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Soil fertility status under mixed pastures in irrigated Tsitsikamma dairy farms: case studies

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Abstract
Animal manures are increasingly receiving renewed interest as an alternative to synthetic fertilizers. While they may improve ecosystem functions, there is limited information on short-term effects of organic amendments on soil reaction and nutrient dynamics in irrigated mixed dairy pastures, especially in the context of the Tsitsikamma region, South Africa. This study examined the soil fertility status of minimum tilled 6-year-old pasture-mixed dairy farms (F1, F2, F3, F4 and F5) in the Upper (UT) and Lower (LT) Tsitsikamma regions treated with different rates of NPK (nitrogen, phosphorus, potassium) fertilizer alone or in combination with poultry manure (PM) and/or dairy effluent (DE). Soil samples were collected at 0–15, 15–30, 30–45 and 45–60 cm depth intervals and analysed for soil pH, P, K, Ca and Mg. Results of this study revealed variable trends on soil pH and nutrient changes between farms, suggesting an influence of some inherent soil properties in addition to the 6-year applied management practices. When averaged over sampled farms, surface placement of soil amendments and limited soil disturbance resulted in surface stratification of soil pH, P, K, Ca and Mg. On the other hand, integration of organic and inorganic fertilizers induced significant changes in nutrient contents and stocks to a depth of 60 cm, especially in the LT region. A combination of NPK fertilizer, PM and/or DE applied in pasture mixtures generally showed potential to improve soil fertility in both regions. As such, adoption of this combination by farmers could cut down reliance on expensive synthetic fertilizers and costs of dairy production. However, studies are still necessary in this region to validate the observed results.

Keywords Animal manure · Mixed dairy pastures · Plant nutrients · Soil fertility · South Africa

1 Introduction

South Africa is the sixth largest milk producer (4 million tons per year) in Africa, with high production coming from the coastal areas due to their mild temperatures and good rainfalls [1–3]. However, adverse effects of climate change and declining soil fertility seem to manifest on pasture and milk production [4]. Conversion of native rangelands to irrigated kikuyu (*Penisetum clandestinum*) pastures was seen as an option to restore soil fertility and improve dairy production [3]. However, due to its dormancy and loss of nutritive value in winter [5, 6], kikuyu grass is currently over-sown with ryegrass (*Lolium perenne*) and clover (*Trifolium spp.*) as cool-season grass species to maintain availability of quality fodder throughout the year and reduce nitrogen (N) fertilizer requirement. Even so, Viljoen et al. [6] is of the opinion that N fertilization is still essential considering that clover, has consistently exhibited vulnerability in terms of competition for resources when over-sown into a mixture of kikuyu and ryegrass.

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Fertilization has direct benefits on soil fertility and forage production, but escalating prices of chemical fertilizers and limited financial support for most farmers, especially in developing countries, are negatively affecting the dairy industry [3]. Farmers are still not proficient in the use of chemical fertilizers, which in most cases results in excessive or insufficient nutrient supply and negative implications to the environment [7, 8]. In addition, fertilizer guidelines that have been declared outdated because they disregard nutrients from other sources such as plant residues and animal excretions are still a common tool among South African farmers [6].

Awareness on environmental pollution by chemical inputs and their increasing costs have led to a resurgence of interest in animal manure as a cheap soil amendment and a plausible alternative to reduce great dependency on chemical fertilizers. Despite the growing interest in the use of organic manure on grass pastures in the southern Cape coastal region [3, 9], there is limited information on soil reaction and nutrient dynamics, especially in the context of Tsitsikamma. In fact, we are not aware of any study that explored effects of different soil amendments on nutrient contents and stocks in this region. The only two studies conducted in the Tsitsikamma dairy farms of the southern Cape coastal region measured soil organic matter (SOM) storage to 10 cm [5] and 60 cm [9] soil depths. Milne and Haynes [5] found that cultivation of annual ryegrass and kikuyu pastures resulted in higher SOM in the lower rainfall, eastern side of Tsitsikamma, but lower SOM in the higher rainfall, western side of Tsitsikamma when compared to the native vegetation. Loke et al. [9] on the other hand, had a different objective where they investigated effects of different fertilizer sources on carbon (C) and total nitrogen (N) fractions. Results of this study revealed that the combined use of lower synthetic fertilizer (N, phosphorus (P) and potassium (K)) rates dairy effluent and poultry manure has potential to improve these SOM indices to 60 cm soil depth.

Although the beneficial effects of animal manure or plant nutrients have been documented [10–13], it has been demonstrated that animal manure are comparatively low in nutrient content, which often prompts larger quantity applications to meet crop demand, as opposed to synthetic fertilizers [7, 14]. Quantities of animal manure needed for fertilization should be less of a problem because a substantial 7 Pg of animal manure is produced each year worldwide [11]. South Africa also produces 3 million tons of animal manure annually, though only 25% is used as fertilizer [10]. In addition, both organic and inorganic fertilizers can be used together to compensate for low nutrient contents, while avoiding high production costs [9]. Therefore, sensitization of farmers on organic manure as a cheap source of plant nutrients is critical considering escalating costs of synthetic fertilizers and predicted future dependency on animal manure as soil amendment [10, 11, 13]. This calls for less studies undertaken in confined research stations where there is limited to no participation of farmers and policy makers.

It is against this backdrop that case studies were chosen to generate baseline information, which would be important for adoption or development of management strategies that can sustain pasture and dairy production and reverse soil degradation, especially in the context of Tsitsikamma region [3, 15]. This study was carried out to assess changes in management practices adopted for pasture production on soil fertility in the upper 60 cm soil depth of Tsitsikamma dairy farms. Management changes that prompted this study included irrigated mixed pastures of kikuyu-ryegrass-clover pasture system as a substitute for a single pasture species either kikuyu grass or ryegrass, applications of organic manure, inorganic fertilizer or their combination, and minimum tillage as a replacement for conventional tillage, all applied for a duration of 6 years. Soil fertility indicators measured form a key component of a soil quality index developed specifically for kikuyu-ryegrass pasture systems [16]. We hypothesized that applications of manure along with NPK fertilizer would enhance soil pH to a range within which most nutrients are available for plant uptake and the contents and stocks of selected essential plant nutrients viz. extractable P and exchangeable K, calcium (Ca), and magnesium (Mg) across the sampled soil profile.

2 Materials and methods

2.1 Study area

This study was carried out in the Tsitsikamma region (32° 13′ S, 26° 35′ E), which is regarded as the 'heart' of the dairy farming industry in the Eastern Cape (Fig. 1). Tsitsikamma forms a narrow belt in the west of Humansdorp between the Kareedouw and Tsitsikamma mountains. Soils are generally sandy (< 10% clay; [17]), acidic (pH(KCl) 3.3–4.5), leached and low in nutrient content, and predominantly show origin of the Table Mountain sandstone [18–20]. However, a narrow strip of Bokkeveld shales exist from Witelsbos towards the Bloukrans River [18]. The dominant soils in this study site [19, 20] include Cartref (Leptic Acrisol), Kroonstad (Albic Stagnosol), Longlands, (Albic Cambisol), Katspruit (Luvic Stagnosol),

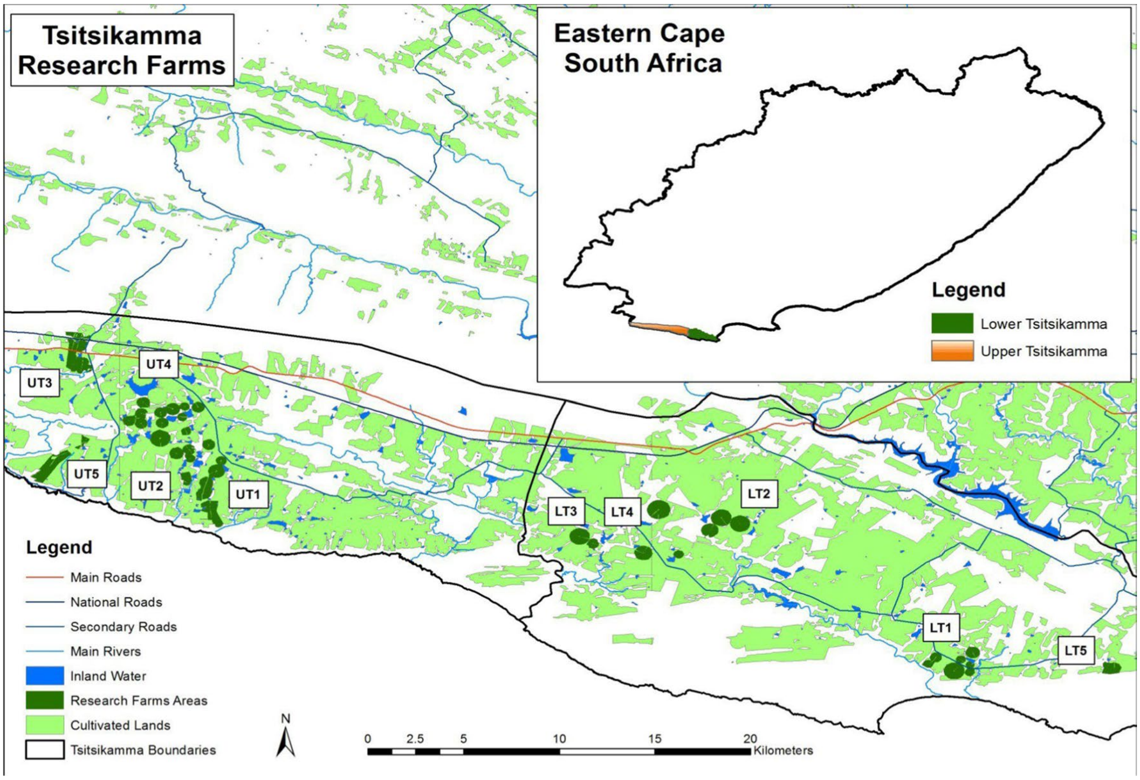

Fig. 1 Six-year-old mixed pasture dairy farms in the Upper (UT) and Lower (LT) Tsitsikamma regions

Constantia (Albic Podzol), and Oakleaf (Petric Durisol) forms, while Clovelly (Haplic Regosol) and Avalon (Plinthic Regosol) forms are less dominant and make up the balance in the better drained areas.

Owing to a change in topography and rainfall, Tsitsikamma is divided into two regions; upper (UT) and lower (LT) regions. As a result, production techniques and adopted enterprises differ in some respects between the two regions. The topography of the UT region is flat to rolling and is broken by deep gorges which run from north to south. The LT region has a rolling topography bisected by gorges, which are not as deep as in the UT region. The altitude ranges from sea level in the LT region to approximately 350 mm in the UT region [18]. Annual rainfall varies from approximately 600 mm in the east to 1250 mm in the west, but the distribution is relatively even throughout the year for each location [2]. The rainfall does however peak in autumn and spring, while summers are relatively dry. Winters are mild, while summers are hot with mean daily temperatures varying from 10 °C in winter and spring to 35 °C in summer and autumn. Frost is rare during winter.

2.2 Management and farm selection criteria

This study was carried out on 10 pasture-based dairy farms in the Tsitsikamma, of which an equal number (five farms per region, represented by F1 to F5) was selected in the UT and LT regions. Selection of the farms in both UT and LT regions was based on the following criteria: (1) pasture mixtures consisting of kikuyu, ryegrass, and clover; (2) adopted minimum tillage practices; (3) six years established pasture mixtures; (4) irrigated pasture mixtures; and (5) availability of accurate fertilizer application rates from the last 6 years. Before conversion to pasture production, the study sites were natural rangelands dominated by Fynbos vegetation. As a result of continuously deteriorating rangeland resources for dairy cattle, these areas were converted into cultivated pasture production systems with kikuyu as the main pasture species [3]. The introduction of pasture production resulted in small patches of native vegetation remaining behind, which belong to the Tsitsikamma Sandstone Fynbos community. This plant community includes a very narrow shoreward band of dune fynbos, which typically consist of a variety of shrubs, herbs, and grasses, having a low stock-carrying capacity [21].

Soils of the selected dairy farms have a more variable and higher plant nutrient status [19] due to fertilization by farmers to ensure adequate pasture production. Established threshold values are 4.5 for pH (KCl), 30 mg kg^{-1} for P, 80 mg kg^{-1}

for K, 500 mg kg^{-1} for Ca, 100 mg kg^{-1} for Mg, and less than 60 mg kg^{-1} for Na [22], implying under- and over-fertilization in some instances.

Although the farms met the selection criteria, they differed in their management practices e.g., they have varying fertilizer application rates, irrigation frequencies and grazing tendencies (Table 1), hence the use of between-subject design in both regions as the layout of the experiment. Differences in management practices were mainly due to availability of resources to farmers. Unfortunately, there were no available records on irrigation frequencies and dairy effluent application rates. Unscreened 2 t ha^{-1} of poultry manure and unknown rates of solid dairy effluent were spread in some farms, while liquid dairy effluent was applied with irrigation water via the centre pivot system. The organic wastes were applied on farms in combination with a blended NPK fertilizer (Table 1). None of these organic wastes' chemical composition was determined. However, in general, the application of N, P, and K through either solid or liquid dairy effluent should be negligible compared to poultry manure which probably amounted to 22–35 kg N ha^{-1}, 17–22 kg P ha^{-1} and 15–23 kg K ha^{-1} [14].

2.3 Soil sampling

A systematic grid procedure was followed for collecting soil data from each centre pivot irrigation system (hereafter referred to as pivot) on a farm. Google Earth was used to locate a farm with existing and working pivots (Fig. 2A). The resulting image was stored on a computer and imported to software that coincides with the Veris hydraulic soil auger (Veris Technologies, Salina, KS, USA; Fig. 2B, C). The boundaries of the pivots were marked and pivot tracks delineated. After the tracks were discarded, a grid was drawn such that the points for sampling represented at least 0.3 ha; i.e. 54 × 54 m, and then converted to a readable format by a Global Positioning System (GPS), and transferred to the GPS (Fig. 2D). However, it should be noted that the area under the pivot was not constant as was determined by the size of the farm and pivot.

The above-mentioned soil auger, equipped with a probe measuring soil reflectance, was used to take absorbance readings at 0–15, 15–30, 30–45, and 45–60 cm soil depths (Fig. 2A). The 15 cm depth interval was selected based on the depth of genetic horizons to avoid mixing parts of different horizons which may lead to misleading information from soil analysis. Four absorbance readings were taken per depth interval at 1 m distances from each other around all grid points. The mean absorbance readings were recorded by a spectrophotometer fixed on the soil auger and the resulting values were stored on an attached computer.

Soil cores from a sufficient number of grid points randomly distributed under a pivot were sampled for the standardization of the spectrophotometer on the soil auger. Three soil cores (60 × 5 cm) were collected with the soil auger's core sampler (Fig. 2C) per depth interval within the 1 m^2 area around a grid point (Fig. 2D). The soil cores were air-dried, mixed, and weighed to estimate bulk density [23]. The composite samples were then sieved through a 2 mm screen and analysed for soil pH using 1:2.5 soil to 1 mol dm^{-3} KCl [24], extractable P using Bray 2 solution [25] and exchangeable K, Ca and Mg with 1 mol dm^{-3} NH_4OAc at pH 7 [26]. Data on SOM indices were attained from Loke et al. [9] for the purposes of running Pearson's correlation analysis.

Table 1 Soil management in the irrigated Upper (UT) and Lower (LT) Tsitsikamma dairy farms

Region	Farm	MA (ha)	PM	Herbicide	Effluent	N	P	K	Ca
						kg ha^{-1}			
UT	F1	202	No	Yes	No	401	15	81	0
	F2	137	No	Yes	No	414	0	269	0
	F3	154	No	Yes	No	376	19	270	0
	F4	293	Yes	Yes	No	870	95	284	0
	F5	92	No	Yes	Yes	308	4	70	0
LT	F1	171	Yes	No	Yes	345	11	60	0
	F2	166	Yes	Yes	Yes	263	14	50	560
	F3	82	No	No	No	234	0	127	0
	F4	143	No	No	No	234	0	127	0
	F5	42	Yes	No	Yes	297	43	80	500

MA milking area, *PM* poultry manure, *N* nitrogen, *P* phosphorus, *K* potassium, *Ca* calcium, *F1 to F5* represent sampled farms

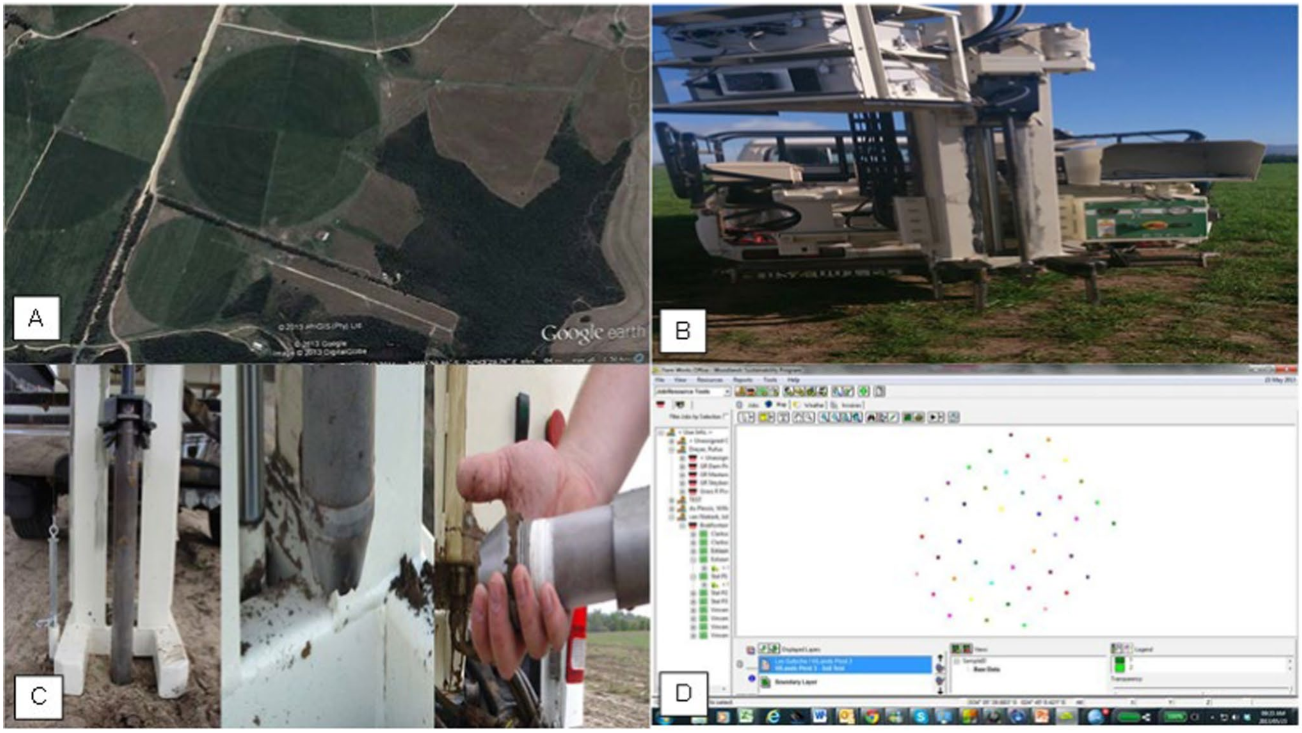

Fig. 2 Sampled farms (**A**), Veris P4000 (**B**), core sampler (**C**) and sampling points under centre pivot (**D**)

2.4 Data processing

Data used for this study are presented in contents (mg kg^{-1}) and in stocks (kg ha^{-1}). Content measurements were obtained from probe absorbance readings and core soil samples whereas stock measurements were obtained from a conversion of the content data to stocks by taking bulk density and sampling depth into account. Linear mixed model analysis, also known as REML analysis [27], was applied to the averages of selected soil fertility indicators over grid points under pivots. A nested and weighted analysis was used as the numbers of centre pivots per category (area, farm, and pivot) were very different and therefore only the first 7 pivots were used for analysis. Fixed effects were specified as main effects (farm and depth) and their interactions per region. The random effect was specified as depth within pivot, pivot within farm, and farm within area. Fisher's protected least significant difference test, with the standardized range [28], was used to compare means at a 1% level, as the farm and pivot variances were not homogeneous [29]. Data were analysed using GenStat® [27]. Pearson correlation coefficients were calculated to assess relationships between selected parameters in the upper 30 cm soil depth. Selection of 15 cm soil depth for correlation analysis was based on treatment effects that seemed to be more pronounced in this layer.

3 Results

Table 2 presents a summary of REML analyses. The main effects of farm and depth had significant effects on soil pH (KCl), extractable P, and exchangeable K, Ca and Mg in both UT and LT regions. The interactive effects of farm and depth were also more pronounced on P, K, Ca and Mg contents and stocks than on soil pH.

Table 2 Summary of the REML analyses on selected soil quality indicators under mixed pastures in the Tsitsikamma dairy farms

Variation	pH (KCl)	Extractable P		Exchangeable K		Exchangeable Ca		Exchangeable Mg	
		Content	Stock	Content	Stock	Content	Stock	Content	Stock
UT									
Farm	Ns	**	**	**	**	**	**	**	ns
Depth	**	**	**	**	**	**	**	**	**
Farm x depth	Ns	**	**	**	**	**	**	**	**
LT									
Farm	**	**	**	**	**	**	ns	**	**
Depth	**	**	**	**	ns	**	**	**	**
Farm x depth	Ns	**	**	**	**	**	**	**	**

P phosphorus, *K* potassium, *Ca* calcium, *Mg* magnesium, ** indicate significant difference at $P < 0.001$, *ns* not significant

3.1 Soil pH

Applied management practices on farms did not influence soil pH in the UT region, but significantly increased soil pH from 4.91 in F4 and 5.13 in F5 to 5.74 in F1 in the LT region (Fig. 3a). In the same region, soil pH was lower in F2 and F3 compared to that recorded in F1, but higher than soil pH in F4 and F5, although differences were not significant. Soil pH exhibited similar trends in both regions when comparisons were made between soil layers as it decreased with an increase in soil depth (Fig. 3b). However, differences were significant between the 0–15 cm and 15–30 cm, 30–45 cm or 45–60 cm soil layers, except in the LT region where soil pH was virtually the same between the 0–15 cm

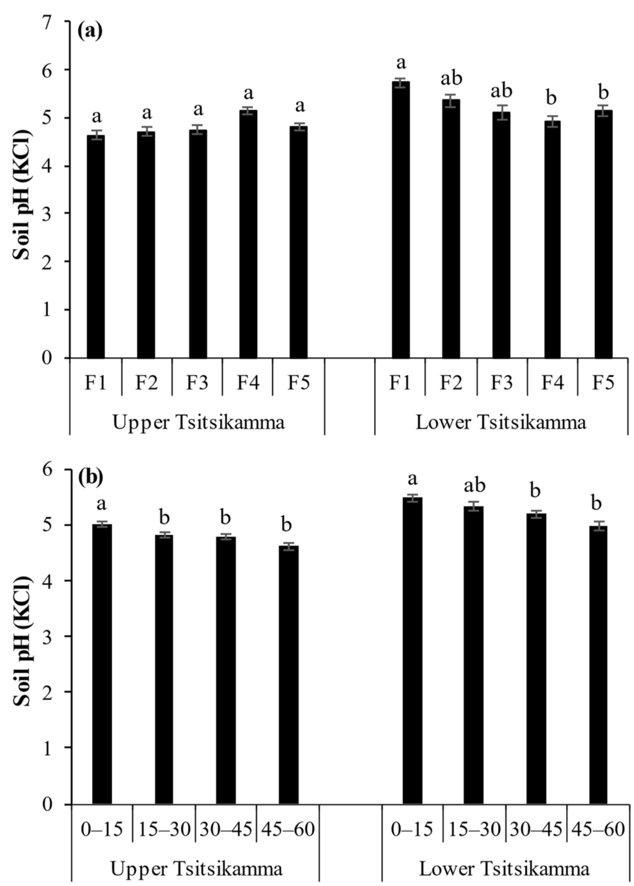

Fig. 3 Effects of different farm management (**a**) and soil depth (**b**) on soil pH under mixed pastures in the Tsitsikamma dairy farms. Error bars indicate standard error of means. Different letters per site indicate significant difference

and 15–30 cm soil layers. As indicated earlier, the interaction of farm and depth did not have much influence on soil pH (Table 2).

3.2 Extractable P

Contents and stocks of P were higher in F4 compared to those conceded in F2, F3 and F5 in the UT region, although differences were not significant between F1 and F4 (Fig. 4a, b). In the LT region, P contents and stocks were highest in F2 and F5 followed in a descending order by F1, F4 and then F3, although differences were not significant between F1 and F2, F4 or F5 (Fig. 4a, b). Similar to soil pH, the P contents and stocks decreased with an increase in soil depth. In the UT region, P contents and stocks were higher in the upper 15 cm soil depth compared to those observed in the 15–30 cm, 30–45 cm and 45–60 cm soil layers (Fig. 4c, d). That is, below 15 cm soil depth, P contents and stocks did not change significantly. In the LT region, the 0–15 cm soil layer had, on average, 51% higher P contents and 42% higher P stocks relative to the 15–30 cm, 30–45 cm and 45–60 cm soil layers, which did not differ significantly in terms of P contents (Fig. 4c) and stocks (Fig. 4d).

The interaction of farm and depth also influenced P contents and stocks (Table 2). In each farm, P contents and stocks were higher in the 0–15 cm soil layer compared to 15–30 cm, 30–45 cm and 45–60 cm soil layers (Table 3). However, differences between soil layers were not significant in F2 and F3 (P stocks) of the UT region and in F1 (P contents and stocks) of the LT region. Comparisons between farms in the UT region show that P contents and stocks in the 0–15 cm soil layer were higher in F4 than in F1, F2, F3 and F5. Below 15 cm soil depth, differences in P contents and stocks between farms were not significant. Although differences were not always significant, P contents and stocks in F3 of the LT region were lower than those recorded in F1, F2, F4 and F5, regardless of soil depth.

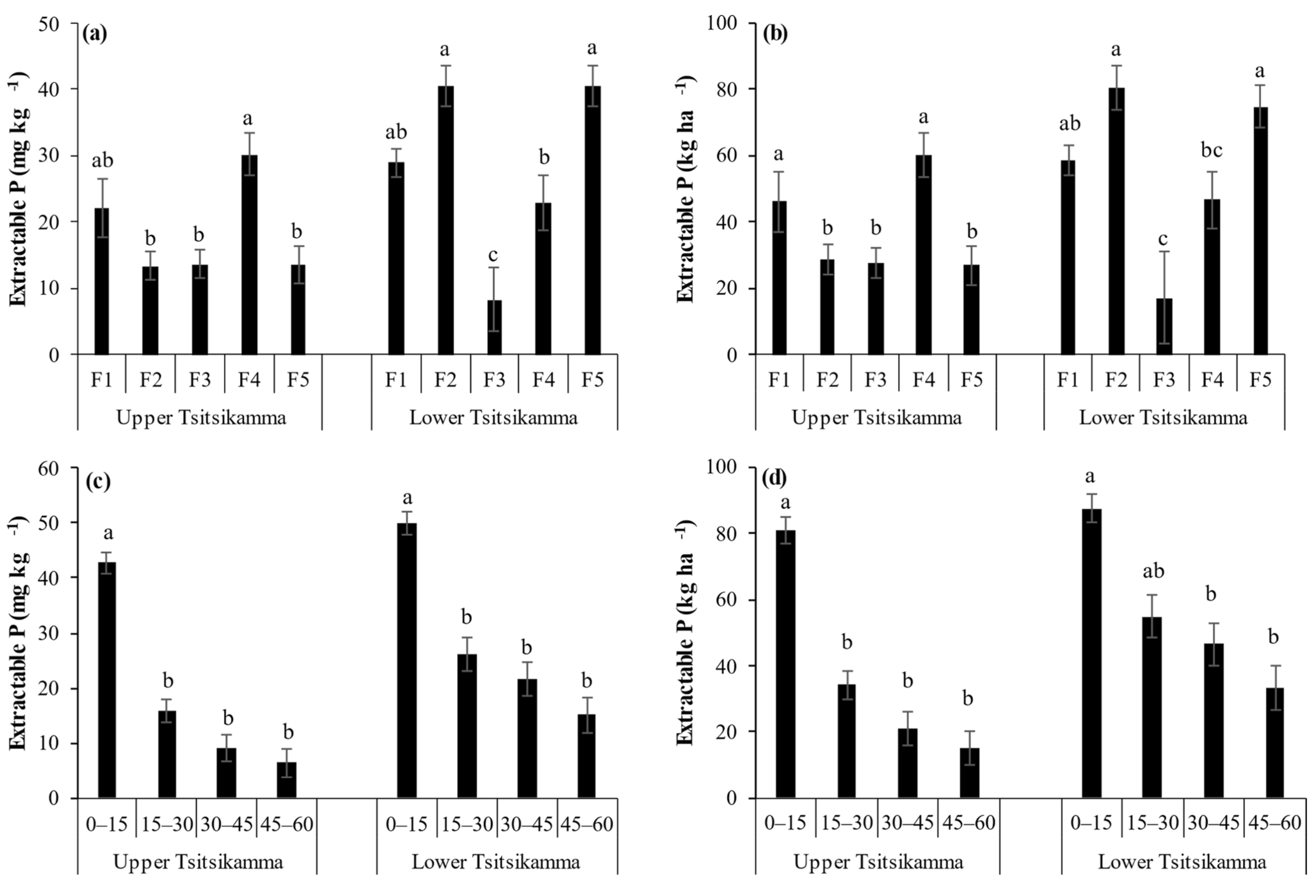

Fig. 4 Effects of different farm management (**a**, **b**) and soil depth (**c**, **d**) on extractable phosphorus (P) contents (**a**, **c**) and stocks (**b**, **d**) under mixed pastures in the Tsitsikamma dairy farms. Error bars indicate standard error of means. Different letters per site indicate significant difference

Table 3 Interactive effects of farm and depth on extractable phosphorus contents and stocks under mixed pastures in the Upper (UT) and Lower (LT) Tsitsikamma dairy farms

Region	Depth (cm)	0–15	15–30	30–45	45–60	0–15	15–30	30–45	45–60
	Farm	mg kg^{-1}				kg ha^{-1}			
UT	F1	51.7(4.9) Aab	18.5(6.3) Ba	12.0(9.8) Ba	5.72(9.8) Ba	103(10) Aab	41.4(13) ABa	27.0(20) Ba	13.2(20) Ba
	F2	24.2(2.4) Ac	14.3(2.4) ABa	8.43(2.5) ABa	6.41(2.6) Ba	47.1(5.1) Ab	31.8(5.1) Aa	19.9(5.3) Aa	16.0(5.5) Aa
	F3	24.5(2.6) Ac	14.4(2.7) ABa	9.12(2.9) ABa	6.48(3.0) Ba	44.9(5.5) Ab	29.3(5.6) Aa	21.8(6.0) Aa	14.8(6.3) Aa
	F4	79.4(5.3) Aa	20.5(5.6) Ba	10.8(5.0) Ba	9.98(5.4) Ba	148(11) Aa	45.4(12) Ba	23.9(10) Ba	22.6(11) Ba
	F5	33.9(4.7) Abc	10.9(5.2) Ba	5.54(4.3) Ba	3.93(4.3) Ba	61.6(9.8) Ab	23.1(11) ABa	13.1(8.8) Ba	9.53(8.8) Ba
LT	F1	32.3(2.7) Ab	34.8(2.6) Aa	29.1(2.5) Aa	19.7(2.5) Aa	59.0(5.6) Abc	73.1(5.5) Aa	60.7(5.3) Aa	41.6(5.3) Aa
	F2	66.7(3.3) Aa	29.6(3.3) Bab	35.4(3.3) Ba	30.5(3.3) Ba	117(7.0) Aa	61.6(7.0) Bab	76.1(7.0) Ba	67.2(7.0) Ba
	F3	24.1(6.5) Ab	6.50(13) Bc	1.75(13) Bb	1.00(13) Bb	49.2(13) Ac	13.3(27) ABc	3.87(27) Bc	2.23(27) Bb
	F4	58.1(5.7) Aa	16.7(6.0) Bbc	11.9(6.8) Bb	4.60(7.0) Bb	112(12) Aa	37.3(12) Bbc	26.3(14) Bb	11.0(14) Bb
	F5	68.7(3.3) Aa	43.6(3.3) Ba	30.4(6.3) BCa	19.6(3.3) Ca	101(6.9) Aab	88.6(6.9) ABa	65.3(7.0) ABa	44.3(7.0) Ba

Different upper-case letters indicate significant differences ($P < 0.001$) among soil layers per farm, while different lower-case letters indicate significant difference ($P < 0.001$) between farms per layer per region. In parentheses are standard errors of means

3.3 Exchangeable K

Exchangeable K differed between farms, with F3 and F4 conceding significantly higher K contents and stocks compared to F2 in the UT region (Fig. 5a, b). In the LT region, F3 had 67 to 72% lower K contents and stocks relative to F2 and F4 (Fig. 5a, b). In both regions, K contents and stocks recorded in F1 and F5 did not differ significantly with those obtained in F2, F3 and F4. Comparisons between sampled soil layers showed that K contents in the 0–15 cm soil layer were, on average 47% higher than K contents in the 15–30 cm, 30–45 cm and 45–60 cm soil layers in the UT region (Fig. 5c), and 51% higher than K contents recorded in the 15–30 cm, 30–45 cm and 45–60 cm soil layers in the LT region (Fig. 5c, d). In both the UT and LT regions, K stocks displayed similar trends, even though differences were not significant in the LT region across the sampled soil profile (Fig. 5d).

The farm x depth interaction had significant effects on exchangeable K (Table 2). In both regions, the 0–15 cm soil layer contained higher K contents and stocks than the 15–30 cm, 30–45 cm and 45–60 cm soil layers across all the farms (Table 4). However, K contents and stocks in F3 of the UT region and F4 of the LT region did not change significantly with an increase in soil depth. Changes in K contents between farms were also not significant in the upper 45 cm soil depth in the UT region, but increased significantly in the 45–60 cm soil layer of F3 compared to F2 and F4. In the LT region, K contents and stocks were lower in F3 than those observed in F1, F2, F4 and F5 across the sampled soil layers, despite that differences were not always significant.

3.4 Exchangeable Ca

Management practices applied per farm did not have much influence on Ca contents or stocks, except on few occasions where F4 had 41% higher Ca contents than F2 in the UT region (Fig. 6a), while F3 had 32–34% lower Ca contents than F1 and F5 in the LT region (Fig. 6a). Ca stocks in the UT region were, on average, 67% lower in F2 than Ca stocks recorded in F3, F4 and F5 (Fig. 6b). In the LT region, Ca stocks were not significantly different between all the five farms (Fig. 6b). Ca contents and stocks also decreased with an increase in soil depth. In both the UT and LT regions (Fig. 6c, d), Ca contents and stocks were higher in the 0–15 cm soil layer than in the 15–30 cm soil layer, which also contained higher Ca contents and stocks relative to those recorded in the 30–45 cm and 45–60 cm soil layers. The only difference between the two regions is that, in the LT region, changes in Ca contents and stocks between the 30–45 cm and 45–60 cm soil layers were significant, while in the UT region Ca remained virtually unaltered when the two layers were compared.

In both the UT and LT regions, the farm x depth interaction resulted in higher Ca contents and stocks in the 0–15 cm soil layer than in the 15–30 cm, 30–45 cm and 45–60 cm soil layers across all farms (Table 5). In the UT region, comparisons between farms per layer also showed that F3, F4 and F5 had higher Ca contents and stocks than F1 and F2, especially in the first two soil layers, although differences were not always significant. There were also no significant

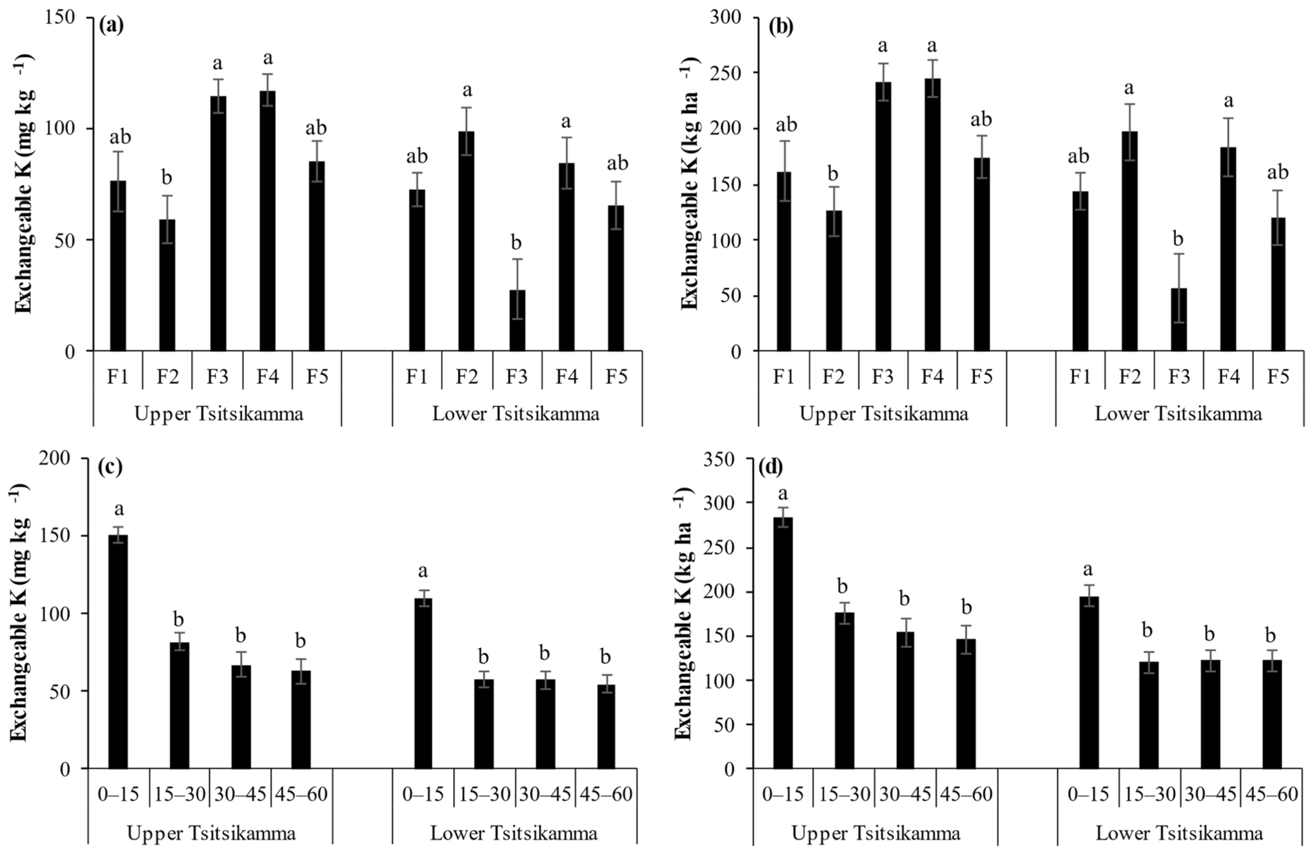

Fig. 5 Effects of different farm management (**a**, **b**) and soil depth (**c**, **d**) on exchangeable potassium (K) contents (**a**, **c**) and stocks (**b**, **d**) under mixed pastures in the Tsitsikamma dairy farms. Error bars indicate standard error of means. Different letters per site indicate significant difference

Table 4 Interactive effects of farm and depth on exchangeable potassium contents and stocks under mixed pastures in the Upper (UT) and Lower (LT) Tsitsikamma dairy farms

Region	Depth (cm)	0–15	15–30	30–45	45–60	0–15	15–30	30–45	45–60
	Farm	Mg kg^{-1}				kg ha^{-1}			
UT	F1	141(14) Aa	65.5(18) Ba	51.0(29) Ba	47.0(29) Bab	280(29) Aa	146(35) ABa	113(54) Ba	107(54) Ba
	F2	123(13) Aa	54.2(14) Ba	32.9(21) Ba	26.7(21) Bb	240(26) Aa	122(28) Aa	76.4(40) Ba	65.9(40) Ba
	F3	139(8.4) Aa	114(8.5) Aa	98.9(8.9) Aa	105(9.2) Aa	255(18) Aa	233(19) Aa	237(19) Aa	243(19) Aa
	F4	184(8.0) Aa	95.8(8.1) Ba	97.4(8.2) Ba	92.1(8.2) Bab	339(18) Aa	213(18) Ba	219(18) Ba	211(18) Ba
	F5	166(14) Aa	78.4(15) Ba	52.7(13) Ba	42.9(13) Bb	302(28) Aa	265(29) ABa	126(26) Ba	105(26) Ba
LT	F1	113(8.7) Aab	60.3(8.4) Ba	64.9(8.4) Ba	50.7(8.5) Bab	206(19) Aab	127(18) ABa	136(18) Ba	107(19) Ba
	F2	150(11) Aa	79.9(11) Ba	80.5(11) Ba	84.9(11) Ba	262(26) Aa	168(26) Bab	172(26) Ba	185(26) Ba
	F3	65.9(14) Ab	16.0(14) Bb	14.1(15) Bb	14.3(15) Bb	135(32) Ab	31.8(32) Bc	30.1(33) Bc	31.4(33) Bb
	F4	114(12) Aab	65.7(12) Aa	78.8(13) Aa	80.3(14) Aa	218(27) Aab	145(27) Abc	176(28) Ab	193(29) Ab
	F5	106(11) Aab	65.6(11) ABa	46.6(11) Bab	42.5(11) Bab	155(26) Aab	131(26) Aa	99.4(26) Aa	93.9(26) Aa

Different upper-case letters indicate significant differences (P < 0.001) among soil layers per farm, while different lower-case letters indicate significant difference (P < 0.001) between farms per layer per region. In parentheses are standard errors of means

changes in Ca contents and stocks. In the 30–45 cm and 45–60 cm soil layers, there were no significant changes in Ca contents and stocks between farms. Similar observations were recorded in the LT region except that Ca contents

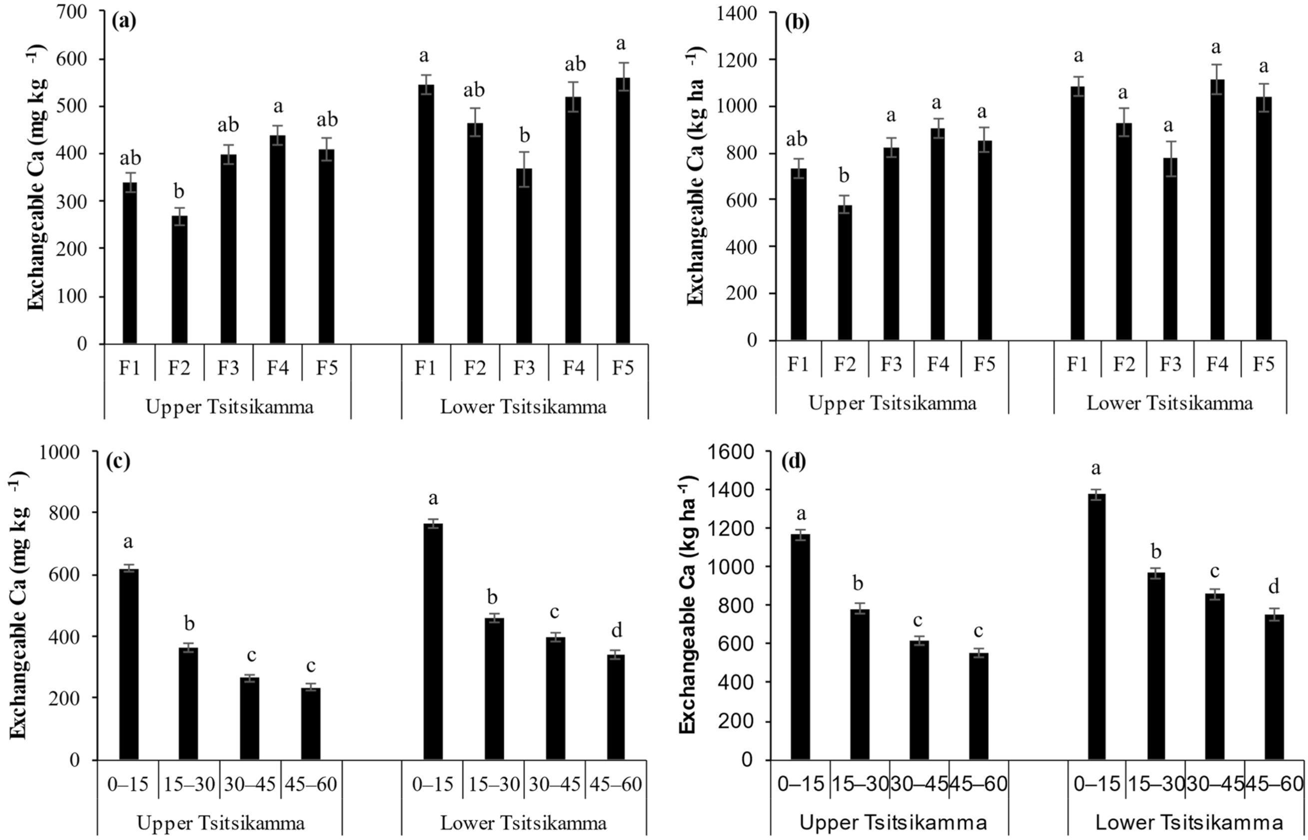

Fig. 6 Effects of different farm management (**a**, **b**) and soil depth (**c**, **d**) on exchangeable calcium (Ca) contents (**a**, **c**) and stocks (**b**, **d**) under mixed pastures in the Tsitsikamma dairy farms. Error bars indicate standard error of means. Different letters per site indicate significant difference

Table 5 Interactive effects of farm and depth on exchangeable calcium contents and stocks under mixed pastures in the Upper (UT) and Lower (LT) Tsitsikamma dairy farms

Region	Depth (cm)	0–15	15–30	30–45	45–60	0–15	15–30	30–45	45–60
	Farm	mg kg^{-1}				kg ha^{-1}			
UT	F1	476(22) Ab	342(22) Bab	296(22) Ba	239(22) Ba	957(45) Ab	767(47) ABa	662(47) Ba	547(47) Ba
	F2	472(21) Ab	250(21) Bb	189(21) Ba	162(21) Ba	916(45) Ab	557(44) ABa	445(45) Ba	400(44) Ba
	F3	621(22) Aab	417(23) Ba	274(24) Ba	285(24) Ba	1141(47) Aab	852(48) ABa	656(51) Ba	654(52) Ba
	F4	749(21) Aa	405(21) Ba	313(21) Ba	288(21) Ba	1369(45) Aa	893(45) Ba	702(45) Ba	659(45) Ba
	F5	778(37) Aa	403(38) Ba	250(34) Ba	199(34) Ba	1449(83) Aa	857(86) Ba	612(75) Ba	497(75) Ba
LT	F1	820(22) Aa	514(22) Bab	419(22) Ba	422(22) Ba	1495(47) Aa	1082(47) Ba	876(47) Ba	891(47) Ba
	F2	799(31) Aab	389(30) Bab	402(30) Ba	273(31) Ba	1439(66) Aa	812(63) Bab	863(63) Ba	600(65) Ba
	F3	587(39) Ab	307(40) Bb	310(40) Ba	265(41) Ba	1203(83) Aa	617(85) Bb	680(84) Ba	597(87) Ba
	F4	776(33) Aab	539(32) Bab	414(32) Ba	347(34) Ba	1516(70) Aa	1197(68) Ba	933(68) Ba	821(72) Ba
	F5	841(30) Aa	564(30) Ba	447(30) Ba	389(30) Ba	1227(63) Aa	1135(63) ABa	937(64) Ba	850(64) Ba

Different upper-case letters indicate significant differences ($P < 0.001$) among soil layers per farm, while different lower-case letters indicate significant difference ($P < 0.001$) between farms per layer per region. In parentheses are standard errors of means

increased in F1 and F2 when compared to F3 in the 0–15 cm and 15–30 cm soil layers, although differences between F1 and F3 in the 15–30 cm soil layer were not significant. Ca stocks also did not differ significantly between farms in the 0–15 cm, 30–45 cm and 45–60 cm soil layers, while in the 15–30 cm soil layer F1, F4 and F5 had significantly higher Ca stocks than F3.

3.5 Exchangeable Mg

Changes in Mg contents and stocks were significant when F3 was compared to F1, F2, F4 or F5 in the UT region, with increases recorded in F3 (Fig. 7a, b). In the LT region on the other hand, F3 had lower Mg contents than F5, while differences were not significant when compared to the rest of other farms (Fig. 7a). Although F3 had lower Mg stocks than F1, F2, F4 and F5 in the LT region, differences were not significant (Fig. 7b). As with soil pH, P, K and Ca, Mg contents and stocks also declined with an increase in soil depth, with the highest values recorded in the 0–15 cm followed by 15–30 cm and then 30–45 cm soil layers, while differences were not significant between the 30–45 cm and 45–60 cm soil layers in both regions (Fig. 7c, d).

As with other nutrients, the interaction of farm and depth improved Mg contents and stocks in the 0–15 cm soil layer compared to the 15–30 cm, 30–45 cm and 45–60 cm soil layers across all the farms, irrespective of the region (Table 6). Mg contents and stocks in the UT region were also higher in F3, F4 and F5 relative to F1 and F2, although differences were not always significant. Higher Mg contents in F4 and F5 compared to F1 and F2 were only observed in the upper two soil layers, while changes in Mg stocks were significant in the 30–45 cm and 45–60 cm soil layers wherein F3 had higher Mg stocks than F1, F2, F4 and F5. On the other hand, Mg contents and stocks in the LT region were lower in F3 compared to F1, F2, F4 and F5, although significant differences were recorded in the 0–15 cm, 15–30 cm and 30–45 cm soil layers (Mg contents) and 15–30 cm soil layer (Mg stocks).

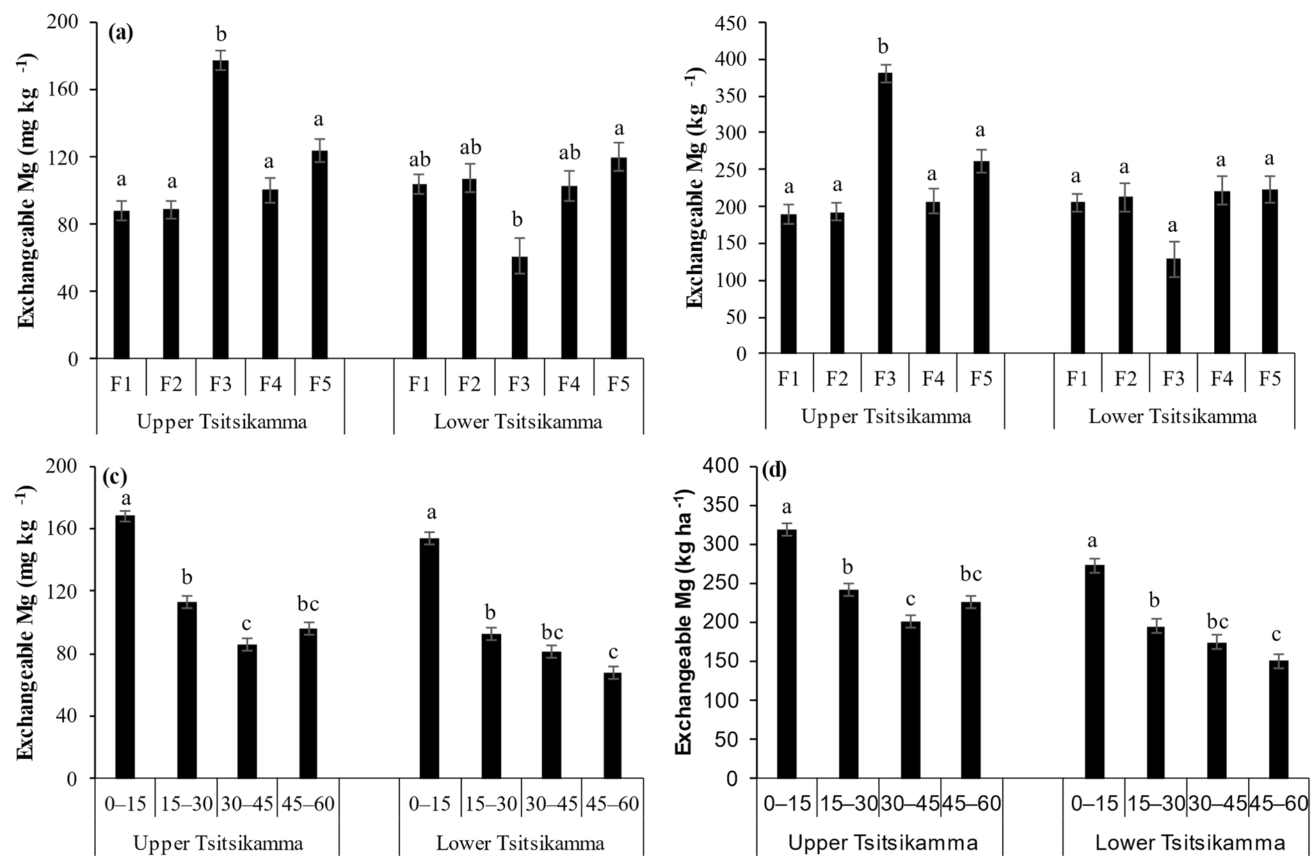

Fig. 7 Effects of different farm management (**a**, **b**) and soil depth (**c**, **d**) on exchangeable magnesium (Mg) contents (**a**, **c**) and stocks (**b**, **d**) under mixed pastures in the Tsitsikamma dairy farms. Error bars indicate standard error of means. Different letters per site indicate significant difference

Table 6 Interactive effects of farm and depth on exchangeable magnesium contents and stocks under mixed pastures in the Upper (UT) and Lower (LT) Tsitsikamma dairy farms

Region	Depth (cm)	0–15	15–30	30–45	45–60	0–15	15–30	30–45	45–60
	Farm	mg kg^{-1}				kg ha^{-1}			
UT	F1	129(6.4) Ab	83(6.5) Bb	74(6.5) Bb	67(6.5) Bb	257(14) Aa	185(14) Aa	164(14) Ab	154(14) Ab
	F2	138(6.2) Ab	85(6.2) ABb	62(6.1) Bb	69(6.2) Bb	269(14) Aa	190(14) ABa	146(14) ABb	166(14) Bb
	F3	193(6.4) Aa	166(6.5) Ba	155(6.8) Ba	196(6.9) Aa	355(14) Ba	341(15) Ba	373(15) Ba	454(16) Aa
	F4	189(10) Aa	80(11) Bb	68(11) Bb	64(13) Bb	357(23) Aa	176(26) Ba	150(26) Bb	147(29) Bb
	F5	191(10) Aa	150(11) Aa	70(9.6) Bb	83(9.6) Bb	354(24) Aa	317(25) Aa	169(22) Bb	209(22) ABb
LT	F1	166(6.3) Aa	105(6.3) Ba	93(6.4) Ba	49(6.4) Ba	303(14) Aa	220(14) ABa	194(14) ABa	104(14) Ba
	F2	178(8.7) Aa	91(8.8) Bab	82(8.8) Ba	78(8.8) Ba	313(19) Aa	190(19) Aa	177(19) Aa	172(19) Aa
	F3	101(11) Ab	48(12) Ab	48(12) Ab	46(12) Aa	208(25) Aa	96(27) Bb	106(27) ABa	105(26) ABa
	F4	140(9.5) Aab	101(9.3) Aa	88(9.4) Aa	82(9.6) Aa	273(21) Aa	223(21) Aa	198(21) Aa	193(21) Aa
	F5	182(8.8) Aa	121(8.8) Ba	94(8.8) Ba	83(8.8) Ba	265(19) Aa	244(19) Aa	198(19) Aa	182(20) Aa

Different upper-case letters indicate significant differences ($P < 0.001$) among soil layers per farm, while different lower-case letters indicate significant difference ($P < 0.001$) between farms per layer per region. In parentheses are standard errors of means

4 Discussion

4.1 Farm

The selected soil fertility indicators did not display clear trends in response to different farm management practices in both regions, suggesting that applied management practices affected these soil fertility indicators differently.

Applied management practices did not have much influence on soil pH in the UT region as there were no significant changes between farms (Fig. 3). Thus, depending on the alkalinity of the added soil amendments, soil pH can increase, decrease or remain constant. In the LT region, an increase in soil pH in F1, which received a combination of organic and inorganic fertilizers, compared to F4 subjected to NPK fertilizer blend or F5 exposed to organic amendments, NPK fertilizer and 500 kg Ca ha^{-1} suggest that the applied fertilizer sources in F1 probably added alkalinity and thus increased soil pH more than fertilizer sources used in F4 and F5 [11, 30].

Changes in soil pH often influence availability of plant nutrients, especially soil P, which is considered to be sensitive to pH changes [8, 14, 31]. Although, extractable P seemed to increase with an increase in soil pH ($r = 0.42$, $P < 0.01$) in the UT region (Table 7), while there were no significant correlations in the LT region (Table 8), management effects on P overshadowed the effects of soil pH across all the farms. An increase in P contents and stocks in F4 in the UT region could be explained by higher P application rates (95 kg ha^{-1}) in combination with poultry manure compared to F1, F2, F3 and F5 that received 0–19 kg P ha^{-1} and neither of the organic amendments except F5 that was subjected to dairy effluent (Table 1).

The chemical composition of applied organic manure in this study is not known, and may have a considerable influence on extractable P. The P content in poultry manure can be within the range of 14–18 g kg^{-1}, which is two-fold higher than that in dairy cow manure [13, 32], and this could further explain higher P contents and stocks in F4 of the UT region. On the other hand, Almeida et al. [12] reported that cow manure can be a viable option to improve P contents than chicken and turkey manure, while Li et al. [32] indicated that animal (dairy cow, broiler, and swine) manure can differ substantially in terms of the P contents and fractions, and therefore induce changes in soil P fractions upon application.

Surprisingly, P contents and stocks in F4 were not significantly different to those recorded in F1 in the UT region wherein P was applied at the rate of 15 kg ha^{-1} (Table 1). There are no valid explanations to support this observation except that F1 probably had higher P saturation deficits, which in turn stimulated rapid P accumulation to match P contents and stocks obtained in F4. In the LT region, farms (F2 and F5) that received P in both organic and inorganic forms in combination with Ca had higher P contents and stocks than farms (F3 and F4) that were not subjected to any form of P amendment. In the same region, Loke et al. [9] found higher SOM in F2 and F5, which could imply that higher SOM as a result of applied organic amendments prevented P sorption, and thus improved P availability and extraction [31, 33, 34]. This is also corroborated by the positive correlations between P and SOC ($r = 0.47$, $P < 0.05$) in the LT region (Table 8).

Table 7 Pearson's correlation coefficients (r) estimated in the 0–15 cm soil layer among soil fertility indicators in the UT region

	pH (KCl)	P	Na	K	Ca	Mg	Total C	Total N	BD	Active C	PMN rate	C/N
pH (KCl)	1											
P	0.42**	1										
Na	−0.27	−0.37*	1									
K	0.20	0.48**	−0.16	1								
Ca	0.37*	0.30	−0.31*	0.36*	1							
Mg	0.38*	0.30	−0.07	0.38*	0.52**	1						
Total C	0.01	0.15	−0.12	−0.12	−0.35*	−0.31*	1					
Total N	−0.11	0.04	−0.89	0.30	0.71**	0.35*	−0.30	1				
BD	−0.16	−0.26	0.48**	−0.29	−0.45**	−0.42**	−0.13	−0.36*	1			
Active C	−0.18	0.03	−0.00	0.20	0.02	−0.04	0.10	0.24	0.06	1		
PMN rate	0.30	0.26	−0.13	0.06	0.13	0.13	0.02	−0.14	−0.21	−0.10	1	
C/N	−0.01	−0.06	0.14	−0.27	−0.82**	−0.48**	0.58**	−0.90**	0.37*	−0.04	0.07	1

** Significant at $P < 0.01$ (two-tailed); * significant at $P < 0.05$ (two-tailed); P, phosphorus; K, potassium; Ca, calcium; Mg, magnesium; C, carbon; N, nitrogen; PMN, potentially mineralizable nitrogen

Table 8 Pearson's correlation coefficients (r) estimated in the 0–15 cm soil layer among soil fertility indicators in the LT region

	pH (KCl)	P	Na	K	Ca	Mg	Total C	Total N	BD	Active C	PMN rate	C/N
pH (KCl)	1											
P	−0.10	1										
Na	−0.33	0.42	1									
K	0.43	0.56*	0.02	1								
Ca	0.25	0.43	0.32	0.73**	1							
Mg	0.14	0.40	0.42	0.64**	0.92**	1						
Total C	0.10	0.47*	0.30	0.64**	0.59**	0.71**	1					
Total N	−0.28	0.20	0.30	−0.08	0.323	0.44	0.37	1				
BD	0.27	−0.57*	−0.35	−0.35	−0.61**	−0.70**	−0.59**	−0.73**	1			
Active C	0.05	0.33	0.45	0.32	0.67**	0.84**	0.68**	0.69**	−0.73**	1		
PMN rate	0.30	−0.30	0.05	0.04	0.13	0.06	0.06	−0.23	0.35	0.03	1	
C/N	0.20	0.27	0.05	0.57*	0.18	0.28	0.69**	−0.35	0.01	0.14	0.20	1

**Correlation is significant at the 0.01 level (two-tailed); * Correlation is significant at the 0.05 level (two-tailed); P, phosphorus; K, potassium; Ca, calcium; Mg, magnesium; C, carbon; N, nitrogen; PMN, potentially mineralizable nitrogen

Responses of K contents and stocks to farm management were a little different from those of extractable P as applications of K amendments did not seem to influence K contents and stocks in the UT and LT regions (Fig. 5a, b). This stems from the fact that F3 in the UT region was fertilized with only NPK fertilizer at 270 kg K ha^{-1}, but had similar K contents and stocks as F4, which received both organic and inorganic K (284 kg ha^{-1}) amendments. On the other hand, F2 received K at 269 kg ha^{-1} with no additions of poultry manure or dairy effluent, but had significantly lower K contents and stocks particularly when compared to F3 and F4. A similar pattern was witnessed in the LT region, where farms (e.g. F1 and F5) that were fertilized with organic and inorganic K amendments had more or less the same K contents and stocks with farms (F3 and F4) that only received K in the form of inorganic fertilizer. Again, F3 in the LT region which received only NPK fertilizer blend had significantly lower K contents and stocks when compared to F2 and F4. Interestingly, K application rates (127 kg ha^{-1}) were the same between F3 and F4.

Based on these results, we could deduce that potential differences in fertilizer sources and K saturation deficits between farms in the UT and LT regions were sources of variation in K contents and stocks between farms, especially in the LT region [12, 13]. The K contents and stocks in this region followed similar trends displayed by soil C and active C (See also [9]). Despite non-significant correlations with active C (Table 8), an increase in soil C ($r = 0.64$, $P < 0.01$) and C/N ratio ($r = 0.57$, $P < 0.05$) probably influenced K contents and stocks in F2 and F4 relative to lower SOM in F3. These results are inconsistent with those obtained by Almeida et al. [12]. They found that repeated applications of animal manure (chicken, turkey, and cow) increased K contents, but resulted in a lower SOM compared to the control. The variations could be due to differences in soil type, saturation deficits and K contents of the fertilizer sources. In this study, all the farms were established on sandy soils, while Almeida et al. [12] tested different organic manure on clayey soil. Nutrient accumulations and losses occur rapidly in sandy soils. However, with higher SOC observed in F2 and F4 relative to F3 in the LT region, nutrients including K could be spared from loss through leaching [3, 9, 13].

There were no Ca applications in F1, F2 and F3 in the UT region (Table 1). Dairy effluent applied in F5 was also probably lower in Ca content compared to poultry manure applied in F4. Thus, higher Ca contents and stocks in F4 could be due to application of poultry manure in combination with NPK fertilizer blend. Adekiya et al. [13] also recorded higher Ca contents in plots that received poultry manure and NPK fertilizer compared to rabbit, cow, green manures and/or NPK fertilizer applied without any additions of organic manure. Such increases were attributed to higher Ca contents in poultry manure compared to other organic manures. Applications of poultry manure along with dairy effluent, NPK fertilizer and Ca also influenced Ca contents in the LT region (Fig. 6a). However, Ca contents and stocks recorded in F4, which received only NK fertilizer at the same rates as F3 were not significantly different from those obtained in F1, F2 or F5 despite that they were fertilized with poultry manure in combination with dairy effluent, NPK fertilizer and Ca. Therefore, it can be inferred that Ca contents and stocks in the LT region were also affected by other soil properties that were unfortunately not measured in this study.

Similarly, Mg contents and stocks were probably affected by other soil properties, especially in the UT region. In both regions, it should be noted that F3 was not fertilized with any form of Mg amendment. As such, higher Mg contents and stocks in F1 and F5 particularly when compared to F3 in the LT region was due to Mg in organic manure applied in F1 and F5, which according to Almeida et al. [12] can vary between 0.1 mg kg^{-1} in cow manure to 0.5 mg kg^{-1} in poultry manure. There were also weak negative (r = -0.35, P < 0.05) or no obvious relationships between SOM indices and Ca or Mg in the UT region, while in the LT region, both Ca and Mg exhibited strong positive relationships with active C (r = 0.67, P < 0.01) and r = 0.84, P < 0.01, respectively) and soil C (r = 0.59, P < 0.01 and r = 0.71, P < 0.01, respectively) (Tables 7, 8), suggesting that active C and soil C probably had some influences on Ca and Mg contents and stocks in this region (see also [9]).

4.2 Soil depth

Effects of management practices on soil pH, P, K, Ca and Mg became more evident when sampled soil layers were compared than when comparisons were made between farms in both the UT and LT regions. However, significant effects of the applied management were restricted in the upper 15 cm soil depth. The measured soil fertility indicators, including SOM indices, also seemed to have influenced each other in the upper 15 cm soil depth, as indicated by the weak to strong correlations among themselves (Tables 7, 8). Similar results have been reported in many soils under conservation agriculture and managed pastures [30, 34–36], attributing such responses to constant placement of soil amendments near the soil surface and lack of soil mixing as has been the common practice in both the UT and LT regions for the last six years. On the other hand, some researchers found lower soil pH levels in the uppermost soil layer of less disturbed soils and ascribed such responses to surface acidification by nitrification of ammonium containing or forming fertilizers as well as decomposition of surface placed crop residues and animal manure [31, 37]. Irrigation can also neutralize soil acidity or leach out soluble base cations in the surface soil, resulting in a higher or lower soil pH, respectively [31]. These contradictions generally suggest that responses of soil fertility indicators to soil management can be site specific and depend on initial soil pH and chemical composition of organic inputs.

Surface stratification of less mobile nutrients can be a disadvantage given that the topsoil layer is more prone to erosive forces and dries out quickly than the lower soil layers. Nutrient stratification can also be a problem for deep-rooted plants such as kikuyu grass as it limits their access to P, K, Ca and Mg, which are mostly taken up through root contact/diffusion. Thus, lower P, K, Ca and Mg contents and stocks below 15 cm soil depth could also be ascribed to removal by plants and/or lower SOM to restrict P and K fixation or hold Ca and Mg against leaching [31, 34, 35, 38]. Our results are consistent with those reported elsewhere under conservation tillage systems mainly because these nutrients, especially P and K, are relatively immobile in the soil and tend to accumulate where they have been placed [14, 33]. Hence some researchers are of the opinion that the use of mouldboard ploughing occasionally could be a good practice to ensure that less mobile nutrients like P and K are evenly distributed throughout the rhizosphere [39]. Conversely, Holanda et al. [31] and Sá et al. [33] found that continuous placement of nutrient inputs near the surface in no-tilled soils tends to saturate the superficial layer with nutrients, which are then deposited in deeper layers by eluviation-illuviation processes, thus enriching lower layers with nutrients. Even so, this is commonly observed in long-term as opposed to short-term experiments [34].

4.3 Farm x soil depth interaction

The interaction of farm and soil depth had strong effects on nutrient contents and stocks in the 0–15 cm soil layer. An increase in P, K, Ca and Mg contents and stocks in the 0–15 cm soil layer compared to the 15–30 cm, 30–45 cm and 45–60 cm soil layers across all the farms could be attributed to an interaction of surface applications of soil amendments and lack of soil inversion [30, 31, 33, 35, 38]. Withdrawals of nutrients from deeper soil layers and their deposition in the surface soil during litter fall could be another reason for lower nutrient contents and stocks in the lower soil layers [30, 35, 38]. Loke et al. [9] reported higher contents and stocks of SOM indices in the 0–15 cm soil layer compared to the lower soil layers in the UT and LT regions, suggesting that SOM played a role in improving nutrient adsorption capacity in the topsoil layer. This is also confirmed by moderate to strong correlations between some nutrients and SOM indices in the upper 15 cm soil depth (Tables 7, 8). Sá et al. [33] also observed higher SOM in the surface soil layer under no-tillage treatments accompanied by strong positive correlations with P and K. In addition, SOM has a high affinity for Ca and Mg [12, 38], and therefore probably restricted their eluviation-illuviation by percolating irrigation and rain water.

Results of this study further revealed that there were significant changes in nutrient contents and stocks when farms were compared per soil layer (Table 2). In the UT region, farms that received little (F3; 19 kg ha^{-1}) to no (F2) P amendments had higher P contents and stocks than farms (F1, F4 and F5) that were fertilized with NPK fertilizer blend and/or poultry manure particularly in the 0–15 cm soil layer, while there were no differences in the lower soil layers. As such, it could be inferred that decomposition rates and the release of P into available form were perhaps slower in F1, F4 and F5 because of high N applications [14]. In the LT region, the trend changed. Higher P contents and stocks in F1, F2 and F5 than in F3 and F4 across all the soil layers could be attributed to constant P applications through organic and inorganic fertilizers, thus probably exceeding the soil's P fixation capacity [31].

Interestingly, the interactive effects of farm and depth on P, K and Mg in the LT region extended to the deeper soil layer (45–60 cm), while Ca responses to farm x depth interactions were not significant below the 30 cm soil depth. These results are in agreement with our hypothesis that a combination of organic and inorganic soil amendments can improve nutrient contents and storage to 60 cm soil depth. Lu et al. [8] also reported higher P fractions in NPK + maize straw and animal manure treated plots in the upper 100 cm soil depth compared to the control or plots treated with NPK fertilizer alone. Therefore, the combination of organic manure and NPK fertilizer may be a potential source of nutrients not only in the surface soil, but also in the subsoil. There were no obvious trends in the UT region when effects of different farm management practices on K, Ca and Mg were compared in each soil layer, suggesting that responses of these nutrients to farm x depth interactions cannot be explained by mere differences in the quantities of soil amendments applied in each farm.

5 Conclusion

Results of this study revealed that applications of a single and/or combined fertilizer sources modified soil fertility indicators, especially P, K, Ca and Mg. The analysed soil fertility indicators did not display clear trends, particularly when comparisons were made between farms in the UT region, suggesting that amounts of applied inputs alone cannot explain differences in nutrient contents and stocks between farms. Therefore, further research, inclusive of other soil properties, preliminary testing of organic manure and nutrient uptake is warranted as they are likely to influence nutrient dynamics in the soil. Regardless of farm management, soil depth or region, the recorded pH levels in this study were within ranges where most nutrients are available for plant uptake. In the LT region, a combination of poultry manure, dairy effluent and NPK fertilizer improved soil pH, P, K, Ca and Mg compared to sole applications of NPK fertilizer. Although the selected soil fertility indicators manifested more in the topsoil layer (0–15 cm) than in the lower soil layers (15–30 cm, 30–45 cm and 45–60 cm) in both UT and LT regions due to surface placement of soil amendments. Constant applications of organic manure in combination with NPK fertilizer generally showed potential to improve P, K, Ca and Mg contents and stocks in the lower soil layers. As such, the use of organic manure at least in combination with synthetic fertilizers should be encouraged among the farming community as it can reduce dependency on expensive chemical inputs, and thus ensures a favourable input to output ratio to dairy farmers in the southern Cape coastal region.

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Data availability The datasets generated during and/or analysed during the current study are available from the corresponding author upon reasonable request.

Declarations

Competing Interests The authors declare no competing interests.

Consent to participate The authors obtained informed consent from all participants in the study to use their data in scientific publication. No minors were involved in this study.

References

1. Milk South Africa. Report on participation in the World Dairy Summit and Business Meetings of the International Dairy Federation in Istanbul, Turkey. 2019. https://milksa.co.za/node/3339 (Accessed 21-09-2022).
2. ARC-ISCW. Agro-climatology database. Agricultural research council-institute for soil, climate and water: Pretoria, South Africa. 2020.
3. Du Preez CC, Van Huyssteen CW, Amelung W. Changes in soil organic matter content and quality in South African arableland. In: Lal R, Stewart BA, editors. Soil degradation and restoration in Africa. Boca Raton: CRC Press; 2020. p. 110–43.
4. Milne RM, Haynes RJ. Comparative effects of annual and permanent dairy pastures on soil physical properties in the Tsitsikamma region of South Africa. Soil Use Manag. 2004;20:81–8.
5. Botha PR, Meeske R, Snyman HA. Kikuyu over-sown with ryegrass and clover: grazing capacity, milk production and milk composition. Afr J Range Forage Sci. 2008;25:103–10.
6. Viljoen C, Van Der Colf J, Swanepoel PA. Benefits are limited with high nitrogen fertiliser rates in kikuyu-ryegrass pasture systems. Land. 2020;9:173.
7. Roba TB. Review on: the effect of mixing organic and inorganic fertilizer on productivity and soil fertility. Open Access Library J. 2018;5: e4618.
8. Lu X, Mahdi A, Han XZ, Chen X, Yan J, Biswas A, Zou WX. Long-term application of fertilizer and manures affect P fractions in Mollisol. Sci Rep. 2020;10:14793.
9. Loke PF, Kotzé E, Du Preez CC. Soil organic matter storage in irrigated Tsitsikamma dairy farms with minimum tilled pasture mixtures: case studies. Agric. 2022;12:858.
10. Okoroghona AOM, Adibisi LO. Animal manure for smallholder agriculture in South Africa. In: Lichthouse E, editor. Farming for food and water security: sustainable agriculture reviews. Dordrecht: Springer; 2012. p. 201–42.
11. Thangarajan R, Bolan N, Tian G, Naidu R, Kunhikrishnan A. Role of organic amendment application on greenhouse gas emission from soil. Sci Tot Environ. 2013;465:72–96.
12. Almeida RF, Queiroz IDS, Mikhael JER, Oliveira RC, Borges EN. Enriched animal manure as a source of phosphorus in sustainable agriculture. Inter J Recycl Org Waste Agric. 2019;8:S203–10.
13. Adekiya AO, Ejue WS, Olayanju A, Dunsin O, Aboyeji CM, Aremu C, Adegbite K, Akinpelu O. Different organic manure sources and NPK fertilizer on soil chemical properties, growth, yield and quality of okra. Sci Rep. 2020;10:16083.
14. Havlin JL, Tisdale SL, Nelson WL, Beaton JD. Soil fertility and fertilizers: an introduction to nutrient management. 8th ed. Pearson: Upper Saddle Valley; 2014.
15. Swanepoel PA, Habig J, du Preez CC, Snyman HA, Botha PR. Tillage effects, soil quality and production potential of kikuyu-ryegrass pastures in South Africa. Grass Forage Sci. 2016;72:308–21.
16. Swanepoel P, du Preez CC, Botha P, Snyman H, Habig J. Soil quality characteristics of kikuyu–ryegrass pastures in South Africa. Geoderma. 2014;232–234:589–99.
17. Phohlo MP. Soil quality of kikuyu, ryegrass and clover pasture mixtures in the Tsitsikamma. MSc Dissertation, University of the Free State, Bloemfontein, South Africa 2016.
18. Land Type Survey Staff. Land types of South Africa: Agricultural Research Council-Institute for Soil, Climate and Water: Pretoria, South Africa. 2000.
19. Soil Classification Working Group. Soil Classification: A Taxonomic System for South Africa. In Memoirs on the Agricultural Natural Resources of South Africa No. 15; Department of Agriculture: Pretoria, South Africa. 1991.
20. Van Huyssteen CW. Relating the South African soil taxonomy to the world reference base for soil resources. Bloemfontein: Sun Media; 2020.
21. Rebelo AG, Boucher C, Helme N, Mucina L, Rutherford MC. Fynbos biome. In L., Rutherford MC (Ed) The Vegetation of South Africa, Lesotho and Swaziland; Strelizia 19; Mucina, South African National Biodiversity Institute: Pretoria, South Africa. 2006.
22. FERTASA Fertilizer Handbook (8th ed.). Fertilizer Association of Southern Africa: Pretoria, South Africa. 2016.
23. Blake GR, Hartge KH. Bulk density. In Klute E (Ed). Methods of Soil Analysis. Part 1. Physical and Mineralogical Methods, 2nd ed.; Soil Science Society of America: Madison, WI, USA. 1986; pp. 363–382.
24. Grossman RB, Reinsch TG. Bulk density and linear extensibility. In: Dane JH and Topp GC (eds) Methods of soil analysis. Part 4. Physical methods. SSSA Book Ser. 5. SSSA, Madison. 2002;pp 201–228.
25. Kuo S. Phosphorus. In Sparks DL (Ed) Methods of Soil Analysis: Part 3: Chemical Methods; SSSA Book Series 5; Soil Science Society of America, American Society of Agronomy: Madison, WI, USA.1996;pp. 869–919.
26. Sumner ME, Miller WP. Cation Exchange Capacity and Exchange Coefficients. In Sparks DL (Ed) Methods of Soil Analysis Part 3: Chemical Methods; SSSA Book Series 5; Soil Science Society of America, American Society of Agronomy: Madison, WI, USA.1996;pp 1201–1230.
27. Payne RW, Murray DA, Harding SA, Baird DB, Souter DM. GenStat for windows (19th ed.) VSN International: Hemel Hempstead, UK. 2017.
28. Snedecor GW, Cochran WG. Statistical methods. 7th ed. Ames: Iowa State University Press; 1980.
29. Glass GU, Peckham PD, Sanders JR. Consequences of failure to meet assumptions underlying the fixed effects analyses of variance and covariance. Rev Edu Res. 1972;42:237–88.
30. Loke PP, Schimper JJ, Kotzé E, du Preez CC. Long-term wheat production management effects on soil fertility indicators in the semi-arid eastern Free State, South Africa. S Afr J Plant Soil. 2021;38:93–106.

31. Sá JCM, Cerri CC, Lal R, Dick WA, Piccolo MC, Feigl BE. Soil organic carbon and fertility interactions affected by a tillage chronosequence in a Brazilian Oxisol. Soil Till Res. 2009;104:56–64.
32. Li G, Li H, Leffelaar PA, Shen J, Zhang F. Characterization of phosphorus in animal manures collected from three (dairy, swine, and broiler) farms in China. PLoS ONE. 2014;9: e102698.
33. Holanda FSR, Mengel DB, Paula MB, Carvaho JG, Bertoni JC. Influence of crop rotations and tillage systems on phosphorus and potassium stratification and root distribution in the soil profile. Comm Soil Sci Plant Anal. 1998;29:2373–94.
34. Ncoyi K, du Preez CC, Kotzé E. Comparison of soil phosphorus after 37 years of wheat production under different management practices in a semi-arid climate. S Afr J Plant Soil. 2020;37:184–93.
35. Kotzé E, du Preez CC. Influence of long-term wheat residue management on acidity and some macronutrients in an Avalon soil. S Afr J Plant Soil. 2008;25:14–21.
36. Swanepoel P, du Preez CC, Botha PR, Snyman HA. A critical view on the soil fertility status of minimum-till kikuyu–ryegrass pastures in South Africa. Afr J Range Forage Sci. 2015;32:113–24.
37. Goulding KWT. Soil acidification and the importance of liming agricultural soils with particular reference to the United Kingdom. Soil Use Manag. 2016;32:390–9.
38. Loke PF, Kotzé E, du Preez CC. Long-term effects of wheat production management practices on exchangeable base cations and cation exchange capacity of a Plinthosol in semi-arid South Africa. Comm Soil Sci Plant Anal. 2014;45:1083–105.
39. Garcia JP, Wortmann CS, Mamo M, Drijber R, Tarkalson D. One-time tillage of no-till: effects on nutrients, mycorrhizae, and phosphorus uptake. Agron J. 2007;99:1093–103.