Hindawi
International Journal of Forestry Research
Volume 2022, Article ID 6165758, 9 pages
https://doi.org/10.1155/2022/6165758

Research Article

Soil Properties Mediated by Topography Influence Carbon Stocks in a Teak Plantation in the Deciduous Forest Zone of Ghana

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Received 29 December 2021; Accepted 30 March 2022; Published 18 May 2022

Academic Editor: Monika Marković

Recent estimates indicate that over 291 million hectares of the Earth's land area are occupied by forest plantations, representing 7% of the world's forest area and 2% of the world's land area. In Ghana, a substantial amount of degraded land found in hilly areas has been used to establish teak plantations for commercial wood and carbon benefits. Information on the potential influence of topography and soil properties on tree growth and carbon stocks in these plantations is however limited. The study was carried out to assess the influence of elevation on tree growth parameters and carbon stocks in a 7-year-old teak stand and also determined the differences in soil properties along the elevation gradient and its influence on biomass and carbon stocks. Although stand density was statistically similar for the three elevations, tree, diameter, and basal area significantly differed among the three elevations. They were higher at the valley than the mid-slope and the summit. The aboveground biomass and belowground biomass were also significantly higher at the valley compared to the mid-slope and summit. Measured SOC and CEC values between the three elevations showed no significant difference while a positive significant correlation between soil depth and biomass along the altitudinal gradient was observed. Overall, the mean percentage of nitrogen in the soil, pH, potassium, sodium levels, hydrogen, and aluminum varied significantly among the three elevations. Our study suggests that in mountainous areas teak stands in valleys are likely to produce higher biomass and carbon stocks than those in higher elevations; therefore, for better accuracy in biomass and carbon stocks estimations, site elevation should be taken into consideration during carbon stock assessments.

1. Introduction

Forests contain approximately 92% of all terrestrial biomass globally, accounting for approximately 400 GtC [1], and are vital in the removal and storage of ecosystem carbon and mediation of climate change [2, 3]. Due to the rapid decline in natural forests in many countries, as a result of rapid deforestation and forest degradation, forest plantation establishment is being encouraged. This is to help supplement both the protective and production functions and services provided by natural forests [4].

Recent estimates indicate that forest plantations occupy over 291 million hectares of the Earth's land area, representing 7% of the world's forest area and 2% of the world's land area [5], and their significance is predicted to increase with time [4]. Forest plantations have been shown to offer ecosystem services such as watershed protection, carbon reservoir, clean water production, habitat for wildlife, mediation of erosion, mitigation of desertification, and restoration of degraded soils [6]. Plantations are expected to play a pivotal function in the provision of round wood to meet the rising global demand which is projected to reach over 6 billion m^3 by 2050 [7, 8]. Financial compensation for environmental services such as the Clean Development Mechanism (CDM) and Reducing Emissions from Deforestation and forest Degradation ($REDD^+$) is other additional benefits of forest plantations [4].

In forest plantation management, the key concern is productivity, as it determines rotation period, yield, and delivery of other ecosystem services. Productivity of forest plantations is also becoming an increasingly important central issue within the carbon market space due to climate change and its associated schemes of financial compensation for carbon offset. It is important, however, to know that productivity is a function of many factors with site conditions, which could be climate or edaphic related, being key among them.

The elevation is one factor among site conditions that is most critical to tree growth and therefore forest productivity. Unfortunately, there is a paucity of information on the influence of elevation on tree growth particularly forest biomass; especially for plantation forests. In the tropics, over 95% of the available studies were conducted in natural forests with little on forest plantations [9]. The available results of previous studies are also not conclusive [10–12]. For example, with regard to biomass, some studies [13–15] reported aboveground biomass (AGB) to increase with increasing elevation and suggested that anthropogenic disturbance at low elevations could be the cause for higher biomass at higher elevations. Other studies [9, 16], on the other hand, reported decreases in AGB with increasing elevation with reduced air and soil temperature (an adiabatic effect) being suggested as the main factors limiting growth rate at high altitude [16]. Most probable explanations provided by these studies have, however, either highlighted climatic factors or edaphic properties of high elevation sites (elevated soil acidity, slow nutrient uptake, soil N mineralization) and aspects [17, 18]. The effects of elevation on soil nutrient dynamics are also important in plantation management. Nitrogen, for example, decreases while phosphorus increases with increasing elevation [10]. In contrast, [16] reported that P availability is known to decline with increasing altitude.

In Ghana, a substantial amount of degraded land is found in hilly areas. Teak plantations have, therefore, been established for commercial wood and carbon benefits on these hilly lands. However, little data exist on the degree to which topography and soil properties along the elevation gradient will influence tree growth and carbon stocks in these plantations. Yet, knowledge of carbon accumulation in carbon pools along elevation gradients will be very useful for accurate carbon estimation and also help commercial teak growers in yield forecasting across the forest landscape with better precision. Additionally, it will be an important tool for carbon payment schemes under CDM and $REDD^+$. The objectives of this study were therefore to (1) assess the influence of elevation (local environment gradient) on tree growth parameters and carbon stocks in a 7-year-old teak stand and (2) determine the differences in soil properties along the elevation gradient and its influence on biomass and carbon stocks.

2. Materials and Methods

2.1. Study Site. This study was conducted in a 7-year-old teak plantation established in 2010 near Kwamoso and Saforo communities within the Akuapim North Municipal Assembly of Ghana under the National Plantation Development Programme (NPDP). The 128-hectare plantation which extends to the Akuapim Mountain Range of Ghana has a minimum elevation of 184 m and a maximum elevation of 313 m above sea level. It lies between Latitudes 05° 55′ 54.6″ N and 05° 57′ 21.0 "N and Longitudes 000° 07′ 22.0" W and 000° 08′ 22.9″ W, in the Moist Semideciduous Forest type of Ghana [19] (Figure 1).

Mean annual precipitation from 2010 to 2017 within the Akuapim North Municipal Assembly where the study area falls ranged between 978.34 mm and 1270.32 mm.

Rainfall was similar among the three elevations. The mean temperature at the summit, mid-slope, and valley was 27.67 ± 0.20°C, 26.82 ± 0.13°C, and 26.82 ± 0.13°C respectively.

2.1.1. Land-Use History. Land-use history was gathered from available records of the Forestry Commission (FC), Ghana, and the Akuapim North Municipal Assembly (ANMA). Additional information was sourced from some retired and present staff of the two institutions and a few workers of the defunct state oil palm plantation established between 1959 and 1961 at the site. The area was an unreserved closed-canopy forest before it was converted into an oil palm plantation between 1959 and 1961. The palm plantation company collapsed in 1985. In 1988, the municipal assembly allocated the site to peasant farmers for the cultivation of food crops. About 97% of farmers within the landscape planted Maize and the remaining 3% intercropped Cassava with Maize annually. The few mixed crop farms (Cassava and Maize) were distributed along the three elevation sites. The same *N* fertilizers and cultural practices were applied within the study landscape. The farming activities continued until May 2010 when the FC established the teak plantation at the site. Prior to the establishment of the stand in 2010, farmers were predominantly using chemicals to control weeds and fertilizers to improve soil fertility in the area between 1988 and 2009. After the establishment of the plantation, manual weed control (weeding) was carried out four times in a year until June 2013 when all silvicultural activities within the area were suspended due to lack of funds. When sampling units were established in May/June 2017, the valley zone had closed canopy but the mid-slope and summit had partially closed canopies. This resulted in a litter layer made up of only dry leaves in the valley zone but a combination of litter and herbs in the undergrowth of the mid-slope and summit. The valley zone consists of sandy loam soil with very little or no coarse fragments (stoniness) but the mid-slope and summit contained a combination of sandy loam and loamy fine sand soils with coarse fragments (stoniness).

2.1.2. Plantation Establishment. Planting materials used in establishing the plantation came from a private permanent nursery at Kumawu in the Ashanti Region of Ghana. Planting was carried out during the major wet season (May–July) with a planting distance of 3×3 m ($1111\ ha^{-1}$) [20]. Dead seedlings were replaced (beating up) during the minor wet season (September-October) of the planting year.

2.2. Sampling Technique. The plantation was divided into three (3) zones according to the elevation with respect to sea level. The three were valley (low land), mid-slope, and summit (crest) with recorded mean elevations of 194, 249, and 305 meters above sea level, respectively. Ten sampling

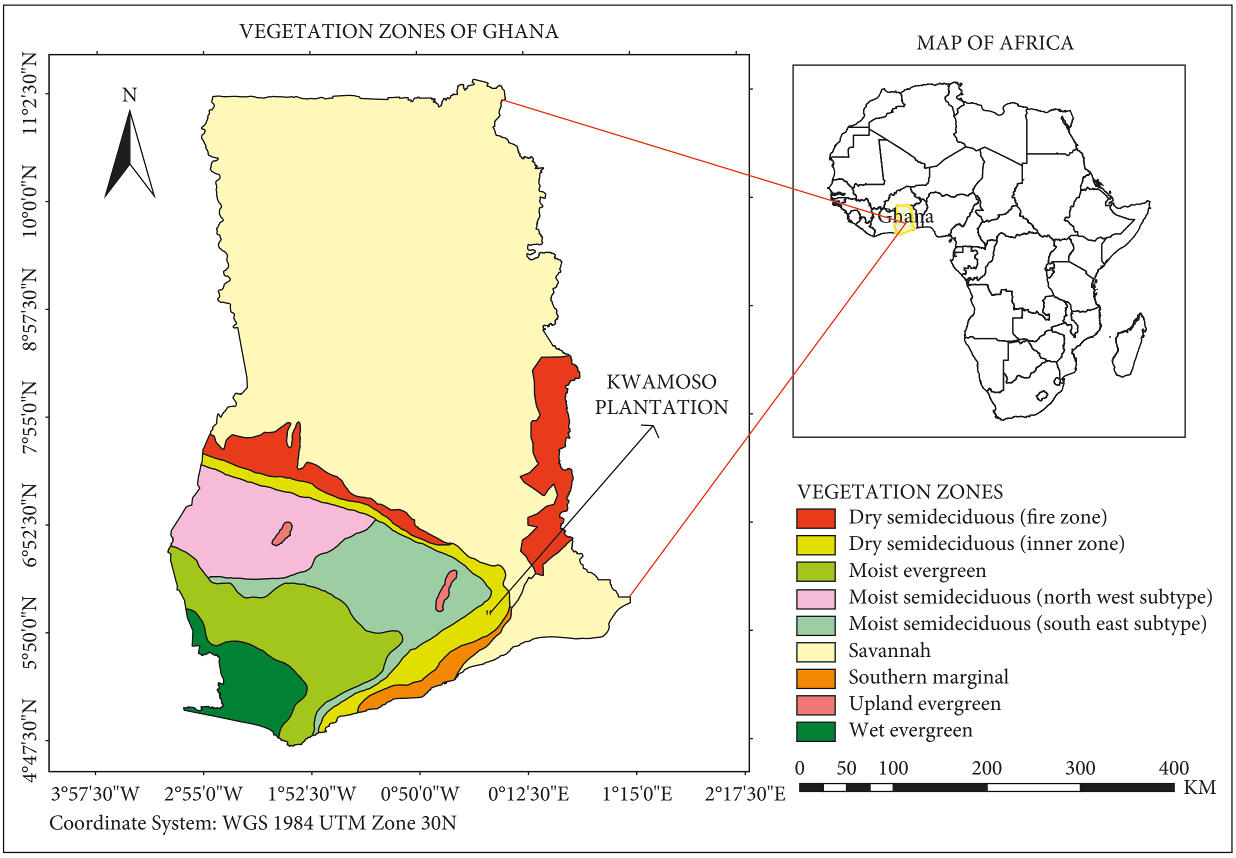

Figure 1: Map of Ghana showing the study site adapted from [20].

plots, each measuring 30 × 30 m with an area of 900 m^2, were established in each zone with distances between plots measuring 100 m. A total of 30 plots were studied covering a cumulative forest plantation area of 2.7 ha. The plots in the valley and summit had no slope, whereas the plots in the mid-slope had a slope that ranged between 9.30 and 11.20 facing the North-West direction.

2.3. Biomass Estimation. The proposed method of biomass and carbon stocks estimation at different elevations by [17] was used with some adjustments. Two methodological approaches were adopted in the measurement of biomass. The first method overlooked the inclination of the plot terrain and calculated with an uncorrected ground area of 900 m^2. The second method considered plot inclination (9.3°–11.2°) of the 10 plots located on the mid-slope and adjusted the horizontal lengths of the plots using the following formula:

$$L_{\text{horizontal}} = L_{\text{field}} \times \cos(\text{slope}), \quad (1)$$

where $L_{\text{horizontal}}$ is the true horizontal length (m), L_{field} is the length measured in the field, parallel with the slope, Slope is the slope, measured in degrees, and Cos is the cosine of the angle.

The two methods produced the same stem densities and stand biomass per plot because the plantation had a planting distance of 3 × 3 m. Even though the area was adjusted on the ground, it did not result in an additional tree.

Ten square plots measuring 30 × 30 m were laid in each zone and used for measuring the various biomass components (trees, herbs, and litter) in all plots. A systematic sampling technique was employed to ensure that sampling plots were fairly distributed for greater precision than random selection. Total heights of trees were measured with calibrated measuring rod and the stem diameter at breast height (dbh) was determined with a diameter tape. Individual tree height data were collected from sample plots in the valley, mid-slope, and summit zones for modeling tree height for each site. Six theoretical growth equations which were suitable for simulating the individual height and DBH growth process of trees were selected. According to the predicted value by model and the measured value of the height and DBH of modeling samples, the percentage relative standard error was calculated for the six growth equations to validate their predictive stabilities. Each model was evaluated by the root mean squared error (RMSE) of the model and the coefficient of determination (R^2) of the model calculated by the following equations:

$$\text{RMSE} = \frac{1}{n}\sum_{i=1}^{n}(Y - \overline{Y})^2,$$
$$R^2 = 1 - \sum_{i=1}^{n}\frac{(Y - \widehat{Y})^2}{(Y - \overline{Y})^2}, \quad (2)$$

where Y is the measured value, $\widehat{Y}$ is thepredicted value, and $\overline{Y}$ is the mean value.

Residual analyses showed that there were no detectable trends in the plots of residuals against the predicted tree heights. Comparing the coefficient of determination (R^2) by Richards, Weibull, and Mitscherlich [21], growth equations had relatively small site-specific values. Michaelis Menten and Power function had the best site-specific coefficient of determination (R^2) but comparing their percentage relative standard errors Michaelis Menten had relatively small values than the Power function model; thus, the Michaelis Menten growth equation was selected (Table 1) and used to determine heights of trees within plots which were not directly measured in the field for the determination of biomass for individual trees. Although the six growth functions were fitted to the same data sets, they resulted in different asymptote coefficients.

2.3.1. Aboveground Tree Biomass (AGB). In the estimation of the AGB, we followed the methods of [20]. In each 900 m^2 sampling plot, diameter at breast height (dbh) was measured for every tree. Twenty trees were sampled from each plot for total height measurements representing 17–31% of the plot population depending on the number of trees in a plot. Mean tree height per plot was determined and used for biomass calculations. To quantify biomass, species-specific allometric equations for teak developed and reviewed at a regional technical workshop in Kumasi in August 2014 for the UN REDD$^+$ program were used [22]. The equation is of the following form:

$$M = 0.0588\left(\rho H D^2\right)^{0.9409}, \tag{3}$$

where M is the aboveground mass of the tree, D is the diameter at breast height (dbh), H is the total height of the tree, and ρ is the density of the wood.

This equation was chosen since it is species (teak) and country-specific and therefore gives a more accurate estimation of biomass than universal ones that ignore regional differences in tree characteristics and assume a constant height-diameter (H : D) ratio, stem taper, and crown mass fraction across regions [23, 24]. The coefficient of determination ($R^2 = 0.9975$) estimated from the original data was also highly significant.

Table 1: Constants and corresponding R^2 produced by Michaelis Menten's growth equation.

Site	Location	a	b	R^2
Valley	Kwamoso	14.7027	2.7783	0.9669
Mid-slope	Kwamoso	14.6233	4.6085	0.8416
Summit	Kwamoso	13.9936	5.0153	0.7578

(1) Standing Tree Carbon. The amount of carbon in a standing tree was computed by multiplying its biomass by the carbon fraction of (0.47) [25] and was expressed as tonne ha^{-1}.

2.3.2. Belowground Tree Biomass (BGB). The BGB carbon pool is made up of live root biomass. BGB has a relationship with AGB, and some researchers [26, 27] have developed regression equations that can predict BGB from AGB. Therefore, the proposed mean root-to-shoot (RS) ratio of 0.26 was used to predict the BGB per hectare [27].

2.3.3. Litter and Herbs. Dead organic matter is defined as organic compounds emanating from the remains of organisms such as plants and animals and their waste products in the environment [28]. Three quadrats measuring 1×1 m were laid in each of the plots for litter/herbs biomass assessment. Fresh weight for all litter/herbs in each quadrat was measured in the field and samples were taken to the laboratory for determination of dry weight [28].

$$\text{Total dry weight}\left(kgm^{-2}\right) = \frac{\text{Total fresh weight}\,(kg) \times \text{Subsample dry weight}}{\text{Subsample fresh weight}\,(g)} \times \text{sample area}\,(m2). \tag{4}$$

The dry weight was multiplied by a carbon fraction of 0.47 to get the estimate of carbon content in liter [25].

2.4. Determination of Soil Chemical and Physical Characteristics, Soil Depth, and Rooting Zone. To determine soil chemical characteristics, soils were collected at depth (0–30 cm), using the cylinder method [29] from 5 sample points within each of the 10 plots per zone for assessment. Percentages of sand, silt, and clay in soil samples were measured for the determination of soil textural class using the particle size distribution proposed by [30] and the textural triangle proposed by [31]. Nutrient levels were also measured to determine soil fertility. Four plots in each zone were randomly selected for the determination of soil depth. A depth of 100 cm was excavated using a pickaxe and shovel in the selected 4 plots per zone for the determination of soil depth and rooting zone (deepest soil depth reached by the roots of an individual tree). The chosen depth (0–100 cm) could not be explored within plots in the mid-slope and summit due to a stoniness and rocky outcrops encountered along the soil profile. Rooting depths were determined by measuring up to the maximum rooting depth of randomly selected trees in each plot.

2.4.1. Laboratory Analysis. The Kjeldahl method was employed as used by [32] in the determination of nitrogen using BUCHI Kjeldahl Digestor MODEL K-446 and Kjeldahl Distillation apparatus model UDK 129. The loss of weight on the ignition method was used for the determination of total carbon with the aid of muffle furnace model L9/S. Phosphorus was extracted through the production of a blue complex of molybdate and thiophosphate in acid solution and analyzed using Buch Scientific Spectrophotometer model 280 *G* [32]. Exchangeable base cations (Na, K) were determined by Volumetric Sodium Tetraphenyl boron method after dry ashing digestion of the soil and the compost samples analyzed with Jenway flame photometer model PFP. Exchangeable Ca and Mg cations were determined by the spectrophotometric method after extraction by ammonium acetate and analyzed with Buck Scientific 280 *G* [32]. Exchangeable acidity (Al and H) was determined by the titration method [33].

2.5. Soil Organic Carbon Estimation (SOC). We followed the approach used by [20] in the determination of SOC. To determine SOC, soils were collected from 5 sample points within each plot for assessment. The loss of weight on the ignition method was used to determine soil organic carbon. The apparatus used for this method consists of a sieve, beaker, chemical balance, oven, and muffle furnace. We measured 5.0 g of sieved soil (<2 mm) into a 50 ml crucible ashing vessel. The crucible with soil was placed in a drying oven set at 105°C and dried for 4 hours. The crucible with the dried soil was removed from the drying oven after 4 hours and placed in a desiccator. When cooled, it was weighed to the nearest 0.01 g. Again the crucible with soil was then placed into a muffle furnace, and the temperature was brought to 400°C and ashed in the furnace for 4 hours. The crucible with the ashed soil was then removed from the muffle furnace, cooled in a dry atmosphere, and weighed to the nearest 0.01 g [32].

The soil organic carbon was calculated as follows:

$$\text{Percent organic matter (OM)} = \frac{(W1 - W2)}{W1} \times 100, \quad (5)$$

where W1 is the weight of soil at 105°C and W2 is the weight of soil at 400°C. The percent of soil organic C is given by % OM × 0.58 [29].

2.6. Determination of Soil Carbon Stocks. The quantity of carbon stock per hectare was calculated by taking into account soil depth (cm), bulk density ($g \cdot cm^{-3}$), and the percentage of soil organic carbon content (SOC). The sampling depth was 0–30 cm as recommended by [25], as 60% of stored carbon has been found at this depth [34] and stored carbon tends to be more stable at lower depth [35]. Bulk density was obtained through the cylinder method [29], collecting 3 samples per sample point between 0 and 30 cm at 3 sample points per plot.

Coarse fragments (stoniness) were catered for by weighing the residue left on a 2 mm sieve when preparing the samples. Stoniness results are expressed as

$$\text{Coarse fragments by weight (\%)} = \frac{\text{Weight not passing } a\ 2\ mm\ sieve}{\text{Weight of total soil sample}} \times 100. \quad (6)$$

The bulk density of both the coarse fragments and the fine Earth was determined and converted to volume measurements [36].

Using the SOC data obtained from the laboratory, the soil carbon stock (SCS) per unit area was estimated using

$$\text{SCS} = [(\text{BD soil}) * \text{Depth soil} * \text{SOC}] * 100, \quad (7)$$

where SCS = Soil Carbon Stocks (t/ha), and SOC = Soil Organic Carbon (%); it must be expressed as a decimal fraction; e.g., 2.8% SOC is expressed as 0.028 in the equation. BDsoil = soil bulk density (g/cm^3), and Depthsoil = soil depth.

2.7. Data Analysis. Variations in tree growth parameters and the variety of soil properties obtained across different elevations and soil depth were tested using a one-way analysis of variance (ANOVA). A post hoc test was also conducted using Tukey's multiple comparison tests to determine the presence of significant differences in tree growth variables and soil properties obtained across the 3 elevation zones. The Pearson correlation coefficient was used to obtain the relationships between biomass and soil's physical and chemical properties.

3. Results

3.1. Accounting for Biomass and Stand Parameters at Different Elevations. Although stand density was statistically similar for the three elevations, tree height [$F\ (2, 27) = 27.52$, $p < 0.0001$], diameter [$F\ (2, 27) = 38.66$, $p < 0.0001$], and basal area $F\ (2, 27) = 20.81$, $p < 0.05$] significantly differed among the three elevations. They were higher at the valley than the mid-slope and the summit. The differences in these parameters between the mid-slope and the summit however were not significantly different (Table 2). The aboveground biomass [$F\ (2, 27) = 30.04$, $p < 0.0001$] and belowground biomass were also significantly higher at the valley compared to the mid-slope and summit. The difference observed between the mid-slope and summit when compared was also not significantly different.

3.2. Soil Carbon Stocks. Soil organic carbon strongly correlated positively with stem density ($r = 0.999$, $P = 0.0029$) and SOM ($r = 0.99$, $P = 0.022$). The result from one-way ANOVA revealed that soil carbon stocks were not influenced by elevation (Figure 2).

Table 2: A comparison of stand parameters at three different elevations for a 7-year-old teak plantation. The values are means and their associated standard error.

Parameters	Valley	Mid-slope	Summit
AGB (mg/ha)	37.89 ± 3.91[a]	23.53 ± 2.16[b]	23.14 ± 2.11[b]
BGB (mg/ha)	9.85 ± 1.02[a]	6.12 ± 0.56[b]	6.02 ± 0.55[b]
Mean height (m)	11.99 ± 0.24[a]	10.21 ± 0.48[b]	9.83 ± 0.43[b]
Mean diameter (cm)	14.43 ± 0.50[a]	11.22 ± 0.61[b]	11.60 ± 0.46[b]
Basal area/ha (m^2)	13.51 ± 1.27[a]	9.51 ± 0.67[b]	9.75 ± 0.66[b]
Stand density/ha	865 ± 64.09[a]	971 ± 67.19[a]	903 ± 29.33[a]
Litter biomass (mg/ha)	12.42 ± 1.14[a]	13.34 ± 2.26[a]	16.11 ± 3.12[a]
SOC (%)	1.86 ± 0.15[a]	2.44 ± 0.39[a]	2.16 ± 0.35[a]

Note. The same superscript means no significant difference while the different superscript implies statistical significance between the three elevations.

3.3. Soil and Rooting Depths Variability at Different Elevations. A soil depth of 100 cm was chosen for rooting depth assessment at the three elevations. However, a depth beyond 37.50 cm and 36.50 cm for the mid-slope and summit could not be explored because of the rocky nature of the soil beneath these depths. Overall, the accessible soil depth varied significantly among the three elevations [F (2, 9) = 52.80, $p < 0.0001$], but a post hoc test revealed no significant difference between mid-slope and summit. Rooting depth also revealed significant variations among the three elevations [F (2, 9) = 7.135, $p < 0.05$] (Table 3). Once again, no significant difference was observed between mid-slope and summit. There was a positive significant correlation between soil depth and biomass along the altitudinal gradient ($r = 1.00$, $p < 0.05$). However, a correlation between biomass and rooting depth revealed a strong positive but not significant relationship [$r = 0.995$, $P = 0.062$].

3.4. Soil Nutrient and Bulk Density Variability at Depth (0–30 cm) at Different Elevations. Overall, the mean percentage of nitrogen in soil [F (2, 27) = 20.48, $p < 0.0001$], pH [F (2, 27) = 16.20, $p < 0.0001$], potassium [F (2, 27) = 4.275. $p < 0.05$], sodium levels [F (2, 27) = 22.70, $p < 0.05$], hydrogen [F (2, 27) = 21.94, $p < 0.0001$], and aluminum [F (2, 27) = 30.12, $p < 0.0001$] varied significantly among the three elevations. However, there was not much consistency and, in most cases, the post hoc test revealed no difference between the mid-slope and summit (Table 4). Phosphorus F (2, 27) = 1.496, p = 0.242] and calcium [F (2, 27) = 2.129, p = 0.139] levels in the soil did not vary significantly among the three elevations.

Measured magnesium values of 2.79 Cmol/Kg and 2.16 Cmol/Kg for valley and mid-slope and 2.16 Cmol/Kg and 1.51 Cmol/Kg for mid-slope and summit showed no significant difference but there was a significant difference between valley and summit [F (2, 27) = 6.060, $p < 0.01$]. Measured CEC and SOC values between the three elevations showed no significant difference ([F (2, 27) = 1.679, p = 0.204] and [F (2, 27) = 2.939, p = 0.07], respectively) (Table 4). Mean bulk density at depth (0–30 cm) which was

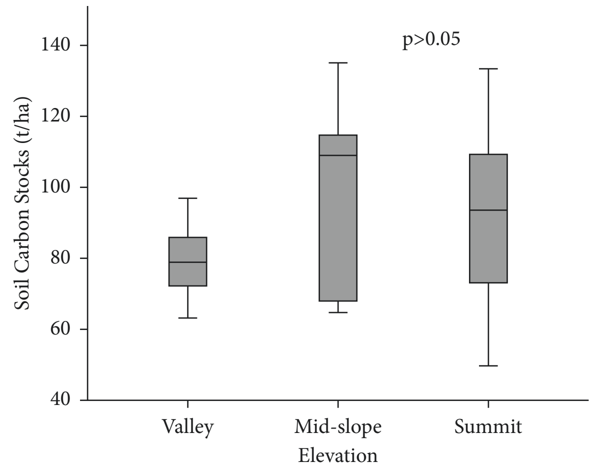

Figure 2: Soil carbon stocks at depth (0–30 cm) within the 7-year-old teak plantation at different elevations. The values represent means and their corresponding standard errors.

Table 3: Comparison between soil depth and rooting depth at different elevations (the values are means and their associated standard error).

Parameters	Valley	Mid-slope	Summit
Soil depth (cm)	100 ± 0[a]	37.50 ± 5.43[b]	36.50 ± 12.97[b]
Rooting depth (cm)	55.25 ± 10.08[a]	33.25 ± 7.05[b]	30.50 ± 8.47[b]

Note. The same superscript means no significant difference while the different superscript implies statistical significance between the three elevations.

Table 4: Variations in soil nutrients under a 7-year-old teak plantation at different elevations. The values are means and their associated standard error.

Parameters	Valley	Mid-slope	Summit
Nitrogen (%)	0.063 ± 0.02[a]	0.129 ± 0.02[b]	0.142 ± 0.01[b]
pH (H_2O)	6.14 ± 0.17[a]	5.36 ± 0.13[b]	5.65 ± 0.23[b]
Phosphorus (mg/kg)	2.17 ± 0.27[a]	1.96 ± 0.27[a]	1.80 ± 0.31[a]
Potassium (cmol/kg)	0.20 ± 0.04[a]	0.29 ± 0.05[b]	0.25 ± 0.03[b]
Sodium (cmol/kg)	0.28 ± 0.02[a]	0.30 ± 0.02[a]	0.16 ± 0.04[b]
Calcium (cmol/kg)	4.28 ± 0.26[a]	3.79 ± 0.47[a]	4.67 ± 0.81[a]
Magnesium (Cmol/kg)	2.79 ± 0.47[a]	2.16 ± 0.40[a]	1.51 ± 0.58[a,b]
Aluminium (Cmol/kg)	0.71 ± 0.11[a]	1.30 ± 0.14[b]	0.69 ± 0.09[a]
Hydrogen (cmol/kg)	0.66 ± 0.06[a]	1.01 ± 0.11[b]	0.48 ± 0.09[a]
CEC (cmol/kg)	8.92 ± 0.51[a]	8.85 ± 0.86[a]	7.76 ± 1.28[a]
C : N	30 : 1	17 : 1	15 : 1
N : P	34 : 1	14 : 1	13 : 1
SOC (%)	1.86 ± 0.15[a]	2.44 ± 0.39[a]	2.16 ± 0.35[a]
Sand (%)	66.51 ± 4.85[a]	71.19 ± 37.4[a]	77.86 ± 3.55[b]
Silt (%)	23.15 ± 4.85[a]	14.53 ± 1.35[b]	13.18 ± 2.38[b]
Clay (%)	10.35 ± 2.39[a]	14.26 ± 2.95	9.99 ± 2.95[a]

Note. The same superscript means no significant difference while the different superscript implies statistical significance between the three elevations.

Table 5: Correlation between aboveground biomass and soil parameters.

Soil parameters	Correlation coefficient (r)	p value
Nitrogen	−0.660	0.0001*
pH	0.654	0.0001*
Phosphorus	0.401	0.028*
Sodium	0.274	0.142
Potassium	−0.557	0.001*
Calcium	−0.070	0.713
Magnesium	0.258	0.168
Aluminium	−0.327	0.078
Hydrogen	−0.173	0.360
CEC	−0.005	0.979
SOC	−0.495	0.005*
Sand	−0.222	0.238
Silt	0.577	0.001*
Clay	−0.363	0.05*

where * means the linear relationship is significant at $p \leq 0.05$.

1.42 g·cm^{-3}, 1.39 g·cm$^{-3,}$ and 1.39 g·cm^{-3} for the valley, mid-slope, and summit did not also vary significantly [$F\,(2, 27) = 2.536,\ p = 0.10$].

3.5. Relationship between Aboveground Biomass and Soil Properties along Altitudinal Gradient. Generally, 53% of the studied soil parameters showed either negative or positive significant relationships with AGB ($p < 0.05$). However, 47% also revealed no significant relationship with AGB ($p > 0.05$) (Table 5). For example, only phosphorous and potassium out of the six basic cations studied showed a significant relationship with biomass ($p < 0.05$).

4. Discussion

4.1. Accounting for Biomass, Carbon Stocks, and Soil Depth Variations at Different Elevations. The studied plantations are of the same age, are situated within the same area, and have experienced the same silvicultural treatments over the years, with elevation levels among the three zones (194 m, 249 m, and 305 m) being the only major delineating factor. Our study revealed that tree height and diameter decreased with increasing altitude. This pattern was also similar for both above and below biomass. This was not a new finding since similar observations have been reported by [16, 37, 38] on tree height, diameter, and biomass along an elevation gradient in tropical mountains even though there is little insight into the underlying causes [17]. In the current study, the reduction in these parameters along the elevation gradient may be attributed to a corresponding reduction in soil and rooting depths along the same gradient. This condition most likely provided smaller soil volume for trees in the upper elevation zone to explore for water and nutrients resulting in decreased productivity along the elevation gradient. This explains why trees in the valley were found to be taller and larger than those in the mid-slope and summit of the mountain, resulting in higher biomass in the valley despite the similarity in stem density across the three sites. Nevertheless, the observed similarity in the rooting and soil depth values between the mid-slope and summit could have resulted in the tree height, diameter, and biomass between these two zones not varying significantly.

We observed in the present study that SOC and litter biomass carbon were not influenced by elevation. Thus, an increase or decrease in altitude did not significantly result in a change in these two parameters. This contradicts the results of previous studies [18, 39, 40] which reported that SOC and litter biomass carbon decrease as altitude increases. A possible explanation may be that the variation in temperature was not significant enough to alter leaf decomposition among the sites. Also, a higher litter production expected from a higher stand basal area at the lower altitude might have been counterbalanced by the combination of litter and herb under the mid-slope and summit due to partial canopy openings. Additionally, acidity slows down decomposition and mineralization rates. The valley with significantly highest pH which was expected to witness a higher leaf turnover because of its higher stand basal area also may have experienced a higher decomposition and mineralization rate than the mid-slope and summit with lower pH. This is consistent with [41]. The two sets of conditions then balanced each other resulting in near equal litter biomass.

4.2. Soil Nutrient Variability as Influenced by Elevation. The study revealed significant variations between some soil properties at the three elevation levels. Some earlier studies [35, 42, 43] have reported similar results and attributed these variations to climatic (temperature, radiation intensity, drought periods) and edaphic conditions (weathering rates, N mineralization rates, soil water availability, leaching intensity, and others) as well as slow litter decomposition associated with altitudinal gradient.

As the results show, soil N and K increased with increasing elevation. The findings agree with [44, 45] but are inconsistent with what was observed by [10, 46] that the availability of N tends to decline with increasing elevation. The lower soil N concentration at the lower elevation in the present study could be attributed to a higher growth rate of trees in the valley [47, 48]. This explains why the valley zone recorded the highest mean height among the 3 elevations. A positive significant correlation between soil pH and stand biomass is an indication of the significant role played by soil pH in mineralization. This revealed that the widely reported assumption that soil nutrients and plants linearly change with altitude could not always be true. This is consistent with [42, 45]. The differences in observations made by different studies may be attributed to numerous factors, with key among them being the height of the mountain and the slope. Also, under a monoculture tree plantation, soil nutrient dynamics may behave differently from a mixed-species stand.

4.3. Relationships between Biomass and Soil Properties along Altitudinal Gradient. The study revealed significant relationships between biomass and some soil properties at different elevations. All the soil nutrients correlated either positively or negatively with AGB but their effect was not significant except for soil N, P, K, SOC, and SOM. The results somehow contradict a study by [17] who looked at the effects of soil chemistry at different elevations on forest biomass in Equatorial Andes. In their study, only exchangeable K out of all the studied soil nutrients (pH, N, C: N, Mg, Ca, Al, K, and P) showed a significant relationship with AGB. The significant variation of soil N and K between elevation zones and the significant relationship between AGB biomass and (N, P, K) as revealed by the current study is an indication that soil fertility might have played an important role in AGB accumulation along the altitudinal gradient. However, the positive significant linear relationship between biomass and both soil depth and rooting depth coupled with significant variations in soil depth and rooting depth between the three elevations probably explains why the valley with the highest soil depth and soil volume with no mechanical restrictions [49] recorded the highest biomass accumulation among the three sites. Similar results have been reported [50, 51].

5. Conclusions

We observed that in the 7-year-old teak plantation, elevation is a limiting factor to tree height, diameter, and aboveground biomass accumulation. Biomass in the valley (37.89 mg/ha) was reduced by 37.90% to (23.53 mg/ha) at the mid-slope and a further 1.66% at the summit to 23.14 mg/ha showing the superiority of lower elevations in supporting teak growth. The significant variation in soil chemical properties especially pH, C : N ratio, and N : P ratio as well as soil depth along the altitudinal gradient accounted for the variation in tree size and biomass. The role of soil P in teak growth may be less important than that of N and K which appears to be depleted by teak growth. SOM and SOC did not vary significantly along the elevation gradient making their role in carbon stock accumulation in teak obscure. In mountainous areas, teak stands in valleys will produce higher biomass and carbon stocks than those in higher elevations implying better accuracy in biomass and carbon stock estimations will be obtained if site elevation is taken into consideration during carbon stock inventories.

Data Availability

The data sets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

Conflicts of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

The authors would like to thank Dr. Kwakye Ameyaw (Forestry Commission, Ghana) and Dr. Adu Bredu of Forestry Research Institute, Ghana (FORIG), for their contributions during data collection and the ideas developed for this paper. The authors are also grateful to the management of FORM Ghana.

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