Heliyon 9 (2023) e16121

Contents lists available at ScienceDirect

Heliyon

journal homepage: www.cell.com/heliyon

Research article

Spatio-temporal change of selected soil physico-chemical properties in grevillea-banana agroforestry systems

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ARTICLE INFO

Keywords:
Banana
Grevillea robusta
Agroforestry system
Soil properties
Central Kenya

ABSTRACT

In Africa, banana is mainly produced by smallscale farmers under complex production systems for both home consumption and income generation. Low soil fertility continually constraints its production and farmers are embarking on emerging technologies such as improved fallow, cover crops, integrated soil fertility management, agroforestry with fast growing tree species to address this challenge. This study aims at assessing the sustainability of grevillea-banana agroforestry systems by investigating the variability in their soil physico-chemical properties. Soil samples were collected in banana sole stands, *Grevillea robusta* sole stands and grevillea-banana intercrops in three agro-ecological zones during the dry and rainy seasons. Soil physico-chemical properties significantly differed among agroecological zones, cropping systems and between seasons. Soil moisture, total organic carbon (TOC), P, N, Mg decreased from the highland to the lowland zone, through the midland zone whereas soil pH, K and Ca showed the opposite trend. Soil bulk density, moisture, TOC, NH_4^+-N, K and Mg were significantly higher in the dry season compared to the rainy season but total N was higher in the rainy season. Intercropping banana with grevillea trees significantly decreased soil bulk density, TOC, K, Mg, Ca and P. Soils under banana sole stands accumulated higher potassium, magnesium, calcium, phosphorus with a higher soil bulk density and pH compared to grevillea-banana intercrops and grevillea sole stands. This suggests that intercropping banana and grevillea trees increases the competition for these nutrients and requires careful attention for the optimization of their interactive benefits.

1. Introduction

Small-scale farmers in Africa produce the majority of beer and cooking bananas, as well as plantains, for both home consumption and market [1,2]. In Kenya for instance, banana cultivation is carried out by approximately 390,000 smallholder farmers on an average acreage of 0.21 ha in subsistence setups [3] and the annual production of the crop was estimated at 1,414,176 Mg in 2018 [4]. In subsistence systems, banana and plantains are cultivated alongside a diverse range of food crops such as roots and tubers, vegetables, legumes, grains, coffee and cocoa, fruit and agroforestry trees [5]. The incremental banana production that has been reported since the last two decades is more as a result of increase in acreage due to land use change favouring banana over other crops [6] than increase in

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https://doi.org/10.1016/j.heliyon.2023.e16121
Received 21 February 2023; Received in revised form 6 May 2023; Accepted 6 May 2023
Available online 18 May 2023

the crop productivity.

Productivity of banana plantations in the Great Lakes Region has been constrained by both biotic and abiotic stresses, resulting in low yields [7]. The most common threats to these banana production systems include low soil fertility, diseases and pests and inadequate banana management practices [8–10]. Soil fertility has declined as a result of continuous farming without fallow, insufficient cultural methods such as low levels of organic amendment assimilation, and cultivation on steep slopes, which causes soil erosion [7]. To overcome this challenge, farmers resort to soil amendments with animal manure, improved fallow, cover crops or agroforestry practices with fast growing tree species. Integrated soil fertility management is the most recommended approach to restore the fertility of these soils [11]. However, animal manure and inorganic fertilizers are out of reach for the majority of Kenya's resource-poor farmers who, struggle to obtain the recommended quantities [12].

Alternatively, banana-legume cover crops and/or nitrogen-fixing tree-based systems are gaining popularity among these small scale farmers for wood, fodder and food needs [13] and indirectly improving their soil fertility. But studies on their effects on soil fertility replenishment have reported controversial results of neutral, positive or negative interactive effects of these crops on majority of soil nutrients [13,14]. *Grevillea robusta* is one of the fast growing tree species which have been widely adopted in forest plantation and as a shade tree in coffee and tea-based agroforestry systems in Central Kenya [15,16]. This tree can thrive on poor soils thanks to its proteoid roots that harvest water and nutrients from low fertility soils [17]. No competitive effects were noticed when it is grown with beans or banana in highlands of Burundi [18] but its cultivation with annual crops like maize resulted in yield decline due to below ground competition in semi-arid condition of Central Kenya, probably due to water scarcity [19]. These studies focused on the effects of grevillea in the juvenile phase (first five years) and grown on station which may change as these trees age or are grown on farms. The objectives of the present study were (1) to characterize grevillea litter and (2) assess the variability of selected soil physico-chemical properties in on-farm grevillea-banana agroforestry systems. Apart from the introduction, this paper is subdivided into three main sections, namely the materials and methods; the results and discussions.

2. Materials and methods

2.1. Study site

This study was conducted in Kirinyaga County, Central Kenya, situated between latitudes 0° 9′ 0.53″ and 0° 46′ 48″ South and longitudes 37° 8′ 44″ and 37° 28′ 45″ East and covers an area of 1478.1 km^2 [15]. It lies between 1158 m asl in the South and 5380 m asl at the Peak of Mount Kenya [20]. The area experiences a bimodal rainfall pattern with long rains from March to May and short rains between October and November [21]. Based on the classification by Jaeztold et al. [21], the study area was subdivided into three agro-ecological zones (AEZ): highland, midland and lowland zones. The highland zone was located in an area referred to as tea-dairy zone (lower highland zone - LH1), the midland zone classified as coffee-tea and main coffee zones (upper midland zones - UM1 and UM2), whereas the lowland zone was found in an area classified as cotton and marginal cotton zones (lower midland zones - LM3 and LM4) [21]. In Kirinyaga County, soil types differ within and across AEZs. As an illustration, soils in the UM2 and UM3 comprise majorly of humic nitosols, acrisols, luvisols, cambisols and ferralsols soil types. In the LM4 however, the dominant soil types include humic nitosols, eutric nitosols and pellic vertisols [21].

2.2. Selection of the farms and soil sampling

Soil samples were collected from banana sole stands, grevillea sole stands and grevillea-banana intercrops in the dry and wet seasons which occurred in April and July 2021, respectively. For each cropping system, three representative farms were randomly selected in each AEZ for soil sampling, at least three km apart. In total, 27 farms were identified within the three AEZs.

Under the banana-grevillea intercrops, soil sampling was done at fixed points around the tree [22] as an adaptation of the method described by Kamau et al. [23]. The area around the selected trees was delineated into four concentric zones, A, B, C and D. Approximately, the sampling point A, B, C and D around the single grevillea tree were always taken at 0.25; 1; 2 and 5 m from the tree stem, respectively, since the average diameter of these trees was 5 m under the current management scheme in the Central Kenya [24]. In banana and grevillea pure stands, two sampling points were marked [25]. From each sampling point, five samples were collected, bulked and mixed thoroughly to make one composite sample from which 1 kg was taken for soil physico-chemical properties determination. A total of 108 soil samples was collected in each of the seasons and samples were transferred into ziplock polythene bags and kept in a cool box before delivery to the laboratory.

2.3. Characterization of *Grevillea robusta* litter

Litter traps measuring one square meter (m^2) were installed in each grevillea sole stands and grevillea-banana intercrop for litter collection and left in place for 50 days, from 4 July 2021 to 22 August 2021. In banana-grevillea intercrops, the litter traps were installed in the zone under the tree canopy whereas in grevillea sole stands they were kept in the middle of the zone delineated by the four closest trees in fields. The litter was weighed and then processed for chemical analyses. Complete oxidation of samples was accomplished using Kjeldahl procedures followed by atomic absorption spectrophotometry for potassium, calcium and magnesium analyses. Phosphorus content in the litter was quantified by the Ascorbic Acid colorimetric method [26]. Lignin content was quantified following the Van Soest fiber analysis [27]. Polyphenols were extracted with methanol as described by Che Sulaiman et al. [28] and total soluble polyphenols were analysed by the Folin-Denis method [26].

2.4. Soil physico-chemical characterization

For the soil physico-chemical analyses, the following parameters were analysed: Soil Organic Mater, Soil Total Nitrogen, Soil ammonium and nitrate nitrogen (NH_4^+-N and NO_3^--N), P, K, Ca, Mg, pH, texture, bulk density and soil moisture content. Soil organic carbon was determined following Walkley-Black method [29,30], total nitrogen was determined by Kjedahl method. Available nitrogen namely NH_4^+-N and NO_3^--N were extracted using 2 M potassium chloride (KCl) method [31] and determined by the steam-distillation methods of analysis on a single 2 M KCl soil extracts [26]. Available K, Ca and Mg were analysed using the Mehlich double acid method followed by atomic absorption spectrophotometer analysis for their quantification whereas phosphorus was quantified by the ascorbic acid colorimetric method as described by Okalebo et al. [26]. Soil pH was measured with an electrical pH-meter in a 1 to 2.5 soil to water solution. Soil moisture content was determined gravimetrically and soil bulk density by the core ring method [25,26].

2.5. Data analysis

To assess the effects of agro-ecological zone, cropping system and season on soil factors, generalised linear mixed models (GLMM) were used using the package lme4 in R [32] because soil data deviated from normality (Shapiro-Wilk test) and lacked homogeneity of variance (Levene's test). When significant effects were obtained from analysis of variance (ANOVA), Tukey's HSD test was carried out for means separation at $p < 0.05$.

3. Results

3.1. Chemical characterization of Grevillea robusta litter

The quality of *Grevillea robusta* litter did not significantly differ between cropping systems. However, K and Mg content differed between AEZs (Table 1). In the lowland zone, K content was significantly higher at 3.75 g kg^{-1} compared to the highland (1.99 g kg^{-1}) and the midland (1.77 g kg^{-1}) zones. The Mg content in litter was significantly lower at 1.78 g kg^{-1} in the highland zone compared to 4.19 g kg^{-1} in the lowland zone. The highland zone produced more litter fall (12.44 Mg ha^{-1}) than the lowland and the midland zones which yielded 8.81 and 6.30 Mg ha^{-1}, respectively. The total organic carbon, organic matter, phosphorus, calcium and phenols in *G. robusta* litter decreased as the altitude increases (Table 1). Conversely, N and lignin content in litter increased from the lowland at 6.93 Mg ha^{-1} and 35.71% to the highland at 7.50 Mg ha^{-1} and 39.62%, respectively. This induced a decreasing C/N ratio trend from the lowland (65.17) to the highland (45.17) zones.

In the exception of the litterfall which was higher in grevillea sole stands (9.89 Mg ha^{-1}) compared to grevillea-banana intercrops (8.48 Mg ha^{-1}), there was no difference in the other parameters of interest in *G. rubusta* litter collected from the two farming systems (Table 1).

3.2. Characterization of soils under grevillea-banana agrosystems

Soil physio-chemical properties significantly differed between seasons (Table 2). For instance, total organic carbon amounted 26.95 g kg^{-1} in the dry season and was significantly higher compared to the one recovered in the rainy season (25.61 g kg^{-1}). The C/N

Table 1
Chemical composition of Grevillea robusta litter from different agro-ecological zones and cropping systems in Kirinyaga County.

	Agroecological zones						*p*-value		
	Lowland		Midland		Highland				
	Cropping systems								
	Grevillea	Grevillea-Banana	Grevillea	Grevillea-Banana	Grevillea	Grevillea-Banana	AEZ	CS	AEZ:CS
Litterfall (Mg/ha)	10.55^a	7.07^a	7.05^a	5.55^a	12.07^a	12.81^a	0.0529	0.4536	0.6438
C (g/kg)	425.40^a	435.97^a	367.07^a	425.37^a	376.37^a	403.55^a	0.1482	0.0622	0.4465
OM (g/kg)	731.69^a	749.86^a	631.35^a	731.63^a	647.35^a	694.11^a	0.1482	0.0622	0.4465
TN (g/kg)	7.17^a	6.70^a	7.30^a	5.57^a	7.43^a	7.57^a	0.4139	0.2739	0.4376
C/N ratio	62.33^a	68.00^a	52.33^a	78.00^a	54.67^a	53.50^a	0.4687	0.1618	0.295
K (g/kg)	3.81^a	3.70^a	1.93^b	1.61^b	1.72^b	2.26^{ab}	0.0053**	0.9361	0.74
P (mg/kg)	427.78^a	419.44^a	413.89^a	338.89^a	355.56^a	344.45^a	0.3611	0.4441	0.7487
Mg (g/kg)	3.81^{ab}	4.58^a	2.61^{ab}	3.01^{ab}	1.80^b	1.77^b	<0.001***	0.1425	0.3944
Ca (g/kg)	9.91^a	10.86^a	8.02^a	10.57^a	8.70^a	11.91^a	0.8255	0.149	0.8164
Lignin (%)	36.4^a	35.03^a	39.66^a	35.86^a	40.31^a	38.93^a	0.1112	0.1144	0.688
Phenol (%)	5.63^a	6.04^a	4.83^a	4.5^a	5.40^a	3.29^a	0.2125	0.3239	0.2714

Abbreviations: TOC = total organic carbon, OM = organic matter, TN = total nitrogen, C = carbon, N = nitrogen, K = potassium, P = phosphorus, Mg = magnesium, Ca = calcium, AEZ = Agroecological zone, CS= Cropping system. Mean separation by Tukey's Honest Significant Difference test. In the row, figures followed by similar letter are not significantly different. *p*-values significance: '***' *p*-value <0.001; '**' *p*-value <0.01; '*' *p*-value <0.05. $n = 3$.

ratio was significantly higher in the dry season at 10.81 compared to the rainy season (8.16). The total soil nitrogen was significantly higher in the rainy season at 3.44 g kg^{-1} than in the dry season at 2.78 g kg^{-1}. Significantly higher NH_4^-N was recovered from these soils during the dry than the rainy season. Soil potassium and magnesium contents were higher in the dry season compared to the rainy season. On the contrary, soil calcium content was higher in the rainy season compared to the dry season (Table 2).

Interactive effects were depicted between AEZs and cropping systems. In the highland zone, grevillea and grevillea-banana agrosystems had significantly higher soil moisture content compared to sole banana stands. Soil organic carbon was significantly lower in grevillea-banana intercrops (25.34 g kg^{-1}) than in grevillea and banana pure stands, which did not differ (28.38 g kg^{-1} and 27.92 g kg^{-1}, respectively). In the midland zone however, a significantly higher soil moisture was observed in banana and grevillea pure stands compared to grevillea-banana intercrop. Grevillea pure stands had a significantly lower soil bulk density than banana pure stands and grevillea-banana intercrops. The soil pH under grevillea pure stands was the lowest (Table 2). In the lowland zone, soil pH under grevillea was the highest whereas grevillea pure stands as well as grevillea-banana intercrops contained 0.03 gP kg^{-1} of phosphorus which was significantly lower than the mean value recorded in banana pure stands (Table 2).

Among the cropping systems, banana pure stands had a higher nitrogen content at 3.23 g kg^{-1} compared to grevillea-banana intercrops (3.10 g kg^{-1}) and grevillea pure stands (3.04 g kg^{-1}). The highest soil magnesium and calcium contents were found in banana pure stands followed by grevillea-banana intercrops and grevillea pure stands. Soil potassium content on its behalf was the highest in banana pure stands followed by grevillea pure stands and grevillea-banana intercrops (Table 2).

Comparing the AEZs, the total soil organic carbon decreased significantly from the highland zone at 28.46 g kg^{-1} to the lowland zone at 24.29 g kg^{-1}. Soil potassium content was significantly higher in the lowland zone (175.22 mgK kg^{-1}) than in the highland zone which was also significantly higher than the one found in the midland zone (Table 2). Soil magnesium content on its behalf increased significantly in the highland than in both the lowland and midland zones, whose soil magnesium contents did not significantly differ. Soil calcium content was not significantly lower in highland and midland zones compared to the lowland zone (Table 2).

4. Discussion

4.1. Effects of agroecological zone on the quality of G. robusta litter

The mean annual litterfall of 9.18 Mg ha^{-1} found in the present study corroborates with values reported by Becker et al. [33] which

Table 2
Physico-chemical properties of soil as influenced by AEZs and cropping systems during the dry and rainy seasons.

	AgroEcological Zones								
	Lowland			Midland			Highland		
	Cropping systems								
	Banana	Grevillea	Grevillea-Banana	Banana	Grevillea	Grevillea-Banana	Banana	Grevillea	Grevillea-Banana
Dry season									
Bulkdensity (g/cm^3)	0.76^{bc}	0.69^{cd}	0.77^{bc}	0.76^{bc}	0.76^{bc}	0.75^{c}	0.91^{a}	0.62^{d}	0.81^{b}
Moisture content (%)	28.53^{c}	28.87^{c}	29.84^{c}	41.98^{ab}	40.53^{ab}	37.77^{b}	42.37^{ab}	44.00^{a}	42.87^{a}
pH	5.76^{ab}	6.50^{a}	5.75^{ab}	5.53^{abc}	4.47^{c}	5.10^{bc}	5.82^{ab}	5.19^{bc}	4.95^{bc}
TOC (g/kg)	26.6^{b}	30.07^{a}	23.9^{b}	26.98^{ab}	27.93^{ab}	27.41^{ab}	29.75^{a}	28.93^{a}	27.39^{ab}
TN (g/kg)	2.42^{a}	3.08^{a}	2.60^{a}	2.35^{a}	2.42^{a}	3.42^{a}	2.93^{a}	2.67^{a}	2.52^{a}
C/N ratio	11.25^{a}	9.86^{a}	9.9^{a}	11.90^{a}	12.54^{a}	9.25^{a}	10.61^{a}	11.82^{a}	12.55^{a}
NH_4–N (mg/kg)	211.42^{a}	223.60^{a}	243.92^{a}	176.08^{a}	195.55^{a}	145.73^{a}	214.41^{a}	186.24^{a}	255.95^{a}
NO_3–N (mg/kg)	134.91^{a}	85.29^{a}	159.38^{a}	67.69^{a}	187.03^{a}	118.68^{a}	86.78^{a}	189.9^{a}	99.95^{a}
P (g/kg)	0.06^{a}	0.02^{c}	0.03^{c}	0.05^{ab}	0.02^{c}	0.02^{c}	0.04^{abc}	0.03^{bc}	0.03^{bc}
K (mg/kg)	170.17^{ab}	178.10^{a}	174.31^{a}	166.01^{ab}	132.66^{bc}	125.74^{c}	154.96^{abc}	159.32^{ab}	155.01^{ab}
Mg (mg/kg)	1092.22^{ab}	787.32^{ab}	499.75^{b}	701.04^{ab}	165.18^{b}	506.56^{b}	1807.14^{a}	242.00^{b}	309.36^{b}
Ca (mg/kg)	803^{a}	739.33^{a}	549.29^{ab}	480.33^{ab}	169.50^{b}	507.75^{ab}	558.83^{ab}	488.33^{ab}	508.58^{ab}
Rainy season									
Bulkdensity (g/cm^3)	0.96^{a}	0.61^{b}	0.7^{b}	0.67^{b}	0.59^{b}	0.73^{b}	0.80^{ab}	0.71^{b}	0.64^{b}
Moisture content (%)	27.71^{bcd}	22.16^{d}	22.74^{d}	27.21^{bcd}	24.01^{cd}	24.64^{cd}	31.78^{abc}	41.17^{a}	33.19^{ab}
pH	5.61^{ab}	5.72^{a}	5.60^{ab}	5.19^{abc}	4.76^{c}	5.10^{bc}	5.23^{abc}	4.93^{bc}	5.08^{bc}
TOC (g/kg)	27.28^{ab}	27.28^{ab}	21.16^{b}	28.16^{a}	26.52^{ab}	23.45^{ab}	28.74^{a}	29.53^{a}	28.75^{a}
TN (g/kg)	3.76^{ab}	2.96^{b}	3.09^{b}	3.64^{ab}	3.01^{b}	3.34^{ab}	4.27^{a}	4.13^{a}	3.63^{a}
C/N ratio	8.04^{a}	9.65^{a}	7.39^{a}	8.51^{a}	10.86^{a}	7.70^{a}	7.03^{a}	7.23^{a}	8.52^{a}
NH4–N (mg/kg)	119.56^{a}	94.55^{a}	113.60^{a}	107.47^{a}	127.98^{a}	115.16^{a}	114.42^{a}	126.48^{a}	105.90^{a}
NO3–N (mg/kg)	135.47^{a}	186.99^{a}	190.81^{a}	100.47^{a}	162.01^{a}	201.47^{a}	188.82^{a}	121.27^{a}	120.67^{a}
P (g/kg)	0.05^{a}	0.04^{ab}	0.03^{ab}	0.05^{a}	0.01^{b}	0.02^{b}	0.03^{ab}	0.03^{ab}	0.03^{b}
K (mg/kg)	173.62^{ab}	183.3^{a}	175.06^{a}	161.07^{ab}	97.69^{c}	105.85^{c}	135.52^{bc}	160.29^{ab}	135.83^{b}
Mg (mg/kg)	289.62^{ab}	230.94^{ab}	169.6^{b}	374.20^{ab}	158.58^{b}	318.67^{ab}	474.34^{a}	338.98^{ab}	428.58^{a}
Ca (mg/kg)	1345.17^{a}	1251.67^{ab}	799.46^{abc}	563.00^{bcd}	73.33^{d}	523^{cd}	447.83^{cd}	439.83^{cd}	429.75^{d}

Abbreviations: TOC = total organic carbon, TN = total nitrogen, C = carbon, N = nitrogen, K = potassium, P = phosphorus, Mg = magnesium, Ca = calcium. Mean separation by Tukey's Honest Significant Difference test. Means followed by the same letter are not significantly different, along the rows. $n = 6$ in banana and grevillea pure stands; $n = 24$ in grevillea-banana intercrop.

ranged from 4.6 to 10.7 Mg ha^{-1} in sites around Mt. Kilimanjaro and those reported by Lu and Liu [34] in evergreen hardwood forests of Central Taiwan which ranged from 6.58 to 9.17 Mg ha^{-1}. The high amount of *G. robusta* litterfall observed in the highland zone compared to the midland and the lowland zones could be explained by the age of the plantations, the planting density and the pruning regimes. In this zone, some *G. robusta* sole stands were more than 20 years old, with high plantation density and trees that had not been pruned since establishment leading to high litter accumulation.

The concentration of macronutrients in *G. robusta* litter decreased with increasing elevation, except N which was higher in the highland zone than the midland and lowland zones. The nutrient resorption trend observed in the present study corroborates with results reported by Lu and Liu [34] in evergreen hardwood forests of Central Taiwan where the litter nutrient fluxes of C, N, P, K, Ca and Mg tended to be higher in forests at low altitude (782 m asl) compared to the mid and the high altitudes (up to 2098 m asl). Besides, the prevailing drought and high temperature in the lowland zone are likely to hamper the nutrient retranslocation from the senescent leaves [35]. The resorption proficiency of P at 0.042% in the lowland zone denotes an incomplete and low P retranslocation [34] compared to the 0.037 and 0.035% found in the midland and highland zones, respectively. Nitrogen, on the other hand, showed a complete resorption in the lowland and midland zones compared to highland zone. These results are consistent with Drenovsky et al. [35] who found that complete P retranslocation in hardwood species was less frequently observed in vertisols, which is the predominant soil type in the lowland zones of Kirinyaga County [21,36], across a range of climatic conditions whereas N retranslocation was complete in the same conditions. Results of nutrient retranslocation in the present study reflect an adaptive behaviour of *G. robusta* to soil fertility, where low soil fertility induces an efficient nutrients retranslocation from senescent leaves to active and/or storage organs [35] as it is the case of most tropical ecosystems with low fertility [37], confirming that *G. robusta* can strive in oligotrophic ecosystems [17].

4.2. Spatial variability of soil physico-chemical properties in grevillea-banana agroforestry systems

The soil organic carbon was significantly higher in the highland zone compared to the midland and the lowland zones, possibly because this zone yielded higher amount of grevillea litter which decompose slowly due to high lignin content [38]. In addition to litter quantity, soil moisture and high temperature of the lowland zone may accelerate microbial and enzymatic activities resulting in faster decomposition rate and organic matter depletion [39–42]. Moreover, the low soil pH recorded in the highland and midland zones compared to the lowland zone can have exerted a selective pressure on the population of decomposers in favour of fungi which are tolerant to low pH values on the expense of bacteria and hence inducing a low decomposition rate [41]. Soil P and Mg were significantly higher in the highland zone compared to the midland and lowland zones whereas K and Ca followed an opposite trend. In the exception of Mg, these results are consistent with the altitudinal gradients of soil chemical properties of maize growing sites of East African highlands [43] as well as the one described along Mount Elgon slope, Eastern Uganda [44]. Since most of the N, P and S remain bound to soil organic matter, which does not decompose sufficiently under low temperature conditions [40,45], it can be assumed that the high amount of P observed in the highland zone compared to the midland and the lowland zones is due to the higher organic carbon reported in this zone.

4.3. Seasonal change in soil physico-chemical properties in grevillea-banana agroforestry systems

The seasonal variation in the bulk density reflects the effects of land preparation as the soil sampling during the dry season coincided with the end of the cropping season whereas soil sampling for the rainy season took place one month after crop establishment. The seasonal variability in total organic carbon and nitrogen can be due to an increasing microbial activity during the rainy season which accelerate mineralisation of organic matter and hence prone to great losses [46]. The high soil total nitrogen during the rainy season in this study did not result in the high amount of NH_4–N in the same season compared to the dry season. This might have been due to leaching, uptake by plants [47] or immobilization in soil microorganisms [48]. The high C/N ratio observed in the dry season compared to the rainy season might have influenced the balance between gross mineralisation, nitrification and nitrogen immobilization. High C/N ratios have been found to increase the activity of heterotrophic organisms, induce immobilization of mineralized nitrogen and slow down nitrification [48]. Unlike organic carbon and total nitrogen, exchangeable K and Mg were significantly higher in the dry season compared to the rainy season. Low soil pH and increasing water supply during the rainy season might have increased the solubility of these nutrients [49] and induce their availability for plant uptake or leaching though deep soil horizons [50] as was the case in grazing lands in Taranaki, New Zealand [51] or mangrove swamps of Nigeria [52]. These results agree with those reported in the Guinean savannah [53] and tropical rainforest ecosystems of southern Nigeria [54] where Ca, Mg, K and Na were higher in the dry season compared to the peak and the end of the rainy seasons.

4.4. Effect of cropping systems on soil physico-chemical properties in grevillea-banana agroforestry systems

The observed significant differences in organic carbon, bulk density, exchangeable bases and P between banana sole stands, grevillea sole stands and grevillea-banana intercrops can be due to differences in farm management practices such as organic matter inputs, inorganic fertilization and tillage practices. Grevillea pure stands produced more litter, as a result of high tree planting density and sporadic or no pruning at all, which is left to decompose on the soil surface resulting in a retarded decomposition [38]. However, in grevillea-banana intercrops, grevillea litter was integrated into the soil during site preparation and the branches were used as firewood, fodder, or combined with animal manure, potentially reducing soil C inputs. Banana sole stands and grevillea-banana intercrops had a higher bulk density compared to grevillea sole stands which was due to the high organic carbon in soils from the grevillea sole stands [55–58]. Moreover, the roots of *G. robusta* may contribute to soil organic matter resulting in increased pore space and low bulk density [59]. This is because *G. robusta* develops a large network of roots with a length density of 1.1–1.7 cm cm^{-3} and 50% of which can be found at less than 30 cm of the soil profile [60].

Exchangeable bases (K, Mg and Ca) and P were always significantly higher in banana sole stands compared to grevillea-banana intercrops and grevillea sole stands. Such a trend was reported by Nesper et al. [61] in coffee-based agroforestry systems where C, Mg, B and available S kept on decreasing with the increase in the density of *G. robusta* on the expense of other native shading trees in India. In addition to a potential competition for soil nutrients between banana and grevillea, differences in soil fertility management might have contributed to the significant difference in exchangeable bases and P between the cropping systems. Apart from the regular and substantial amounts of manure applied to banana sole stands compared to *G. robusta* sole stands, banana sole stands would benefit from the inorganic fertilizers applied on vegetable or cereal intercrops. Besides, banana sole stands were located in the vicinity of the homestead, where they could increasingly receive organic inputs in form of kitchen waste and crop residues, whereas *G. robusta* pure stands were owned by schools or located far from homestead. These results agree with Okumu et al. [8] and Muthamia et al. [62] who found a soil fertility gradient with increasing distance from the homestead in banana production areas of Central Highlands of Kenya. Similar results have been reported from Central Uganda where soil fertility management was more intense near the homestead than at distant points in banana farms [10].

5. Conclusion

Intercropping *G. robusta* with banana significantly decreased the measured soil nutrient content in the exception of soil N (total and available N). Soils under banana sole stands accumulated higher potassium, magnesium, calcium, phosphorus with a higher soil bulk density and pH compared to grevillea-banana intercrops and grevillea sole stands. Intercropping banana and grevillea trees increases the competition for these nutrients. In this condition, it is assumed that the growth and productivity of the intercrops might be affected, inducing a malfunctioning of the resulting agroforestry system. Moreover, the suitability of *G. robusta* as an agroforestry species can be questionable given that it had negative effects on the measured soil physico-chemical factors. However, knowledge about the best agroforestry practices that can guarantee its safe integration in agricultural settings is still lacking. Thus, studies to determine the grevillea tree spacing, pruning regime and maximum age that minimize the above and below-ground competition in a banana-grevillea intercrops are required to address on-farm tree management practices and optimum land allocation.

Author contribution statement

Musongora Kambale Muyisa, Karanja Nancy, Kimenju Wanga John, Kamau Solomon: Conceived and designed the experiments; Performed the experiments; Analysed and interpreted the data; Wrote the paper.

Musongora Kambale Muyisa Musongora and Kamau Solomon: Contributed reagents, materials, analysis tools or data.

Data availability statement

Data will be made available on request.

Additional information

No additional information is available for this paper.

Declaration of competing 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

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