


# Market access and resource endowment define the soil fertility status of smallholder farming systems of South-Kivu, DR Congo

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## Abstract

This study verified the inter-related effect of ‘market distance’, defined as walking time, ‘farm typology’, defined as resource endowment, and ‘site’, defined as geographic location with contrasting agro-ecologies, as well as farmers’ indigenous knowledge on soil fertility variability in smallholder farming systems in two distinct regions (Bushumba, Mushinga) of South-Kivu, DR Congo. A total of 384 soil samples were selected from representative farmers’ fields and analysed for soil pH, soil organic carbon (SOC) content and quality, as well as nutrient contents, using mid-DRIFTS (mid-infrared diffuse reflectance Fourier transform spectroscopy) and wet chemistry analyses. MidDRIFTS was also used to calculate SOC stability indexes as SOC quality proxies. ‘Market distance’ and ‘farm typology’ were key determinants of soil fertility variability, both with contrasting trends in Bushumba and Mushinga. Decreasing soil fertility with increasing market distance was noted across all farm typologies. ‘Farm typology’ was related to exchangeable calcium and magnesium, while ‘site’ resulted in a difference of plant available phosphorus. SOC quality indexes were related to ‘site’, interacting with ‘market distance’. A ‘market distance’ effect became obvious in the medium wealthy and poor farms of Mushinga, where a lower SOC quality in remote fields plots was noted with increasing market distance. In agreement with farmers’ indigenous knowledge, soil fertility levels were higher in deep than shallow soils, which were reflected in higher nutrient stocks in deep soils receiving organic amendments. Our results inferred that soil fertility variability across smallholder farms must consider various inter-related determinants as basis for site-specific fertility management interventions.

## KEYWORDS

farm typology, farmers’ indigenous knowledge, market distance, midDRIFTS, soil fertility variability

# 1 | INTRODUCTION

In the South-Kivu region of the Democratic Republic of Congo (DRC), the rural population currently has approximately 3.8 million people (250 inhabitants per km<sup>2</sup>; Mbadu Muanda et al., 2018; World Bank, 2018). More than 80% of this population are smallholders relying on subsistence agriculture as their main activity for income generation (Ministère du Plan RDC/DSRP, 2005). Because of the annual growth rate of the rural population of 3.3% (UNPD, 2017), the region of South-Kivu has been facing low agricultural productivity, a consequence of extraordinarily high levels of soil fertility depletion resulting from intensive cultivation without adequate nutrient replenishment (Pypers et al., 2011; Vanlauwe et al., 2017). A similar trend has been noted in many other regions of sub-Saharan Africa (SSA) (Tadele, 2017; Tully et al., 2015). As a consequence, food insecurity has become a major societal challenge putting people in South-Kivu at severe risk (FAO et al., 2018; Murphy et al., 2015). There is a central demand for intensified food production in the region, while building up and maintaining soil fertility through integrated soil fertility management (ISFM) interventions, including both organic and mineral fertilizers, remains challenging (Sanginga & Woome, 2009; Vanlauwe et al., 2010).

Inadequate infrastructure, such as the bad status of roads and transportation systems, affects market access, a prerequisite for agricultural development in smallholder farming systems of South-Kivu (Ulimwengu & Funes, 2009). A study in Uganda performed by Yamano and Kijima (2010) revealed positive correlations between household income and soil fertility with adequate road infrastructure. Availability and accessibility of appropriate infrastructure supported the economic development with access to cash and fertilizer inputs that enhance overall soil fertility status. It could be proposed that income of farmers is determined by market access, yet there is no knowledge on how market access (Birachi et al., 2013; Crawford et al., 2003; Minten & Kyle, 1999), especially the distance from the field plots to the market, sets the baseline for smallholder farmers to optimize soil fertility to the extent of their socio-economic capabilities and biophysical contexts. Therefore, prioritization of appropriate ISFM technologies for smallholder farmers remains challenging, as further aggravated by the huge agro-ecological variability across landscapes and the generally limited information on the soil fertility status along market gradients in Central and Eastern Africa (Rahn et al., 2018). Besides, in South-Kivu, rural communities are heterogeneous (Cox, 2012), reflected in highly variable resource endowments for individual households, a similar circumstance reported for Western Kenya (Ojiem et al., 2006; Tittonell et al., 2010). This has resulted in a large variation in soil fertility levels between farms and even between field plots within a farm, affecting decisions of

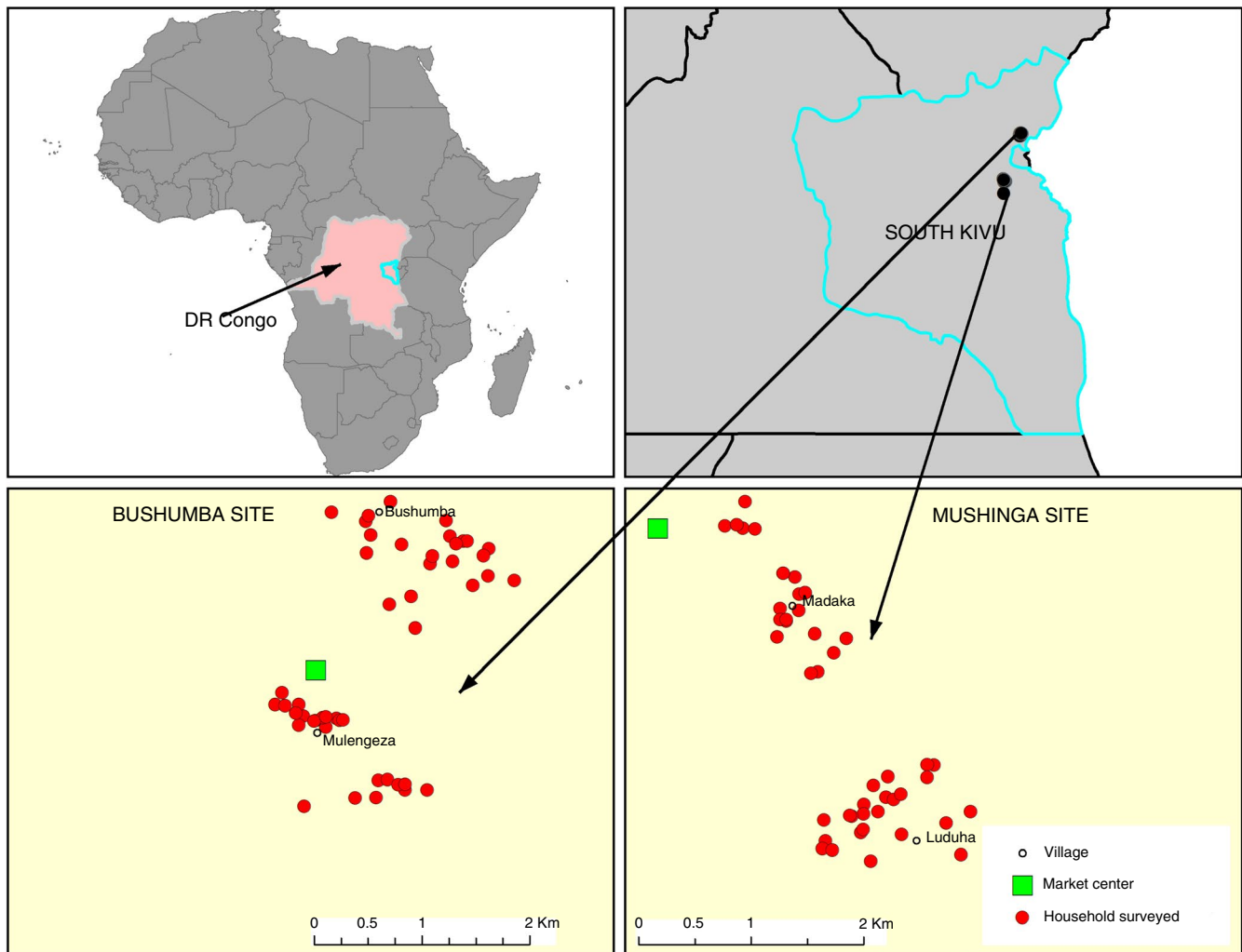
## Highlights

- Soil fertility decreases with increasing market distance across farm typologies.
- Poor farmers' resource endowment increased soil fertility variability.
- Farmers' soil fertility indicators (soil depth) agreed with laboratory-based analyses.

farmers regarding on-farm soil fertility investment (Tittonell et al., 2005).

There is still a considerable barrier to soil fertility management prioritization as previous assessments of soil fertility in DRC (Dontsop-Enguet et al., 2016) did not consider the integration of socio-economic and biophysical factors. Socio-economic factors including resource endowment, farmers' decision (i.e. perception), market distance and biophysical factors (e.g. agroecology, landscape heterogeneity) influence soil fertility levels of smallholder farming systems across spatial scales (Crawford et al., 2003; Tittonell & Giller, 2013; Vanlauwe et al., 2016). Assessment of interactions between socio-economic and biophysical factors is difficult since soil type heterogeneity between and within farms, which is further associated with land use and management practices, resulted in obvious soil fertility distinctions at farm level and across farms (Vanlauwe et al., 2006). Currently, both scientists and farmers collaborate intensely to develop applicable solutions through participatory research (Vanlauwe et al., 2017). However, for soil fertility management strategies, it remains vague as to how farmers' soil fertility assessment aligns with that of scientifically verified quantitative methods, although smallholder farmers have developed the ability to perceive heterogeneity of soil fertility across landscapes (Yeshaneh, 2015). It would be useful to accompany such process with scientific evidence since incorrect farmers' perception of soil fertility (e.g. knowledge to distinguish fertile and less fertile soils based on local indicators such as soil depth, colour or texture) may lead to inappropriate ISFM interventions (Kuria et al., 2019). Science-based approaches, on the other hand, generate a rather general understanding of soil fertility that may not present realistically local conditions with their complex socio-economic characteristics. Indigenous knowledge of smallholder farmers could be a critical aid to guiding agricultural interventions to sustain farm productivity and provide support tools for quantitative soil fertility surveys (Dawoe et al., 2012).

To estimate soil fertility levels across spatial scales, mid-DRIFTS (mid-infrared diffuse reflectance Fourier transform spectroscopy) has been evaluated as a suitable tool to assess soil fertility variability in and among African agricultural farming systems (Cobo et al., 2010; Shepherd & Walsh, 2007; Vågen



**FIGURE 1** Maps of the two study sites Bushumba (bottom left) and Mushinga (bottom right) in South-Kivu (DR Congo). Soil samples were collected on smallholder farms (red dots) in the four villages Bushumba and Mulengeza (site Bushumba) as well as Madaka and Luduha (site Mushinga) with different distances to the market centres (green squares)

et al., 2006). Basically, midDRIFTS employs a non-destructive estimation of physico-chemical soil properties allowing the analysis of spatial variability of soil properties across agro-ecologies (McCarty et al., 2002; Shepherd & Walsh, 2014). Coupled with partial least squares regression (PLSR)-based prediction, midDRIFTS is suited to process large batches of soil samples (Cobo et al., 2010; Rasche et al., 2013). MidDRIFTS also enables the spectroscopic assessment of soil organic carbon (SOC) quality (e.g. functional groups of SOC (such as aliphatic and aromatic compounds), providing a measure of SOC stabilization in agricultural soils (Demyan et al., 2012; Mirzaeitalarposhti et al., 2015).

The first objective of this study was to assess the inter-related influence of market distance and resource endowment classes on soil fertility status of smallholder farming systems of South-Kivu in DRC, as a case study for Central Africa. The second objective was to verify, under contrasting socio-economic and agro-ecological contexts, that farmers' indigenous knowledge is a valuable proxy to assess soil fertility status across landscapes

complementing a science-based approach. As market access was suggested as a determinant of agricultural development in DRC, it was hypothesized that with increasing market distance, the soil fertility status of smallholder farming systems decreases since field plots from remote areas, irrespective of the smallholder wealth status, do not have the opportunity to benefit from improved soil fertility management. It was further hypothesized that both farmers' indigenous knowledge and a science-based approach result in a similar reflection of on-farm soil fertility across agro-ecologies.

## 2 | MATERIAL AND METHODS

### 2.1 | Study site description

The soil fertility survey was conducted in the 'Territoire de Kabare', 'groupement' of Bushumba (Site #1, 2°21'S and 28°49'E, 1,740 m above sea level [m a.s.l.]), and 'Territoire de

Walungu', 'groupement' of Mushinga (Site #2, 2° 46'S and 28° 41'E, 1,604 m a.s.l.) in South-Kivu in DRC (Figure 1). At Bushumba, the soil fertility survey was performed in the villages of Mulengeza and Bushumba, while in Mushinga, it was conducted in Madaka and Luduha (Figure 1). This survey strategy enabled a random distribution of sampling locations to test the effects of the main research factors 'market distance', 'farm typology' and 'site' on the soil fertility status of assayed smallholder farms. Mushinga (1,200–1,800 mm annual rainfall) is characterized by a slightly drier climate than Bushumba (1,500–1,800 mm). Soils in Bushumba are classified as Nitisols (IUSS Working Group WRB, 2015) and characterized by a dominant textural fraction of clay (48%–69%) and 25%–27% sand. Total carbon ranged from 1.6% to 5.2%, pH (CaCl<sub>2</sub>) was 5.1, and total nitrogen was approximately 0.45% (Lunze et al., 2012; Muliele et al., 2015). Soils in Mushinga (Ferrasols; (IUSS Working Group WRB, 2015) are characterized by a wide variation in textural fractions of clay (17%–70%), a sand content of 20%–29%, pH (CaCl<sub>2</sub>) of 4.8, low base saturation (6.6 cmol<sub>(+)</sub> kg<sup>-1</sup>) and a low total carbon ranging from 1.2% to 3.0% (Pypers et al., 2011). Overall, soils in Bushumba are considered as medium fertile soils since they are developed from recent rejuvenation by volcanic ash depositions (Baert et al., 2012; Moeyersons et al., 2004). Highly weathered soils from Mushinga are characterized as less fertile with low available phosphorus and high aluminium saturation since they developed during Pleistocene eruptions (Pypers et al., 2011).

## 2.2 | Farm characterization

Villages and households included in this study were selected based on socio-economic indicators, such as market access and population density (Barrett, 2008; Cox, 2012). For population density, villages with more than 500 households and a population density greater than or equal to 100 inhabitants km<sup>-2</sup> were considered. Walking distance from the field plots to the closest regional market was measured in minutes and ranged from 15 to 200 min. For socio-economic indicators, village meetings and focus group discussions with farmers were conducted to define farm typology classes based on resource endowment. From these discussions, total land area (ha) owned by a household was considered as the prevailing typology indicator (Chikowo et al., 2014; Rusinamhodzi et al., 2012; Tittonell et al., 2005). No additional wealth indicators such as livestock numbers and rates of mineral fertilizer application were used because of their absence or lack of use, respectively. Finally, a total of 96 households (farms) were selected with regard to land holding size: (a) 'wealthy' (>2 ha), (b) 'medium wealthy' (1–2 ha) and (c) 'poor' (<1 ha).

To assess farmers' indigenous knowledge on soil fertility, household heads from selected farms were separated into

male and female groups and interviewed. Focus group discussions and participatory rural appraisals were used through semi-structured interviews (Chambers, 1992). Key information on criteria and indicators used to distinguish 'fertile' from 'less fertile' field plots was recorded. Interviews were performed with the same farmers invited for the soil fertility survey. In total, 93 farmers were interviewed, while the remaining 3 farmers were not available. To validate farmers' indigenous knowledge on the fertility status, each household was requested to indicate their most and less fertile field plots to allow a representative survey of soil fertility variability across each farm. Household heads were also interviewed for information regarding the most relevant soil fertility indicators (e.g. soil colour, soil depth, soil texture, soil drainage).

## 2.3 | Soil sampling and soil analysis

Soil samples were obtained using the Y-shaped scheme technique (Vågen et al., 2012). The Y-frame with 12.2 m in diameter was placed in the centre of each field to avoid any edge effects and extended 5.64 m to each sub-plot. During the sampling campaign, samples from the top layer (0–20 cm) and a deeper layer (20–50 cm) of the soils were collected in 4 sub-plots of 0.01 ha. Finally, a total of 384 geo-referenced soil samples on 96 farms for the entire study area were obtained (2 study sites × 2 villages per site × 3 farm typologies per village × 8 farms per typology × 2 plots per farm × 2 soil depths per plot). Out of 384 soil samples collected, 24 soil samples were excluded because of mislabelling during soil sample collection. Remaining soil samples ( $n = 360$ ) were air-dried, passed through a 2 mm sieve and shipped for further analysis to University of Hohenheim, Stuttgart (Germany).

The midDRIFTS analysis of soil samples was performed according to Rasche et al. (2013), while midDRIFTS coupled with partial least square regression (PLSR)-based prediction of soil chemical properties (i.e. SOC, TN, soil pH,  $P_{av}$ ,  $K_{av}$ ) was done according to Mirzaeitalarposhti et al. (2015). As prerequisite for property prediction, a defined proportion of the entire sample set was subjected to wet chemistry (see supplementary materials of this manuscript). Briefly, SOC and total soil nitrogen (TN) contents were analysed by dry combustion. Soil pH (CaCl<sub>2</sub>) was determined according to Houba et al. (2000). Available phosphorus ( $P_{av}$ ) was measured based on Bray1 extraction (Bray & Kurtz, 1945) and plant available potassium ( $K_{av}$ ) according to Schüller (1969). Since predictions of exchangeable calcium (Ca<sub>ex</sub>) and magnesium (Mg<sub>ex</sub>) were not successful, all soil samples were processed by wet chemistry according to Mehlich (1984).

The midDRIFTS-based SOC stability indexes (ratios of aromatic to aliphatic functional groups (1620:2930 1530:2930 1159:2930)) were calculated based on the relative peak area of four selected midDRIFTS peaks (2,930 cm<sup>-1</sup> [aliphatic C-H

**TABLE 1** MidDRIFTS peaks representing organic functional groups considered for SOC quality analysis

Peak name	Integration limit (cm <sup>-1</sup> )	Assignment of functional group	SOC stability potential
2930	3,010–2,800	Aliphatic C-H stretching <sup>a</sup>	Labile
1620	1,754–1,559	Aromatic C = C, COO <sup>-</sup> stretching <sup>a</sup>	Intermediate
1530	1,546–1,520	Aromatic C = C stretching <sup>a</sup>	Intermediate
1159	1,172–1,148	C-O bonds of poly-alcoholic and ether groups <sup>b</sup>	Recalcitrant

<sup>a</sup>Baes and Bloom (1989).

<sup>b</sup>Demyan et al. (2012).

**TABLE 2** Effects of market distance, farm typology and sites with their interactions on soil fertility properties (for data values see Figures 3 and 4)

Properties	Factors and interactions				
	Market distance	Farm typology	Site	Market distance × Farm typology	Market distance × Site
SOC (g/kg)	**	ns	ns	ns	*
TN (g/kg)	***	ns	***	ns	***
Soil pH (CaCl <sub>2</sub> )	ns	ns	ns	ns	*
P <sub>av</sub> (mg/kg)	ns	ns	*	ns	ns
K <sub>av</sub> (mg/kg)	ns	ns	ns	ns	ns
Ca <sub>ex</sub> (cmol <sub>(+)</sub> kg <sup>-1</sup> )	ns	**	***	*	ns
Mg <sub>ex</sub> (cmol <sub>(+)</sub> kg <sup>-1</sup> )	*	***	*	***	ns
Peak 2930 (cm <sup>-1</sup> )	ns	ns	***	ns	**
Peak 1620 (cm <sup>-1</sup> )	***	ns	**	**	ns
Peak 1530 (cm <sup>-1</sup> )	***	ns	ns	ns	***
Peak 1159 (cm <sup>-1</sup> )	**	ns	***	ns	ns
Ratio of 1620:2930	ns	ns	***	ns	ns
Ratio of 1530:2930	ns	ns	***	ns	**
Ratio of 1159:2930	ns	ns	***	ns	ns
Clay (%)	*	ns	*	ns	ns
Sand (%)	**	ns	*	ns	ns
Silt (%)	ns	ns	ns	ns	ns

Note: Significance levels:  $p < 0.001$  '\*\*\*',  $p < 0.01$  '\*\*',  $p < 0.05$  '\*',  $p > 0.05$  'not significant (ns)'.

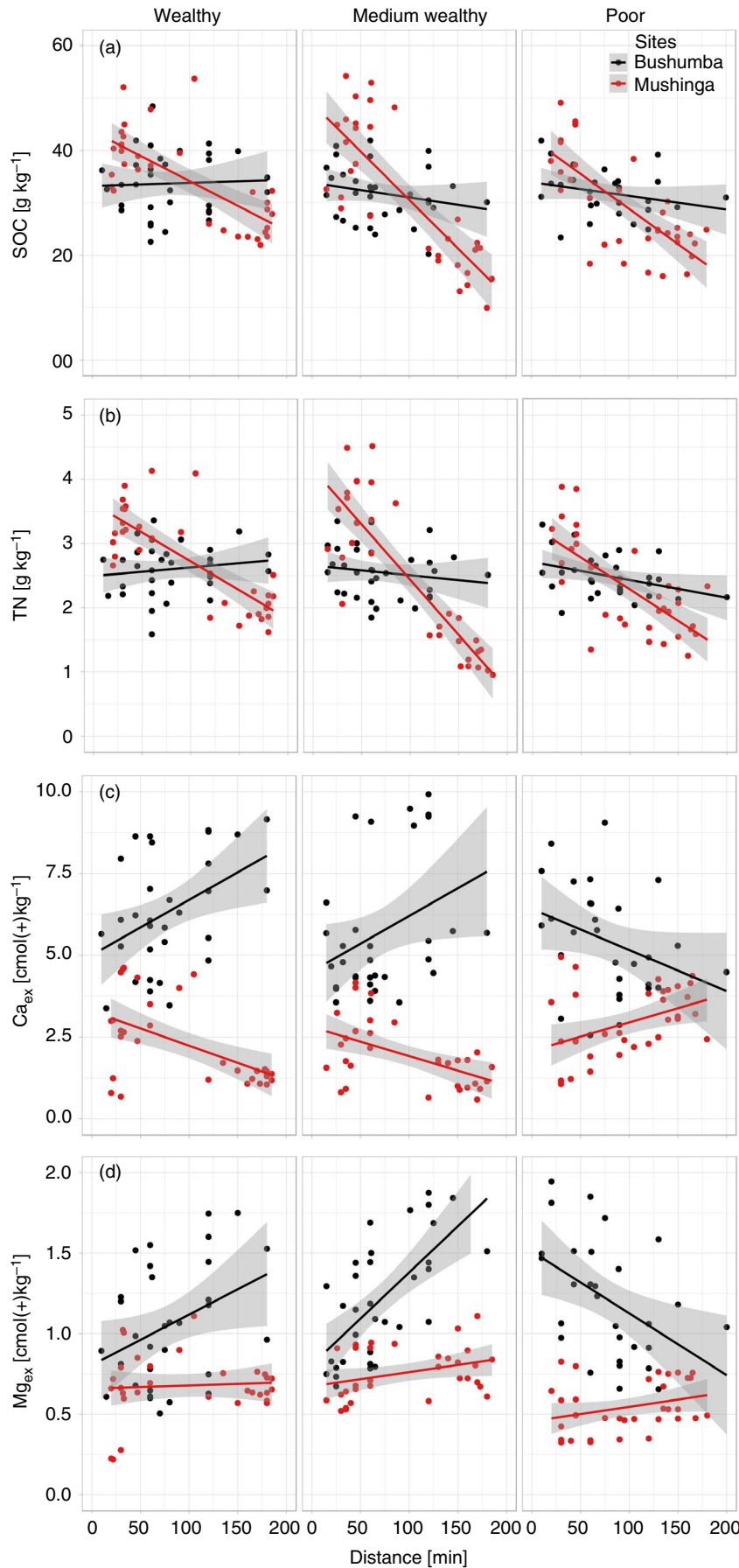
Farm typology (wealthy, medium wealthy and poor) refers to farmers' wealth class based on farm size.

Sites (Bushumba and Mushinga) located in the region, where the soil fertility survey was conducted.

stretching], 1,620 cm<sup>-1</sup> [aromatic C = C, COO<sup>-</sup> stretching], 1,530 cm<sup>-1</sup> (aromatic C = C stretching) and 1,159 cm<sup>-1</sup> [C-O bonds of poly-alcoholic and ether groups]) (Table 1; Demyan

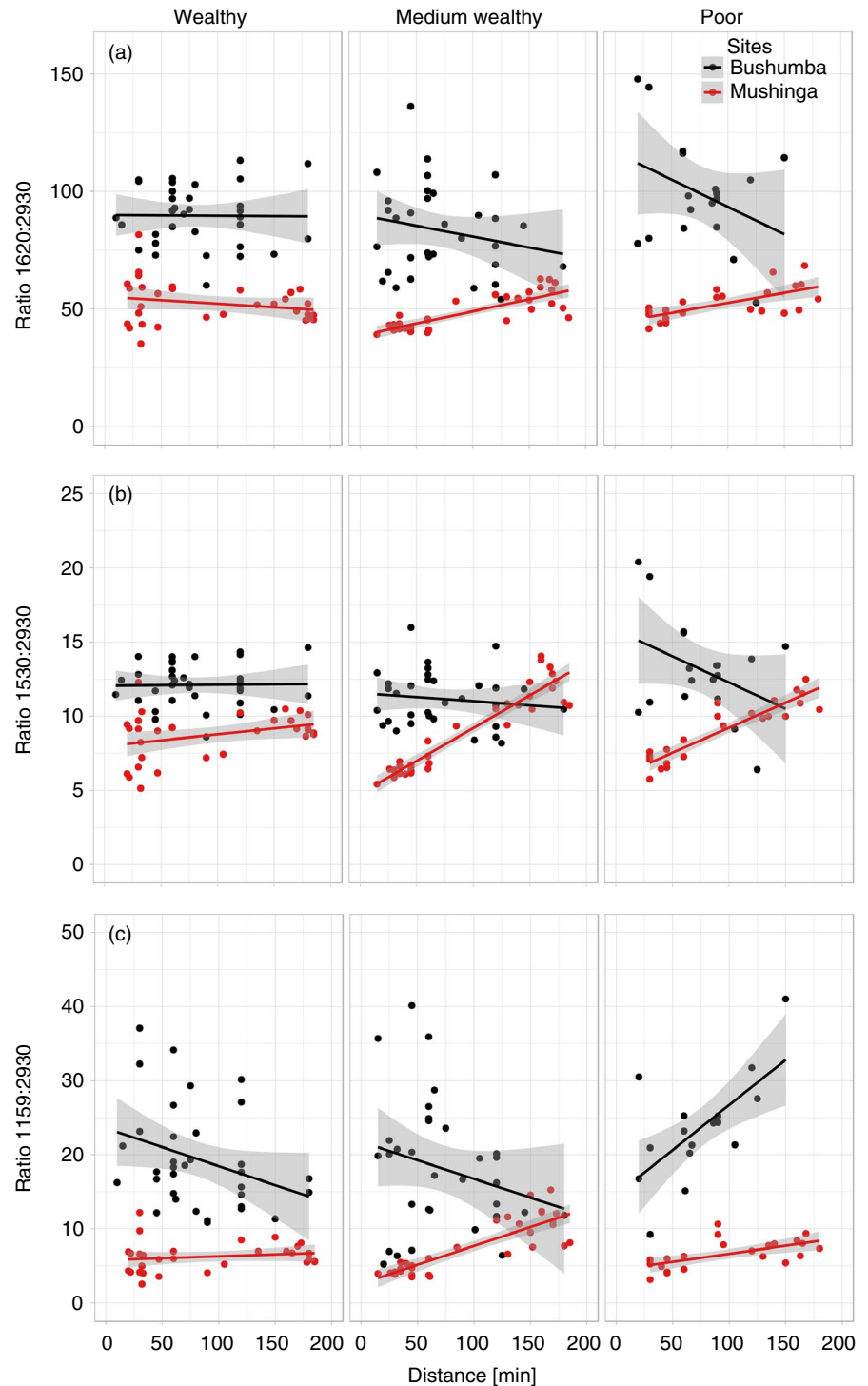
et al., 2012). Further information on midDRIFTS-based analysis can be retrieved from the supporting information of this manuscript.





**FIGURE 2** Contents of total organic carbon (SOC,  $p < .05$ ; a) and total nitrogen (TN,  $p < .05$ ; b), as well as exchangeable calcium ( $Ca_{ex}$ ,  $p < .01$ ; c) and magnesium ( $Mg_{ex}$ ,  $p < .01$ ; d) in soils of surveyed smallholder households in the two sites Bushumba (dots and regression line black coloured) and Mushinga (dots and regression line red coloured) considering the two factors ‘farm typology’ and ‘market distance’. Grey colour in scatter plots represents the confidence interval

**FIGURE 3** Ratios of midDRIFTS peaks 1620:2930 (a) 1520:2930 (b) and 1159:2930 (c) displaying the SOC quality of soils of surveyed smallholder households in the two sites Bushumba and Mushinga considering the two factors ‘farm typology’ and ‘market distance’. Grey colour in scatter plots represents confidence intervals



## 2.4 | Statistical data analysis

The data set was analysed in a mixed model procedure (Piepho et al., 2003) implemented in R statistical software version 3.6.0 (R Core Team, 2019). Analysis of variance (ANOVA) was performed for market distance, farm typology (resource endowment class), site, and farmers' knowledge as fixed factors, while farm sampling plots entered as random terms for prediction of soil chemical properties using

lmerTest package (Kuznetsova et al., 2017). Model selection was based on Akaike's information criterion (AIC). Means comparison and their separation between factors and their interactions were performed according to Searle et al. (1980). Linear regressions were applied to reveal relationships between soil chemical properties and hypothesized soil fertility determinants (i.e. market distance, farm typology, farmers' indigenous knowledge and site). Linear Pearson's correlations were calculated to validate links between SOC and

midDRIFTS peak data (i.e. relative peak area, SOC stability indexes). The chi-squared test for independence was applied to determine significant differences within local soil fertility indicators used by smallholder farmers.

### 3 | RESULTS

#### 3.1 | Inter-related effects of market distance, farm typology, and sites on soil fertility properties

There was no clear inter-related effect of market distance and farm typology (i.e. resource endowment) on soil fertility properties, which was only significant for  $\text{Ca}_{\text{ex}}$  ( $p < 0.05$ ) and  $\text{Mg}_{\text{ex}}$  ( $p < 0.001$ ) (Table 2, Figure 2). The inter-related effect of market distance and sites showed a significant effect for TN ( $p < 0.001$ ) (Table 2, Figure 2). As a single factor, however, market distance revealed a significant effect for SOC ( $p < 0.01$ ), TN ( $p < 0.001$ ) and  $\text{Mg}_{\text{ex}}$  ( $p < 0.05$ ) (Table 2, Figure 2). This was corroborated by linear regression analyses showing negative relations between market distance and SOC ('wealthy' [ $R^2 = 0.20$ ,  $p < 0.01$ ], 'medium wealthy' [ $R^2 = 0.42$ ,  $p < 0.001$ ], 'poor' [ $R^2 = 0.30$ ,  $p < 0.001$ ]), and TN ('wealthy' [ $R^2 = 0.20$ ,  $p < 0.01$ ], 'medium wealthy' [ $R^2 = 0.38$ ,  $p < 0.001$ ], 'poor' [ $R^2 = 0.27$ ,  $p < 0.001$ ]) (Figure 2a,b). A significant positive influence of farm typology was found for  $\text{Ca}_{\text{ex}}$  and  $\text{Mg}_{\text{ex}}$  in Bushumba, while a negative correlation was noticed in Mushinga with increasing market distance ( $p < 0.01$ ). Considering factor site only, a significant difference of TN,  $P_{\text{av}}$ ,  $\text{Ca}_{\text{ex}}$  and  $\text{Mg}_{\text{ex}}$  contents was observed ( $p < 0.05$ ; Table 2).

The relative peak areas of four representative peaks at 2930 (aliphatic C-H stretching), 1620 (aromatic C = C and COO<sup>-</sup> stretching), 1530 (aromatic C = C stretching), 1159 (C-O bonds of poly-alcoholic and ether groups)  $\text{cm}^{-1}$  and respective SOC stability indexes (i.e. 1620:2930 1530:2930 1159:2930) were considered as SOC quality indicators (Table 1). Market distance exposed a significant effect on relative areas of peaks 1,620, 1,530 and 1,159  $\text{cm}^{-1}$  ( $p < 0.01$ ) (Table 2, Figure 3). Its interaction with farm typology was significant for peak 1620, which increased in farm typology 'wealthy' with increasing market distance ( $p < 0.01$ ; Table 2). Factor 'site' had the strongest effect on SOC quality proxies, which was significant for all peak areas, except 1,530  $\text{cm}^{-1}$  ( $p < 0.01$ ; Table 2, Figure 3). Peaks 2,930 and 1,530  $\text{cm}^{-1}$  revealed a significant interaction between market distance and site ( $p < 0.01$ ); as market distance increases, peaks 2,930 and 1,530  $\text{cm}^{-1}$  in Bushumba increased, while they were reduced in Mushinga for the medium wealthy class (Table 2, Figure 3). Similar results were noticed for 1,530  $\text{cm}^{-1}$  in Mushinga. Moreover, site had a significant effect on all 3 SOC stability indexes

**TABLE 3** Pearson's correlation ( $r$ ) between SOC content and midDRIFTS peak area analysis derived SOC quality indicators

Variables	$r$	$F$ test
Peak 2930 ( $\text{cm}^{-1}$ )	0.24	**
Peak 1620 ( $\text{cm}^{-1}$ )	0.48	***
Peak 1530 ( $\text{cm}^{-1}$ )	-0.27	***
Peak 1159 ( $\text{cm}^{-1}$ )	-0.31	***
Ratio 1620:2930	-0.11	ns
Ratio 1530:2930	-0.26	***
Ratio 1159:2930	-0.22	**

Note: Significance levels:  $p < 0.001$  '\*\*\*',  $p < 0.01$  '\*\*',  $p > 0.05$  'not significant (ns)'.

( $p < 0.001$ ), and for the ratio 1530:2,30 showing also a significant interaction with market distance and site ( $p < 0.01$ ) (Table 2, Figure 3). Except for the ratio of 1620:2930, all midDRIFTS-derived SOC quality indicators revealed a significant positive correlation with SOC content (Table 3).

#### 3.2 | Farmers' indigenous knowledge across sites to predict soil fertility variability

Smallholder farmers used different indicators to assess soil fertility, whereby soil depth ('deep' as representative for fertile and 'shallow' for less fertile soils) and soil colour ('black' as representative for fertile and 'red' for less fertile soils) were the main indicators (Table 4). Complementary, laboratory analysis revealed higher concentrations of SOC and  $P_{\text{av}}$  in 'deep' than 'shallow' soils ( $p < 0.05$ ) (Figure 4a,b), with similar trends for TN,  $K_{\text{av}}$ ,  $\text{Ca}_{\text{ex}}$  and  $\text{Mg}_{\text{ex}}$  (Table 5). In agreement with farmers' indigenous knowledge, wet chemistry analyses revealed higher concentrations of  $P_{\text{av}}$  in 'dark' than 'red' soils ( $p < 0.05$ ) (Table 5, Figure 4d). SOC, on the other hand, disagreed with farmers' indigenous knowledge, revealing higher values in the 'red' than 'dark' soils ( $p < 0.05$ ) (Table 5, Figure 4c). The same trend was true for TN, while remaining soil chemical properties did not reveal a significant effect between 'dark' and 'red' soils ( $p > 0.05$ ; Table 4).

### 4 | DISCUSSION

#### 4.1 | Market distance, farm typology and sites as key determinants of soil fertility variability

Smallholder farming systems in South-Kivu (DR Congo) are influenced by various socio-economic and agro-ecological factors. Our study demonstrated that not only the distance of farmers to markets, but also farm typology were



**TABLE 4** Proportional contribution (%) of farmers to the ranking ( $\chi^2$ ) of selected soil fertility indicators across sites

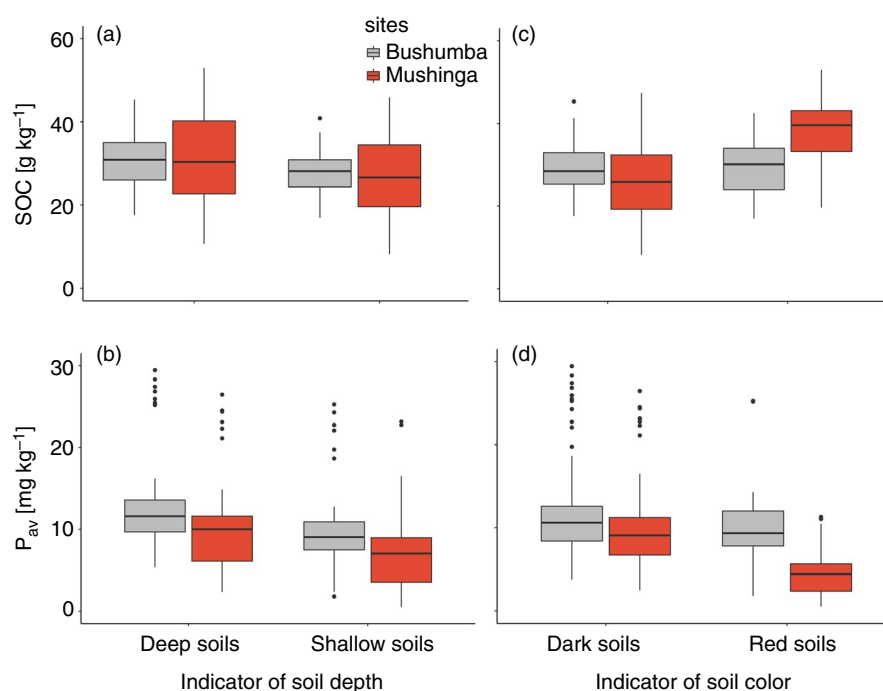
Indicators for soil fertility	$\chi^2$	Proportion (%)
Soil depth	22.1 ***	49
Soil colour	9.5*	22
Soil texture	6.9ns	16
Soil drainage	4.9ns	11
Distance from homestead	1.0ns	2

Note: Significance levels:  $p < 0.001$  '\*\*\*',  $p < 0.05$  '\*',  $p > 0.05$  'not significant (ns)'.

key determinants of soil fertility, both with contrasting trends in the two study regions Mushinga and Bushumba. Specifically, decreasing soil fertility, as exemplified by SOC and TN, with increasing market distance was noted across all farm typologies and was most pronounced in Mushinga. This trend was explained by farmers' opportunities to access external inputs available in close proximity to the markets (Soule & Shepherd, 2000). However,  $P_{av}$  and  $K_{av}$  were more related to site specificity, probably because of the influence of both soil mineralogy and pH levels that differed between sites. Farmers close to markets purchase and transport mineral and organic fertilizers at lower costs than farmers in remote areas exposed to unfavourable road infrastructure and transportation opportunities. Moreover, the proximity to markets provides farmers with the opportunity to sell surplus yields of crops. This generates extra income to support increased access to organic fertilizers, irrespective of the wealth status of the farmers. These benefits translate into soil fertility improvement masking

partially the hypothesized effect of farm typology. This assumption was corroborated by earlier studies conducted in Kenya and Uganda, observing that the proximity of farms to markets influenced strongly the amount of applied fertilizers across farms regardless of the wealth status (Tittonell et al., 2005; Yamano & Kijima, 2010).

The survey of the SOC content as a proxy of soil fertility was complemented with SOC stability indexes, as calculated from relative areas of selected midDRIFTS peaks (i.e. 1620:2930 1530:2930 1159:2930; Demyan et al., 2012). However, neither distance to market nor farm typology alone had a significant effect on the three SOC stability indexes, which was explained by the lack of both, inorganic and organic fertilizers, leading to lower SOC quality. Only the factor site revealed a clear distinction, which was also reflected in its significant interaction with factor market distance (i.e. 1530:2930). A comparable, but non-significant interaction was found for the ratio 1620:2930. The effect of market distance became most obvious in the medium



**FIGURE 4** Box plot of farmers' classification of soil fertility according to their local indicators ('soil depth' [deep versus shallow soils] and 'soil colour' [dark versus red soils]), as exemplified for determined soil organic carbon (SOC) and available phosphorus ( $P_{av}$ ) contents at different sites combining top- and subsoil

**TABLE 5** Averages of selected local soil fertility indicators in soil chemical properties measured across the two sites from top- and subsoil (SOC, TN, soil pH,  $\text{Ca}_{\text{ex}}$ ,  $\text{Mg}_{\text{ex}}$ ,  $n = 360$ ), and ( $P_{\text{av}}$ ,  $K_{\text{av}}$ ,  $n = 96$ )

Selected indicator	Sites	Soil chemical properties						
		SOC (g/kg)	TN (g/kg)	Soil pH	$P_{av}$ (mg/kg)	$K_{av}$ (mg/kg)	$Ca_{ex}$ (cmol(+)kg <sup>-1</sup> )	$Mg_{ex}$ (cmol(+)kg <sup>-1</sup> )
Soil depth (0–50 cm)								
Deep	B	3.05 (1.20) <sup>ab</sup>	0.24 (0.11) <sup>ab</sup>	4.87 (0.52) <sup>b</sup>	12.54 (8.53) <sup>c</sup>	222.07 (208.40) <sup>ab</sup>	5.20 (2.40) <sup>b</sup>	1.04 (0.43) <sup>b</sup>
Shallow	B	2.80 (1.12) <sup>a</sup>	0.22 (0.10) <sup>a</sup>	4.53 (0.49) <sup>a</sup>	9.16 (7.99) <sup>b</sup>	186.77 (169.85) <sup>a</sup>	4.38 (2.11) <sup>b</sup>	0.81 (0.36) <sup>a</sup>
Deep	M	3.45 (1.22) <sup>b</sup>	0.27 (0.11) <sup>b</sup>	4.70 (0.54) <sup>ab</sup>	8.75 (6.20) <sup>ab</sup>	273.9 (191.07) <sup>b</sup>	2.63 (2.36) <sup>a</sup>	0.77 (0.40) <sup>a</sup>
Shallow	M	2.98 (1.22) <sup>a</sup>	0.24 (0.11) <sup>ab</sup>	4.60 (0.45) <sup>a</sup>	5.67 (8.63) <sup>a</sup>	223.64 (200.03) <sup>ab</sup>	2.32 (2.36) <sup>a</sup>	0.71 (0.42) <sup>a</sup>
		**	*	***	***	*	*	*
Soil colour								
Deep	B	2.90 (1.03) <sup>a</sup>	0.23 (0.09) <sup>a</sup>	4.75 (0.45) <sup>a</sup>	11.26 (7.33) <sup>b</sup>	194.56 (174.83) <sub>a</sub>	4.98 (2.03) <sup>b</sup>	0.94 (0.37) <sup>c</sup>
Shallow	B	2.95 (1.01) <sup>a</sup>	0.23 (0.09) <sup>a</sup>	4.65 (0.44) <sup>a</sup>	10.44 (7.21) <sup>b</sup>	214.28 (156.89) <sup>a</sup>	4.60 (1.93) <sup>b</sup>	0.91 (0.34) <sup>bc</sup>
Deep	M	2.60 (1.05) <sup>a</sup>	0.20 (0.10) <sup>a</sup>	4.63 (0.47) <sup>a</sup>	9.32 (7.54) <sup>b</sup>	242.78 (170.12) <sup>a</sup>	2.68 (2.05) <sup>a</sup>	0.77 (0.037) <sup>ab</sup>
Shallow	M	3.84 (1.05) <sup>b</sup>	0.31 (0.10) <sup>b</sup>	4.67 (048) <sup>a</sup>	5.10 (7.76) <sup>a</sup>	254.76 (175.59) <sup>a</sup>	2.27 (2.09) <sup>a</sup>	0.71 (0.34) <sup>a</sup>
		**	***	ns	***	ns	*	*

Note: Site: B = Bushumba, M = Mushinga.  
Standard deviation is given in parentheses.  
Superscript letters display statistical differences from the interaction indicator with site.  
Significance levels:  $p < 0.001$  ‘\*\*\*’,  $p < 0.01$  ‘\*\*’,  $p < 0.05$  ‘\*’,  $p > 0.05$  ‘not significant (ns)’.

wealthy and poor farms surveyed in Mushinga. For these farm typologies, an increasing ratio of 1530:2930 with increasing market distance was noted, implying a lower SOC quality because of limited or absent organic inputs. This assumption was corroborated by the negative correlation between the ratio of 1530:2930 and SOC content. A comparable trend was found on the field plots of the poor farmers with remote distance to markets in Bushumba for peaks at 1,530 and 1,159  $\text{cm}^{-1}$ . This corroborated the former argument that primarily wealthy farmers were able to purchase farm yard manure as the only locally available fertilizer (Soule & Shepherd, 2000). However, contrasting trends of respective SOC stability indexes were obtained with increasing market distance. Even though Veum et al. (2013) and Ding et al. (2002) have suggested that the high ratio of poly-alcoholic and ether groups over that of aliphatic compounds (1159:2930) may be related to a lower SOC quality, further research is needed to understand the underlying mechanism of the results obtained in this study. Because of detection limit, no clear effect of tested factors was revealed for peak 2,930  $\text{cm}^{-1}$ , representing the labile SOC pool (Baes & Bloom, 1989), which was explained by generally low inputs of organic materials (e.g. farm yard manure, crop residues) exposed to high turnover (Demyan et al., 2012).

In contrast to SOC and TN, contents of exchangeable Ca and Mg were driven by the interaction of both market distance and farm typology. The two sites revealed reverse trends for these cations with increasing market distance. While decreasing soil nutrient stocks with increasing market distance were expected, as noted in Mushinga, Bushumba revealed the opposite for wealthy and medium wealthy farmers. It was assumed that these farmers with market proximity had favourable economic opportunities, exerting considerable production pressure on their land to maximize yield and income (Bationo et al., 2006; Kansime et al., 2018). As a result of such continuously high cultivation pressure, the poor farmers in Mushinga depleted their soils in Ca and Mg. Meanwhile in Bushumba, wood ash derived from kitchen waste (Bekunda & Woomer, 1996) is broadcasted on farm plots close to the market increasing soil nutrient contents. The positive effect of this fertilization strategy is more pronounced on farms with less land (<1 ha) than on wealthy and medium wealthy farms that have more land (>2 ha), as observed by Place et al. (2003). In contrast to farm plots near to markets, remote field plots are less depleted of nutrients because of lower cultivation pressure. Consequently, adequate levels of Ca and Mg stocks are maintained in the soil.

#### 4.2 | Indigenous knowledge to validate soil fertility status across market gradients

Existing farmers' knowledge to assess soil fertility has been based mainly on local indicators, including soil colour and

soil depth (Dawoe et al., 2012; Desbiez et al., 2004). This study has evaluated correspondence and discrepancies between farmers' indigenous and scientific knowledge about the soil fertility status of contrasting farm typologies, by testing whether soils considered fertile or less fertile by farmers show a similar fertility status according to science-based measurements using the midDRIFTS approach. The laboratory analysis conducted in this study was in agreement with the assessment of soil fertility by smallholder farmers, except for soil colour, a finding in line with Yeshaneh (2015) and Murage et al. (2000). A range of soil fertility indicators, such as soil depth, soil colour, soil texture and soil drainage, have been developed by smallholder farmers to distinguish between productive (fertile) and non-productive (less fertile) farm plots. Our study found soil depth and soil colour are the most common indicators used by the farmers across sites. In agreement with farmers' knowledge, soil fertility levels were higher in deep than shallow soils, which were reflected in generally higher nutrient concentrations in deep soils across surveyed field plots receiving organic amendments. Although soil colour was the second most important indicator, a clear correlation to our laboratory measurements was not found. Additionally, SOC and TN contents were higher in red than black soils. We assumed that soil colour was more related to soil physical properties such as soil texture. Dawoe et al. (2012) and Gray and Morant (2003) also found a red soil colour to indicate a sandy soil texture, while a grey colour was related to a loamy soil texture. In this respect, the Madaka site, with a generally high agricultural potential, was dominated by a sandy soil texture with the typical reddish colour originating from basaltic rocks (van Engelen et al., 2006).

## 5 | CONCLUSIONS

This study has found that the inter-related effect of market distance and farm typology are a main driver of soil fertility variability across the study sites. Soil fertility, as displayed by SOC and TN concentrations, decreased with increasing market distance, with exception of the wealthy farm class of Bushumba. This implied that within the market distance gradients (i.e. close, medium, remote), site effects including soil type and climate played a significant role in shaping the soil fertility variability across surveyed farms. It was also evident that farmers' management practices and resource endowment contributed to soil fertility variability, particularly in farms plots remote to markets.

Laboratory measurements of soil chemical parameters agreed with farmers' assessment on soil fertility status. This suggested that farmers' indigenous knowledge is a valuable proxy for soil fertility surveys and may be integrated in prospective science-based soil fertility assessments. However, care should be taken as some indicators

used by farmers, such as soil colour, may not only relate to soil fertility status, but also reflect soil mineralogy and soil texture.

Our results further inferred that ISFM interventions in smallholder farms must consider various inter-related features to determine soil fertility variability across smallholder farmers. We have complemented these features by the variable market distance to distinguish soil fertility levels across spatial scales. Our assumptions were based primarily on land size, used as key feature to define the wealth status (farm typology) of targeted smallholder farms in the study area. In this regard, prospective soil fertility surveys should not only consider resource endowment (land size) to characterize the wealth status of farmers, but also other socio-economic indicators, including, but not limited to, livestock holding (limited in the discussed study area), availability of labour and use of mineral and organic fertilizers. Such advanced knowledge will contribute essentially to the development of niche-based ISFM intervention strategies in soil fertility constrained smallholder farming systems across SSA.

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## SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section.

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