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ORIGINAL PAPER

Comparative analysis of carbon stock and litter nutrient concentration in tropical forests along the ecological gradient in Kenya

Timothy Namaswa[1,2] · Brexidis Mandila[3] · Joseph Hitimana[3] · Judith Kananu[4]

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Abstract The study determined the carbon stocks and litter nutrient concentration in tropical forests along the ecological gradient in Kenya. This could help understand the potential of mitigating climate change using tropical forest ecosystems in different ecological zones, which are being affected by climate change to a level that they are becoming carbon sources instead of sinks. Stratified sampling technique was used to categorize tropical forests into rain, moist deciduous and dry zone forests depending on the average annual rainfall received. Simple random sampling technique was used to select three tropical forests in each category. Modified consistent sampling technique was used to develop 10 main 20 m × 100 m plots in each forest, with 20 2 m × 50 m sub-plots in each plot. Systematic random sampling technique was used in selecting 10 sub-plots from each main plot for inventory study. Non-destructive approach based on allometric equations using trees' diameter at breast height (DBH), total height and species' wood specific gravity were used in estimating tree carbon stock in each forest. Soil organic carbon (SOC) and litter nutrient concentration (total phosphorus and nitrogen) were determined in each forest based on standard laboratory procedures. The results indicated that, whilst trees in rain forests recorded a significantly higher ($p < 0.001$) DBH (20.36 cm) and total tree height (12.1 m), trees in dry zone forests recorded a significantly higher ($p < 0.001$) specific gravity (0.67 kg m^{-3}). Dry zone tropical forests stored a significantly lower amount of total tree carbon of 73 Mg ha^{-1}, compared to tropical rain forests (439.5 Mg ha^{-1}) and moist deciduous tropical forests (449 Mg ha^{-1}). The SOC content was significantly higher in tropical rainforests (3.9%), compared to soils from moist deciduous (2.9%) and dry zone forests (1.8%). While litter from tropical rain forests recorded a significantly higher amount of total nitrogen (3.4%), litter from dry zone forests recorded a significantly higher concentration of total phosphorus (0.27%). In conclusion, ecological gradient that is dictated by the prevailing temperatures and precipitation affects the tropical forests carbon stock potential and litter nutrient concentration. This implies that, the changing climate is having a serious implication on the ecosystem services such as carbon stock and nutrients cycling in tropical forests.

Keywords Carbon stock · Climate change · Ecological gradient · Ecosystem services · Litter nutrients · Tropical forests

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✉ Timothy Namaswa
t.namaswa.22@abdn.ac.uk

1 School of Biological Sciences, University of Aberdeen, St Machar Drive, Aberdeen AB24 3UU, Scotland, UK

2 National Forest Products Research Programme, Kenya Forestry Research Institute, P. O. Box 64636–00620, Nairobi, Kenya

3 School of Agricultural Sciences & Natural Resources, University of Kabianga, P.O. Box 2030-20200, Kericho, Kenya

4 University of Nairobi, P.O. Box 30197-00100, Nairobi, Kenya

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Introduction

Globally, over 38% of the total ecosystem services' value comes from forest ecosystems, with carbon sequestration and nutrient cycling showing higher values than other services (Ninan and Inoue 2013; Pastur et al. 2018; Giweta 2020; Grammatikopoulou and Vackarov 2021). In total, forest carbon stock is 662 giga tonnes, accounting for 60% of global terrestrial carbon pool, of which, soil organic carbon (SOC) and carbon in forest tree biomass accounts for 45% and 55% of the total forest carbon respectively (Food and Agricultural Organization 2020; Joshi et al. 2021). Therefore, forest ecosystems are potential solution to climate change mitigation and global warming through carbon sequestration.

Forest ecosystems differ from one another depending on local abiotic and biotic factors, which may affect the total possible ecosystem services that can be accrued (Salk et al. 2014; Krishna and Mohan 2017). For example, the carbon sequestration potential of forest ecosystems is affected by its growing conditions, plant growth, level of disturbance/degradation and the wood density, which in turn depend on climatic and soil conditions (Laurance et al. 1999; Salk et al. 2014; Ali et al. 2023). The soil nutrient concentration is mainly influenced by the availability of litter, litter nutrient concentration and litter decomposition rates (Giweta 2020; Nonghuloo et al. 2020). Wood density also varies depending on species, age, site, silvicultural activity and genotype (Cown 2001). Litter nutrient concentration dynamics are influenced by species composition, temperature and precipitation (moisture) (Krishna and Mohan 2017; Giweta 2020). Therefore, the carbon stock and litter nutrient concentration in two forests may differ because of underlying environmental conditions.

Africa's tropical forests make up only 20% of global forest and cover only 13% of Africa's land mass (Chapman et al. 2022). However, they account for more than 90% of the carbon stored in the continent's terrestrial ecosystem (Mayaux et al. 2013; Chapman et al. 2022). These forests are located in diverse ecological conditions, ranging from humid forests to deserts, and from montane temperate forests to coastal mangrove swamps (Nair and Tieguhong 2004; Siyum 2020). Superimposed on this ecological diversity are varying degrees of environmental stresses, which have driven the establishment of diverse vegetation and multi-functional landscape types (Nair and Tieguhong 2004; Asefa et al. 2020). This implies that, tropical forests in Africa differ in terms of carbon sequestration potential and litter nutrients depending on the prevailing environmental conditions.

The ecological heterogeneity of Sub-Saharan Africa (SSA) presents a critical natural condition, which can be used to evaluate the responses of tropical forests' ecosystem services to the changing ecological conditions over time and space (Asefa et al. 2020). Therefore, there is a need to use such natural ecological gradient to test the hypothesis that the dynamics of carbon sequestration and litter nutrient concentration in tropical forests could be influenced by environmental variability, especially in the context of climate variability (Asefa et al. 2020; Siyum 2020). This will generate insightful information on the potential impact of climate change on forest carbon sequestration in SSA. This information could help understand the potential of mitigating climate change using these ecosystems, which may be affected by climate change to an unclear direction (Zhang and Justice 2001; Mitchard et al. 2018; Kairo et al. 2021). This knowledge could form a scientifically sound background for policy formulation in relation to climate change and global warming mitigation through forestry options (Zhang and Justice 2001).

Therefore, we hypothesised that the functioning of tropical forests along the ecological gradient in Kenya is influenced by climate variability. The specific research questions were: (1) Are there significant differences in the functional traits of trees in the tropical forests along the ecological gradient in Kenya? (2) Are there significant differences in the biomass and soil carbon stocks in the tropical forests along the ecological gradient in Kenya? (3) Are there significant differences in litter nutrient concentration in the tropical forests along the ecological gradient in Kenya?

Materials and methods

Study sites

The study was conducted in Kenya, a country located in East Africa neighbouring Uganda to the West, Tanzania to the Southwest, Indian Ocean to the Southeast, Somalia to the East, Ethiopia to the North, and Southern Sudan to the Northwest. The country lies on latitude 4° North to 4° South and longitude 34° East to 41° East. At the coast, the country experiences warm and humid climates, the climate is cooler along savannah grasslands, hot and dry climates around further inland regions of Lake Victoria. The North-eastern parts of the country experiences arid and semi-arid climates with near desert landscapes.

Kenya has four major forest eco-regions namely coastal forests, dry zone forests, montane forests and western rain forests. The Kenyan coastal forests are located on the coastal strip at an altitude of less than 300 m, with plateaus reaching 448 m above sea level bound by step scarps descending to 150–300 mm (Sutton et al. 2002). Presently, the Kenyan coastal forests have reduced to 145 fragmented patches with Arabuko Sokoke and Shimba hills being largest remaining patches (Ngumbau et al. 2020). The eco-region is underlain by coarse grained quartz-felspathic and mazaras sunstone, with well drained, extremely deep red, sandy clay loam soils (Sutton et al. 2002). The climate is tropical with annual mean rainfall ranging from 900 to 1200 mm and mean temperatures of between 25 to 30 °C (Fungomeli et al. 2020). The coastal forests host a mosaic of different vegetation types such as swampy forests, dry forests and grasslands with *Fabaceae, ponceau, Rubiaceae, Malvaceae* and *Cyperaceous* being the top five most common families. (Ngumbau et al. 2020).

The montane forests are in high altitude regions of above 1500 mm above sea level and dominated by alternating hills and bottoms (Hitimana et al. 2004; Kenya Forest Service 2013). The forests experience mean annual temperature range of 18–25 °C, with bimodal annual rainfall peaking in May to August and averaging to over 1600 mm (Hitimana et al. 2004). They have fertile soils formed from tertiary basic igneous rocks and volcanic ashes (Hitimana et al. 2004). The species composition differs because of climate and altitude variation, with moist broad-leaved forests dominating the windward side whilst drier coniferous mixed forests dominating the leeward side, and highland bamboo dominating the higher altitude (Ministry of Environment and Forestry 2020).

The Western forests are characterized by Guineo-Congolean features such as significantly taller and larger trees (Kenya Forest Service 2013). They are in Western part of Kenya with an altitude range of 1500–1700 m above sea level, receives an average annual rainfall of 2000 mm and maximum temperatures of 26 °C (Mutoko et al. 2015). The eco-region lies on Nandi hills escarpment and underlain by outcrop of basement rock system of Precambrian, locally covered by young alluvial material (Fischer et al. 2010). The soils are granitic in origin, which have transformed into well drained, deep clay-loam, clay and sandy-clay soils (Fischer et al. 2010). They contain a variety of vegetation types including grasslands, bushlands, secondary and near-natural forests. The most dominant species includes: *Syzygium guineense*, *Vangueria*, *madagascariensis*, *Croton macrostachyus* and *Ehretia cymose* (Obonyo et al. 2023).

Dry zone forests are found in arid and semi-arid regions with annual rainfall ranging from 500–1000 mm (Cuni-Sanchez 2019; Muiruri 2021). They are located in different regions of Kenya with altitude ranging from 605 to 1950 m above the seal level with a series of step faults dropping from neighbouring escarpments. The dominant species includes *Combretum*, *Platycepheliumvoense* and *Manilkara.*

The study was conducted in 9 tropical forests, namely: Mt. Elgon forest, Cherangani hills forest, Marsabit forest, Kakamega forest, South Nandi Forest, Mau Forest, Nyangweta forest, Shimba hills forest and Kibwezi forest (Fig. 1).

Sampling technique

The study used a multi-stage sampling technique. Stratified random sampling technique was used to categorize tropical forests in Kenya into rain, moist deciduous and dry zone tropical forests (Osman 2013). Rain forests, moist deciduous and dry zone tropical forests were forests found in ecological regions that receive more than 1700 mm, between 1200 and 1700 mm and less than 1200 mm of annual average rainfall respectively. Simple random sampling technique was used in selecting three forests in each of the categories from the list of tropical forests in Kenya (Table S1).

Modified consistent sampling technique as used by Stegen et al. (2011) was used in developing ten main plots in each forest. Simple random sampling technique based on random points (coordinates) created using Google earth software were used in creating centre points for the 10 main 20 m × 100 m plots in each forest. However, during data collection, main plots exhibiting large openings were avoided and new centre points generated. This requirement aimed at ensuring relative homogeneity among plots and forests to attain a meaningful and representative data (Mueller-Dombois and Ellenberg 1974). In each of the main plot, 20 sub-plots measuring 2 m by 50 m were developed. Using systematic random sampling technique, ten sub-plots were selected from each of the main plot, where the first sub-plot was selected randomly, and subsequent sub-plots selected by skipping one sub-plot from the preceding sub-plot.

The functional traits of trees and stem density in tropical forests in Kenya

The functional traits are biological attributes such as tree height that directly or indirectly affect plant fitness and adaptation to environmental conditions. Trees' functional traits were determined based on the tree stem diameter at breast height (DBH), tree stem total height and species-specific gravity. The tree stem DBH of each stem in the selected sub-plot was measured using a diameter tape. The tree stem total height was measured using a suunto clinometer method as described by Abed and Stephens (2003). Wood specific gravity of each stem in the selected sub-plot in every forest was estimated by first identifying the tree species (Table S2). Then, the wood specific gravity of each of the identified tree species was obtained from literature and other existing databases such as Global Wood Density Database, Wood Species Database, Tree Functional Attributes and Ecological Database. In case the species was not represented in available databases, it was estimated as genus or family averages. In case wood specific gravity data were lacking for a given genus and family, the average specific gravity of other individuals in the forest was used as advised by Stegen (2011). The tree stem density was estimated by counting the number

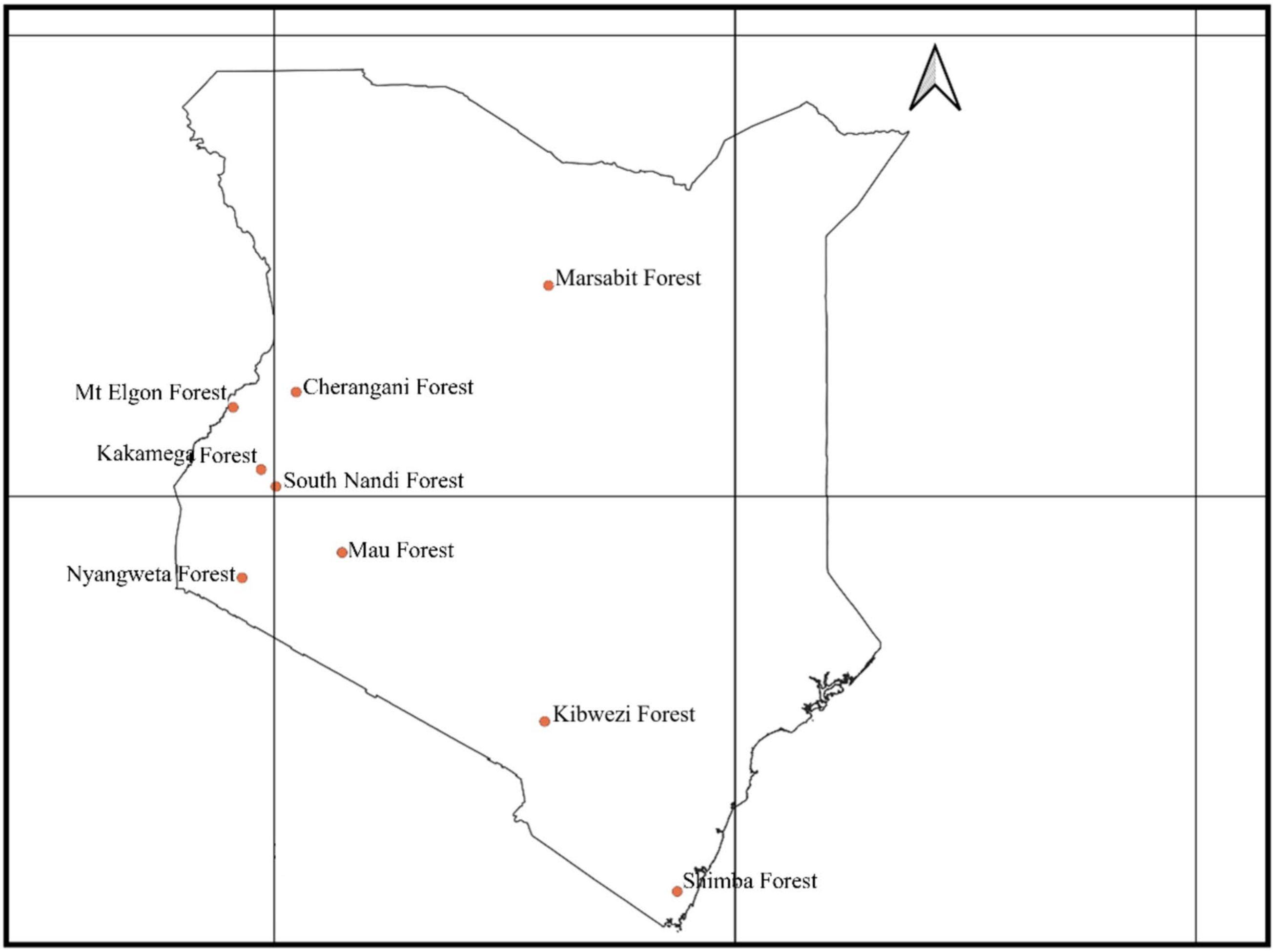

Fig. 1 A map of Kenya indicating geographical locations of selected tropical forests for this study

of tree stems in each of the selected sub-plot and calculated per unit area.

Tree carbon Stock

Tree carbon stock was estimated based on above ground tree carbon stock, below ground tree carbon stock and the total tree carbon stock: using non-destructive allometric equation method. The Non-destructive approach was used because some trees species in the tropical forest are endangered; therefore, cutting them may have negative implication on species diversity.

The above ground tree carbon stock was estimated using above ground tree biomass potential, which was determined based on improved pan-tropical mixed species biomass estimation allometric equation by Chave et al. (2014) (Eq. 1):

$$\mathrm{AGB} = 0.0673 \times (\rho D^2 H)^{0.976} \quad (1)$$

where, AGB is above ground tree biomass (kg), D is diameter at breast height (cm), H is total tree height (m), and ρ = Wood specific gravity (kg m^{-3}).

The total tree height, diameter at breast height of all trees and wood specific density of identified species was estimated as described in Sect. 2.3 of this paper. The above ground tree carbon stock (AGBC) was determined by assuming that carbon accounts for 46% of total above ground tree biomass (AGB) (Quinkenstein et al. 2011). Therefore, above ground tree carbon stock was estimated using Eq. (2):

$$\mathrm{AGBC} = 0.46 \times (\mathrm{AGB}) \quad (2)$$

The below ground tree carbon stock (BGC) was determined based on allometric equations developed by Mokany et al. (2006) (Eqs. 3 and 4):

$$\mathrm{BGC} = 0.235 \times (\mathrm{AGC}),\ \text{if AGC} > 62.5\ \mathrm{t\ ha^{-1}} \quad (3)$$

$$\mathrm{BGC} = 0.205 \times (\mathrm{AGC}),\ \text{if AGC} \leq 62.5\ \mathrm{t\ ha^{-1}} \quad (4)$$

The total tree carbon stock (TTC, t ha^{-1}) in a forest was obtained by adding above and below ground carbon stock (t ha^{-1}) (Eq. 5):

$$TTC = AGC + BGC \tag{5}$$

Soil organic carbon content

In each sub-plot, three pits were dug systematically at 0, 25 and 50 m from the edge of the sub-plot to a depth of 1 m. A depth of 1 m ensured that soils mixed with litter and humus was avoided. The sample preparation and carbon content determination were done at Kenya Forestry Research Institute (KEFRI) as explained by Okalebo et al. (2002).

Litter nutrient concentration

In each of the selected sub-plot, three quadrants measuring 2 m by 5 m were established systematically. The litter in each quadrant was collected, well mixed to form a composite sample, and one sample taken for laboratory nitrogen and phosphorus nutrient concentration test at KEFRI. The sample preparation and laboratory procedures were conducted as explained by Okalebo et al. (2002).

Data analysis

Data were analysed using R software. The significant differences in carbon stock and litter nutrient concentration in different types of tropical forests (rain, moist deciduous and dry zone) were analysed using a one-way analysis of variance (ANOVA). Post hoc analysis based on Turkey tests was used to make pairwise comparisons between each forest categories.

Results

Stem density and functional traits of trees in the tropical forests in Kenya

Table 1 indicates the means of tree stem density per hectare (ind. ha^{-1}), the DBH (cm), total tree height (m) and specific gravity also called relative density (kg m^{-3}) of trees in rain forests, moist deciduous forests and dry zone forests. One-way ANOVA showed that the means of tree stem density, stem DBH, stem height and specific gravity varied significantly between the three tropical forest categories in Kenya (Table 2).

Turkey's post-hoc test indicated that, while the mean stem density in rain forests (923 ind. ha^{-1}) was not significantly lower than the mean stem density in moist deciduous forests (945 stems ha^{-1}) ($p = 0.994$), it was significantly lower than the mean stem density in dry zone forests (1568 ind. ha^{-1}) ($p = 0.046$). Contrary, the mean stem density in moist deciduous forests was not significantly lower than the stem density recorded in dry zone forest ($p = 0.075$). Further, the means of DBH (20.36 cm) and total tree height (12.1 cm) in rain forests, were significantly higher than in moist deciduous forests ($p < 0.001$) and dry zone forests ($p < 0.001$). The means of DBH (14.07 cm) and total tree height (8.29 m) recorded in moist deciduous forest were significantly higher than the mean DBH (6.6 cm) and total tree height (4.72 m) recorded in dry zone forests ($p < 0.001$). The mean of wood specific

Table 1 Estimated means of tree stem traits in rain, moist deciduous and dry zone tropical forests in Kenya

Forest category	Stem density (ind. ha^{-1})	Average DBH (cm)	Average height (m)	Specific gravity (kg m^{-3})
Rain forests	923.00 ± 200.00	20.36 ± 26.50	12.10 ± 10.30	0.57 ± 0.11
Moist deciduous	945.00 ± 138.00	14.07 ± 21.00	8.29 ± 7.00	0.63 ± 0.10
Dry zone	1568.00 ± 303.00	6.60 ± 11.00	4.72 ± 4.00	0.67 ± 0.10

Table 2 One-way ANOVA Output for functional traits of trees in different tropical forest categories in Kenya

Parameter	Stem density		Stem/tree DBH		Stem/tree height		Specific gravity	
	Density (ind. ha^{-1})	Residuals	DBH (cm)	Residuals	Height (m)	Residuals	Specific gravity (kg m^{-3})	Residuals
df	2.00	6.00	2.00	9358.00	2.00	9358.00	2.00	9358.00
Sum Sq	761725.04	33.92	278184.92	3859044.26	709221.22	524411.14	13.65	141.09
Mean Sq	380862.52	56320.37	139092.46	412.38	35460.61	56.04	6.83	0.02
F value	6.76		337.29		632.79		452.68	
Pr (> F)	0.38		< 0.0001		< 0.0001		< 0.0001	

gravity of tree species in dry zone forests (0.67 kg m^{-3}), was significantly higher than the means of wood specific gravity of tree species recorded in moist deciduous forests (0.63 kg m^{-3}) ($p < 0.001$) and rain forests (0.57 kg m^{-3}) ($p < 0.001$). Also, the mean of wood specific gravity of tree species in moist deciduous forests was significantly higher than the wood specific gravity of trees in rain forests ($p < 0.001$). These results showed that, trees in different ecological regions exhibit different functional traits in terms of stem density, DBH, total height and wood specific gravity.

Tree carbon stock potential in different tropical forest categories in Kenya

Figure 2 indicates the means of above ground tree carbon stock, below ground tree carbon stock and total tree carbon stock along the ecological gradient in Kenya. Table 3 indicates that, the above ground tree carbon stock, below ground tree carbon stock, and total tree carbon stock recorded in rain forests, moist deciduous forests and dry zone forests were significantly different ($p = 0.003$).

Turkey's post-hoc test indicated that, the means of carbon stocks (above ground tree carbon stock (59.0 Mg ha^{-1} C), below ground tree carbon stock (13.9 Mg ha^{-1} C) and total tree carbon stock (73.0 Mg ha^{-1}C)) recorded in dry zone forests were significantly lower than the respective means recorded in rain forests ($p = 0.005$) and moist deciduous forests ($p = 0.007$). Contrarily, the means of carbon stocks recorded in rain forests were not significantly different from the respective means recorded in moist deciduous forests ($p = 0.990$). These findings indicate that tree carbon stocks in Kenya increases from dry zone forests to rain forests then to moist deciduous forests.

However, 19.77%, 21.29% and 24.25% of total tree carbon stock in rain forests, moist deciduous forests and dry zone forests was attributed to top ten tree species respectively (Table 4). The species that recorded higher carbon stock were *Croton macrostachyus* in rain forests, *Podocarpus falcatus* in moist deciduous forests and *Croton megalocarpus* in dry zone forests.

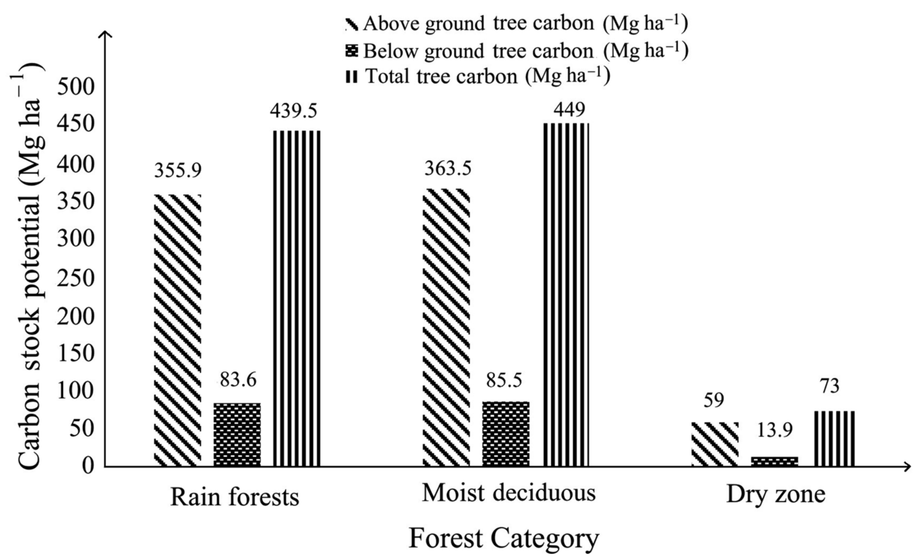

Fig. 2 The means of above ground, below ground and total tree carbon stock in the three categories of tropical forests in Kenya

Table 3 One-way ANOVA of total above ground tree carbon stock, total below ground tree carbon stock and total tree carbon stock in the three categories of tropical forests in Kenya

Parameter	Above-ground tree carbon stock		Below-ground tree carbon stock		Total tree carbon stock	
	TAGBC (Mg ha^{-1})	Residuals	TBGBC (Mg ha^{-1})	Residuals	TBC (Mg ha^{-1})	Residuals
df	2.00	6.00	2.00	6.00	2.00	6.00
Sum Sq	168706.831	22791.23	9316.23	1256.24	257275.89	34765.02
Mean Sq	84353.42	3798.54	4658.14	209.37	128637.94	5794.17
F value	22.21		22.25		22.20	
Pr (>F)	0.003		0.003		0.003	

TAGBC denotes total above ground biomass carbon, TBGBC is total below ground biomass carbon and TBC is total biomass carbon

Table 4 The list of top ten tree species contributing to tree carbon in the tropical forests along the climatic gradient in Kenya

Rain Forests		Moist Deciduous Forests		Dry zone Forests	
Tree species	Total tree carbon (Mg ha^{-1})	Tree species	Total tree carbon (Mg ha^{-1})	Tree species	Total tree carbon (Mg ha^{-1})
Croton macrostachyus	18.40	*Podocarpus falcatus*	13.00	*Croton megalocarpus*	3.90
Strombosia scheffleri	11.20	*Tabarnaemontana stapfiana*	12.20	*Drypetes gerrardii*	2.80
Trilepisium madagascariense	9.70	*Syzygium guineense*	11.90	*Teclea simplicifolia*	2.20
Funtumia africana	8.30	*Olea europaea*	10.40	*Croton dichogamus*	1.50
Heinsenia diervilleoides	6.20	*Rapanea melanophoeos*	10.20	*Celtis mildbraedii*	1.40
Croton megalocarpus	9.60	*Podocarpus latifolius*	9.80	*Combretum exalatum*	1.40
Casearia battiscombei	8.00	*Dombeya torrida*	9.50	*Cynometra suaheliensis*	1.30
Bersama abyssinica	5.70	*Juniperus procera*	9.10	*Diospyros abyssinica*	1.10
Vangueria apiculata	5.50	*Macaranga kilimandscharica*	4.90	*Cassipourea malosana*	1.10
Olea capensis	4.30	*Strombosia scheffleri*	4.60	*Memecylon sansibaricum*	1.00
Total	86.90		95.60		17.70
Grand total carbon stock (Fig. 2)	439.50		449.00		73.00
Contributed by dominant species (%)	19.77		21.29		24.25

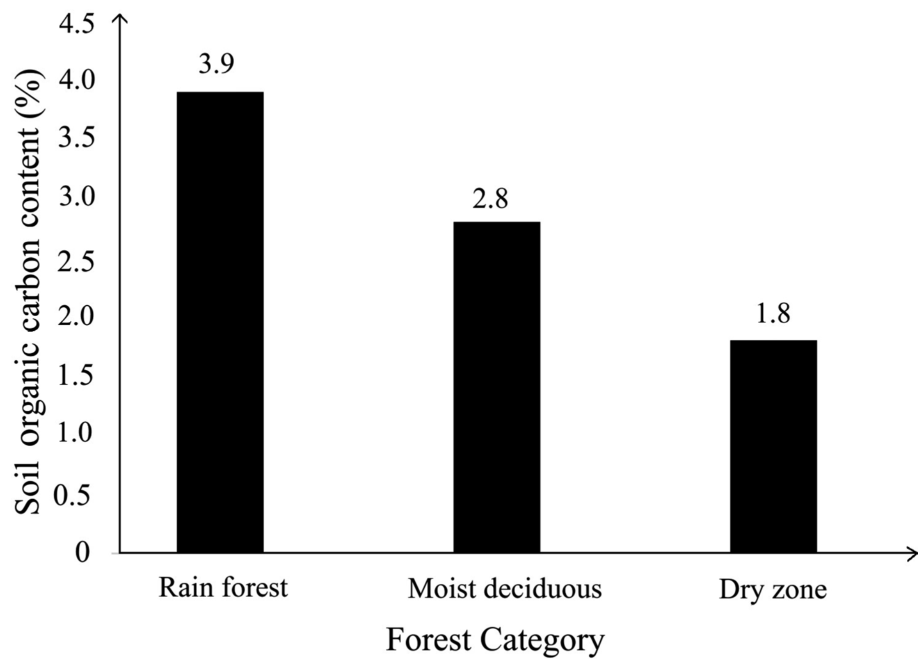

Fig. 3 The mean soil organic carbon content in tropical rain, moist deciduous and dry zone forests in Kenya

Soil organic carbon content in tropical forests of Kenya

The SOC content reduced from rain forests (3.9%), moist deciduous forests (2.8%) to dry zone forests (1.8%) (Fig. 3). One-way ANOVA indicates that the differences in the means of SOC recorded in tropical rain forests, moist deciduous forests and in dry zone forests were significantly different ($p < 0.001$) (Table 5).

Table 5 One-way ANOVA of soil organic carbon in tropical rain, moist deciduous and dry zone tropical forests in Kenya

	df	Sum Sq	Mean Sq	*F* value	Pr (> F)
SOC (%)	2.00	1936.81	968.40	318.19	< 0.0001
Residuals	2845.00	8658.69	3.04		

The post hoc analysis showed that the mean of SOC recorded in rain forest was significantly higher than the means of SOC recorded in moist deciduous ($p < 0.001$) and dry zone forests ($p < 0.001$). Moreover, the mean of SOC recorded in moist deciduous forests was significantly higher than the mean of SOC recorded in dry zone forests ($p < 0.001$). Therefore, while rain forests recorded higher means of SOC, dry zone forests recorded lower means of SOC.

Litter nutrient concentration in the tropical forests of Kenya

Figure 4 indicates that nitrogen concentration was higher in litter from rain forests (3.4%), compared to litter from moist deciduous (2.3%) and dry zone forest (3.3%). On the other hand, litter from rain forests recorded least phosphorus concentration (0.12%) compared to moist deciduous forests (0.13%) and dry zone forests (0.27%) increased from rain forest (0.12%) to moist deciduous forests (0.13%) to dry zone forests (0.26%) (Fig. 4). One-way ANOVA indicated that there were statistically significant differences in the means of nitrogen ($p = 0.027$) and the means of phosphorus ($p < 0.001$) concentration in litter collected from rain forests, moist deciduous forests and dry zone forests in Kenya (Table 6).

The pairwise analysis indicated that, the mean of nitrogen concentration in litter collected from moist deciduous forests (2.25%) was significantly lower than the mean of nitrogen concentration in litter collected from rain forests (3.39%) ($p < 0.001$) and in dry zone forests (3.25%) ($p < 0.001$). However, the mean of nitrogen concentration in litter collected from moist deciduous forests was not significantly different from the mean of nitrogen concentration in litter collected from dry zone forests ($p < 0.446$). On the other hand, the mean of phosphorus concentration in litter collected from dry zone forests (0.27%), was significantly higher than the means of phosphorus concentration in litter collected from rain forests (0.12%) ($p < 0.001$), and moist deciduous forests (0.13%) ($p < 0.001$). however, there was no significant difference in the mean of phosphorus concentration in litter collected from rain forests and moist deciduous forests ($p < 0.255$).

Discussion

Stem density and functional traits of trees in tropical forests along the ecological gradient

The results showed that dry zone tropical forests have smaller sized trees, high stem density and comprise of tree species with high wood specific gravity, compared to tree stems in rain and moist deciduous tropical forests. On the other hand, rain and moist deciduous tropical forests were dominated by larger trees of lower wood specific gravity. The trend may be attributed to harsh climatic and edaphic conditions in dry forest ecological zones, which does not favour tree growth to higher heights and diameters. Harsh climatic

Table 6 One-way ANOVA of the concentration of nitrogen and phosphorus in litter from the rainforest, moist deciduous forests and dry zone forests in Kenya

Parameter	Nitrogen (N)		Phosphorus (P)	
	N (%)	Residuals	P (%)	Residuals
df	2.00	2845.00	2.00	2845.00
Sum Sq	4735.25	19131.61	1233.42	35595.59
Mean Sq	367.63	6.73	616.71	1.25
F value	54.67		492.90	
Pr (> F)	< 0.0001		< 0.0001	

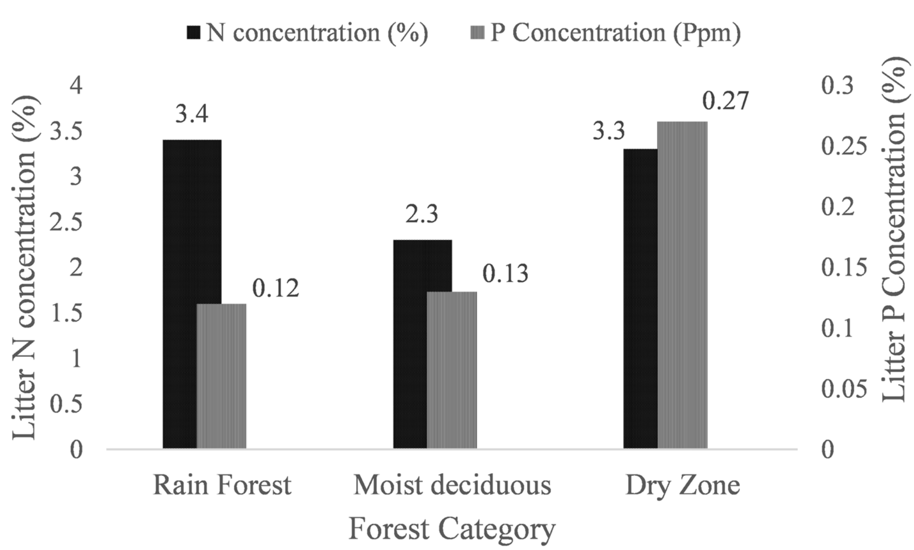

Fig. 4 Litter nutrient concentration in different tropical forest categories in Kenya

conditions such as low rainfall leads to soil water deficit, which reduces canopy conductance through increased vapour pressure deficit (Li et al. 2024a). High vapour pressure deficit causes physiological stresses and limits vegetation photosynthesis that reduces tree growth potential in terms of total height and DBH (Sha et al. 2022). In addition, prolonged periods of droughts in dry zone ecology increases mortality of larger trees (Wan et al. 2024). This is because it creates greater resistance in water transport, resulting from longer hydraulic paths, causing a decline in average total tree height and DBH (Bennett et al. 2015; Schlickmann et al. 2020). On the other hand, larger and taller trees in rain forests and moist deciduous forests, provide shading conditions beneath, a condition that inhibit regeneration and growth of shade intolerant young species, leading to low stem density (Hitimana et al. 2004; Nabais et al. 2018).

On wood specific gravity, our findings concur with Wiemann and Williamson (2002) and Mildrexler et al. (2020), that there are substantial differences in wood specific gravity between and within tree species depending on environmental conditions. Forests located in warmer and dry regions have higher proportions of dense species compared to forests in cool and wet regions (Wiemann and Williamson 2002; Mildrexler et al. 2020). According to Oliveira et al. (2022) and Nabais et al. (2018), over 96% of wood specific gravity variation within tree species is explained by variations in climatic conditions, where elevated temperatures and low rainfall favours development of tree species with higher wood specific gravity.

The study also found that the variations in climatic conditions could also affect litter nutrient concentration as a functional trait. This may also be as a result of differences in forest species composition. For example, litter from tree species with longer leaf life span on standing trees, have lower nutrient concentration due to high leaf nutrient resorption efficiency that lowers the litter quality (Huang et al. 2007). Moreover, low moisture content in dry zones reduce leaf decomposition rates due to slowed microbial activities, leading to slower release of nutrients contained in litter to the environment (Qu et al. 2020, 2024). High precipitation also causes high intensity of forest litter nutrient leaching, leading to reduced litter nutrient concentration as most nutrients are soluble in water (Mani and Cao 2019). However, the microbial activities will also reduce under extremely cold and wet conditions, leading to higher concentration of nutrients in litter (Chen et al. 2018; Yang et al. 2021).

This study found a negative association between phosphorus concentration and precipitation. Contrary, litter from moist deciduous forests recorded the least total nitrogen concentration, while litter from rain forests recorded slightly higher concentration of nitrogen (3.4%) compared to litter from dry zone forests (3.3%). Although old decaying litter may contain lower concentration of nutrients compared to fresh green litter (Wang et al. 2022), this reason may not explain the trend observed in our study. This is because litter used in phosphorus concentration analysis was the same litter used for total nitrogen concentration analysis, yet the trend of nitrogen concentration in litter was not affected. Therefore, the trend of total nitrogen concentration observed in our study may not be explained by climatic conditions, but other factors such as the concentration of other nutrients such as potassium, carbon–nitrogen ratio, geology and the chemical conditions of water and soil in the region (Mani and Cao 2019; Yang et al. 2021), which were out of this study's scope.

Tree and soil carbon stock potential in the tropical forests along the ecological gradient

Despite dry zone forests recording higher wood specific gravity and stem density compared to other categories of tropical forests, dry zone forests recorded the least above-ground, below-ground and total tree carbon stocks. This depicts that tree stem DBH, and total stem heights are significant factors affecting carbon sequestration potential in tropical forests. These findings concur with Mildrexler et al. (2020) and de Souza et al. (2021) that total tree carbon stock is driven by large trees in a forest. This is because of a significant positive relationship between total tree height and DBH with total carbon stock (Mildrexler et al. 2020). Harsh climatic conditions such as low rainfall, prolonged droughts and elevated temperatures that characterize dry zone ecological regions (Bailey 2014), constrain tree growth that eventually reduce their carbon sequestration potential (Oliveira et al. 2022; Sha et al. 2022; Mensah et al. 2023). However, below ground tree carbon in dry zone forests could have been underestimated in this study. According to Gao et al. (2018), tree species in arid and semi-arid regions have deep-root system. However, this was not considered in the equation used in calculating carbon potential in this study.

Although moist deciduous forests recorded slightly higher above-ground, below-ground and total tree carbon stocks compared to rain forests, the difference was not statistically significant. However, the difference shows that extremely high rainfalls and low temperatures will cause a decline in the carbon sequestration potential of tropical forests. The decline may be attributed to forest productivity, which increases with an increase in annual precipitation in dry to moderate climates, but decreases in extremely wet conditions (Schuur 2003). This is because extremely wet conditions coupled with extremely low temperatures constrains germination, root growth and water up-take, which affects tree growth and stem density (Li et al. 2024b). However, these findings contradict Stegen et al (2011) that recorded unnoticeable relationship between climatic conditions and forest biomass. This discrepancy may be attributed to the differences in scale of spatial extent and sample sizes between the two studies. Whilst spatial extent of Stegen et al. (2011) study ranged from 40.7° S to 54.6° N latitude with 256 plots, ours ranged from 5° S to 5° N latitude with 90 plots. This is because the impact of climatic factors usually decreases as the spatial scale increases (Liu et al. 2023).

Lower carbon stocks in dry zone forests indicates that the projected increase in temperature by 2.5 °C by 2050, accompanied by over 40% chances of annual drought recurrence, and increased rainfall interannual variability (Ondiko and Karanja 2021; Ayugi et al. 2022; Climate Centre 2022), will decline the carbon sequestration potential of tropical forests. This is because the extreme climatic conditions will lower the tropical forests' functional traits such as DBH and alter the forests' species composition, resulting to a change in their carbon sequestration ability (Nabais et al. 2018; Oliveira et al. 2022; Mensah et al. 2023). This is evident in our results on the list of top ten species contributing largely to carbon sequestration in each forest category. Although *Croton megalocarpus* is found in rain forests such as Kakamega forest and moist deciduous forests such as Cherangani forest in Kenya (Busuru et al. 2018), the species does not appear on the top list in the two forest categories. According to Li et al. (2024b), the functional traits of trees depend on complex biological tree growth processes, which are highly dependent on the prevailing climatic conditions.

The variations in SOC content exhibited in our results, suggest that SOC content in tropical forests is influenced by climatic conditions. This is because climatic factors such as temperatures and precipitation affect SOC content as they influence soil organic matter mineralization (Liu et al. 2023). According to Wilhelm et al. (2022), high precipitation causes oxygen deficiency and changes in soil pH due to soil flooding, which limits microbial activities responsible for decomposing soil organic matter to SOC. Climatic factors also influence vegetation type and biomass productivity in an ecosystem, which in turn induces SOC variations through plant-soil feedback loops (Dinakaran and Krishnayya 2008; Cao et al. 2013; Yao et al. 2023). Therefore, extreme climatic conditions resulting from climate change may have a significant impact on SOC content in the tropical forest.

Conclusion and recommendations

The potential of tropical forests to provide ecosystem services especially tree carbon sequestration, soil carbon and nutrient cycling varied along the ecological gradient. This is partly due to differences in climatic conditions such as precipitation that dictates the composition of tree species, the tree functional traits and other biological and chemical processes within tropical forests. This demonstrates that climate change and global warming are affecting the functioning of tropical forests, and eventually their ability to provide ecosystem services sustainably. Therefore, while tropical forests are sustainable options of climate change mitigation and adaptation, they are also susceptible to climate change impacts. Thus, there is an urgent need to institute sustainable policies and management strategies to minimize other risks affecting tropical forests such as anthropogenic threats. In addition, other measures such as efficient use of renewable energy sources instead of fossil fuels and enhanced carbon storage and capture should be emphasized in climate change mitigation, instead of over relying on forests.

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