch. ex Blume). These forests are found in all geographic aspects and at elevations ranging between 700 and 1000 m above sea level (m asl).

2.2. Sample Design and Data Collection

A map of the study area was laid out, and randomization was performed to obtain the required number of sample plots in a sampling frame using geographic points of the CFs. The list of geographic positions was used from the operational plan of CFs, and they were uploaded to geographical positioning system (GPS) instruments. Finally, the sampling plots were tracked using GPS to lay out concentric circular sample plots (CCSP) throughout the forest. Circular plots were chosen because they are easier to lay out and cover a greater area with a smaller perimeter, reducing bias on border trees regarding whether to measure them or not [42]. The details of the methods have been referenced from a previous study [38], and the sampling techniques, designs, data collection procedures, and protocols were adopted from these past studies [38,42].

A total of 269 hectares of forest was used for the study, with a sampling intensity of 0.83%, which covered an area of 2.23 hectares. The total number of sample plots in the forests was determined based on previously available (Statistics asserted from the Operational Plan of Community Forests) data. A simple random sampling technique was employed to determine the sample size for data collection. A total of 89 plots were established: plots with a radius of 8.92 m were used for tree measurement (DBH ≥ 5 cm), plots with a 5.56 m radius were used for sapling measurement (DBH < 5 cm), and plots with a 1 m radius were used for seedling counts (height < 1.30 m). Of these sample plots, 20 were in plantation forests and 69 were in natural mixed forests within the study area.

Trees were first marked by starting from the edge of the plot and working inward to prevent accidental double counting. Once marked, the trees were numbered from the middle to the edge, beginning at the north and moving in a clockwise direction. Each tree was recorded along with its species name. Trees on the border were included if more than 50% of their basal area fell within the plot; otherwise, they were excluded. All trees were measured for their diameter at 130 cm above-ground level (DBH) from the uphill side. The total height of each tree was measured using a Vertex IV and a Transponder. The wood density of each species was obtained from the secondary literature [17]. Other variables such as soil cover, slope, exposure, crown cover, the presence of wildlife, the degree of anthropogenic disturbances, the incidence of bushfires, etc., were also recorded in all sample plots.

Besides these measurements in all sample plots as mentioned above, the sample plots that were in the planted Pine forests were utilized as an experimental site, and a Swedish Pressler's tree corer was used to core the selected trees of *Pinus* at breast height (1.30 m) to determine the age and thereby time-based biomass production. Altogether, 63 trees were cored from the 20 sample plots. The coring was carried out at exactly breast height. Along with coring, DBH, total height, whorls count, and girth at the base (15 cm) were measured, and regeneration, ground cover, slope, and aspect were accounted for in every sample plot of Pine. This study also aimed to determine the mean annual increment (MAI), which serves as a benchmark for comparing natural tree growth nearby. Therefore, the *Pinus* plantation acted as a reference area within the study's naturally occurring environment. The average age of the natural mix forests adjacent to the Pine forests was estimated by interpolating DBH and total height as suggested by previous research carried out in Nepal [15].

The cores of Pine trees were put into straws bigger than the core size for safe handling and transportation. They were transported from the field to the laboratory in which they were labeled. The cores were smoothed with sandpaper until the distinct tree rings were visible to the naked eye. Visual, hand lens, and microscopic analyses were performed to count the number of rings and estimate the age of the trees [32]. The analysis was carried out at the Research Laboratory of the Central Department of Botany, Tribhuvan University, assuming only a single ring would form each year in *Pinus* in Nepal's climate [15]. Also, the rate of tapering was estimated using simple trigonometric and geometric relationships between the girth at breast height (GBH), DBH, and their derivatives.

Variables such as age, height, DBH, wood density, biomass, increment, biomass production, and carbon stock in the existing scenario and the predicted scenarios were compared between the natural and planted forests. Additionally, the characteristics of these forests were also discussed from the perspective of sustainability considering the socio-economic benefits and carbon sequestration potential to harness environmental challenges such as climate change and social demands such as ecosystem goods and services. The fundamental characteristics of the forest types are presented in Table 1 and the details of the data collection sheet used for this study are presented in Appendix A.

Table 1. The basic characteristics of study sites.

Variables	Planted Pine Forest	Natural Mix Forest	Remarks
Tentative area of forest	20 ha	249 ha	Both forests lie in contagious landscape
Sample plot taken for measurement	20	69	100 m^2 in size for each plot

Table 1. *Cont.*

Variables	Planted Pine Forest	Natural Mix Forest	Remarks
Zones	Sub-tropical	Sub-tropical	Same zone
management	Community managed	Community managed	Conventional protection-based
Topographic characteristics	East-south facing, gentle to moderate slope	East-south facing, gentle to moderate slope	Similar topographic features
Interventions	Traditional protection-based management and pruning	Traditional-protection based management	Communities manage forests as per the forest operational plan of community forests
Tree cover	Mostly dominant by trees, dense canopy	Mostly dominant by a pole-sized, sparse canopy	
Regeneration	Nil except for intermittent enrichment plantation	Natural regeneration	
Bushes	Nil except for some invasive species in some plots	Presence in almost all plots	
Exposed soil	Almost all plots	Almost nil	
Litter cover	Pine needles	Natural decomposing	
Sign of wildlife	Almost nil	Wildlife signs were in abundance	
Climber	Absent	Present	
Fern cover	Nil	occasional	
Lopping	Absent	Fodder collection	
Diversity	Monoculture (single species)	Diverse species composition (more than 26 species)	

2.3. Biomass Estimation

This study estimated the above-ground tree biomass (AGTB) using an allometric equation as suggested by Chave et al. (2005) (for the category of moist forests, of which Gorkha district falls under this) [43], which has relatively better performance compared with other models [44].

$$AGTB = 0.0509\ \rho\ D^2H \quad (1)$$

where AGTB = above-ground tree biomass (kg); ρ = wood specific density (kg/m^3); D = tree diameter at breast height (DBH) (cm); H = tree height (m). The value of species-specific wood density was ascertained by the Department of Forest Research and Survey [17] and also highlighted by the forest carbon measurement directives [45]. For *Pinus roxburghii*, the values of a, b, and c are taken as −2.977, 1.9235, and 1.0019, respectively; ρ = 650 kg/m^3; Ln is the natural log base value, taken as 2.71828. The biomass stock density of a sampling plot was converted into carbon stock density using the Intergovernmental Panel on Climate Change (IPCC) default carbon fraction of 0.47 [46].

To simplify the process of estimating below-ground biomass, we used a root-to-shoot ratio value of 1:5 as prescribed by MacDicken (1997) who stated that the below-ground biomass is considered to be 20% of the above-ground tree biomass [47].

2.4. Data Analysis

Student's *t*-distribution is suitable when the sampling distribution of the means of sample variables is small [48]. When the distribution of the sample means follows Student's *t*-distribution, the *t*-test can be applied to test the mean of each sample for homogeneity analysis. In our study, we utilized *t*-tests, regression analysis, and correlation tests based on our data. The Mann–Kendall trend test was used to test whether the DBH–class distribution had any significant trend for both planted Pine and natural mixed forests. Correlation tests were conducted to assess the degree of association between two variables, while regression analysis was employed to estimate and predict biomass production. Biomass is a function of wood density, DBH (diameter at breast height), and the total height of trees (Model 1). These variables were estimated using different strategies: wood densities were referenced from past studies [17], the time-based DBH increment was estimated using tree coring, and time-based height growth was predicted using the tree tapering function [49,50]. After obtaining these variables on a periodic scale, eleven different biomass estimation models were tested against each other for the given dataset. Their performance was evaluated using statistical criteria such as R^2, Akaike's Information Criterion (AIC), and the root mean squared error (RMSE) [51]. Additionally, the models' performances and output errors were tested using the Shapiro–Wilk Normality test and the errors were plotted to determine if they were normally distributed [52]. Based on the relatively better-performing model that considered field characteristics as suggested [43,44], the selected model *[i.e., predicted biomass = 0.0509 × wood density of particular species ×* $DBH_t^{\hat{}2}$ *× total height of the trees*$_t$, $_t$ *= time in year ranging from 1 to rotation age of the tree species, and other variables have their usual meanings and units]* was used for the estimation and prediction of biomass using regression analysis because of its merit and commonality in practice [53]. All statistical analyses and tests were conducted using R libraries of version 4.2 such as multcom, agricolae, lm, glm [54] and MS Excel 2007.

3. Results

3.1. Statistics of the Forests under Study

Almost a dozen parameters were considered for the comparative study of the two types of forests. The results showed higher mean age, DBH, height, biomass density, carbon stock density, and mean annual increment (MAI) in plantation forests but the forest had very little undergrowth, signs of frequent fire, lower wood density, and the absence of regeneration. Meanwhile, a higher mean density of wood, stock per hectare (both trees and regeneration), and under-growth biomass, the absence of fire signs, and good conditions of natural regeneration were found in natural mixed forests (Table 2).

Table 2. The characteristics of natural and plantation forests from the study area (MAI is mean annual increment; other variables have their usual meaning).

S.N.	Parameters	Planted *Pine*	Natural Mix Forest	Remarks
1	Mean age (years)	24	16	Natural forest's age has been derived from Jackson, 1994 [15] (with interpolation of mean DBH and height)
2	Mean height (m)	15.73	6.7	
3	Mean DBH (cm)	23.13	10.47	
4	No. of plots	20	69	
5	No. of trees	1582	3346	
6	Mean wood density (kg/m^3)	0.65	0.83	
7	Biomass (ton/ha)	409.76	133.87	Root-shoot ratio 1:5
8	MAI (t/ha)	17.07	8.37	
9	Carbon Stock (C t/ha)	189.77	62.82	
10	Stock (number/ha)	1080-trees 100-reg.	1557-trees 35,217-reg.	Reg. = regenerations
11	Tentative area studied (ha)	20	249	
12	Undergrowth	Nil or nominal	Profound	Source: field survey
13	The presence of frequent fire	Present	Absent	Source: field survey
14	Natural regeneration	Absent	Present	Source: field survey

The mean values of all continuous variables (Table 2) between plantation and natural forests were significantly different (Table 3) for given sites. The test results showed a significant ($p < 0.05$) difference in biomass production concerning the types of forests. The highest variability between the planted Pine and the natural mixed forest was found in biomass content per plant in the study area, whereas the lowest variation was observed in wood density as indicated by the standard deviation of the respective variables. Further, the study found similar variations in the DBH distribution for both forests (Table 3).

Table 3. Comparison between variables using *t*-test and their respective standard deviation for plantation and natural mixed forests from the study area (SD stands for standard deviation and other variables have their usual meaning; units of the SD for both forest types correspond to Table 2).

Variables	*p*-Value	SD-Planted Pine	SD-Natural Mixed Forest
Basal girth at 15 cm	<0.05	23.66	26.08
Girth at breast height	<0.05	20.65	21.18
DBH	<0.05	6.57	6.74
Total height	<0.05	2.52	6.74
Wood density	<0.05	0	0.08
Biomass per tree	<0.05	170.24	246.83
Carbon per tree	<0.05	80.01	116.01

3.2. Stand Structure of the Forests

The DBH–height relationship showed wide variability but a high degree of positive correlation (r = 0.71) and a significant ($p < 0.05$) association. In plantation forests, there were larger-sized trees in terms of both mean DBH and height (Figure 2), and as a result, higher biomass (or biomass carbon) was found in the plantation forest than in the natural mixed forest. However, the lower regeneration and density of trees, absence of undergrowth, and smaller coverage diminish the future potentiality of the plantation forest for continuous carbon sequestration (Table 2, Figure 3). The Mann–Kendall test showed that there was no significant DBH–class distribution trend for plantation forests and Sen's slope value was positive. In contrast, the natural mix forests showed a significant ($p < 0.05$) negative trend of DBH–class distribution, which signifies the formation of a reverse J-shaped curve and the consistent size gradation of the trees (Figure 2).

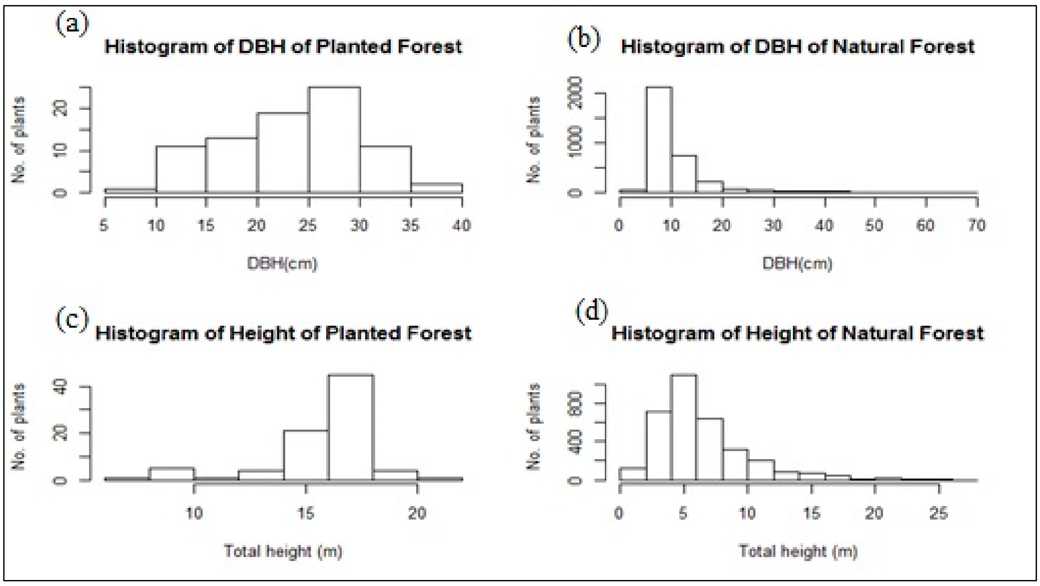

Figure 2. Frequency distribution of DBH and height of planted Pine and natural mixed forests from the study area (almost unimodal distribution of DBH for plantation forest (**a**); positively skewed DBH distribution for natural forest (**b**); negatively skewed distribution of height for plantation forest (**c**); and height for natural forest (**d**).

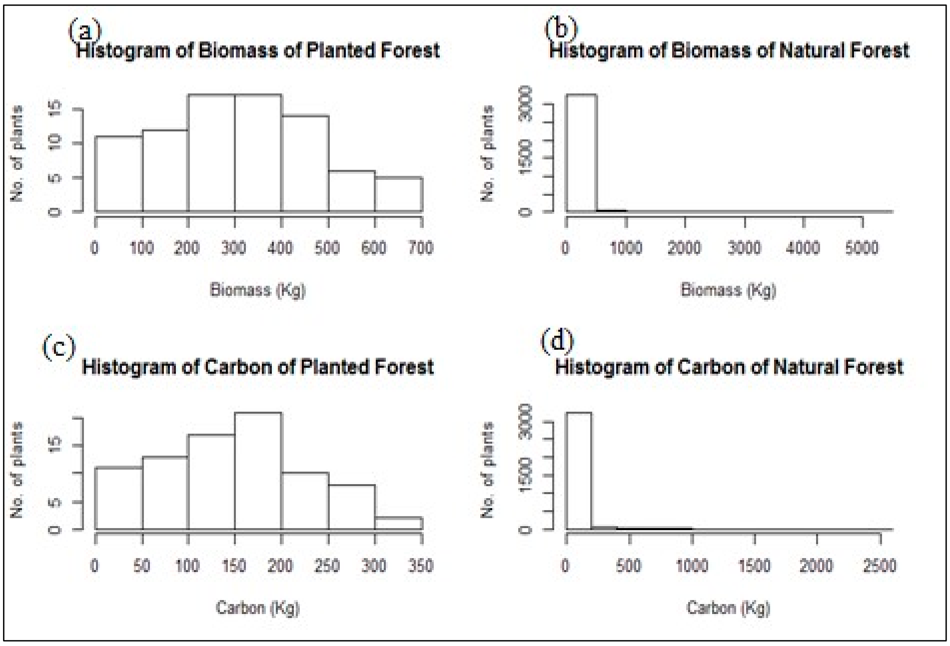

Figure 3. Biomass and carbon density distribution in planted Pine and natural mixed forests in the study area (almost unimodal distribution of biomass and carbon for plantation forest (**a**,**c**); the positively skewed distribution of biomass and carbon density for natural forest (**b**,**d**)).

The biomass (and biomass carbon) was concentrated on medium-sized trees in the case of plantation Pine forests, whereas smaller-sized trees composed the main weight of biomass for natural mixed forests (Figure 3).

3.3. Comparison Based on Predicted Biomass

The results show the mean age of the *Pinus* plantation was 24 years and the broadleaved was 16 years. The plantation forests had a higher MAI than the natural ones, and this will be higher than natural forests in the near future (Table 4).

Table 4. Comparison of predicted biomass.

S.N.	When	Mean Age of *Pinus*	*Pinus* Biomass (t/ha)	The Mean Age of Natural Forest	Natural Mixed Forest Biomass (t/ha)
1	Ten years ago	14	239.03	6	50.2
2	Five years ago	19	324.4	11	92.04
3	Field survey	24	409.76	16	133.87
4	After five years	29	495.13	21	175.7
5	After 10 years	34	580.49	26	217.54
6	After 15 years	39	665.86	31	259.37

The *Pinus* plantation stand exhibits significantly higher biomass production and increment compared to natural mixed forests. It is projected that the *Pinus* plantation forest will increase carbon stock by approximately three times more than natural mixed forest in the coming decades (Table 4). Observing cored samples, it was estimated that the approximate age of *Pinus* was around 24 years, ranging between 16 and 32 years. Similarly, the rate of stem diameter (tapering) decreased by a rate of 3 cm for each 100 cm height increment. Also, we analyzed the MAI of *Pinus*, which was found to be 15 kg per tree per year of biomass increment. Further, the details of stand structure, age, and homogeneity testing of the mean of the variables of the planted Pine forests are mentioned in Appendix A.

4. Discussion

Assessing forest structures and attributes is essential for sustainable forest management. Comparing forests based on their mode of regeneration under similar socio-environmental conditions offers pathways to optimize benefits for both people and the ecosystem. In summary, this study offers insights into managing both planted and natural forests to maximize societal and environmental benefits for Nepal and beyond.

4.1. Planted Pine Forest and Its Sustainability Perspective

Our findings reveal that despite their higher biomass and carbon sequestration, planted Pine forests exhibit unimodal stand structures, indicating a lack of age gradation. This undermines sustainable production, necessitating human interventions. Silvicultural practices like intermediate thinning, canopy opening, and promoting natural regeneration can enhance growth rates by reducing resource competition, facilitating recruitment, and tapping resin for additional economic returns. However, challenges such as the absence of natural regeneration, frequent fires, and the high risk of soil erosion limit the societal benefits of fuelwood, timber, and bedding materials, offering little support for plant and wildlife diversity, thus hindering the long-term sustainability of artificial forests.

Plantation forests initially exhibit higher biomass density and have the potential for greater carbon sequestration than natural forests in the short term (5 to 10 years) under various scenarios. However, the absence of regeneration in *Pinus* plantation areas suggests limited potential for long-term biomass increase, despite initial predictions. The mean stand age in our study was 24 years, with a recommended rotation period of 45 years for *P. roxburghii* [13]. However, to maximize product volume, final felling at 30–35 years is recommended for plantation areas in Nepal. Over time, the lack of regeneration and minimal undergrowth due to frequent fires, dense canopy cover, and acidic *Pinus* needles will further reduce the carbon sink potential in these forests. Intensive management practices such as canopy opening, thinning, pruning, needle collection, enrichment planting, and promoting natural seed germination are necessary to maintain a continuous forest structure. However, these forests may not achieve other ecosystem services. These findings are valuable for the 3% of planted forest area in Nepal [14] or the entire forest area in the country (44.74%) [17] and globally [8], contributing to sustainable forest management to ensure continuous ecosystem services.

The analysis reveals a bell-shaped distribution of DBH, total height, biomass, and age in the planted forest, indicating a dominant pole-size stand structure. This structural complexity highlights the forest's naturalness [55]. However, this unimodal structure suggests an unstable population, hindering long-term sustainability. In contrast, other forests in Nepal typically exhibit a reversed J-shape DBH distribution, indicating a continuous population structure [12,17]. This homogenous stand structure impedes regeneration and tree size diversity, compromising sustainability [7]. In plantation forests, biomass stock is expected to decrease significantly over time due to the bell-shaped DBH distribution and challenges such as minimal regeneration, acidic *Pinus* needles, and frequent fires hindering natural regeneration. Consequently, the future potential of *Pinus* plantations as carbon sinks diminishes. Similar findings from northeast India suggest higher biomass density in plantation forests compared to natural forests, attributed to uniform stand structure, fast-growing *Pinus* species, and management practices like pruning and thinning [35]. The higher biomass density in the plantation stand compared to the natural forests may be attributed to a more uniform stand structure resulting from site factors, species characteristics (fast-growing *Pinus*), and adapted management practices (such as pruning). Silvicultural management interventions are essential for intermittent material returns and economic benefits for forest-dependent communities. Intermediate thinning, for example, can enhance growth rates, carbon sequestration, latewood proportion, and ring average density [29]. Given the strong positive correlation between DBH and other variables, this unimodal distribution characterizes biomass and carbon in the study area. Forest management strategies must integrate the maintenance of crucial structural components and patterns into timber production to support biodiversity conservation and sustainable forestry [55].

The plantation stand is expected to have greater potential for carbon sequestration in the short term, assuming consistent conditions. However, factors such as the absence of natural regeneration, limited undergrowth due to frequent fires, dense canopy cover, and the acidic nature of Pinus needles hinder its long-term carbon sink potential. Intensive management practices like canopy opening, thinning, pruning, and needle removal are necessary for plantation stands to reduce the environmental risk including bushfires [27]. Despite these efforts, weaknesses in plantation forests may pose less concern for carbon emission reductions and Emissions Trading through mechanisms like REDD+ due to the need for long-term continuity and climate change mitigation [5,32,56]. This makes them a potentially low priority for the carbon market and REDD+ scenarios [2,37]. To qualify for this Emissions Trading (ET) mechanism, plantation forests, especially Pine, have two options: either convert to natural broadleaved forests in the next rotation period or maintain age (size) gradation through systematic planting at intervals or the promotion of natural regeneration of the same species through community-driven silvicultural operations [38].

Further, examining the tree rings in Pine trees provides an opportunity to assess past environmental catastrophes and improve future planning. Age assessment helps determine the rotation period of forest stands and identify significant environmental changes. Various types of false rings indicate major environmental disturbances [24,57]. However, our study did not find such false rings in *Pinus*. Verification with local elders during field visits confirmed that they had not experienced notable environmental adversities, such as prolonged drought or severe frost, in their lifetimes. Thus, periodic assessments of tree rings provide insights for environmental disaster planning [32] and are, therefore, suggested for future research as well.

4.2. Natural Mixed Forest and Its Sustainability Perspective

Unlike planted Pine forests, naturally regenerated forests demonstrate a gradual process of carbon capture (biomass generation), offering fewer immediate prospects for rapid economic transformation but providing significant social benefits. These benefits include fodder and fuelwood, grazing opportunities, less bushfire risk, and reduced soil erosion due to multistory canopy coverage and ground cover by ferns and grasses. Additionally, they provide poles for domestic use by local communities. Naturally regenerated forests exhibit a consistent age class distribution, minimal fire incidents, abundant regeneration, greater biodiversity, and lower regeneration costs. However, they still require some artificial intervention to optimize societal and environmental benefits, such as the potential of REDD+ for compensating improved forest management, biodiversity conservation, and reducing the gap in social demand for forest products and services.

From a biomass growth perspective, particularly in terms of greenhouse gas emissions and carbon sequestration, natural regenerated forests have a greater potential to sequester carbon due to the abundance of younger trees and natural regeneration, where good regeneration ensures the forest ecosystem's sustainability. Consistent with this finding, studies reported that old-growth forests have less potential for carbon sequestration as older trees cease to grow [8,58,59]. Beyond maturity, trees generally have marginal carbon sequestration capability [38,60]. However, small trees in naturally regenerated forests enhance future carbon stock due to their high sequestration potential [5,35]. Therefore, improved management practices are needed to maintain a fixed proportion of density or size classes, as suggested by past studies for both types of forests [13,61]. Community forests with many smaller trees can significantly reduce emissions, as these trees grow and add carbon as biomass. Simple management practices can maintain a balanced number of trees of different sizes, ensuring a perpetual carbon sink and sustainable material returns [38].

The stock number density is higher in natural forests than in plantation forests. Our regression analysis shows that biomass growth does not match estimates from allometric equations. The wide variation in structure and composition, higher plant density leading to resource competition, and the presence of slow-growing trees in natural forests contribute to lower biomass density. In contrast, naturally regenerated forests exhibit a slow and steady increase in biomass density, offering a high potential for carbon sequestration. These forests provide better options for sustainable forest management and maintain size gradations. They have greater coverage and lower regeneration costs, offering multiple benefits beyond carbon emission reduction through the Emissions Trading (ET) mechanism under REDD+ [5,60]. Numerous studies indicate that implementing REDD+ could provide crucial compensation to forest users for adopting improved management practices, either alone or with other economic incentives [37]. This approach would elevate REDD+ to a top priority for financing forest conservation and sustainable forest management in developing countries [59]. Considering the findings on carbon sequestration in soil, minimal disturbance to the forest soil and prevention of land-use changes are recommended.

Overall, our study aimed to estimate the age of forest stands, both naturally regenerated and artificially planted, to project time-based forest goods production for scenario planning. We collected data from two community-managed forests in the mid-hills of Nepal. However, we acknowledge limitations in comparing natural Pine forests with natural mixed forests across various geographical regions, which could be explored in future research. Additionally, we recognize the influence of local and indigenous preferences on species selection for both societal and commercial purposes, though our focus was primarily on the sustainability of forest stands. We assessed factors such as biomass production, age distribution, soil erosion, ground cover, risk of bushfires, and species diversity. Numerous other variables could be explored in future studies to compare planted and naturally regenerated forest stands from social, economic, and environmental perspectives. Nonetheless, our findings serve as a valuable reference for sustainable forest management planning and actions in these areas.

5. Conclusions

Assessing forest structure and attributes is crucial for sustainable forest management. Comparing forests based on their mode of regeneration under similar socio-environmental conditions offers pathways to optimize benefits for both people and the ecosystem. Our findings show that unimodal stand structures in planted Pine forests, despite higher biomass and carbon sequestration, indicate a lack of age gradation, compromising sustainable production and necessitating interventions like thinning, canopy opening, and promoting natural regeneration. Challenges such as the absence of natural regeneration, frequent fires, and soil erosion limit the long-term sustainability of these forests. Naturally regenerated forests, in contrast, provide gradual carbon capture and significant social benefits, including fodder, fuelwood, reduced fire risk, and less soil erosion due to diverse canopy coverage. These forests show a consistent age distribution, minimal fire incidents, abundant regeneration, greater biodiversity, and lower regeneration costs but still require moderate interventions to optimize benefits.

Further, our study is pioneering through the use of tree rings to assess biomass production and carbon accumulation in both planted and natural forests, offering critical insights for forest management. Age determination aids in rotation planning and environmental monitoring, with findings indicating stable conditions over time. The bell-shaped distribution in planted forests suggests unstable stand structures, requiring silvicultural interventions for sustainable management. Naturally regenerated stands demonstrate steady biomass progression, offering greater potential for sustainability. Mechanisms like REDD+ can provide monetary incentives for carbon enhancement without sacrificing other ecosystem services. These insights are valuable for policymakers aiming to optimize societal and environmental benefits through sustainable forest management, applicable to both artificially regenerated and naturally occurring forests worldwide.

Author Contributions: H.P.P. and S.P. conceived the study, designed the methodology, participated in data collection data analysis, and prepared the original draft. T.N.M. was involved in analysis, English checking, and supervision. All authors were involved in reviewing and editing the manuscript. All authors have read and agreed to the published version of the manuscript.

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Appendix A

Appendix A.1. Data Collection Sheet Used in the Study

Forest analysis form no.: ....
Analyzer: ....
Plot: .... m asl: .... Date: .... GPS: .... & .... Aspect: .... Slope: .... degree sign of wildlife: ....
% Trees: .... Bushes: .... herbs/ferns: .... grass: .... moss: ....
% Exposed soil: ....Litter: .... Rock: ....
Disturbance (0–3): Lopped: .... Cut: .... Droppings: ....

Local/Nepali name	Tree species (Latin name)	Basal Girth (at 15 cm)	Girth at Breast ht. (1.30 m)	H (height in m)	cut	1	2	3	4
Bushes species									
Climber species									

Seedling and sapling: species numbers in subplots

Local name	Latin name	Sub-plot 1		Sub-plot 2		Sub-plot 3		Sub-plot 4	
		seedling	sapling	seedling	sapling	seedling	sapling	seedling	sapling

Appendix A.2. Stand Structure of Pine Trees Selected for Coring

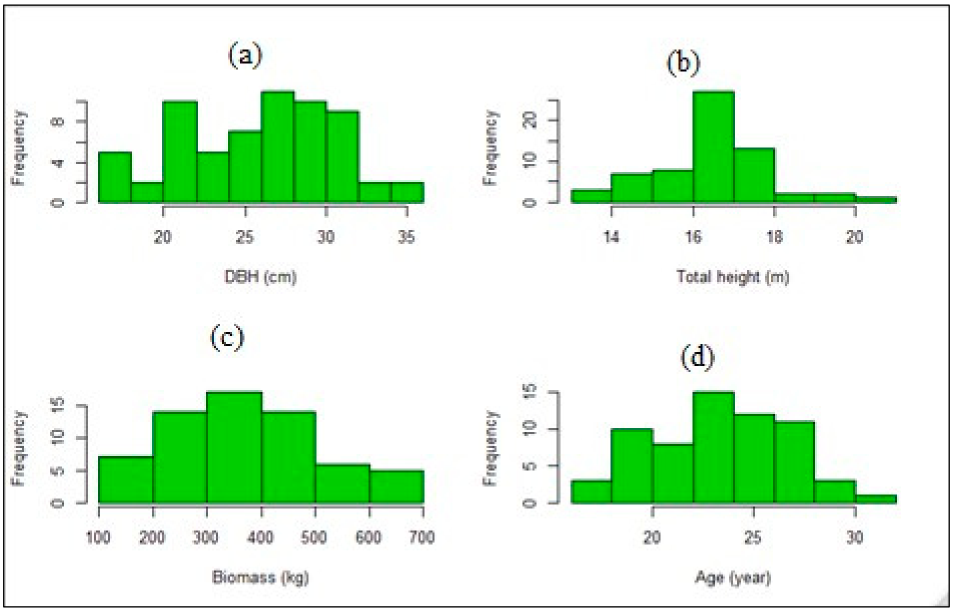

Figure A1. Bar graphs showing the stand structure of the *Pinus roxburghii* in the study area. (**a**) The DBH distribution; (**b**) the total height distribution; (**c**) the biomass distribution as predicted by Equation (1); and (**d**) age distribution.

Table A1. A homogeneity *t*-test of different variables of *Pinus* forest.

Variables	Mean Value	*p*-Value	Significance
DBH (cm)	25.78	$<2.2 \times 10^{-16}$	Yes
Height (m)	16.48	$<2.2 \times 10^{-16}$	Yes
Mean age (year)	23.97	$<2.2 \times 10^{-16}$	Yes
Biomass density estimated (kg/tree)	375.39	0.00027	Yes
Basal girth at 30 cm height (cm)	91.82	0.00027	Yes
Girth at breast height (cm)	80.99	$<2.2 \times 10^{-16}$	Yes
Carbon density conversion (t/ha)	176.43	0.00027	Yes

Appendix A.3. Correlation Test among Variables of Pine Forest

Table A2. The correlation between the variables using Karl Pearson's product–moment correlation test.

Variables	Correlation Coefficient (r)	*p*-Value	Significance
Age vs. DBH	0.68	1.2×10^{-9}	Yes
Age vs. Height	0.08	0.534	No
Age vs. Biomass	0.65	7.58×10^{-9}	Yes
Age vs. Volume	0.65	8.42×10^{-9}	Yes
DBH vs. Volume	0.97	2.2×10^{-16}	Yes
Height vs. Volume	0.36	0.003318	Yes
DBH vs. Height	0.14	0.279	No
DBH vs. Biomass	0.97	2.2×10^{-16}	Yes
Height vs. Biomass	0.36	0.0042	Yes
Basal girth vs. GBH	0.96	2.2×10^{-16}	Yes

Appendix A.4. Visual Relationship between the Variables of the Pine Forest in the Study Area

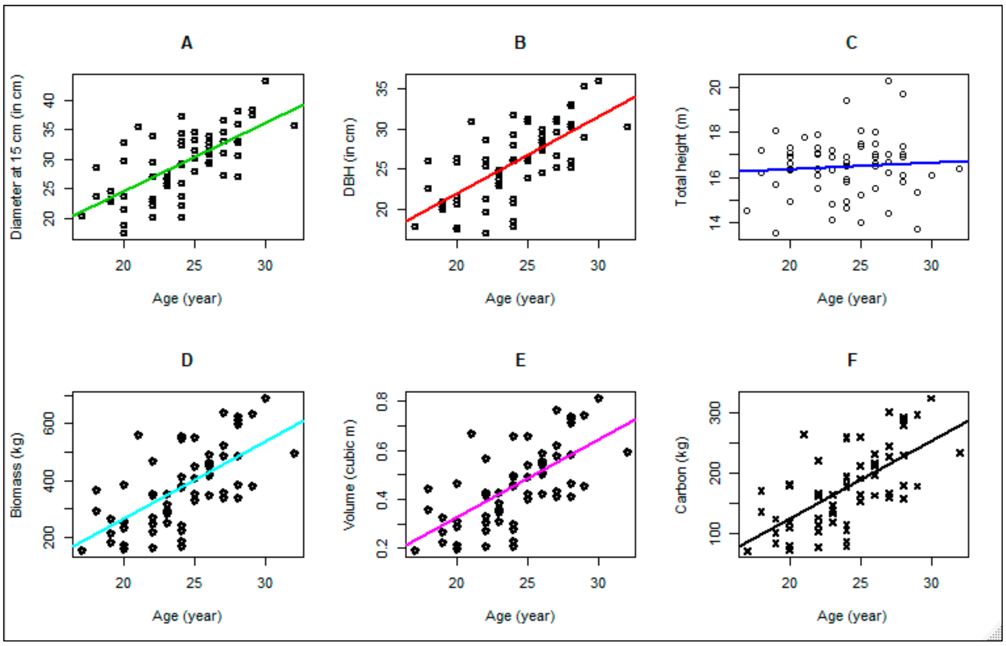

Figure A2. Relationship between various variables and the age of the *Pinus roxburghii* stands in the study area. (**A**) The relationship between age and diameter at 15 cm height; (**B**) the relationship between age and DBH; (**C**) the relationship between total height and age; (**D**) Equation (1) predicts the relationship between age and biomass; (**E**) the relationship between age and volume; and (**F**) the relationship between age and carbon predicted by Equation (1) and converted by the fraction of 0.47 of biomass.

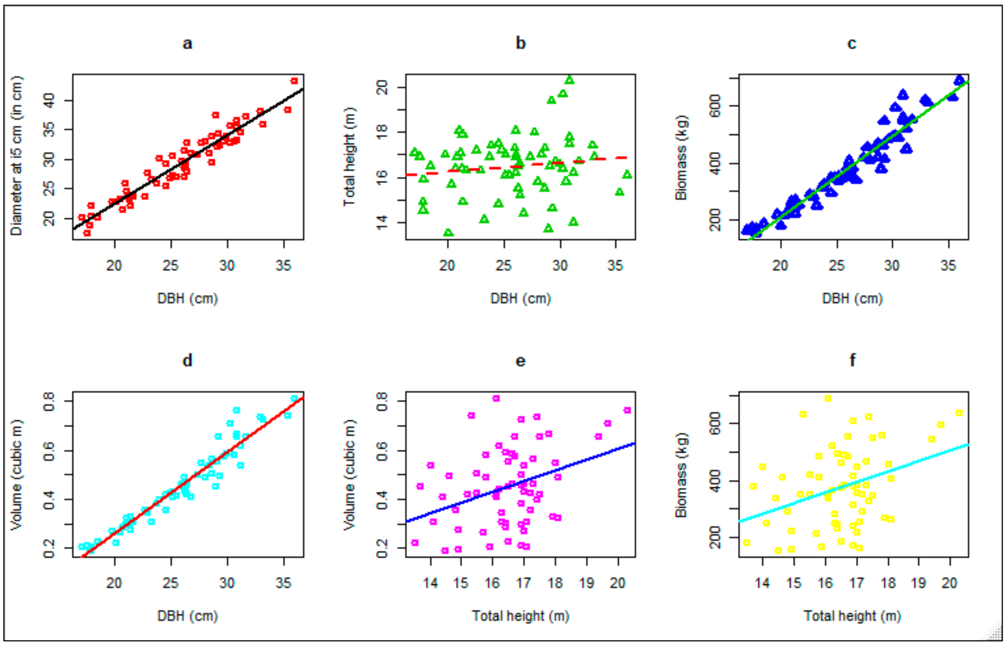

Figure A3. The graphical presentation and relationship between various variables of the *Pinus roxburghii* stand from the study area. (**a**) The relationship between DBH and diameter at 15 cm height; (**b**) the relationship between total height and DBH; (**c**) the relationship between DBH and biomass estimated by Equation (1); (**d**) the relationship between DBH and volume; (**e**) the relationship between total height and volume; and (**f**) the relationship between total height and biomass predicted by Equation (1).

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