forests

Article

Identification of Key Soil Quality Indicators for Predicting Mean Annual Increment in *Pinus patula* Forest Plantations in Tanzania

Joshua Maguzu [1,*], Salim M. Maliondo [1], Ilstedt Ulrik [2] and Josiah Zephaniah Katani [1]

[1] College of Forestry, Wildlife and Tourism, Sokoine University of Agriculture, Chuo Kikuu, Morogoro P.O. Box 3009, Tanzania; salim.maliondo@gmail.com (S.M.M.); josiahkatani@yahoo.com (J.Z.K.)
[2] Department of Forest Ecology and Management, Swedish University of Agricultural Sciences, Skogsmarksgränd, SE-901 83 Umeå, Sweden; ulrik.ilstedt@slu.se
* Correspondence: joshua.maguzu@tafori.or.tz

Abstract: There is an unexplored knowledge gap regarding the relationship between soil quality and mean annual increment (MAI) in forest plantations in Tanzania. Therefore, this study aimed to identify soil quality indicators and their impact on the mean annual increment (MAI) of *Pinus patula* at Sao Hill (SHFP) and Shume forest plantations (SFP) in Tanzania. The forests were stratified into four site classes based on management records. Tree growth data were collected from 3 quadrat plots at each site, resulting in 12 plots in each plantation, while soil samples were taken from 0 to 40 cm soil depth. Analysis of variance examined the variation in soil quality indicators between site classes at two *P. patula* plantation sites. Covariance analysis assessed the differences in MAI and stand variables across various site classes, taking into account the differing ages of some stands, with stand age serving as a covariate. Linear regression models explored the relationship between soil quality indicators and MAI, while partial least squares regression predicted MAI using soil quality indicators. The results showed that, at SHFP, sand, organic carbon (OC), cation exchange capacity, calcium (Ca), magnesium (Mg), and available P varied significantly between site classes, while silt, clay, and available P varied significantly at SFP. At SHFP, sand and clay content were positively correlated with MAI, while at SFP, silt content, available P (Avail P), potassium (K), Ca, and Mg showed significant positive correlations. Soil quality indicators, including physical and chemical properties (porosity, clay percentages, sand content, and OC) and only chemical (K, Mg, Avail P, and soil pH) properties were better predictors of the forest mean annual increment at SHFP and SFP, respectively. This study underscores the importance of monitoring the quality of soils in enhancing MAI and developing soil management strategies for long-term sustainability in forests production.

Keywords: soil quality indicators; mean annual increment; forest productivity; site classes; partial least square regression; variable important projection

check for updates

Citation: Maguzu, J.; Maliondo, S.M.; Ulrik, I.; Katani, J.Z. Identification of Key Soil Quality Indicators for Predicting Mean Annual Increment in *Pinus patula* Forest Plantations in Tanzania. *Forests* **2024**, *15*, 2042. https://doi.org/10.3390/f15112042

Academic Editors: Milton Cesar Costa Campos, Flavio Pereira de Oliveira and Bruno Campos Mantovanelli

Received: 9 October 2024
Revised: 28 October 2024
Accepted: 4 November 2024
Published: 19 November 2024

1. Introduction

Forests are a critical component of the global ecosystem, playing a significant role in mitigating the effects of climate change, sustaining biodiversity, and providing livelihoods to millions of people worldwide [1,2]. There is a growing interest in forest plantations to meet the increasing global demand for timber products [3]. In 2020, forest plantations covered approximately 293 million hectares worldwide, representing an increase of 2.4 million hectares from 2015 [4]. The role of forest plantations in meeting the global demand for timber products underscores the importance of understanding the relationship between soil quality and forest productivity, which varies widely across different regions [5]. *Pinus patula's* adaptability to diverse ecological conditions allows it to occupy over 60% of the total area planted, while the remaining area is shared among hardwoods and other softwood species. This tree's economic significance as a source of timber and pulpwood highlights its importance in Tanzania's forestry landscape [6]. Ongoing research aims to improve management practices to ensure the sustainable use of this valuable resource. Productive soils are essential and should be managed to enhance forest productivity and ecosystem services and aid in mitigating climate change through carbon sequestration [7]. The recent interest in using forest biomass for energy production and restoration of forests severely affected by drought or insects [8] further highlights the need to understand the importance of soil quality to forest productivity.

Soil quality is characterized as "the ability of soil to function within the boundaries of an ecosystem to support biological productivity, uphold environmental quality, and enhance the health of plants and animals" [9]. The relationship between soil quality and forest productivity is influenced by intricate interactions among the soil's physical and chemical characteristics and various external natural factors [7,10]. Generally, the quality of forest soil improves its capacity for water retention, carbon (C) sequestration, and plant productivity [11]. To ensure the sustainability of forest ecosystems, it is essential to maintain soil quality, particularly regarding nutrient levels and the organic matter content of mineral soils [12].

The literature extensively discusses the connection between soil quality and Mean Annual Increment (MAI). It stresses the importance of soil quality in sustaining plant productivity and environmental health, both of which significantly impact crop outputs, including MAI [13]. Various studies have demonstrated that high-quality soil, which encompasses factors like soil fertility and moisture availability, can significantly affect MAI in forest plantations. A study by Sariyildiz et al. [14] revealed that soil quality plays a vital role in determining the growth and yield of commercial forest plantations. Similarly, a recent study by Li et al. [15] underscored the importance of soil nutrients and water-holding capacity for the growth of forest trees. Furthermore, a study by Wang et al. [16] conducted in China discovered that soil organic matter content, total nitrogen, and Avail P were positively associated with the wood production of Masson pine plantations. Likewise, a study by Piotto et al. [17] in Costa Rica found that soil organic matter content and Avail P were positively correlated with the production in teak plantations. Schoenholtz et al. [11] analyzed how the physical and chemical properties of soils can be utilized to evaluate the quality of forest sites. They identified organic matter, total nitrogen, phosphorus availability, pH, texture, and soil depth as key factors for assessing forest soil quality. These studies have demonstrated that soil quality significantly influences forest MAI. Given the importance of soil quality on MAI, it is essential to comprehend the factors that impact soil quality and their effect on commercial forest plantations in Tanzania.

Despite the significant role that soil quality plays in forest MAI, there is still a knowledge gap in understanding the relationship between soil quality and MAI in Tanzanian forest plantations. By viewing soil quality as a comprehensive measure that encompasses both physical and chemical properties, investigating the connection between soil quality and forest MAI could provide insights into the ecological mechanisms that govern plant-soil interactions. Understanding this relationship is essential for promoting sustainable forest management and facilitating tailored management practices that preserve the site's productivity [18]. We, therefore, aimed to (i) examine the variation in soil quality indicators between site classes at two *P. patula* plantations sites; (ii) assess the variability of mean annual increment and other stand attributes between site classes; and (iii) identify the principal relations between the soil quality and mean annual increment (iv) predict forest mean annual increment using soil quality indicators.

2. Material and Method

2.1. Description of the Study Areas

This study was carried out in Tanzania, focusing on two representative forest plantations: Sao Hill Forest Plantation (SHFP) in the southwestern highlands and Shume Forest Plantations (SFP) in the northeastern highlands (Figure 1). SHFP is situated between latitudes 8°18′ and 8°33′ S and longitudes 35°6′ and 35°20′ E in the Iringa Region, with an elevation ranging from 1400 to 2000 m above sea level, averaging 1634 m above sea level.

The region experiences mean annual rainfall between 750 and 2010 mm, predominantly from November to April, and temperatures ranging from 15 to 25 °C annually [6]. The total area of SHFP is 135,903 hectares, of which 86,003 hectares are designated for commercial tree planting, while 48,200 hectares are preserved for natural forest, river valleys, and potential future expansion [19].

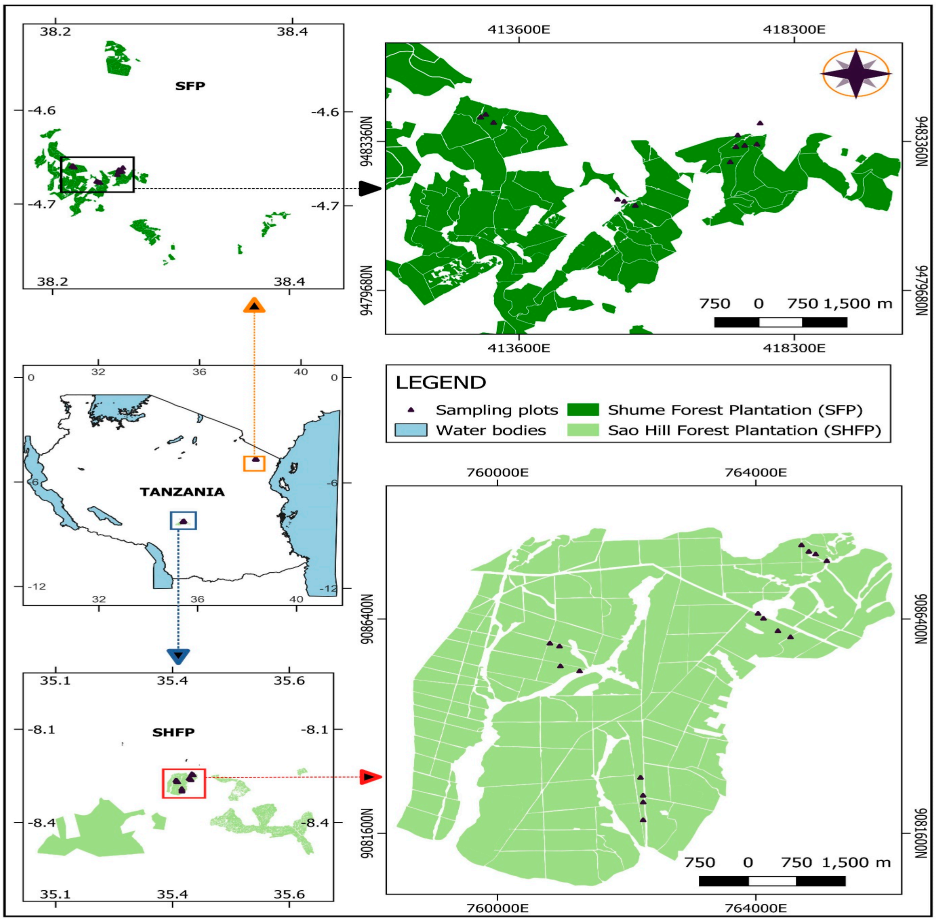

Figure 1. Locations of soil sampling plots at Sao Hill and Shume Forest Plantations in Tanzania.

Shume Forest Plantation is situated in the western part of the Usambara Mountains within the Lushoto district of the Tanga region. The coordinates for this area are 04°40′ S and 38°15′ E, with an elevation ranging from 1650 to 2120 m above sea level [20]. It experiences two rainy seasons, occurring from September to November and from March to April, with average annual rainfall between 800 mm and 2000 mm, and temperatures ranging from 16 °C to 22 °C [21]. There is also a minor and inconsistent rainfall period (Mluwati) that sometimes occurs in August and September. The total area of the plantation spans approximately 4863 hectares.

The study utilized a stratified experimental design in which each plantation was stratified into four site classes (SC) (I, II, III, and IV) based on forest management records and area coverage. Quadrat plots with an area of 20 m × 20 m were established in each site class at SHFP and SFP along the soil catena. A total of 24 replicates (plots) were assessed at both SHFP and SFP, with 869 individual trees measured at SHFP and 544 at SFP for tree growth analysis. Within each plot, the diameter at breast height (DBH) of all trees was recorded. To estimate the height of other trees in each site class, six trees per plot were selected based on size (smallest, medium, and largest DBH) and measured for height. Additionally, the five tallest trees in each plot were measured to determine the dominant height (Hdom) for both locations. Measurements of tree DBH and height were conducted using a vernier caliper and a vertex, respectively. Physiographic characteristics of each sample plot, such as slope percentage and elevation, were also recorded. Slope percentages were determined at the four corners of each plot using a clinometer, and the average values were calculated. Slope positions were identified by examining contour lines, and elevations were documented with a Garmin GPSMAP 65 Series device.

2.2. Soil Sampling and Determination of Physical and Chemical Factors

Soil sampling was carried out at three 20 m × 20 m quadrat plots in each site class, positioned along the soil catena based on slope position (i.e., summit, mid, and lower slopes), resulting in 12 sampling plots with 24 soil samples for each studied site. Undisturbed soil samples were obtained using a core cylinder of a specified volume, while loose soil samples were gathered with a soil auger at depths of 0–20 cm and 20–40 cm, taken from five distinct points within each plot. The depth of the soil measured is linked to nutrient capacity and the availability of water for plants, as well as influencing biological activity [22]. Loose soil samples from each sampling depth were combined to make one composite sample. Particle size distribution test was carried out using the hydrometer method [23], the bulk density was determined by the core method [24], and the porosity was determined by assuming the soil particle density of 2.65 g/cm^3 [25]. The pH (1 M $CaCl_2$) in a soil at a solution ratio 1:2.5 was measured by glass electrode method. Organic carbon (OC) was determined using Walkley-Black chemical oxidation procedures [26]. Total nitrogen was determined by micro-Kjeldahl digestion distillation methods [27] while available phosphorus (avail P) was extracted by the Bray 1 method [28]. The cation exchange capacity (CEC) was determined using the 1 mol/L NH4OAc (pH 7.0) exchange method, followed by the leaching of ammonia (NH_3) with KCl and measured using a flame-photometer device. The concentration of soil exchangeable bases (Ca and Mg) was determined by atomic absorption spectrophotometry (Richmond Scientific, Richmond, UK, ICE Series 3500), while potassium (K) was measured by flame emission spectrophotometer. In general, analyzed laboratory composite samples from 0–20 and 0–40 cm topsoil layers were taken for statistical analysis.

2.3. Statistical Analysis

The measured height of dominant trees (Hdom) in each plot affected the site classification, as indicated in the forest management records. At SHFP, only site classes II, III, and IV were present, while site classes I, II, and III were found at SFP. We conducted an Analysis of Variance (ANOVA) to examine the variation in soil quality indicators between site classes at two *P. patula* plantations. Additionally, we utilized Covariance Analysis (ANCOVA) to assess differences in mean annual increment and stand variables across various site classes, taking into account the differing ages of some stands, with stand age serving as a covariate. When significant differences were identified, we applied Tukey's post-hoc test to determine which means were significantly different ($p \leq 0.05$). To investigate the potential linear relationship between soil quality indicators and mean annual increment, we employed linear regression analysis, aiming to understand how comprehensive soil quality indicators influence forest mean annual increment. Furthermore, we implemented partial least squares regression (PLSR) to tackle multicollinearity issues [29] while predicting mean annual increment (MAI) [30]. To identify the most effective predictors of MAI, we utilized the variable importance for projection (VIP) statistic [31], excluding predictor variables with VIP values less than 1 from the model. All statistical analyses were carried out using R software version 4.3.3 (R Core Team, 2024)—manufacturers, suppliers, and software companies located in the United States in various cities, including New York City, Boston (Massachusetts), and Seattle (Washington).

3. Results

3.1. Variation of Soil Physical Properties in Different Site Classes at SHFP and SFP

The results showed a difference in sand content among the various site classes at SHFP, with SCIV having a notably higher sand content. In contrast, no significant differences were observed in silt and clay content. The soil textures were classified as loamy for SCII and

SCIII, while SCIV was identified as sandy loamy. At SFP, however, significant differences were noted in both silt and clay content among the site classes, with SCIII exhibiting a considerably higher silt content and SCIV containing more clay. Sand content, on the other hand, did not show significant variation in this area. The soil textures were loamy for SC I and II, while SC III was characterized as silt loamy. (Figure 2). Moreover, results also did not show significant variation in BD values and soil porosity between site classes at SHFP and SFP. However, relatively high BD with lower porosity was observed in SC II at SHFP and SFP (Figure 2).

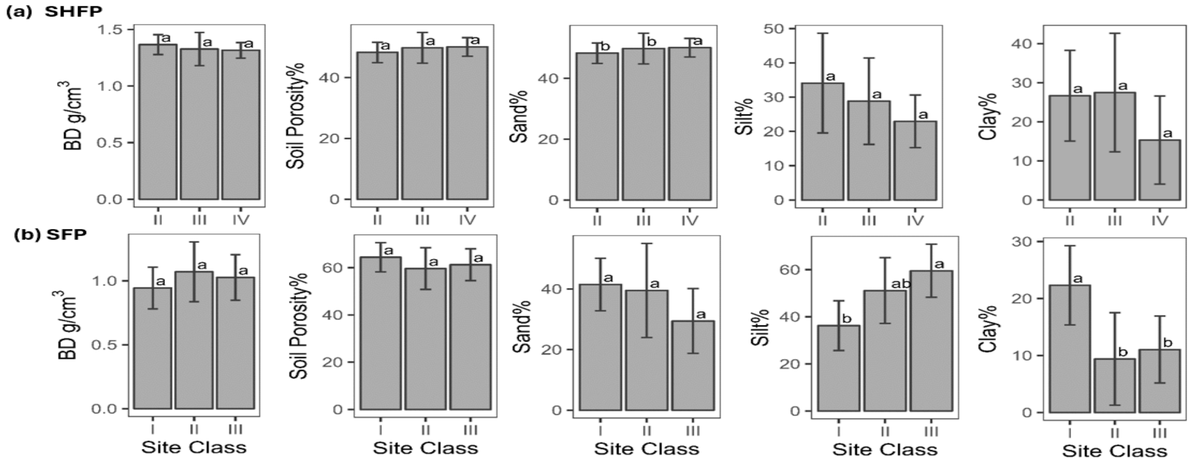

Figure 2. Variation of soil physical properties among the site classes. Plotted above the error line, distinct lowercase letters signify significant differences among site classes at Sao Hill and Shume Forest Plantations.

3.2. Variation of Soil Chemical Properties in Different Site Classes at SHFP and SFP

The results indicated significant differences in OC, Avail P, CEC, Ca, and Mg between site classes at the SHFP with only Avail P showing differences at SFP (Figure 3). Notably, SCIV exhibited significantly higher levels of OC, Ca, and Mg at SHFP. Additionally, nitrogen (N), CEC, and potassium (K) were relatively higher at Site SCIII while Avail P was higher at SCII. Meanwhile, SCI showed significantly higher levels of OC, Avail P, N, and K at SFP, while CEC, Ca, and Mg were elevated at SCIII (Figure 3). Moreover, no significant variation was observed in pH level between site classes, but SCIV and II exhibited lower levels pH at SHFP and SFP, respectively.

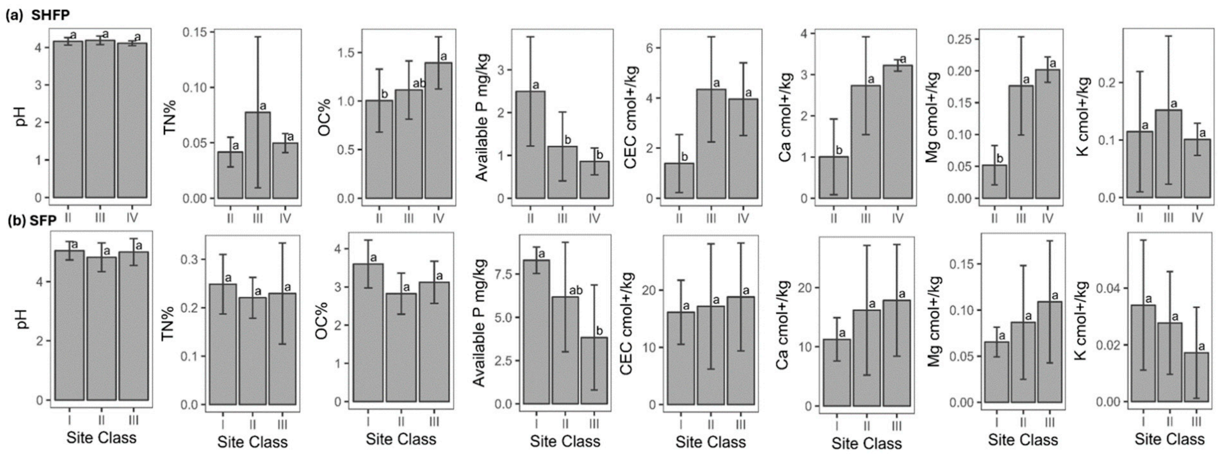

Figure 3. Variation of soil chemical properties among the site classes. Plotted above the error line, distinct lowercase letters signify significant differences among site classes at Sao Hill and Shume Forest Plantations in Tanzania.

3.3. Distribution Characteristics of Mean Annual Increment and Other Stand Attributes in the Site Classes at SHFP and SFP

Results of the analysis of covariance showed that the mean annual increment and stand variables at site classes (SC) II and III were comparable and higher than those at SCIV at SHFP (Figure 4). At SFP, the results revealed significant differences in mean annual increment among the different site classes. The dominant height at SHFP was notably greater in SCII and III, while at SFP, it was notably higher in SCI and II (Figure 4).

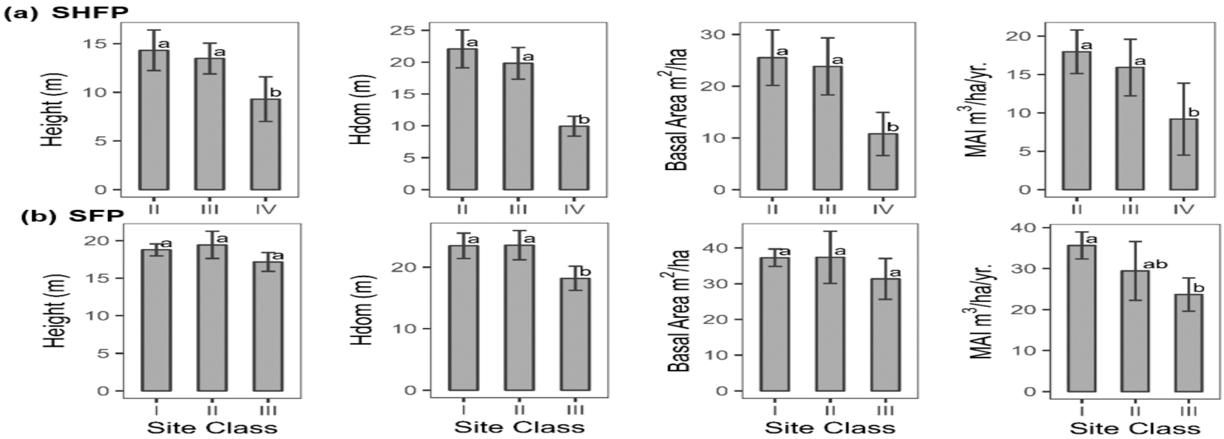

Figure 4. Distribution difference of mean annual increment and other stand attributes in different site classes. Above the error line, different small letters indicate that there are significant differences among different site classes.

3.4. Coupling Relationship Between the Soil Quality Indicators and Mean Annual Increment SHFP and SFP

The determined forest productivity, as MAI (Figure 4a,b), was ultimately used for linear regression analysis with soil quality indicators. Significant correlations between the soil quality indicators and MAI were observed. For example, at SHFP, sand and clay content were significantly correlated with MAI (Figure 5a), while at SFP, silt content, avail P, K, Ca, and Mg were significantly correlated with MAI (Figures 5b and 6b).

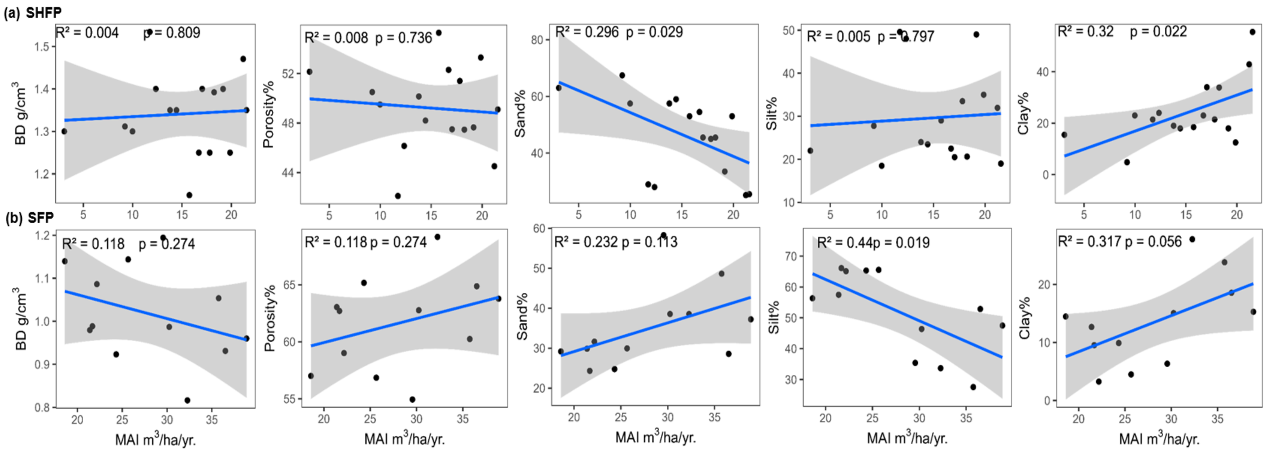

Figure 5. Illustrates the correlations between soil physical properties and mean annual increment. The fitted linear relationships reflect the potential relationship of MAI-physical properties interactions at Sao Hill and Shume Forest Plantations in Tanzania.

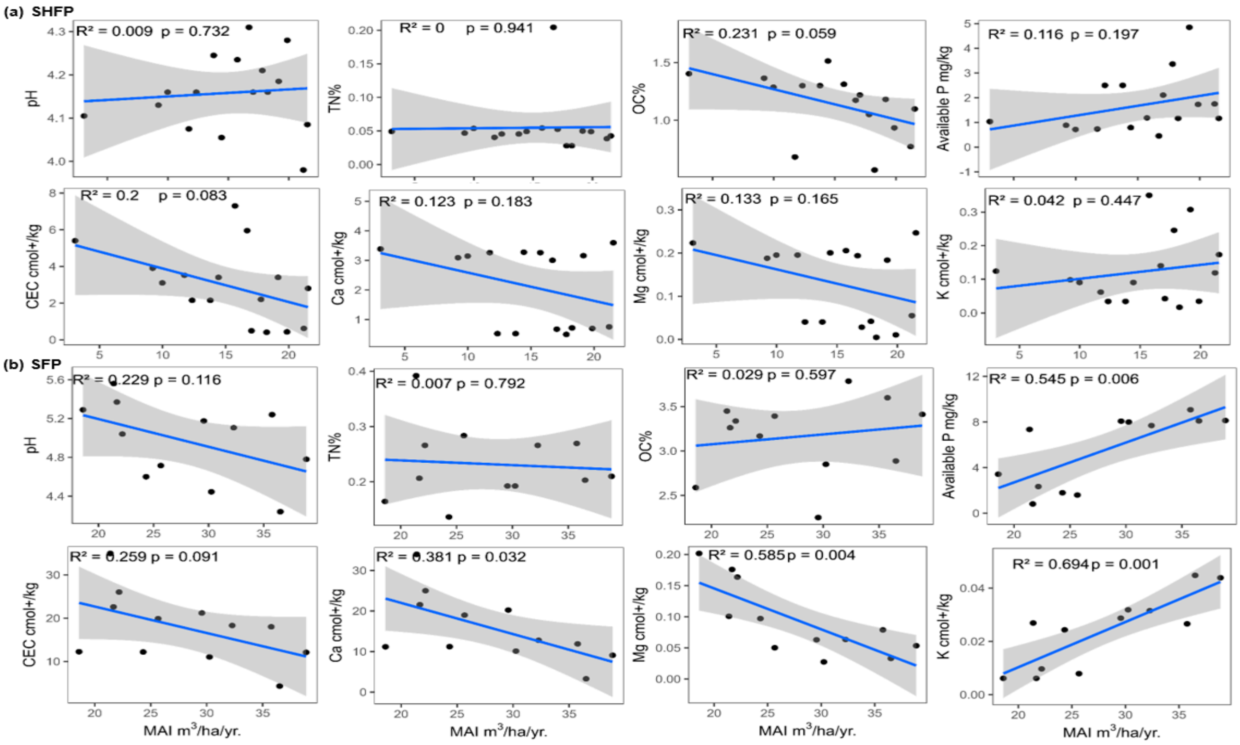

Figure 6. Illustrates the correlations between soil chemical properties and mean annual increment. The fitted linear relationships reflect the potential relationship of MAI-chemical properties interactions at Sao Hill and Shume Forest Plantations in Tanzania.

3.5. Prediction of Forest Mean Annual Increment Using Soil Quality Indicators at SHFP and SFP

We used partial least squares analysis of which both the chemical and physical properties of the soil were utilized as independent variables to predict MAI. We conducted a thorough examination of all possible combinations of soil variables to determine the most effective predictors for MAI. The resulting coefficients of variation (R^2), root mean square error (RMSE), and slope were employed to assess the candidate model and identify the optimal regressor variables (Table 1). Predictor variables with VIP values < 1 were excluded from the model to prevent overfitting and to address potential outliers. After calibrating the best candidate model, we checked for distance and possible outliers using k-fold cross-validation with a classical approach. The results indicated that the soil quality indicators, including soil porosity, clay, OC, sand, and CEC, along with K, Mg, Avail P, and soil pH, each demonstrated VIP > 1 in the partial least squares regression (PLSR) analysis for both SHFP and SFP (Table 1). When PLSR was carried out using these variables, the cumulative percentages of variance in MAI and predictor variables were (50.2 and 82%) and (92.8 and 90.1%) at SHFP and SFP, respectively. The PLSR coefficients and the goodness-of-fit statistics indicate that the model was well-fitted (Table 2).

Table 1. VIP values for the candidate soil variables in different stages of PLSR analysis for estimation of MAI of *Pinus patula* at Sao Hill and Shume Forest Plantations in Tanzania.

Site		BD	Porosity	SAND	SILT	CLAY	pH	TN	OC	AvP	CEC	Ca	Mg	K	SQI
SHFP	Stage1	0.15	0.37	1.30	0.60	1.81	0.23	1.15	1.22	1.07	1.19	1.06	0.97	0.61	0.82
	Stage2	0.00	2.25	1.26	0.00	2.02	0.00	0.00	1.32	0.00	1.24	0.00	0.00	0.00	0.00
SFP	Stage1	0.95	0.95	0.45	0.87	0.79	1.04	0.53	0.53	1.51	0.65	0.79	1.53	1.78	0.37
	Stage2	0.00	0.00	0.00	0.00	0.00	1.31	0.00	0.00	1.89	0.00	0.00	1.93	2.23	0.00

Table 2. PLSR regression statistics model based on PLS scores, coefficients of determination (R^2), root mean square error of prediction (RMSEP) for all data, and regression slope.

Site		X-Score	Y-Score	R^2	RMSE	Slope	Bias	RPD
SHFP	Calibration	82.9	50.2	0.937	1.092	0.937	0.0000	4.21
	Validation			0.675	2.482	0.882	−0.2145	1.86
SFP	Calibration	90.1	92.8	0.928	1.878	0.928	0.0000	4.09
	Validation			0.877	2.459	0.796	0.8732	3.34

4. Discussion

The present study's results showed significant differences in sand content at SHFP. This is consistent with the findings of Atwell et al. [32], who noted significant variations in sand content across different sites within the plantation, which were attributed to various environmental factors, including microclimate conditions. According to Zhang et al. [33], variations in soil texture, particularly in sand content, impact vegetation growth, ecosystem health, and productivity. Furthermore, there were significant variations in silt and clay content between different site classes at SFP, which contradicts the findings of Leopold et al. [34], who reported no changes in soil texture including silt and clay content across different sites. This trend did not align with the observations of various other studies which indicated that soil texture exhibits temporal and spatial variations within forest plantations [35,36]. Among the evaluated physical soil quality indicators, bulk density (BD) is considered a key factor in soil quality control, relating to porosity, soil moisture availability, hydraulic conductivity, and soil compaction, having indirect effects on root growth and crop yield [37,38]. Our study found only higher BD in SCII for both SHFP and SFP (Figure 2). The high bulk density and low porosity observed in site class II suggest that these site classes have faced challenges related to soil compaction, which could affect plant growth and ecosystem function. This finding is supported by studies of Ahukaemere et al. [39] and Awdenegest et al. [40], who observed a similar increase in BD across different sites in forest plantations in Nigeria and Ethiopia. The higher BD has been attributed to continuous cultivation and other agricultural practices, which negatively impacts soil quality and fertility in the studied regions. The elevated BD values identified in the study fall within the optimal range, indicating favorable soil conditions for forest production. This observation is in line with the findings of Wander et al. [41], who suggested that a BD value of <1.2 g cm^{-3} and a porosity range of 40% to 60% are indicative of good soil quality for production. We recorded low BD and high total porosity values at SCIV and SCIII at SHFP and SCI and SCIII at SFP, consistent with the findings of Amacher et al. [42], who associated low BD and high porosity values have been attributed by the distribution of soil organic materials. Additionally, Shah et al. [43] reported that loose topsoil tends to have lower BD compared to compact subsoil.

The pH level of the soil has a significant impact on controlling soil biogeochemical processes, which in turn affects the stability of soil ecosystem structure and function [44]. Our findings indicate that the pH values ranged from 3.9–4.3 and 4.2–5.6 for SHFP and SFP, respectively, which are <7, indicating strong acidity due to the high organic matter content in the soil [45]. Interestingly, there were no significant differences in pH among the site classes in both study sites. However, we noticed that SCII and SCIII at the SHFP and SCI and SCIII at SFP had a slightly higher pH, which indicates rapid decomposition of litter that releases basic cations, thereby reducing soil acidity [46]. It is worth noting that soil pH not only impacts chemical reactions between water and soil minerals but also influences the availability of various soil indicators, such as nutrient availability [47]. Furthermore, we found significant differences in organic carbon (OC), cation exchange capacity (CEC), Ca, Mg, and Avail P between site classes at SHFP, while only Avail P showed significant differences between site classes at SFP. The higher exchangeable base cations (Ca and Mg) at SCIV and CEC at SCIII in SHFP and higher exchangeable base cations (Ca and Mg) and CEC at SCIII in SFP were attributed to the content of organic matter that releases significant amounts of exchangeable cations [48]. The higher CEC also provides a more remarkable ability to retain water and nutrients for plant growth [49]. The study sites exhibited limited Avail P levels in the site classes of both plantations, as resulted from the high levels of Avail P being taken up by plants and stored in the tree biomass [50]. According to Landon [51], Avail P > 50 mg/kg is classified as high, 15–50 mg/kg as medium, and <15 mg/kg as low. The availability of P reduces is influenced by annual litter input and soil organic matter [52]. The higher availability of P can also be attributed to a higher organic matter content [53]. Consistent with previous research, we noticed higher concentrations of soil organic carbon (SOC) in SCIV at SHFP and SCI at SFP for the topsoils [54,55]. Parihar et al. [56] also noted that subsoil has low SOC. The lower SOC to other site classes is attributed to the buildup and formation of organic material and humus, as well as the higher turnover of above and below-ground biomass [57–59]. SOC plays a crucial role in soil chemical properties and is considered an essential factor for evaluating soil quality in sustainable forest management [60].

Regarding the distribution characteristics of mean annual increment and other stand attributes in our study in SHFP, it was observed that site classes (SC)II and III showed similar and higher values compared to SCIV (Figure 4). In the case of SFP, our findings showed significant variation in mean annual increment among different site classes. Unlike in SHFP, the dominant height (Hdom) in SFP was notably greater in site classes I and II (Figure 4). These disparities in forest mean annual increment and stand variables are influenced by a combination of factors, such as soil quality, including fertility and moisture availability, as discussed by Pretzsch et al. [61]; Toïgo et al. [62]; and Forrester and Bauhus [63], as well as management practices and environmental factors such as light availability and microclimate conditions, as highlighted by Skovsgaard and Vanclay [64].

By assessing the relationship between soil quality indicators and mean annual increment we found that at SHFP, sand and clay content was significantly correlated with MAI (Figure 4a). The significant correlations found between soil clay content and MAI demonstrate the importance of clay in storing OC and nutrients in tropical forest soils [65]. Implementing management practices can significantly mitigate the adverse effects associated with high sand content or low silt/clay levels, leading to improved soil health and forest productivity in affected areas [66]. Meanwhile, SFP silt content and soil nutrients (avail P, K, Ca, and Mg) significantly correlated with MAI. Contrary to Clark et al. [67] who reported that soil nutrient content did not show a significant relationship with forest mean annual increment, similar to what was observed by Oberleitner et al. [68] in measurements of an increase in wood above ground biomass in forests plantations of Costa Rica. Soil quality indicators, primarily physical and chemical properties, can have a direct or indirect impact on forest yield [69]. Shao et al. [70] assessed soil quality under different forest types in China and found that soil indicators like soil texture, bulk density, organic carbon, and nutrient levels varied significantly and positively correlated with the growth of the forest stands. Soil indicators play a role in the exchange and circulation of materials and energy in terrestrial ecosystems, supplying essential water and nutrients for the growth of aboveground vegetation and creating favorable habitat conditions, ultimately affecting forest wood production [71]. The study suggests that soil quality indicators can be considered a primary factor in sustainable forestry management, as they are closely associated with forest mean annual increment and growth rates.

Our model using Partial Least Squares Regression (PLSR) to predict MAI from soil quality indicators, with VIP > 1 as the selection criterion for SHFP and SFP, revealed that porosity, clay percentages, OC, sand content, and CEC were significant predictors at SHFP. The impact of porosity on the average annual growth of forests is consistent with the findings of Luna et al. [72], who observed that higher porosity in soils aids in the movement of soil water, exchange of soil gases, and retention of soil nutrients, which ultimately affects plant growth. The composition of the soil is a critical factor in predicting the amount of aboveground forest production [73]. Studies by Albaugh et al. [74] and Carlson et al. [75] found that sand soils are less fertile than clay soils in southeastern U.S. forests, supporting our negative correlations between MAI and sand percentages. Higher OC leads to higher CEC, enhancing soil fertility and forest productivity in SHFP. This result is consistent with Wu et al. [49], who found that soils with high CEC have high water-holding capacity, benefiting plant growth and, thus, mean annual increment. However, K, Mg, Avail P, and soil pH were significant at a VIP level of >1 for SFP. We found that MAI can be influenced by the availability of K at SFP. For example, more generally, the K nutritional status in the soil impacts phloem sap mobility [76]. The ability of Mg to predict MAI is higher, suggesting that Mg plays a crucial role as a macronutrient in enhancing the chlorophyll molecule involved in photosynthetic processes [77,78]. Richter et al. [79] also reported a similar discovery, explaining that Mg limits the mean annual increment of loblolly pine. They found that after 28 years of forest development, the depletion of Mg from the upper layer of the soil was nearly higher than that of K in loblolly pine planted on an old field in South Carolina. Our research also highlights Avail P as a crucial macronutrient that influences forest mean annual increment, as noted by Zeng et al. [80] and Bai et al. [81]. Previous studies have indicated that Avail P is the primary limiting factor for tree growth, negatively impacting root growth and soil microorganisms. Consequently, increasing the application of P fertilizer can effectively enhance stand growth. Cunha et al. [82] and Manu et al. [83] also support these findings, reporting that Avail P is generally seen as the most limiting element in optimizing forest mean annual increment across various forest types globally.

5. Conclusions

The study found significant variations in soil quality indicators such as sand, OC, CEC, Ca, Mg, and avail P between in the site classes at SHFP, while silt, clay and avail P varied between site classes at SFP. Moreover, the study revealed that at SHFP, site classes II and III exhibited similar and higher forest mean annual increments than site IV, while SFP displayed a more pronounced variation in MAI between site classes, with Hdom being higher in site classes I and II. In general, soil texture, mainly sand and clay content, significantly correlated with MAI at SHFP, while silt content and available nutrients (Avail P, K, Ca, and Mg) demonstrated significant correlations with MAI at SFP. The study's findings further highlight that physical and chemical properties (porosity, clay percentages, sand content, and OC) and only chemical properties (K, Mg, Avail P, and soil pH) are most crucial in predicting MAI at SHFP and SFP, respectively. By understanding the link between soil quality indicators and forest growth, forest managers can make informed decisions regarding species selection and silvicultural practices to optimize forest mean annul increment and sustainability.

Author Contributions: Data collection, data curation, formal analysis, methodology, writing original draft and writing—review & editing J.M. Conceptualization, Data curation, methodology, writing-revision and editing of the main manuscript I.U. and J.Z.K.; and conceptualization, data curation, methodology, writing—review & editing the manuscript, S.M.M. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by Swedish International Development Agency (SIDA) Grant Number 13394.

Data Availability Statement: Data will be made available on request.

Acknowledgments: The authors thank the Swedish International Development Agency (SIDA) (Grant Number 13394) for their generous financial support through the REFOREST Programme, coordinated by the esteemed Sokoine University of Agriculture (SUA). This funding was instrumental in facilitating the soil survey and sample collection in our study areas. The authors also extend their heartfelt thanks to Coordinator of the REFOREST Programme, for his invaluable guidance during the implementation of this study.

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

References

1. UNFF. *Ministerial Declaration of the High-Level Segment of the Eleventh Session of the United Nations Forum on Forests, International Arrangement on "The Forests We Want: Beyond 2015"*; ECOSOC: New York, NY, USA, 2015; p. 4. Available online: https://www.un.org/esa/forests/2015/index.html (accessed on 8 October 2024).
2. Phillips, P. Changes in Forest Production, Biomass and Carbon: Results from the 2015 UN FAO Global Forest Resource Assessment. Research Gate. 2013. Available online: https://www.researchgate.net/ (accessed on 8 October 2024).
3. FAO. *Global Forest Resources Assessment 2015. How Are the World's Forests Changing?* 2nd ed.; FAO: Rome, Italy, 2016; p. 56. Available online: http://www.fao.org/3/a-i4793e.pdf (accessed on 11 July 2024).
4. FAO. *Global Forest Resources Assessment 2020—Main Report*; FAO: Rome, Italy, 2020.
5. Bünemann, E.K.; Bongiorno, G.; Bai, Z.; Creamer, R.E.; De Deyn, G.; de Goede, R.; Fleskens, L.; Geissen, V.; Kuyper, T.W.; Mäder, P.; et al. Soil quality—A critical review. *Soil Biol. Biochem.* **2018**, *120*, 105–125. [CrossRef]
6. Ngaga, Y.M. *Forest Plantations and Woodlots in Tanzania*; African Forest Forum Working Paper Series; African Forest Forum: Nairobi, Kenya, 2011; Volume 16, pp. 1–80.
7. Page-Dumroese, D.S.; Busse, M.D.; Jurgensen, M.F.; Jokela, E.J. Sustaining forest soil quality and productivity. *Soils Landsc. Restor.* **2021**, *3*, 63–93. [CrossRef]
8. He, L.X.; English, B.C.; de la Torre Ugarte, D.G.; Hodges, D.G. Woody biomass potential for energy feedback in the United States. *J. For. Econ.* **2014**, *20*, 174–191.
9. Doran, J.W.; Zeiss, M.R. Soil health and sustainability: Managing the biotic component of soil quality. *Appl. Soil Ecol.* **2000**, *15*, 3–11. [CrossRef]
10. Juhos, K.; Szabó, S.; Ladányi, M. Influence of soil properties on crop yield: A multivariate statistical approach. *Int. Agrophys.* **2015**, *29*, 433–440. [CrossRef]
11. Schoenholtz, S.H.; Van Miegroet, H.; Burger, J.A. A review of chemical and physical properties as indicators of forest soil quality: Challenges and opportunities. *For. Ecol. Manag.* **2000**, *138*, 335–356. [CrossRef]
12. Shen, Y.; Li, J.; Chen, F.; Cheng, R.; Xiao, W.; Wu, L.; Zeng, L. Correlations between forest soil quality and aboveground vegetation characteristics in Hunan Province, China. *Front. Plant Sci. Spec. Sect. Funct. Plant Ecol.* **2022**, *13*, 1009109. [CrossRef]
13. Nischith, B.J.; Kavitha, R. The impact of soil quality on plant growth and crop yields. *IRJMETS* **2024**, *6*, 1602–1616. [CrossRef]
14. Sariyildiz, T.; Yalcin, D.; Tuna, S. Soil quality and forest productivity. *J. For. Res.* **2018**, *29*, 1–10.
15. Li, H.; Li, Y.; Xu, Y.; Lu, X. Biochar phosphorus fertilizer effects on soil phosphorus availability. *Chemosphere* **2020**, *244*, 125471. [CrossRef]
16. Wang, X.R.; Hu, W.J.; Pang, H.D.; Cui, H.X.; Tang, W.P.; Zhou, W.C. Study on soil physical and chemical properties and soil quality of main forest types in hubei province. *J. Cent. South Univ., For. Technol.* **2020**, *40*, 156–166. [CrossRef]
17. Piotto, D.; Figueiredo, C.C.; de Oliveira, A.D.; Dos Santos, I.L. Soil organic matter content and available phosphorus in relation to teak plantation productivity in Costa Rica. *For. Ecol. Manag.* **2019**, *448*, 1–10.
18. Richardson, B.; Kimberley, M.; Ray, J.W.; Coker, G.W. Indices of interspecific plant competition for *Pinus radiata*. *Can. J. For. Res.* **1999**, *29*, 1551–1563. [CrossRef]
19. MNRT. *Management Plan 2018–2023 for Sao Hill Forest Plantation*; MNRT: Dodoma, Tanzania, 2018; p. 106.
20. Lovett, J.C. Elevational and latitudinal changes in tree associations and diversity in the Eastern Arc Mountains of Tanzania. *J. Trop. Ecol.* **1996**, *12*, 629–650. [CrossRef]
21. Haruyama, S.; Toko, A. Local Forest management in Tanzania: A case study from Lushoto District, Usambara Mountain. *Soc. Nat.* **2005**, *1*, 586–603. [CrossRef]
22. Horst-Heinen, T.Z.; Dalmolin, R.S.D.; Caten, A.T.; Moura-Bueno, J.M.; Grunwald, S.; Pedron, F.D.A.; Rodrigues, M.F.; Rosin, N.A.; da Silva-Sangoi, D.V. Soil Depth Prediction by Digital Soil Mapping and Its Impact in Pine Forestry Productivity in South Brazil. *For. Ecol. Manag.* **2021**, *488*, 118983. [CrossRef]
23. Gee, G.W.; Bouder, J.W. Particle size analysis. In *Methods of Soil Analysis. Part I: Physical and Mineralogical Methods*; Klute, A., Ed.; American Society of Agronomy/Soil Science Society of America: Madison, WI, USA, 1986.
24. Blake, G.R.; Hartge, H. Bulk Density. Methods of Soil Analysis, Part 1. Physical and Mineralogical Methods. *Am. Soc. Agron. Madison* **1986**, *101*, 365–375.
25. Hao, X.; Ball, B.C.; Culley, J.L.B.; Carter, M.R.; Parkin, G.W. Soil density and porosity. In *Soil Sampling and Method of Analysis*, 2nd ed.; Taylor and Francis: Boca Raton, FL, USA, 2008; pp. 743–759.
26. Nelson, D.W.; Sommers, L.E. Total carbon, organic carbon and organic matter. In *Methods of Soil Analysis, Part 2: Chemical and Microbiology Properties*; Page, A.L., Ed.; Agronomy Monograph, No. 9; American Society of Agronomy, Crop Science Society of America, and Soil Science Society of America: Madson, WI, USA, 1982; pp. 539–579.
27. Bremner, J.M.; Mulvaney, C.S. Methods of soil analyses, part 2: Chemical and mineralogical properties. In *Nitrogen Total*; Miller, R.H., Keeney, D.R., Eds.; American Society of Agronomy, Soil Science Society of America: Madison, WI, USA, 1982; pp. 595–624.
28. Bray, R.H.; Kurtz, L.T. Determination of total organic and available Phosphorus in soils. *Soil Sci. Soc. Am. Proc.* **1945**, *39*, 39–45. [CrossRef]
29. Chun, H.; Keles, H. Sparce partial least squares regression for simultaneous dimension reduction and variable selection. *J. R. Stat. Soc. B Stat. Methodol.* **2010**, *72*, 3–25. [CrossRef]

30. Subedi, S.; Fox, T.R. Modeling repeated fertilizer response and one-time midrotation fertilizer response in loblolly pine plantations using FR in the 3-PG process model. *For. Ecol. Manag.* **2016**, *380*, 90–99. [CrossRef]
31. Mahieu, B.; Qannari, E.M.; Jaillais, B. Extension and significance testing of variable importance in projection (VIP) indices in partial least squares regression and principal components analysis. *Chemom. Intell. Lab. Syst.* **2023**, *242*, 104986. [CrossRef]
32. Atwell, M.A.; Wuddivira, M.; Fiedler, S.; Oatham, M.; Herrmann, L.; Glasner, B.; Vetter, V.M.S.; Jungkunst, H.F. Influence of soil geomorphic factors on vegetation patterns in a model white sands ecosystem complex. *Catena* **2023**, *225*, 107044. [CrossRef]
33. Zhang, X.M.; Cao, W.H.; Li, H.R.; Zhang, Y.J.; Wang, C.G.; Ma, B. Interannual and intra-annual temporal dynamics of vegetation pattern and growth in East Africa. *Environ. Earth Sci.* **2023**, *82*, 249. [CrossRef]
34. Leopold, L.B.; Wolman, M.G.; Miller, J.P.; Wohl, E.E. *Fluvial Processes in Geomorphology*; Courier Dover Publications, Freeman: San Francisco, CA, USA, 2020.
35. Onweremadu, E.U.; Akamigbo, F.O.R. Spatial changes in distribution of exchangeable cations in soil of forest hilly landscape. *Res. J. For.* **2007**, *1*, 55–65.
36. Alletto, L.; Coquet, Y.; Roger-Estrade, J. Two-dimensional spatial variation of soil physical properties in two tillage systems. *Soil Use Manag.* **2010**, *26*, 432–444. [CrossRef]
37. Logsdon, S.D.; Karlen, L.D. Bulk density as a soil quality indicator during conversion to no-tillage. *Soil Tillage Res.* **2004**, *78*, 143–149. [CrossRef]
38. Walter, K.; Don, A.; Tiemeyer, B.; Freibauer, A. Determining soil bulk density for carbon stock calculations: A systematic method comparison. *Soil Sci. Soc. Am. J.* **2016**, *80*, 579–591. [CrossRef]
39. Ahukaemere, C.M.; Ndukwu, B.N.; Agim, L.C. Soil quality and soil degradation as influenced by agricultural land use types in the humid environment. *Int. J. Fores. Soils Eros.* **2012**, *2*, 186–190.
40. Awdenegest, M.; Melku, D.; Fantaw, Y.; Yihenew, G.S. Land use effects on soil quality indicators: A case study of Abo-Wonsho Southern Ethiopia. *Appl. Environ. Soil Sci.* **2013**, *2013*, 784989.
41. Wander, M.M.; Walter, G.L.; Nissen, T.M.; Bollero, G.A.; Andrews, S.S.; Cavanaugh-Grant, D.A. Soil quality: Science and process. *Agron. J.* **2002**, *94*, 23–32. [CrossRef]
42. Amacher, M.C.; Neill, K.P.O.; Perry, C.H.; Service, F. *Soil Vital Signs: A New Soil Quality Index (SQI) for Assessing Forest Soil Health*; Research Paper RMRS-RP-65WWW; U.S Department of Agriculture, Forest Service, Rocky: Fort Collins, CO, USA, 2007; 12p.
43. Shah, A.N.; Tanveer, M.; Shahzad, B.; Yang, G.; Fahad, S.; Ali, S.; Bukhari, M.A.; Tung, S.A.; Hafeez, A.; Souliyanonh, B. Soil compaction effects on soil health and crop productivity: An overview. *Environ. Sci. Pollut. Res.* **2017**, *24*, 10056–10067. [CrossRef] [PubMed]
44. Hong, S.; Piao, S.; Chen, A.; Liu, Y.; Liu, L.; Peng, S.; Sardans, J.; Sun, Y.; Peñuelas, J.; Zeng, H. Afforestation neutralizes soil pH. *Nat. Commun.* **2018**, *9*, 1–7. [CrossRef] [PubMed]
45. Hong, S.; Gan, P.; Chen, A. Environmental controls on soil pH in planted forest and its response to nitrogen deposition. *Environ. Res.* **2019**, *172*, 159–165. [CrossRef]
46. Wang, Y.; Chen, H.; Zhu, Q.; Peng, C.; Wu, N.; Yang, G.; Zhu, D.; Tian, J.; Tian, L.; Kang, X.; et al. Soil methane uptake by grasslands and forests in China. *Soil Biol. Biochem.* **2014**, *74*, 70–81. [CrossRef]
47. Imran, M.; Khan, A.; Hassan, A.; Kanwal, F.; Liviu, M.; Amir, M.; Iqbal, M.A. Evaluation of physico-chemical characteristics of soil samples collected from Harrapa-Sahiwal (Pakistan). *Asian J. Chem.* **2010**, *22*, 4823–4830.
48. Kassa, H.; Dondeyne, S.; Poesen, J.; Frankl, M.; Nyssen, J. Impact of deforestation on soil fertility, soil carbon and nitrogen stocks: The case of the Gacheb catchment in the White Nile Basin, Ethiopia. *Agric. Ecosyst. Environ.* **2017**, *247*, 273–282. [CrossRef]
49. Wu, T.; Milner, H.; Diaz-Perez, J.; Ji, P. Effects of Soil Management Practices on Soil Microbial Communities and Development of Southern Blight in Vegetable Production. *Appl. Soil Ecol.* **2015**, *91*, 58–67. [CrossRef]
50. Fisher, R.F.; Binkley, D. *Ecology and Management of Forest Soils*, 3rd ed.; John Wiley: New York, NY, USA, 2000; pp. 23–30.
51. Landon, J.R. *Booker Tropical Soil Manual: A Handbook for Soil Survey and Agricultural Land Evaluation in the Tropics and Sub Tropics*; Booker Agricultural International, Longman Scientific and Technical Publications, Harlon: London, UK, 1991.
52. Zhang, Y.; Xu, X.; Li, Z.; Liu, M.; Xu, C.; Zhang, R.; Luo, W. Effects of vegetation restoration on soil quality in degraded karst landscapes of southwest China. *Sci. Total Environ.* **2019**, *650*, 2657–2665. [CrossRef]
53. Piotrowska-Długosz, A.; Kobierski, M.; Długosz, J. Enzymatic activity and physicochemical properties of soil profiles of Luvisols. *Materials* **2021**, *14*, 6364. [CrossRef]
54. Ostertag, R.; Marín-Spiotta, E.; Silver, W.; Schulten, J. Litterfall and decomposition in relation to soil carbon pools along a secondary forest chronosequence in Puerto Rico. *Ecosystems* **2008**, *11*, 701–714. [CrossRef]
55. Tang, J.W.; Cao, M.; Zhang, J.H.; Li, M.H. Litterfall production, decomposition and nutrient use efficiency varies with tropical forest types in Xishuangbanna, SW China: A 10-year study. *Plant Soil.* **2010**, *335*, 271–288. [CrossRef]
56. Parihar, C.M.; Singh, A.K.; Jat, S.L.; Ghosh, A.; Dey, A.; Nayak, H.S.; Parihar, M.D.; Mahala, D.M.; Yadav, R.K.; Rai, V. Dependence of temperature sensitivity of soil organic carbon decomposition on nutrient management options under conservation agriculture in a sub-tropical Inceptisol. *Soil Tillage Res.* **2019**, *190*, 50–60. [CrossRef]
57. Jha, P.; Mohapatra, K.P.; Dubey, S.K. Impact of land use on physico-chemical and hydrological properties of ustifluvent soils in riparian zone of river Yamuna, India. *Agrofor. Syst.* **2010**, *80*, 437–445. [CrossRef]
58. Liu, Y.; Liu, W.; Wu, L.; Liu, C.; Wang, L.; Chen, F.; Li, Z. Soil aggregate-associated organic carbon dynamics subjected to different types of land use: Evidence from ^{13}C natural abundance. *Ecol. Eng.* **2018**, *122*, 295–302. [CrossRef]

59. Zhou, H.; Zhang, D.G.; Jiang, Z.H.; Sun, P.; Xiao, H.L.; Wu, Y.X.; Chen, J.G. Changes in the soil microbial communities of alpine steppe at Qinghai-Tibetan Plateau under different degradation levels. *Sci. Total Environ.* **2019**, *651*, 2281–2291. [CrossRef]
60. Tanaka, S.; Kendawang, J.J.; Yoshida, N.; Shibata, K.; Jee, A.; Tanaka, K.; Ninomiya, I.; Sakurai, K. Effects of shifting cultivation on soil ecosystems in Sarawak, Malaysia IV. Chemical properties of the soils and runoff water at Niah and Bakam experimental sites. *J. Soil Sci. Plant Nutr.* **2005**, *51*, 525–533. [CrossRef]
61. Pretzsch, H.; Bielak, K.; Block, J.; Bruchwald, A.; Dieler, J.; Ehrhart, H.-P.; Zingg, A. Productivity of mixed versus pure stands of oak (*Quercus petraea* (Matt.) Liebl. and *Quercus robur* L.) and European beech (*Fagus sylvatica* L.) along an ecological gradient. *Eur. J. Forest Res.* **2013**, *132*, 263–280. [CrossRef]
62. Toïgo, M.; Vallet, P.; Perot, T.; Bontemps, J.-D.; Piedallu, C.; Courbaud, B.; Canham, C. Overyielding in mixed forests decreases with site productivity. *J. Ecol.* **2015**, *103*, 502–512. [CrossRef]
63. Forrester, D.I.; Bauhus, J. A review of processes behind diver-sity–productivity relationships in forests. *Curr. For. Rep.* **2016**, *2*, 45–61. [CrossRef]
64. Skovsgaard, J.P.; Vanclay, J.K. Forest site productivity: A review of the evolution of dendrometric concepts for even-aged stands. *Forestry* **2008**, *81*, 13–31. [CrossRef]
65. Soong, J.L.; Janssens, I.A.; Grau, O.; Margalef, O.; Stahl, C.; Langenhove, L.V.; Urbina, I.; Chave, J.; Dourdain, A.; Ferry, B.; et al. Soil properties explain tree growth and mortality, but not biomass, across phosphorus-depleted tropical forests. *Sci.Rep.* **2020**, *10*, 2302. [CrossRef] [PubMed]
66. Lal, R. Soil Conservation and Management in the Humid Tropics: A Review. In *Soil Conservation and Management in the Humid Tropics*; Greenland, D.J., Lal, R., Eds.; Wiley: Chichester, UK, 2015; pp. 1–283.
67. Clark, D.A.; Brown, S.; Kicklighter, D.W.; Chambers, J.D.; Thomlinson, J.R.; Ni, J.; Holland, E. Net primary production in forest. An evaluation and synthesis of existing field data. *Ecol. Appl.* **2001**, *11*, 371–384. [CrossRef]
68. Oberleitner, F.; Egger, C.; Oberdorfer, S.; Dullinger, S.; Wanek, W.; Hietz, P. Recovery of aboveground biomass, species richness and composition in tropical secondary forests in SW Costa Rica. *For. Ecol. Manag.* **2021**, *479*, 118580. [CrossRef]
69. Russell, K.N.; Beauchamp, V.B. Plant species diversity in restored and created Delmarva bay wetlands. *Wetlands* **2017**, *37*, 1119–1133. [CrossRef]
70. Shao, G.; Ai, J.; Sun, Q.; Hou, L.; Dong, Y. Soil quality assessment under different forest types in the Mount Tai, central Eastern China. *Ecol. Indic.* **2020**, *115*, 106439. [CrossRef]
71. Holmes, P.M. Shrubland restoration following woody alien invasion and mining: Effects of topsoil depth, seed source, and fertilizer addition. *Restor. Ecol.* **2010**, *9*, 71–84. [CrossRef]
72. Luna, L.; Vignozzi, N.; Miralles, I.; Solé-Benet, A. Organic amendments and mulches modify soil porosity and infiltration in semiarid mine soils. *Land Degrad. Dev.* **2018**, *29*, 1019–1030. [CrossRef]
73. Reich, P.B.; Grigal, D.F.; Aber, J.D.; Gower, S.T. Nitrogen mineralization and productivity in 50 hardwood and conifer stands on diverse soils. *Ecology* **1997**, *78*, 335–347. [CrossRef]
74. Albaugh, T.J.; Allen, H.L.; Dougherty, P.M.; Kress, L.W.; King, J.S. Leaf area and above- and below-ground growth responses of loblolly pine to nutrient and water additions. *J. For. Sci.* **1998**, *44*, 317–328.
75. Carlson, C.A.; Fox, T.R.; Allen, H.L.; Albaugh, T.J. Modeling mid-rotation fertilizer responses using the age-shift approach. *For. Ecol. Manag.* **2008**, *256*, 256–262. [CrossRef]
76. Epron, D.; Cabral, O.M.R.; Laclau, J.-P.; Dannoura, M.; Packer, A.P.; Plain, C.; Battie-Laclau, P.; Moreira, M.Z.; Trivelin, P.C.O.; Bouillet, J.-P.; et al. In situ 13CO2 pulse labelling of field-grown eucalypt trees revealed the effects of potassium nutrition and throughfall exclusion on phloem transport of photosynthetic carbon. *Tree Physiol.* **2016**, *36*, 6–21. [CrossRef] [PubMed]
77. Rance, S.J.; Cameron, D.M.; Emlyn, R.; Williams, E.R.; Carl, R.; Gosper, C.R. Fertilisation with P, N and S requires additional Zn for healthy plantation tree growth on low fertility savanna soils. *Soil Res.* **2024**, *62*, SR23128. [CrossRef]
78. Chaudhry, H.; Vasava, H.B.; Chen, S.; Saurette, D.; Beri, A.; Gillespie, A.; Biswas, A. Evaluating the soil quality index using three methods to assess soil fertility. *Sensors* **2024**, *24*, 864. [CrossRef]
79. Richter, D.D.; Markewitz, D.; Wells, C.G.; Allen, H.L.; April, R.; Heine, P.R. and Urrego, B. Soil Chemical Change during Three Decades in an Old-Field Loblolly Pine (*Pinus Taeda* L.) Ecosystem. *Ecology.* **1994**, *75*, 1463–1473. [CrossRef]
80. Zeng, J.; Pan, Y.L.; Liu, J.; Zhang, L.; Hu, D.N. Effects of phosphorus and potassium fertilizer on growth and oil-production of *Cinnamomum camphora*. *For. Res.* **2019**, *32*, 152–157.
81. Bai, Y.F.; Chen, S.Y.; Shi, S.R.; Qi, M.J. Effects of different management approaches on the stoichiometric characteristics of soil C, N, and P in a mature Chinese forest plantation. *Sci. Total Environ.* **2020**, *723*, 137868. [CrossRef] [PubMed]
82. Cunha, H.F.V.; Andersen, K.M.; Lugli, L.F.; Santana, F.D.; Aleixo, I.F.; Moraes, A.M.; Garcia, S.; Di Ponzio, R.; Mendoza, E.O.; Brum, B.; et al. Direct evidence for phosphorus limitation on Amazon forest productivity. *Nature* **2022**, *608*, 558–562. [CrossRef]
83. Manu, R.; Corre, M.D.; Aleeje, A.; Mwanjalolo, M.J.G.; Babweteera, F.; Veldkamp, E.; van Straaten, O. Responses of tree growth and biomass production to nutrient addition in a semi-deciduous tropical forest in Africa. *Ecology* **2022**, *103*, e3659. [CrossRef]