Received: 5 March 2018 | Revised: 17 June 2019 | Accepted: 2 July 2019

DOI: 10.1111/sum.12534

RESEARCH PAPER

Soil Use and Management | WILEY

Mulching effects on soil nutrient levels and yield in coffee farming systems in Rwanda

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Funding information
Netherlands Organization for International Cooperation in Higher Education, Grant/Award Number: NPT/RWA/061

Abstract

Different combinations of organic mulch were applied in smallholder coffee farming systems to assess their effects on soil nutrient contents and coffee yield at three sites in different agro-ecological zones in Rwanda. Mulching systems consisted of *Cymbopogon* spp. (T1), *Panicum* spp. (T2), *Cymbopogon* spp. and *Panicum* spp. (T3), *Eucalyptus* spp. and *Cymbopogon* spp. (T4), mixed residues (T5) and unmulched coffee used as control (T6). Mulch had significant and specific effects at each site ($p < 0.001$). T3 reduced soil pH value and exchangeable acidity at Kibirizi, while at Karongi and Ruli, these effects were observed with T4 and T5. T4 and T5 significantly increased the content of soil carbon (C), nitrogen (N), phosphorus (P), potassium (K), calcium (Ca) and magnesium (Mg). The amount of nutrients released was regulated by the amount and type of mulch applied, the agro-ecological conditions and the soil properties at each site. The increased soil nutrient levels led to improved soil fertility conditions and increased coffee yields. The coffee yields were significantly increased with T1 at Karongi ($p < 0.05$) by up to 1.9 t ha^{-1}. T2 and T3 had significantly higher yields at Kibirizi. Yields at Kibirizi were 48% lower compared to yields at Karongi; at this site, T1, T2, T3, T4 and T5 increased yields by 57%, 26%, 31%, 20% and 28%, respectively, when compared to the no mulching treatment (T6). However, coffee yields over 1.9 t ha^{-1} can only be obtained with additional applications of inorganic fertilizer at different rates depending on the agro-ecological zone and soil type.

KEYWORDS

coffee yield, fertilizer recommendations, organic mulch, soil management

1 | INTRODUCTION

Coffee is an important cash and export crop in East and Central African countries. In Rwanda, coffee (*Coffea arabica L.*) is mainly grown by smallholder farmers who use organic mulch to improve soil fertility conditions and coffee productivity (Bucagu, Vanlauwe, & Giller, 2013). Mulching is an agronomic practice, universally used to improve soil moisture, reduce soil temperature and evaporation (Wu, Huang, Zhang, & Jia, 2016), suppress weed growth (Thankamani, Kandiannan, Hamza, & Saji, 2016), reduce soil losses (Nzeyimana et al., 2017) and improve soil fertility (Mwango et al., 2016).

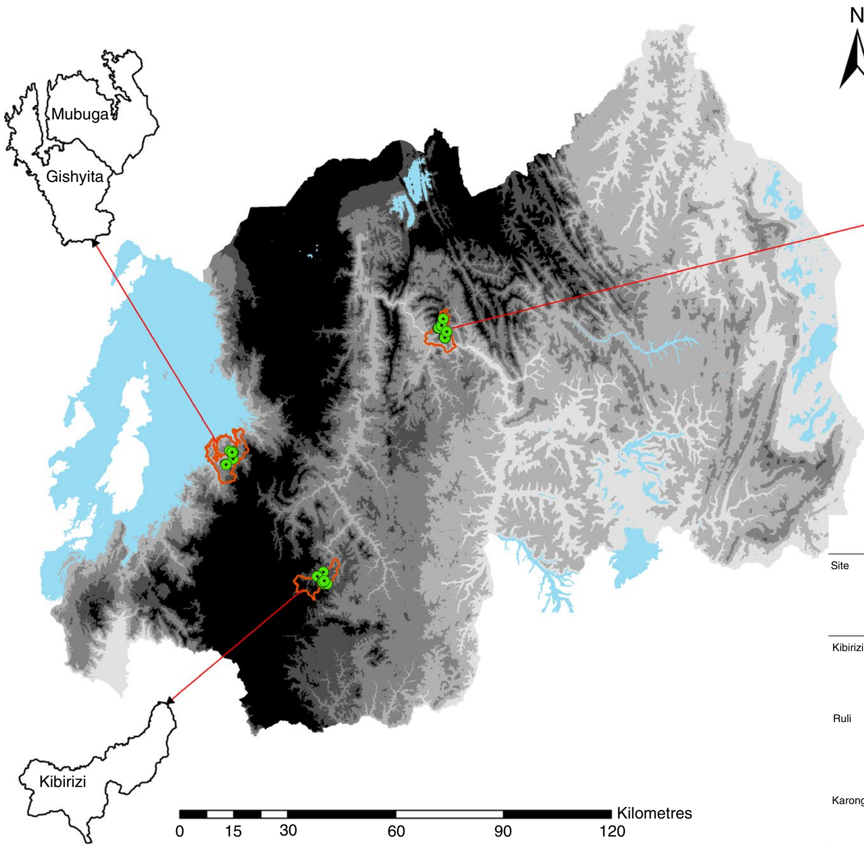
Different mulches have different effects in supplying nutrients to soils depending on the quality of the mulch materials, climatic conditions and soil types (Adekiya, Agbede, Aboyeji, & Dunsin, 2017; Awopegba, Oladele, & Awodun, 2017). Mulching with legume materials has been reported to produce higher concentrations of soil nutrients compared to grasses and crop residues (Adekiya et al., 2017). However, due to the scarcity of legume mulch, coffee farmers use low-quality mulches such as *Hyparrhenia* spp., *Eragrostis* spp., *Panicum* spp. *and Pennisetum purpureum* (Bucagu et al., 2013).

Soils under coffee farming in Rwanda are characterized by very low pH values (<5.0) with high soil aluminium (Al) saturation (>30%), and very low Ca (<30%), Mg (<10%), N (<0.16%), P (<20 ppm), K (<5.8%), sulphur (<20 ppm), zinc (<1 ppm) and boron (<0.8 ppm) (Cordingley, 2009). N is often the most limiting nutrient in coffee production, with P the second limiting factor (Bote, Zana, Ocho, & Vos, 2018). Ca and Mg deficiencies are also common in most coffee farming systems throughout the country due to high Al toxicity in acid soils. Depending on the coffee variety, yields in Rwanda are generally low (1 t ha^{-1} year^{-1} on average) (Nzeyimana, Hartemink, & Geissen, 2014). In neighbouring countries, with improved varieties, higher coffee yields varying from 2.2 to 2.6 t ha^{-1} year^{-1} have been reported in Ethiopia (Kufa, Ayano, Yilma, Kumela, & Tefera, 2011) and Uganda (Wang et al., 2015). Data on the effectiveness of mulch in improving soil fertility and coffee yield are scarce in the Rwanda highlands despite the importance of the crop for most smallholders. The objective of the present study was to assess the effects of the different organic mulches applied in coffee farming on soil fertility and coffee yields in different agro-ecological zones of Rwanda.

2 | MATERIALS AND METHODS

2.1 | Site description

The study sites were located in Nyamagabe District, Kibirizi Sector in the Southern Province, Gakenke District, Ruli Sector in the Northern Province and in the Gishyita-Mubuga Sectors, Karongi District in the Western Province (Figure 1). The sites were located in three agro-ecological zones (AEZ); the site in Kibirizi was located in the cold and humid southern highlands at the Congo-Nile Watershed Divide AEZ, with sandy loam, loam and clayey soils (Nzeyimana et al., 2014). The Ruli site was located in the cold and humid northern highlands at the Central Plateau and granitic ridge AEZ,



Site	Location	Agro-Ecological zone (AEZ)	Altitude (m)	*Min. and Max. Temp. (°C)	*Min. and max. rainfall (mm)	Days with rainfall	Parent material	Dominant soil Order
Kibirizi	South	Congo Nile Watershed Divide	1900-2500	14-24	1300-2000	273	Schistose rock	Ultisols, Inceptisols
Ruli	North	Plateau Central on granitic ridge	1900-2300	16-29	1100-1500	243	Granite	Ultisols, Inceptisols
Karongi	West	Lake Kivu Borders	1500-1900	19-23	1200-1300	212	Shales and granite	Ultisols, Inceptisols

*N.B. * Mean values from a 30-year period*

FIGURE 1 Map of Rwanda with the locations of the three study sites (Kibirizi, Karongi and Ruli) dominated by sandy clay loam and sandy loam soils. The site in Karongi was located in the western mid-altitude along the shores of Lake Kivu where the climate was cool. The soils here were dominated by sandy clay loams and sandy loams (Nzeyimana et al., 2014).

2.2 | Field experimental design

Field experiments were carried out from 2007 to 2009. Five mulching systems were applied as treatments as described in Table 1. The mulching systems were selected from the most dominant mulching materials used in coffee plantations by smallholder farmers in Rwanda. The mulching systems were applied in coffee plantations where the same mulch material had been applied annually at an average rate of 15 to 21 t ha^{-1} for at least three consecutive years previously before starting the field experiments in 2007. The size of each experimental plot was 10 x 10 m, and each plot contained 25 coffee trees (i.e. 2,500 trees per ha) spaced 2 m apart. The amount and thickness of the applied mulch were measured using a 1 m^2 metal frame, and the percentage of the soil cover was estimated. The experiment consisted of a randomized complete block design (RCBD) of six treatments replicated on two soil types (i.e. inceptisols and ultisols) at three sites (i.e. Kibirizi, Ruli and Karongi); at each site, the treatments were replicated three times, site location being the main factor.

2.3 | Soil sampling and analysis

Composite soil samples (0–20 cm) were taken at the cross-diagonal intersection of 4 coffee trees using a 7 cm Edelman auger. Mulch and crop residues were removed from the soil

TABLE 1 Soil texture at the experimental sites

		Inceptisols			Ultisols		
Treatment[a]	Particle size (%)	Kibirizi	Ruli	Karongi	Kibirizi	Ruli	Karongi
T1	Sand	56.2 ± 2.20[b]	53.6 ± 0.58	71.8 ± 4.16	38.1 ± 1.72	50.7 ± 4.73	48.5 ± 1.16
	Clay	15.3 ± 3.06	25.7 ± 1.16	10.7 ± 1.01	19.7 ± 5.86	27.7 ± 1.53	27.1 ± 3.69
	Silt	28.5 ± 0.99	20.7 ± 0.58	17.3 ± 4.51	42.2 ± 7.15	21.7 ± 3.21	24.4 ± 4.84
	Texture	Sandy loam	Sandy clay loam	Sandy loam	Loam	Sandy clay loam	Sandy clay loam
T2	Sand	67.1 ± 3.67	55.7 ± 1.53	68.2 ± 3.45	45.7 ± 4.15	43 ± 1.00	56.2 ± 11.70
	Clay	8.3 ± 2.52	24 ± 1.00	16.9 ± 2.00	17.3 ± 5.03	34.3 ± 1.53	24.1 ± 2.73
	Silt	24.5 ± 1.29	20.3 ± 1.53	11.7 ± 2.08	36.9 ± 1.03	22.7 ± 2.31	19.8 ± 12.58
	Texture	Sandy loam	Sandy clay loam	Sandy loam	Loam	Sandy clay loam	Sandy clay loam
T3	Sand	29.1 ± 0.39	54 ± 1.73	70.3 ± 2.82	27.2 ± 3.19	50.7 ± 1.15	49.7 ± 5.42
	Clay	64.7 ± 3.22	23.3 ± 2.52	11.1 ± 0.42	66 ± 2.00	31 ± 3.61	28.5 ± 3.16
	Silt	6.3 ± 2.83	22.7 ± 1.15	18.3 ± 3.51	6.7 ± 1.79	21.7 ± 5.13	22.2 ± 6.75
	Texture	Clay	Sandy clay loam	Sandy loam	Clay	Sandy clay loam	Sandy clay loam
T4	Sand	24.7 ± 2.34	53.7 ± 2.08	47.4 ± 2.91	31.6 ± 1.17	48 ± 1.00	38.8 ± 3.28
	Clay	65 ± 3.61	21.7 ± 2.08	26.6 ± 4.36	23.3 ± 1.16	32 ± 2.00	31.8 ± 2.54
	Silt	10.3 ± 1.44	24.7 ± 2.08	26 ± 2.00	45.07 ± 2.17	19.3 ± 0.58	29.3 ± 2.89
	Texture	Clay	Sandy clay loam	Sandy clay loam	Loam	Sandy clay loam	Clay loam
T5	Sand	63.1 ± 1.45	54.7 ± 1.53	76.5 ± 1.15	41.6 ± 5.62	42.3 ± 1.53	73.3 ± 0.32
	Clay	8.7 ± 1.16	22 ± 1.00	8.9 ± 0.00	12.7 ± 2.08	30.7 ± 2.08	13.1 ± 2.04
	Silt	28.2 ± 0.62	23.3 ± 1.53	14.7 ± 1.15	45.8 ± 4.31	27 ± 2.00	13.3 ± 2.31
	Texture	Sandy loam	Sandy clay loam	Sandy loam	Loam	Clay loam	Sandy loam
T6	Sand	27.1 ± 2.24	56.7 ± 1.53	68.2 ± 2.54	30.7 ± 1.12	43.7 ± 0.58	37.6 ± 5.69
	Clay	67.3 ± 1.16	21 ± 1.00	20.9 ± 2.31	47 ± 1.00	30.7 ± 0.58	30.7 ± 1.57
	Silt	5.6 ± 1.43	22.3 ± 1.53	14.7 ± 1.15	22 ± 2.00	25.7 ± 0.58	31.4 ± 6.40
	Texture	Clay	Sandy clay loam	Sandy loam	Clay	Clay loam	Clay loam

[a]The treatments are coffee plots with different mulching systems: T1: *Cympobogon* spp. applied at 15 t mulch ha^{-1} and with 22 mm mulch thickness; T2: *Panicum* spp. applied at 15 t mulch ha^{-1} and with 20 mm mulch thickness; T3: *Cympobogon* spp. and *Panicum* spp. applied at 17 t mulch ha^{-1} and with 31 mm mulch thickness; T4: *Eucalyptus* spp. and *Cympobogon* spp. applied at 20 t mulch ha^{-1} and with 40 mm mulch thickness; T5: mixed residues applied at 21 t mulch ha^{-1} (i.e. sorghum thatch, maize and beans residues, banana leaves, Eucalyptus leaves and branches, *Panicum* spp., and sugar cane) and with 41 mm mulch thickness; T6: un-mulched coffee used as control. [b]Standard deviation (n = 108).

surface before sampling. The composite samples were taken from 10 locations per plot and mixed in a bucket. The samples were analysed in the laboratory at the University of Rwanda for the following properties: particle size distribution (Table 1), soil pH, soil organic carbon (SOC), Ca, Mg, K, available P, total N (N_{tot}), Na, exchangeable Al and cation exchange capacity (CEC). The analytical methods used are described in the manual for laboratory methods (Okalebo, Gathua, & Woomer, 2002).

2.4 | Mulch sampling and analysis

To analyse the dry matter and nutrient content, 10 samples of litter were taken randomly and mixed in a bucket to make a composite sample of 0.5 kg. The litter samples were oven-dried at 60°C to constant weight, then weighed and ground. Total N was analysed after Kjeldahl digestion, available P using the ascorbic acid method, and K was analysed by flame photometry. The Ca and Mg concentrations were determined using atomic absorption spectrometry (Anderson & Ingram, 1993; Okalebo et al., 2002).

2.5 | Yield measurement

Coffee yield was calculated by sampling three twigs (middle, low and high) independently from each other. Five randomly selected trees in each plot were sampled to create a composite sample of 500 g of berries sampled from the three twigs. The coffee berries were harvested on the selected trees every week between April and September 2009. The berries were cleaned and oven-dried at 60°C for 48 h until they reached constant weight. Coffee yield was determined for each randomly selected tree, and a spatial mean plot value was calculated using the following equation:

$$\bar{y} = \frac{1}{n} \sum_{i=1}^{n} yi \tag{1}$$

where $\bar{y}$ (t ha^{-1} year^{-1}) is the average coffee yield measured from April to September; n is the number of sample points; and y_i (t ha^{-1} year^{-1}) is the yield at sample point i

2.6 | Nutrient budget

The concentrations of N, P, K, Ca and Mg in the mulch were expressed as g kg^{-1} of mulch applied and converted into kg ha^{-1}. Additional nutrient rates were calculated to supplement deficiencies and balance the nutrient budget for coffee.

The amounts of N, P, K, Ca and Mg were calculated separately using the coffee nutrient requirements of NPK (22-6-12) applied at 200 kg ha^{-1} year^{-1} and Ca-Mg (60-16) applied at 1 kg of lime per tree (Cordingley, 2009). The N, P, K, Ca and Mg balances were calculated as the sum of all required inputs (n) minus the outputs of the system using Equation 2:

$$\sum_{i=1}^{n} [N]_{Required} = \sum_{i=1}^{n} [N]_{Organic} + \sum_{i=1}^{n} [N]_{Soil} + \sum_{i=1}^{n} [N]_{losses} \tag{2}$$

where $\sum_{i=1}^{n} [N]_{Required}$ (kg ha^{-1} year^{-1}) is the sum of required concentrations 'n'; $\sum_{i=1}^{n} [N]_{Organic}$ (kg ha^{-1} year^{-1}) is the sum of organic inputs from mulch; $\sum_{i=1}^{n} [N]_{Soil}$ (kg ha^{-1} year^{-1}) is the sum of inputs retained into the soil; and $\sum_{i=1}^{n} [N]_{losses}$ (kg ha^{-1} year^{-1}) is the sum of 'n' concentrations lost from the system with the harvested crop.

2.7 | Data analysis

All data were subjected to normality and heterogeneity tests using Shapiro–Wilk and Levene tests. Significant differences between soil chemical properties, mulch nutrient concentrations and coffee yields were subjected to factorial two-way ANOVA using a general linear model. The effects of interactions between the different treatments and the soil types on soil nutrient levels and coffee yields were also assessed. Duncan's multiple range test was applied to compare treatment means and rank them in descending order. Principal component analysis (PCA) was conducted using CANOCO 5 statistical software to assess the effects of interactions between the factors on the soil properties and coffee yield.

3 | RESULTS

3.1 | Soil pH and exchangeable soil Al

The mulch had specific effects on soil acidity and exchangeable soil acidity at each site (Table 2). All soils were acidic with a soil pH below 5, and exchangeable Al contents reached 0.34 mmol$^{(+)}$ kg^{-1}. The application of treatment T3 resulted in a significantly higher soil pH value ($p < 0.05$) and lower Al levels at Kibirizi, where the exchangeable soil acidity was reduced by 40%. At Karongi, T4 and T5 resulted in a significantly higher soil pH and lower Al than the control T6 ($p < 0.05$). T5 had the same effect on the soils of Ruli, and the soil exchangeable acidity was reduced by 43% (Table 2).

3.2 | Soil nutrient availability and soil property improvements

Significant differences in soil nutrient concentrations were observed between the treatments ($p < 0.001$) (Table 3a–c). The effects of the mulching systems were site-specific; at Kibirizi, the soils under T5 and T2 had significantly high SOC

TABLE 2 Effect of treatments on soil acidity at Kibirizi, Karongi and Ruli (mean and standard deviation)

	Kibirizi				Karongi				Ruli			
Treatment[a]	pH (H_2O)	Al^{3+} ($mmol^{(+)}kg^{-1}$)	H^+ ($mmol^{(+)}$ kg^{-1})	Al. sat. (%)	pH (H_2O)	$Al3^+$ ($mmol^{(+)}$ kg^{-1})	H^+ ($mmol^{(+)}$ kg^{-1})	Al. sat. (%)	pH (H_2O)	$Al3^+$ ($mmol^{(+)}$ kg^{-1})	H^+ ($mmol^{(+)}$ kg^{-1})	Al. sat. (%)
T1	4.21 ± 0.21b[b]	0.29 ± 0.09a	0.17 ± 0.02a	38.7 ± 13.9ab	4.39 ± 0.15b	0.16 ± 0.02ab	0.02 ± 0.01b	25.0 ± 4.8b	4.55 ± 0.23b[b]	0.29 ± 0.12a	0.20 ± 0.07a	38.6 ± 18.0a
T2	4.45 ± 0.38ab	0.34 ± 0.15a	0.03 ± 0.01c	53.5 ± 16.4a	4.59 ± 0.18ab	0.12 ± 0.03b	0.03 ± 0.01b	16.0 ± 2.9c	4.48 ± 0.19b	0.29 ± 0.08a	0.23 ± 0.07a	36.6 ± 9.7 a
T3	4.87 ± 0.21a	0.10 ± 0.02b	0.11 ± 0.02b	8.9 ± 3.2c	4.51 ± 0.19ab	0.17 ± 0.05ab	0.04 ± 0.02b	22.6 ± 8.1bc	4.44 ± 0.12b	0.33 ± 0.13a	0.22 ± 0.09a	42.1 ± 15.6a
T4	4.28 ± 0.36b	0.26 ± 0.11a	0.10 ± 0.04b	33.2 ± 16.0b	4.86 ± 0.36a	0.15 ± 0.04ab	0.09 ± 0.06a	15.6 ± 3.2c	4.44 ± 0.33b	0.34 ± 0.18a	0.20 ± 0.05a	39.8 ± 19.2a
T5	4.64 ± 0.57ab	0.27 ± 1.88a	0.03 ± 0.02c	33.0 ± 18.3b	4.82 ± 0.46a	0.14 ± 0.05b	0.05 ± 0.03b	16.5 ± 7.0c	4.84 ± 0.25a	0.13 ± 0.0b	0.17 ± 0.11a	17.2 ± 8.6b
T6	4.42 ± 0.12b	0.31 ± 0.07a	0.04 ± 0.02c	53.1 ± 3.5a	4.30 ± 0.15b	0.20 ± 0.05a	0.06 ± 0.04ab	35.2 ± 7.4a	4.60 ± 0.17b	0.33 ± 0.12a	0.20 ± 0.05a	39.6 ± 12.3a
Mean of soil types												
Inceptisols	4.62 ± 0.37	0.18 ± 0.08	0.08 ± 0.05	28.9 ± 16.0	4.73 ± 0.37	0.15 ± 0.06	0.05 ± 0.05	19.8 ± 9.2	4.48 ± 0.32	0.34 ± 0.14	0.18 ± 0.08	41.2 ± 15.1
Ultisols	4.34 ± 0.35	0.34 ± 0.14	0.08 ± 0.06	44.6 ± 20.2	4.42 ± 0.19	0.16 ± 0.03	0.05 ± 0.02	23.8 ± 8.5	4.64 ± 0.13	0.24 ± 0.11	0.22 ± 0.05	30.1 ± 15.1
	ANOVA (*p*-value)											
Mulch	$p < 0.05$	ns	$p < 0.001$	$p < 0.05$	$p < 0.05$	$p < 0.05$	$p < 0.05$	$p < 0.001$	$p < 0.05$	ns	ns	$p < 0.05$
Soil	ns	$p < 0.05$	ns	$p < 0.05$	$p < 0.05$	ns	ns	$p < 0.001$	ns	ns	ns	ns
Mulch*Soil	$p < 0.001$	$p < 0.001$	ns	$p < 0.001$	ns	ns	$p < 0.05$	ns	$p < 0.001$	$p < 0.05$	$p < 0.05$	$p < 0.05$
Mulch*Soil*Site	$p < 0.001$	$p < 0.001$	$p < 0.001$	$p < 0.001$	$p < 0.001$	$p < 0.001$	$p < 0.001$	$p < 0.001$	$p < 0.001$	$p < 0.001$	$p < 0.001$	$p < 0.001$

[a]See Table 1 for the notes; ns: not significant at $p < 0.05$; a>b>c; $n = 36$. [b] For each parameter, values in the same column with the same letter are not statistically different.

TABLE 3 (a) Effects of mulching systems on availability of soil nutrients and coffee yield at Kibirizi (mean and standard deviation). (b) Effects of mulching systems on availability of soil nutrients and coffee yield at Karongi (mean and standard deviation). (c) Effects of mulching systems on availability of soil nutrients and coffee yield at Ruli (mean and standard deviation)

Treatment [a]	O.C (g kg^{-1})	Tot N (g kg^{-1})	P_Olsen (mg kg^{-1})	Na^+ (mg kg^{-1})	K^+ (mg kg^{-1})	Ca^{2+} (mg kg^{-1})	Mg^{2+} (mg kg^{-1})	(Ca+Mg)/K (mg kg) $^{-1}$	ECEC (mg kg^{-1})	Base sat. (%)	Yield (t ha^{-1})
(a)											
T1	26.3 ± 2.4b[b]	1.85 ± 0.05bc	14.78 ± 3.87a	0.07 ± 0.04bc	0.41 ± 0.24bc	0.77 ± 0.36c	0.31 ± 0.20d	2.73 ± 0.82b	7.72 ± 0.62b	19.7 ± 8.3d	1.09 ± 0.03bc
T2	33.3 ± 5.9a	2.03 ± 0.28b	5.78 ± 1.96bc	0.40 ± 0.05a	0.22 ± 0.08c	1.31 ± 0.45c	0.47 ± 0.22bcd	8.87 ± 4.13a	6.09 ± 1.07 cd	40.7 ± 14.5b	1.26 ± 0.17a
T3	20.8 ± 1.7b	1.50 ± 0.11d	6.73 ± 3.80b	0.05 ± 0.01c	1.28 ± 0.28a	2.17 ± 0.49b	1.10 ± 0.27a	2.61 ± 0.60b	11.28 ± 1.57a	40.5 ± 2.9b	1.17 ± 0.02ab
T4	23.5 ± 7.2b	1.73 ± 0.24c	8.32 ± 4.33b	0.15 ± 0.17b	0.46 ± 0.20b	1.29 ± 0.44b	0.60 ± 0.20bc	4.68 ± 2.09b	7.94 ± 0.62b	31.5 ± 10.6c	1.01 ± 0.18bc
T5	37.2 ± 5.2a	2.38 ± 0.21a	8.60 ± 1.31b	0.44 ± 0.05a	0.46 ± 0.04b	2.90 ± 0.65a	0.67 ± 0.23b	7.67 ± 1.14a	7.48 ± 1.75bc	62.5 ± 17.6a	1.01 ± 0.14bc
T6	15.4 ± 1.5c	1.31 ± 0.08d	2.58 ± 0.79c	0.45 ± 0.03a	0.21 ± 0.09c	1.28 ± 0.27c	0.37 ± 0.04 cd	8.56 ± 2.08a	5.88 ± 1.04d	39.3 ± 2.2b	0.96 ± 0.17c
Mean of soil types											
Inceptisols	25.9 ± 9.4	1.75 ± 0.33	9.04 ± 4.84	0.27 ± 0.20	0.53 ± 0.34	1.67 ± 0.71	0.70 ± 0.31	6.08 ± 3.56	7.18 ± 2.25	45.9 ± 17.2	1.10 ± 0.12
Ultisols	26.3 ± 7.9	1.85 ± 0.45	6.56 ± 4.28	0.25 ± 0.19	0.19 ± 0.50	1.57 ± 0.96	0.47 ± 0.30	5.63 ± 3.18	8.29 ± 1.86	32.1 ± 12.7	1.06 ± 0.20
ANOVA (*p*-value)											
Mulch	$p < 0.001$	$p < 0.001$	$p < 0.001$	$P < 0.001$	$p < 0.05$	$p < 0.001$	$p < 0.05$	$p < 0.001$	$p < 0.05$	$p < 0.05$	$p < 0.05$
Soil	ns	ns	$p < 0.05$	ns	ns	ns	$p < 0.05$	ns	ns	$p < 0.05$	ns
Mulch*Soil	ns	$p < 0.05$	ns	ns	$p < 0.001$	ns	ns	ns	$p < 0.05$	$p < 0.001$	$p < 0.001$
Mulch*Site	$p < 0.001$	$p < 0.001$	$p < 0.001$	$p < 0.001$	$p < 0.001$	$p < 0.001$	$p < 0.001$	ns	$p < 0.001$	$p < 0.001$	$p < 0.001$
(b)											
T1	13.5 ± 2.1c[b]	1.63 ± 0.50bc	7.77 ± 3.46c	0.34 ± 0.20bc	0.20 ± 0.04b	3.86 ± 0.44b	0.22 ± 0.07c	21.8 ± 8.1a	6.46 ± 0.56 cd	71.4 ± 4.7a	1.87 ± 0.02a
T2	17.0 ± 3.7bc	2.04 ± 0.23ab	9.55 ± 2.38bc	0.57 ± 0.08a	0.26 ± 0.09b	4.67 ± 0.60ab	0.49 ± 0.27bc	22.9 ± 11.2a	7.48 ± 1.13bc	80.0 ± 3.1a	1.50 ± 0.06bc
T3	14.5 ± 3.3c	2.06 ± 0.46ab	8.24 ± 2.97bc	0.53 ± 0.10ab	0.23 ± 0.06b	4.34 ± 1.04ab	0.35 ± 0.22bc	21.2 ± 5.2a	7.54 ± 0.89bc	71.6 ± 9.7a	1.56 ± 0.17b
T4	25.7 ± 5.6a	2.47 ± 0.42a	13.87 ± 2.06a	0.64 ± 0.22a	0.42 ± 0.13a	5.24 ± 0.61a	1.06 ± 0.61a	15.9 ± 3.7a	9.83 ± 1.98a	75.3 ± 6.6a	1.43 ± 0.07c
T5	21.0 ± 7.4ab	2.25 ± 0.67a	11.57 ± 4.17ab	0.58 ± 0.28a	0.26 ± 0.05b	4.99 ± 0.97a	0.74 ± 0.61ab	21.5 ± 2.1a	8.40 ± 1.32ab	77.8 ± 10.5a	1.52 ± 0.13bc
T6	12.2 ± 3.5c	1.28 ± 0.22c	6.79 ± 0.93c	0.19 ± 0.15c	0.16 ± 0.08b	2.70 ± 0.88c	0.22 ± 0.04c	22.5 ± 11.8a	5.84 ± 1.45d	55.8 ± 9.2b	1.19 ± 0.06d
Mean of soil types											
Inceptisols	18.4 ± 7.0	2.08 ± 0.52	10.47 ± 4.12	0.55 ± 0.26	0.29 ± 0.12	4.40 ± 1.01	0.70 ± 0.57	19.2 ± 6.0	7.94 ± 1.81	74.1 ± 12.2	1.46 ± 0.23
Ultisols	16.2 ± 5.7	1.83 ± 0.61	8.79 ± 2.90	0.40 ± 0.19	0.22 ± 0.09	4.20 ± 1.24	0.33 ± 0.24	22.8 ± 8.9	7.24 ± 1.73	69.8 ± 8.9	1.56 ± 0.21
ANOVA (*p*-value)											
Mulch	$p < 0.001$	$p < 0.001$	$p < 0.001$	$P < 0.001$	$p < 0.05$	$p < 0.05$	$p < 0.05$	ns	$p < 0.05$	$p < 0.05$	$p < 0.05$
Soil	$p < 0.05$	$p < 0.05$	$p < 0.05$	$p < 0.001$	ns	ns	$p < 0.05$	ns	ns	$p < 0.05$	ns
Mulch*Soil	ns	ns	ns	ns	$p < 0.05$	ns	$p < 0.05$	$p < 0.05$	ns	ns	$p < 0.001$
Mulch*Site	$p < 0.001$	$p < 0.001$	$p < 0.001$	$p < 0.001$	$p < 0.001$	$p < 0.001$	$p < 0.001$	ns	$p < 0.001$	$p < 0.001$	$p < 0.001$
(c)											
T1	21.0 ± 6.9a [b]	2.74 ± 0.83a	9.89 ± 3.52ab	0.42 ± 0.06b	0.22 ± 0.09b	1.53 ± 0.85ab	0.62 ± 0.37b	10.1 ± 5.0a	7.74 ± 1.01a	35.12 ± 13.9b	1.39 ± 0.07a
T2	21.1 ± 9.9a	2.12 ± 0.97a	7.49 ± 4.60ab	0.42 ± 0.07b	0.16 ± 0.06b	1.63 ± 0.93ab	0.60 ± 0.30b	14.0 ± 4.3a	7.97 ± 0.99a	34.19 ± 12.0b	1.28 ± 0.21ab
T3	24.9 ± 11.8a	2.59 ± 0.89a	6.01 ± 4.43b	0.47 ± 0.03b	0.13 ± 0.06b	1.29 ± 0.90b	0.49 ± 0.33b	13.3 ± 4.9a	7.84 ± 1.12a	29.6 ± 13.4b	1.19 ± 0.13b

(Continues)

TABLE 3 (Continued)

Treatment [a]	O.C (g kg^{-1})	Tot N (g kg^{-1})	P_Olsen (mg kg^{-1})	Na^+ (mg kg^{-1})	K^+ (mg kg^{-1})	Ca^{2+} (mg kg^{-1})	Mg^{2+} (mg kg^{-1})	(Ca+Mg)/K (mg kg)$^{-1}$	ECEC (mg kg^{-1})	Base sat. (%)	Yield (t ha^{-1})
T4	18.6 ± 7.3a	2.72 ± 1.49a	9.24 ± 5.88ab	0.44 ± 0.04b	0.22 ± 0.08b	1.75 ± 1.03ab	0.59 ± 0.31b	12.6 ± 10.1a	8.38 ± 0.65a	36.2 ± 15.2b	1.26 ± 0.14ab
T5	14.3 ± 4.2a	1.73 ± 0.79a	5.51 ± 4.37b	0.42 ± 0.04b	0.34 ± 0.15a	2.48 ± 0.69a	1.36 ± 0.33a	12.0 ± 2.3a	7.31 ± 0.65a	63.2 ± 16.4a	1.34 ± 0.15ab
T6	21.3 ± 11.0a	1.67 ± 0.63a	11.70 ± 1.10a	0.53 ± 0.02a	0.22 ± 0.06b	1.62 ± 0.37ab	0.61 ± 0.24b	10.9 ± 4.7a	8.34 ± 0.64a	35.8 ± 7.50b	1.39 ± 0.11a
Mean of soil types											
Inceptisols	24.1 ± 8.9	2.76 ± 1.06	8.66 ± 5.21	0.46 ± 0.06	0.20 ± 0.12	1.58 ± 0.94	0.64 ± 0.48	11.8 ± 5.1	7.98 ± 1.14	36.3 ± 20.0	1.27 ± 0.17
Ultisols	16.3 ± 7.2	1.76 ± 0.67	7.95 ± 3.81	0.44 ± 0.06	0.23 ± 0.08	1.85 ± 0.76	0.79 ± 0.34	12.5 ± 6.0	7.88 ± 0.56	41.8 ± 12.6	1.34 ± 0.13
ANOVA (p-value)											
Mulch	Ns	ns	$p < 0.05$	$p < 0.05$	$p < 0.05$	$p < 0.05$	$p < 0.05$	ns	ns	$p < 0.05$	$p < 0.05$
Soil	$p < 0.05$	$p < 0.05$	ns	$p < 0.05$	ns	ns	ns	ns	ns	ns	ns
Mulch*Soil	Ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	$p < 0.05$
Mulch*Site	$p < 0.001$	$p < 0.001$	$p < 0.001$	$p < 0.001$	$p < 0.001$	$p < 0.001$	$p < 0.001$	ns	$p < 0.001$	$p < 0.001$	$p < 0.001$

Notes: N.B. Coffee nutrient requirements are equivalent to 44 N, 5.2 P, 19.9 K, 1072 Ca and 482 Mg kg ha^{-1} year^{-1} (Cordingley, 2009). ECEC= effective cation exchange capacity.

[a]See Table 1 for the notes; significant differences ($p < 0.05$); ns: not significant at $p < 0.05$; a>b>c; n=36. [b] For each parameter, values in the same column with the same letter are not statistically different.

content, total N and base saturation compared to the control T6 ($p < 0.05$), while available P had increased 5.7 times with T1. SOC was positively correlated with total N and available P (Figure 2). At Karongi, T4 had significantly high SOC content, high total N, high available P and significant base saturation ($p < 0.05$). Positive relationships between these soil properties were observed on sandy clay loams (Figure 2). Available P was positively correlated with exchangeable Al at Ruli, particularly with T6, T4 and T1 (Figure 2). Similar effects were observed with T3 and T5 at Kibirizi, and with T4 at Karongi (Figure 2).

3.3 | Coffee yield

Mulch significantly increased coffee yields on average from 1.2 to 1.9 t ha^{-1} ($p < 0.05$) (Table 3a–c). The effects of mulch and the interactions between the mulching systems and soil types were significantly different for each site ($p < 0.001$). At Kibirizi, compared to the no mulching treatment (T6), T2 and T3 increased coffee yields by 31 and 22%, respectively. At Karongi, compared to T6, T1, T2, T3, T4 and T5 increased coffee yield by 57%, 26%, 31%, 20% and 28%, respectively. T1 increased coffee yield by 48% when compared to the highest yield obtained with T2 at Kibirizi. The interactions between mulch and soil properties influenced coffee yield, particularly on sandy clay loam soils (with T1, T2, and T3) in contrast to clay loam soils (Figure 3). On the other hand, at Ruli, there were no effects of mulching practices on coffee yields (Table 3c).

3.4 | Nutrients in the mulch

There was differential release of N, P, K, Ca and Mg from mulches, depending on type of materials applied at each site (Table 4). Significant differences were observed between the treatments ($p < 0.001$). The highest dose of N was supplied with mulch collected at Kibirizi under T1. The highest doses of available P and Ca were supplied with mulch collected from Karongi under T4. With mulch collected at Ruli, the highest dose of Mg was observed under T5. The K concentrations were similar at all sites (Table 4).

3.5 | Fertilizer recommendations

The mulch alone cannot supply sufficient nutrients to compensate for the removal by the coffee crop and other losses; therefore, the additional needs for N, P, K, Ca and Mg have been estimated. Maximum additions of 27 kg N ha^{-1}; 4.4 kg P ha^{-1}; 15 kg K ha^{-1}; 1039 kg Ca ha^{-1}; and 466 kg Mg ha^{-1} are needed for coffee farms at Kibirizi, whereas at Karongi, 32 kg N ha^{-1}; 3.6 kg P ha^{-1}; 16 kg K ha^{-1}; 1040 kg Ca ha^{-1}; and 458 kg Mg ha^{-1} are needed as additional inorganic nutrient inputs, and at Ruli, 34 kg N ha^{-1}; 4.7 kg P ha^{-1}; 18 kg

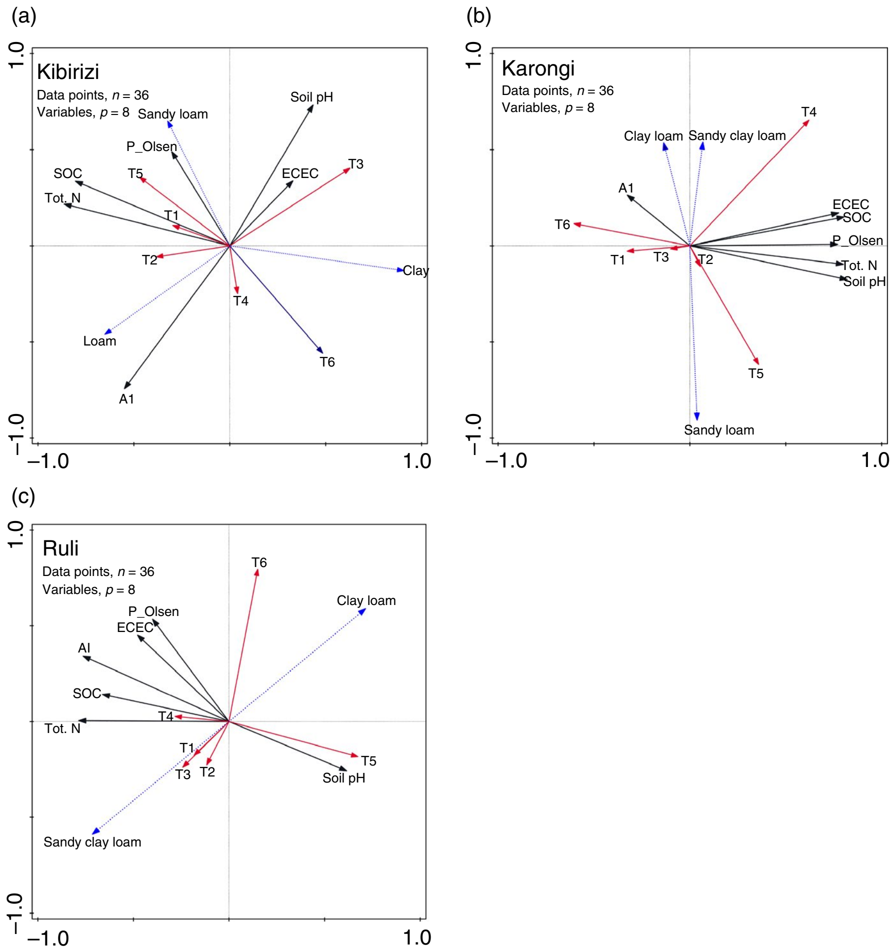


FIGURE 2 Relationship between different mulching systems (T1 to T6) and soil properties (Al; N; P; pH; SOC: soil organic carbon; ECEC: effective cation exchange capacity) at three study sites (Karongi, Kibirizi and Ruli) located in three different agro-ecological zones

TABLE 4 Nutrient contents[a] in the organic mulch applied at Kibirizi, Karongi and Ruli (mean and standard deviation)

	Kibirizi					Karongi	
Treatment [b]	N (kg ha^{-1})	P (kg ha^{-1})	K (kg ha^{-1})	Ca^{2+} (kg ha^{-1})	Mg^{2+} (kg ha^{-1})	N (kg ha^{-1})	P (kg ha^{-1})
T1	17.0 ± 1.0c	1.44 ± 0.05c	10.95 ± 3.36a	32.9 ± 1.2e	16.1 ± 1.0d	11.8 ± 1.2d	1.64 ± 0.36c
T2	22.9 ± 2.5b	1.23 ± 0.10d	11.00 ± 1.26a	35.3 ± 1.1d	42.6 ± 20.9c	14.3 ± 2.2b	2.01 ± 0.13c
T3	32.5 ± 4.0a	2.28 ± 0.09b	8.14 ± 0.85b	47.1 ± 1.0c	64.9 ± 27.0b	13.4 ± 2.3 cd	3.21 ± 0.35b
T4	31.7 ± 3.2a	0.84 ± 0.05e	5.40 ± 0.76d	54.4 ± 3.0b	71.3 ± 1.8b	27.2 ± 1.8a	3.73 ± 0.37a
T5	25.0 ± 1.6b	2.83 ± 0.17a	6.72 ± 0.32c	57.4 ± 0.9a	100.1 ± 6.2a	26.7 ± 1.6b	3.03 ± 0.89b
T6	-	-	-	-	-	-	-
Mean of soil types							
Inceptisols	25.5 ± 6.7	1.71 ± 0.73	9.25 ± 3.25	45.1 ± 9.9	63.6 ± 29.1	18.7 ± 5.9	2.59 ± 0.66
Ultisols	26.2 ± 6.3	1.74 ± 0.79	7.63 ± 1.97	45.8 ± 10.7	54.4 ± 35.4	17.4 ± 7.2	2.86 ± 1.12
ANOVA (*p*-value)							
Mulch	$p < 0.001$	$p < 0.001$	$p < 0.05$	$p < 0.001$	$p < 0.05$	$p < 0.001$	$p < 0.05$
Soil	ns	ns	ns	ns	ns	ns	ns
Mulch*Soil	ns	ns	$p < 0.001$	$p < 0.001$	$p < 0.001$	ns	$p < 0.001$
Mulch*Soil* Site	$p < 0.001$	$p < 0.001$	$p < 0.001$	$p < 0.001$	$p < 0.001$	$p < 0.001$	$p < 0.001$

Notes: For each parameter, values in the same column with the same letter are not statistically different.
[a]Calculated based on the concentrations of N, P, K, Ca and Mg (g kg^{-1}) of mulch applied (T1: 15 t ha^{-1}; T2: 15 t ha^{-1}; T3: 17 t ha^{-1}; T4: 20 t ha^{-1} and T5: 21 t ha^{-1}).
[b]See Table 1 for the notes; T6 = control (not mulched); significant differences ($p < 0.05$): a>b>c>d>e; $n = 30$.

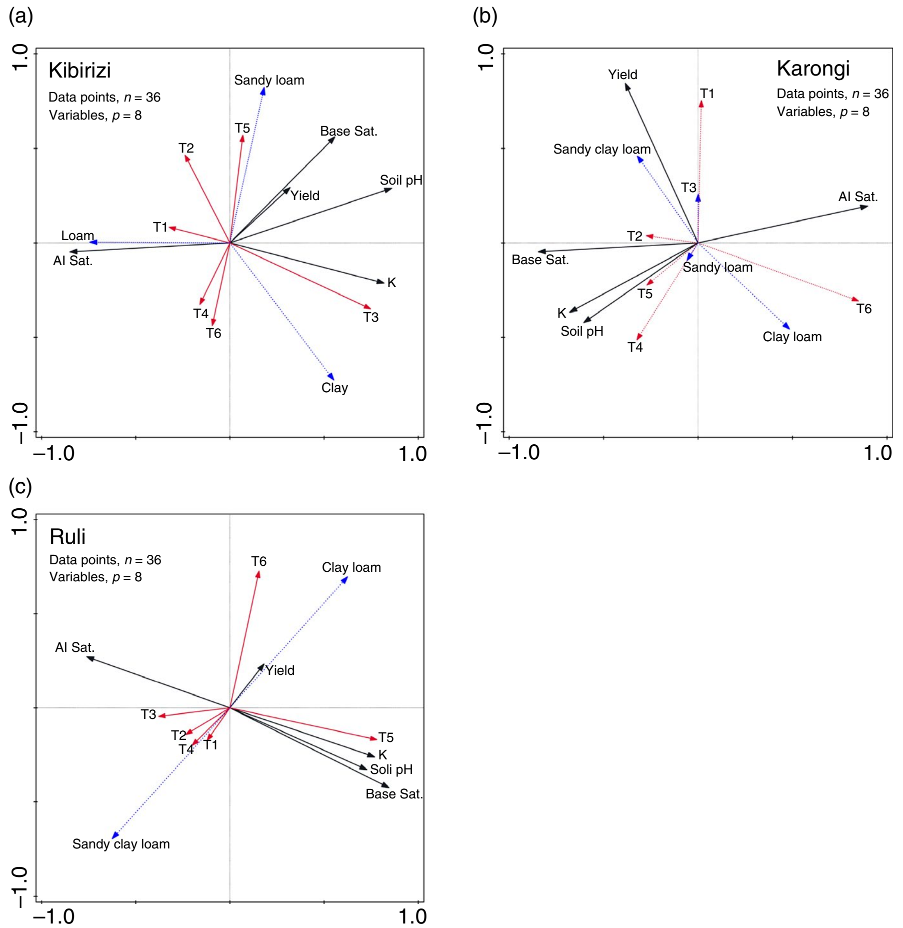


FIGURE 3 Relationship between different mulching systems (T1 to T6), coffee yield and soil properties (Al Sat.: aluminium saturation; Base sat.: base saturation; pH; K) at three study sites (Karongi, Kibirizi and Ruli) located in three different agro-ecological zones

			Ruli				
K (kg ha^{-1})	**Ca^{2+} (kg ha^{-1})**	**Mg^{2+} (kg ha^{-1})**	**N (kg ha^{-1})**	**P (kg ha^{-1})**	**K (kg ha^{-1})**	**Ca^{2+} (kg ha^{-1})**	**Mg^{2+} (kg ha^{-1})**
3.54 ± 1.12c	31.3 ± 1.5d	24.5 ± 2.5d	10.3 ± 0.9d	0.58 ± 0.08e	2.06 ± 0.12c	49.2 ± 4.2c	36.2 ± 5.1d
5.21 ± 1.50bc	41.8 ± 1.5c	25.4 ± 1.4d	12.8 ± 1.6c	0.81 ± 0.16c	2.67 ± 0.16c	51.1 ± 5.1c	34.7 ± 4.2d
6.36 ± 1.88b	39.7 ± 2.8c	50.2 ± 1.5c	12.5 ± 1.9c	0.65 ± 0.09d	2.46 ± 0.74c	62.4 ± 7.7b	55.1 ± 9.3c
8.90 ± 1.88a	75.1 ± 16.0a	52.8 ± 5.0b	20.7 ± 3.1a	1.20 ± 0.14b	8.16 ± 3.72b	68.1 ± 1.4a	85.8 ± 12.3b
9.45 ± 2.04a	66.6 ± 3.9b	60.8 ± 2.6a	17.7 ± 2.1b	1.29 ± 0.13a	9.70 ± 2.55a	62.3 ± 9.8b	108.9 ± 9.2a
-	-	-					
7.44 ± 2.32	47.8 ± 14.6	43.7 ± 15.3	14.1 ± 3.3	0.80 ± 0.29	4.05 ± 2.05	63.5 ± 8.17	68.0 ± 27.7
5.94 ± 3.04	53.9 ± 21.9	41.7 ± 16.0	15.5 ± 5.2	1.01 ± 0.31	5.97 ± 4.88	53.8 ± 8.1	60.3 ± 33.6
$p < 0.001$	$p < 0.05$	$p < 0.001$	$p < 0.05$	$p < 0.001$	$p < 0.05$	$p < 0.05$	$p < 0.001$
$p < 0.05$	ns	ns	ns	$p < 0.001$	ns	$p < 0.05$	ns
Ns	$p < 0.001$	$p < 0.001$	$p < 0.001$	$p < 0.05$	$p < 0.001$	$p < 0.001$	$p < 0.001$
$p < 0.001$	$p < 0.001$	$p < 0.001$	$p < 0.001$	$p < 0.001$	$p < 0.001$	$p < 0.001$	$p < 0.001$

TABLE 5 Inorganic fertilizer recommendations (N-P-K-Ca-Mg) at Kibirizi, Karongi and Ruli (mean and standard deviation)

	Kibirizi					Karongi	
Treatment [a]	N (kg ha^{-1})	P (kg ha^{-1})	K (kg ha^{-1})	Ca^{2+} (kg ha^{-1})	Mg^{2+} (kg ha^{-1})	N (kg ha^{-1})	P (kg ha^{-1})
T1	27.0 ± 1.0a[b]	3.80 ± 0.05c	8.98 ± 3.36 d	1038.5 ± 1.2a	466.3 ± 1.0a	32.3 ± 1.2a[b]	3.60 ± 0.36a
T2	21.1 ± 2.5b	4.01 ± 0.10b	8.92 ± 1.26 d	1036.1 ± 1.1b	439.7 ± 20.9b	29.8 ± 2.2b	3.23 ± 0.13a
T3	11.5 ± 4.0c	2.96 ± 0.09d	11.79 ± 0.85c	1024.3 ± 1.0c	417.5 ± 27.0c	30.6 ± 2.3ab	2.03 ± 0.35b
T4	12.3 ± 3.2c	4.40 ± 0.05a	14.53 ± 0.76a	1017.0 ± 3.0d	411.0 ± 1.8c	16.8 ± 1.8d	1.51 ± 0.37c
T5	19.0 ± 1.6b	2.41 ± 0.18e	13.21 ± 0.32b	1014.0 ± 0.9e	382.3 ± 6.2d	20.3 ± 1.6c	2.21 ± 0.89b
T6	-	-	-	-	-	-	-
Mean of soil types							
Inceptisols	18.5 ± 6.7	3.53 ± 0.73	10.7 ± 3.3	1026.3 ± 9.9	418.8 ± 29.1	25.3 ± 5.9	2.65 ± 0.66
Ultisols	17.8 ± 6.3	3.50 ± 0.79	12.3 ± 1.98	1025.6 ± 10.7	427.9 ± 35.4	26.6 ± 7.2	2.38 ± 1.12
ANOVA (*p*-value)							
Mulch	$p < 0.001$	$p < 0.001$	$p < 0.05$	$p < 0.001$	$p < 0.05$	$p < 0.001$	$p < 0.05$
Soil	ns	ns	ns	ns	ns	ns	ns
Mulch*Soil	ns	ns	$p < 0.001$	$p < 0.001$	$p < 0.001$	ns	$p < 0.001$
Mulch*Soil*Site	$p < 0.001$	$p < 0.001$	$p < 0.001$	$p < 0.001$	$p < 0.001$	$p < 0.001$	$p < 0.001$

[a]See Table 1 for the notes; T6 = control (not mulched); significant differences ($p < 0.05$): a>b>c>d>e; $n = 30$. [b]For each parameter, values in the same column with the same letter are not statistically different.

K ha^{-1}; 1023 kg Ca ha^{-1}; and 448 kg Mg ha^{-1} are needed (Table 5).

4 | DISCUSSION

4.1 | Effect of mulching on exchangeable acidity and nutrient immobilization

The Al toxicity and exchangeable acidity were higher at Ruli and Kibirizi compared to the Karongi site, indicating a natural low soil fertility status at Ruli and Kibirizi. Kibirizi and Ruli belong to agro-ecological zones, naturally characterized by cold and humid highlands, with high soil acidity due to the formation of schist, mica schist and micaceous granite. Most soils under coffee in Rwanda have a low pH (<5.0) with high soil Al levels (>30%) (Cordingley, 2009). These conditions might have accelerated soil acidification under the organic mulching treatments T1 and T2, depending on the chemical composition of the mulches, their rates of decomposition and mineralization. Organic materials rich in polyphenols and lignin decompose more slowly, particularly under humid conditions (Abbasi, Tahir, Sabir, & Khurshid, 2015); hence, this is likely contributed to nutrient immobilization (Fageria & Nascente, 2014).

An increase in soil pH values at Ruli and Kibirizi sites was observed under T3, T4 and T5. This might be due to the decomposition of these mulches which tends to improve soil organic carbon and exchangeable bases while reducing exchangeable acidity (Awopegba et al., 2017). T5 was predominantly composed of mixed residues that contain low concentrations of polyphenols and lignin (Abbasi et al., 2015). Thus, the increase in SOM mitigated soil acidification as the Al and H ions were adsorbed by negatively charged exchange sites of the SOM (Li & Johnson, 2016).

4.2 | Effect of mulching on C and N mineralization and availability

The soil C and N contents varied with geographic location and the environmental conditions of the study sites which influenced the decomposition and mineralization of the mulches. At Karongi, the favourable climate induced repeated dry-wet cycles that may have enhanced faster microbial degradation of the mulch, resulting in increased C and N stocks and improved soil quality. At Kibirizi and Ruli, cold conditions and low soil pH may have contributed to C and N immobilization, particularly under T1 and T2 which may have contained high concentrations of polyphenols and lignin (Abbasi et al., 2015). Losses of dissolved organic C and N have been reported in acid soil in humid zones, where the organic matter stock has decreased (Abbasi et al., 2015). On the other hand, the greater SOC content and total N in treatments T4 and T5, particularly at Kibirizi and Karongi, indicated the potential of these mulches to increase C and N availability. In addition, the increase in N mineralization is probably explained by the low C/N ratios of the mulch. Mulches with a high C/N ratio have resulted in high

			Ruli				
K (kg ha^{-1})	Ca^{2+} (kg ha^{-1})	Mg^{2+} (kg ha^{-1})	N (kg ha^{-1})	P (kg ha^{-1})	K (kg ha^{-1})	Ca^{2+} (kg ha^{-1})	Mg^{2+} (kg ha^{-1})
16.4 ± 1.1a	1040.2 ± 1.5a	457.9 ± 2.5a	33.7 ± 0.9a[b]	4.66 ± 0.08a	17.9 ± 0.1a	1022.2 ± 4.2a	446.2 ± 5.1a
14.7 ± 1.5ab	1029.7 ± 1.5b	457.0 ± 1.4a	31.2 ± 1.5b	4.43 ± 0.16c	17.3 ± 0.2a	1020.3 ± 5.1a	447.7 ± 4.2a
13.6 ± 1.9b	1031.7 ± 2.8b	432.2 ± 1.5b	31.5 ± 1.9b	4.59 ± 0.08b	17.5 ± 0.7a	1009.0 ± 7.7b	427.3 ± 9.3b
11.0 ± 1.9c	996.4 ± 16.0d	429.5 ± 5.0c	23.3 ± 3.1d	4.04 ± 0.14d	11.8 ± 3.7b	1003.4 ± 1.4c	396.6 ± 12.2c
10.5 ± 2.0c	1004.8 ± 3.9c	421.6 ± 2.6d	26.3 ± 2.1c	3.95 ± 0.12e	10.2 ± 2.6c	1009.1 ± 9.8b	373.5 ± 9.2d
-	-	-					
12.5 ± 2.3	1023.6 ± 14.6	438.7 ± 15.3	29.9 ± 3.3	4.44 ± 0.29	15.8 ± 2.1	1007.9 ± 8.2	414.4 ± 27.7
14.0 ± 3.0	1017.5 ± 21.9	440.7 ± 16.0	28.5 ± 5.2	4.23 ± 0.31	14.0 ± 4.9	1017.7 ± 8.1	422.1 ± 33.6
$p < 0.001$	$p < 0.05$	$p < 0.001$	$p < 0.05$	$p < 0.001$	$p < 0.05$	$p < 0.05$	$p < 0.001$
$p < 0.05$	ns	Ns	ns	$p < 0.001$	ns	$p < 0.05$	ns
ns	$p < 0.001$	$p < 0.001$	$p < 0.001$	$p < 0.05$	$p < 0.001$	$p < 0.001$	$p < 0.001$
$p < 0.001$	$p < 0.001$	$p < 0.001$	$p < 0.001$	$p < 0.001$	$p < 0.001$	$p < 0.001$	$p < 0.001$

C and N contents. Similar research findings were also reported by Abbasi et al. (2015) and Adekiya et al. (2017).

4.3 | Effect of mulching on phosphorus fixation and availability

Our results indicated that the concentration of P was low in all the soils; most soils in Rwanda with excessive acidity and high Al are P deficient (Mbonigaba, Nzeyimana, Bucagu, & Culot, 2009). At Kibirizi and Ruli, retention and fixation of P in the soils has limited its availability due to the high exchangeable acidity. Increased P concentrations were observed at Karongi after decomposition and mineralization of T4 and T5 mulches. The amount of P released depended on the types and amount of the added mulches as also reported by Adekiya et al. (2017).

Our results also revealed that P retention varied among soil types and depended on soil organic matter binding properties. P was retained and fixed in sandy clay soils, and was positively correlated with the soil organic carbon. This indicated that the P released was readily available due to increases in soil organic matter. The presence of clay minerals in soils enriched with organic matter released from organic mulch decomposition enhances the retention process of P which will provide additional energy for bio-cycling C and N (Cui et al., 2019). The structure of soils such as sandy clays is improved by soil organic carbon released from the decomposition and mineralization of the added mulches (Nzeyimana et al., 2017), hence improving the soil fertility (Adekiya et al., 2017).

4.4 | Effect of mulching on cations

The tested mulches demonstrated low to moderate effects on the retention capacity of the major soil nutrients, hence indicating low to moderate soil fertility; this could be related to slower decomposition of the tested organic mulches since most of the C/N ratios of the mulches were above 12 (Murphy et al., 2016). The Ca and Mg levels were positively correlated and were also correlated with the available P, K, and Na. The low base saturation was significantly affected by the increase in the soil Al saturation, particularly at Kibirizi and Ruli. For soils of Rwanda, 70% of base saturation can reduce Al saturation to <20% (Mbonigaba et al., 2009). Our results also confirmed this trend, mainly at Karongi, where 80% base saturation had increased available soil nutrients. At the Kibirizi and Ruli, the increased soil acidity also resulted in lower soil (Ca + Mg)/K, as the prominent contributor to yield gaps. Positive correlation between (Ca+Mg)/K and base saturation indicates possibilities to raise Ca and Mg contents of the soils by liming to precipitate the exchangeable acidity and Al (Carducci et al., 2015). Furthermore, the concentration of (Ca+Mg)/K was negatively correlated with K contents, suggesting a need for additional inorganic K to increase the ECEC.

4.5 | Effect of mulching on coffee yield

The effects of mulching practices on coffee yield were determined by geographic location and demonstrated the influence of the agro-ecological conditions of the study sites. The highest yield (1.9 t ha^{-1} $year^{-1}$ of green coffee) was observed at Karongi located in the middle altitude, where T1 increased yield by 57% compared to the no mulching treatment; the coffee yield was positively influenced by the changes in soil nutrient concentrations particularly the reduced exchangeable soil acidity, increased SOC, total N, available P, increase in base saturation, and exchangeable K, Ca and Mg concentrations. At Kibilizi, the yield increased by 31% with T2, while at Ruli, there were no effects of mulching practices on coffee yield, indicating that yields were negatively affected by high Al saturation and low K levels, predominately found at these sites. Kibirizi and Ruli, being located in the highlands, coffee yields were also affected by cold and humid environmental conditions in addition to the high Al saturation and low soil fertility status. In Uganda, Wang et al. (2015) also found that elevation was a strong limitating factor for coffee yield. Coffee yields are known to be limited by soil acidity and deficiencies in N, P, and K, key nutrients in the development of the coffee plant and coffee berries (Cordingley, 2009; Wang et al., 2015).

Coffee yields in the Rwandan smallholder farming system ranged from 1.0 to 1.9 t ha^{-1} $year^{-1}$; coffee yields close to 1.8 t ha^{-1} $year^{-1}$ are considered high (Nzeyimana et al., 2014). In Uganda, coffee yields varying between 0.2 and 2.2 t ha^{-1} $year^{-1}$ of green coffee were reported for large-scale monoculture farming and smallholder farming systems (Wang et al., 2015). Arabica coffee yields higher than 5 t ha^{-1} $year^{-1}$ have been obtained in unshaded large-scale coffee blocks in Latin-American countries such as Brazil, Colombia, Ecuador and Costa-Rica (Wang et al., 2015).

4.6 | Fertilizer recommendations to improve coffee yield

Our results have demonstrated that soil nutrient levels increased with the amount of mulch applied, as also reported by Adekiya et al. (2017) and Awopegba et al. (2017). However, more land will be required to produce such large amounts of mulch biomass. In Rwanda currently, the land available for agriculture is gradually being reduced as it is being dedicated to other types of land use such as the development of new settlements. Furthermore, most smallholder farmers hold on average 0.3 ha of land (NISR, 2018). This accentuates the fact that a combination of organic mulch and mineral fertilization is the best alternative to boost productivity (Wang et al., 2015).

Taking into account the concentrations of the nutrients released into the soils at each site, nutrient gaps can be closed by implementing site-specific additional inorganic fertilizer recommendations to address the limiting factors affecting coffee yields. For Rwanda, based on coffee nutrient requirements of 44 N, 5.2 P, 20 K, 1072 Ca and 482 Mg kg ha^{-1} $year^{-1}$ (Cordingley, 2009), the addition of inorganic fertilizer inputs applied as NPK fertilizer (14-5-9) at 200 kg ha^{-1} and lime (Ca: 58% and Mg: 15.5%) applied at 2.5 t ha^{-1} is recommended for Kibirizi. In Ruli, 200 kg ha^{-1} of NPK fertilizer (17-5-11) and 2.5 t ha^{-1} of lime (Ca: 57% and Mg: 15%) are recommended. In Karongi, the NPK fertilizer (16-4-10) and lime (Ca: 58% and Mg: 15%) are recommended. P and Ca could also be supplied through rock phosphates or phosphorus fertilizer. These fertilizer rates are very low compared to those used by big coffee producing countries in Latin-America. To boost high coffee yields, Ecuador, Capa, Perez-Esteban, and Masaguer (2015) demonstrated that medium and high fertilizer rates (over 150 N, 44 P and 62 K kg ha^{-1} $year^{-1}$ in the first year and 300 N, 87 P and 125 K kg ha^{-1} $year^{-1}$ for the second year) could not support the environmental and economic sustainability of monoculture coffee farming. Conversely, it was recommended that the application of fertilizer rates of about 70 N, 22 P and 31 K kg ha^{-1} $year^{-1}$ in the first year and 200 N, 65 P and 62 K kg ha^{-1} $year^{-1}$ for the second year were both environmentally and economically sustainable (Capa et al., 2015).

5 | CONCLUSION

While the use of mulching material in coffee farming in Rwanda is still scarce due to the unavailability of the required biomass, the strategy for managing locally available mulches in improving soil fertility and coffee yield needs to be emphasized. Our findings demonstrated that the tested organic mulches strongly improved soil nutrient levels. The amount of nutrients released into the soils was regulated by the amount and type of mulch biomass applied and the environmental conditions of the specific study site. Adding high quantities of organic mulches to the soils did not necessarily improve soil fertility. Thus, organic mulching in coffee smallholder farming should be considered as part of the improved soil management technologies aimed at improving soil fertility and yield. Although we hypothesized that the use of organic mulch in coffee smallholder farming could be used as a substitute for mineral fertilizer to alleviate the high cost for fertilizers, it is also important to understand that in situations where land is a limiting factor, a combination of mineral and organic fertilizers would be profitable for smallholder coffee farmers with limited incomes.

ACKNOWLEDGEMENTS

We would like to acknowledge the financial support of the Government of Rwanda in partnership with NUFFIC of the

Netherlands and the University of Rwanda under the NPT/RWA/061 project. We take also this opportunity to thank the Ministry of Agriculture and Animal Resources that provided us with essential institutional support. Our sincere gratitude goes to the coffee farmers who provided their fields for data collection and experimentation.

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How to cite this article: Nzeyimana I, Hartemink AE, Ritsema C, Mbonigaba JJM, Geissen V. Mulching effects on soil nutrient levels and yield in coffee farming systems in Rwanda. *Soil Use Manage*. 2019;00:1–13. https://doi.org/10.1111/sum.12534