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Agro-ecology, resource endowment and indigenous knowledge interactions modulate soil fertility in mixed farming systems in Central and Western Ethiopia

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Abstract

Site-specific soil fertility management requires a fundamental understanding of factors that modulate soil fertility variability in the local context. To verify this assumption, this study hypothesized that soil fertility variability across two regions in Central and Western Ethiopia is determined by inter-related effects of agro-ecological zones and farmers' resource endowment ('wealthy' versus 'poor' farmers). Mid-infrared spectroscopy coupled to partial least squares regression (midDRIFTS-PLSR) and wet-laboratory analyses were used to assess the soil fertility (soil pH, total soil carbon [TC] and nitrogen [TN], plant-available phosphorous [P_{av}] and potassium [K_{av}]) across four agro-ecological zones: 'High-Dega' (HD), 'Dega' (D), 'Weina-Dega' (WD) and 'Kola' (K). MidDRIFTS peak area analysis of spectral frequencies (2,930 [aliphatic C-H], 1,620 [aromatic C = C], 1,159 [C-O poly-alcoholic and ether groups] cm^{-1}) was applied to characterize soil organic carbon (SOC) quality and to calculate the SOC stability index (1,620:2,930). Higher TC in HD, as well as higher TN and K_{av} contents in K were found in fields of wealthy compared with poor farmers. Resource endowment dependent soil fertility management options revealed SOC of higher quality in wealthy compared with poor farms in D. Agro-ecological zones distinctions contributed to these soil fertility differences. Farmers distinguished visually fertile and less fertile fields based on soil colour. Higher pH in K and WD as well as P_{av} in K and HD were found in fertile (brown/black) than less fertile (red) soils. To conclude, tailor-made soil fertility management in the local context must consider agro-ecological zones and resource endowment interactions along with farmers' indigenous knowledge.

KEYWORDS

agro-ecological zones, farmers' indigenous knowledge, midDRIFTS, resource endowment, SOC stability index, soil fertility variability

1 | INTRODUCTION

Integrated soil fertility management (ISFM) is an intervention strategy to counteract the problem of soil fertility depletion of smallholder farming systems in sub-Saharan Africa (SSA) (Vanlauwe et al., 2010). Its adoption across different regions of SSA remains, however, challenging (Vanlauwe et al., 2015). This is mainly due to resource shortcomings (e.g., land size, capital) that force resource-constrained farmers to expand into marginal lands, while wealthy farmers continue investing in fertile lands. This situation is aggravated by insecure tenure systems, prohibiting farmers from investing in their land, along with limited access to fertilizer inputs (Stevenson et al., 2019). These features have led to highly variable soil fertility levels across and within regions, magnified by inherent heterogeneity of agro-ecological zones and a wide range in socio-economic status among smallholder farmers (Tittonell et al., 2005). Heterogeneity of soil fertility does not allow uniform soil management strategies in larger areas, making ISFM adjusted to local contexts more essential. To tailor demand-oriented ISFM interventions to smallholder conditions under different local contexts, factors modulating soil fertility variability must be understood, considering farmers' resource endowment (i.e., their wealth) and indigenous knowledge (Tittonell et al., 2005; Vanlauwe et al., 2015).

Previous soil fertility assessments in Eastern (e.g., Kenya) and Southern (e.g., Zimbabwe) Africa revealed the influence of densely populated landscapes, biophysical factors, farmers' resource endowment and distance of cultivated fields from homesteads on soil fertility management options (Nyamangara et al., 2011; Tittonell et al., 2010; Tittonell, Vanlauwe, Leffelaar, Rowe, et al., 2005). These studies were, however, not based on generic and harmonized soil surveying procedures, making direct comparisons across different agro-ecological zones and smallholder farming systems difficult. Africa Soil Information Service (AfSIS) (**Vågen et al.,** 2010) and Ethiopian Soil Information System (EthioSIS) (Amare et al., 2018) have made important progress in consolidating existing soil fertility survey protocols for several African countries, including Ethiopia. Nevertheless, (a) the inter-related effects of agro-ecological zones and farmers' resource endowments, along with (b) farmers' indigenous knowledge as additional proxies for soil fertility assessment have so far been neglected and thus need further investigation. This is justified as it could be suggested that continuous knowledge transfer among farmers within and across agro-ecological zones (Leta et al., 2018), as well as contrasting agro-ecological and geological contexts (Mengistu, 2003) modulate soil fertility variability. Hence, it was our first objective to perform a local soil fertility survey to test the hypothesis that not only individual but also inter-related effects of agro-ecological zones and farmers' resource endowments affect soil fertility variability in a local context. Our second objective was to verify that farmers' indigenous knowledge of soil fertility status is not driven by inter-related effects of agro-ecology and farm typology. This assumption was based on the continuous transfer of knowledge among farmers within and across agro-ecological zones (Leta et al., 2018).

2 | MATERIAL AND METHODS

2.1 | Site selection and farm typology characterization

The soil fertility survey was conducted in four contrasting agro-ecological zones of Central and Western Ethiopia, which were defined according to Mengistu (2003) and Hurni (1998): (a) 'Kola' (K) (<1,500 m a.s.l., average temperatures of 15–27°C, average rainfall of 2,037 mm), and (b) 'Weina-Dega' (WD) (1,500–2,500 m a.s.l., 15–27°C, 1,376 mm), (c) 'Dega' (D) (2,500–3,200 m a.s.l., ≤9°C, 938 mm) and (d) 'High-Dega' (HD) (3200–3500 m a.s.l., ≤9°C, 938 mm). Agro-ecological zones K (Lelisadimtu [36°24'E; 9°02'N]) and WD (Fromsa [36°45'E; 9°03'N]) are subsistence maize-dominated crop-livestock farming systems and Nitisols with clay texture (FAO, 2015), while D (Kolugelan [38°9'E; 9°22'N]) and HD (Chilanko [38°11'E; 9°20'N]) are dominated by market-oriented potato/barley systems as well as Luvisols and Alisols with clay texture (FAO, 2015). Lelisadimtu and Fromsa were located in Diga District (Western Ethiopia), while Kolugelan and Chilanko were located in Jeldu district (Central Ethiopia) (Table 1; Figure S1).

Farm typologies (resource endowment) at the target sites (villages) were defined during village meetings and focus group discussions. Two to three focus group discussions with a total of 16–18 household heads with an equal share of females and males as well as young and old farmers were held in each agro-ecological zone. The main farm typology indicators were farm size (landholdings (LH)), livestock ownership and level of agricultural inputs (i.e., chemical fertilizer) (Haileslassie et al., 2006; Kebede et al., 2019). Thresholds set by farmers in all villages were <2 ha farm size, <6 tropical livestock units (TLU), and relatively low chemical fertilizer rates to categorize farmers as 'Eyeessaa (poor)', while a LH of ≥4 ha, ≥8 TLU and use of full fertilizer rates (100 kg urea and 100 kg DAP) were defined as 'Ditta (wealthy)'. This is because wealthy farmers frequently intend to maximize crop productivity by applying fertilizer, whereas poor farmers cannot follow a similar strategy due to a lack of cash to purchase fertilizer. To confirm the agreed farm typology thresholds, detailed data on farm typology indicators were collected on 90 predefined wealthy and poor households (10% of the total population) (Table 1).

TABLE 1 Average values of socio-economic indicators (farm size, number of livestock and amount of fertilizer used) for the different farm typologies in the selected study regions (Lelisa Dimtu (Kola (K)), Fromsa (Weina-Dega (WD)), Kolu-Gelan (Dega (D)) and Chilanko (High-Dega (HD)); Number of households = 90

Agro-ecology	Typology	Farm size [ha]	Livestock holding [TLU]	Fertilizer (DAP + Urea) rate [kg ha^{-1}]
Kola (K)h	Wealthy (Ditta)	5.7 (1.0)^{ab}	11.7 (1.8)^{a}	117 (25)^{bc}
	Poor (Eyeessaa)	0.8 (1.0)^{d}	3.2 (1.8)^{d}	64 (35)^{c}
Weina-Dega (WD)	Wealthy (Ditta)	4.4 (0.9)^{abc}	8.6 (1.59)^{abc}	121 (35)^{abc}
	Poor (Eyeessaa)	1.1 (1.0)^{d}	4.5 (1.8)^{cd}	72 (35)^{c}
Dega (D)	Wealthy (Ditta)	4.9 (0.9)^{ab}	9.02 (1.5)^{abc}	192 (46)^{ab}
	Poor (Eyeessaa)	1.8 (1.1)^{cd}	5.9 (2.0)^{bcd}	180 (30)^{ab}
High-Dega (HD)	Wealthy (Ditta)	7.0 (1.0)^{a}	9.5 (1.7)^{ab}	198 (27)^{a}
	Poor (Eyeessaa)	1.8 (1.0)^{cd}	5.4 (1.70)^{bcd}	135 (20)^{abc}
P-level (agro-ecology)		ns	ns	***
P-level (typology)		***	**	ns
P-level (agro-ecology × typology)		ns	ns	ns

Abbreviation: TLU, Tropical livestock unit.

Significance levels: ns, not significant at $p < 0.05$; *$p < 0.05$; **$p < 0.01$; ***$p < 0.001$.

2.2 | Soil sampling

In each agro-ecological zone ($n = 4$), 14 individual households (seven wealthy, seven poor) per farm typology were selected (Dawoe et al., 2012; Nyamangara et al., 2011). On each farm, the head of the household was requested to indicate the most and least fertile field plots based on their individual indigenous knowledge about soil fertility status. Hence, two field plots per household (fertile and poor) were selected for soil sample collection (Vågen et al., 2012). According to Yeshaneh (2015), farmers use soil colour as the most important indicator of soil fertility, where black and brown soils were considered as fertile and red soils as less fertile.

During soil sampling, the household head indicated the colour of the specified soil of the field plot. According to the sampling procedure, a total number of 224 geo-referenced soil samples were collected (four agro-ecological zones (K, WD, D, HD) × 2 farm typologies (wealthy, poor) × 7 farms per typology × 2 fields per farm (fertile and less fertile) × 2 soil depths (0–20 cm, 21–50 cm)). Soil samples were air-dried and passed through a 2 mm sieve prior shipping to the University of Hohenheim (Stuttgart, Germany) for further analysis.

2.3 | Soil analysis

Soil pH ($CaCl_2$) was measured according to Houba et al. (2000). Total carbon (TC) and nitrogen (TN) were analysed by dry combustion. Available phosphorus (P_{av}) was measured colorimetrically at 720 nm using the Bray1 method (Bray and Kurtz (1945). Available potassium (K_{av}) was analysed using ICP-OES (Agilent 5100) (Schüller, 1969). Calcium-acetate-lactate was used as extractant for both phosphorous and potassium.

MidDRFIFTS-based analyses were performed according to Mirzaeitalarposhti et al. (2015), Rasche et al. (2013) and Demyan et al. (2012). MidDRIFTS-PLSR-based prediction models for each soil chemical property (i.e., TC, TN, pH, P_{av} and K_{av}) were constructed with the OPUS-QUANT2 package of OPUS v7.5 (Bruker Optik GmbH) (Rasche et al., 2013). Similarly, peak area integration by midDRIFTS using OPUS 7.5 software (Bruker Optik GmbH) (Demyan et al., 2012) was conducted to provide an additional measure of the soil fertility status. Three prominent peaks (i.e., 2,930, 1,620 and 1,159 cm^{-1}) with their respective integration limits (3,000–2,800, 1,770–1,496, 1,180–1,126 cm^{-1}) representing different organic functional groups of SOC were used as additional soil fertility indicators (Baes & Bloom, 1989; Demyan et al., 2012; Senesi et al., 2003). Peak 2,930 cm^{-1} represents less stable aliphatic C-H groups, components of the active SOC pool (Demyan et al., 2012; Laub et al., 2019). Peak 1,620 cm^{-1} represents more stable aromatic C = C bonds as part of the recalcitrant SOC pool (Demyan et al., 2012; Laub et al., 2019). The third peak at 1,159 cm^{-1} represents C-O poly-alcoholic and ether groups, commonly regarded as very stable C compounds (Demyan et al., 2012; Senesi et al., 2003). The ratio of the functional groups 1,620 and 1,159 versus 2,930 cm^{-1} is commonly calculated as the SOC stability index, which is used as a soil quality indicator. Further methodological details are given in the Supporting information of this paper.

2.4 | Statistical analysis

Univariate analysis using Kolmogorov–Smirnov tests was conducted to determine if the data met the assumptions of normality. Except for P_{av} and K_{av}, all soil chemical properties met the assumption. For P_{av} and K_{av}, logarithmic and square root transformations were performed, respectively. Factorial analysis of variance (ANOVA) was conducted to assess the effect of agro-ecology, farm typology (resource endowment class), farmers' indigenous knowledge and their interaction on soil fertility status, using a mixed model with restricted maximum likelihood (REML) (Piepho et al., 2003) (SAS statistical software, version 9.4; SAS Institute). Agro-ecology, farm typology and soil fertility status as defined by farmers were considered as fixed effects, while each field and the interaction between individual factors were included as random effects (Piepho et al., 2004). Means separation ($p < 0.05$) was done using pdiff LINES command in GLIMMIX (SAS Institute).

3 | RESULTS

3.1 | Inter-related effect of agro-ecological zones and farmers' resource endowment on soil fertility

Analysis of variance showed that not only agro-ecological zone but also farmers' resource endowment had a significant effect on soil fertility indicators (i.e., TC, TN, K_{av}; $p < 0.01$) (Figure 1). However, pH and P_{av} were only influenced by agro-ecological zone ($p < .01$). An interaction effect between agro-ecological zone and resource endowment was observed for K_{av} ($p < 0.01$) (Figure 1d). The higher K_{av} values (234 mg kg^{-1}) were noted for fields of wealthy farmers in 'Kola' (K), while the lowest K_{av} values (62 mg kg^{-1}) were recorded on wealthy farms in 'Dega' (D) ($p < 0.01$) (Figure 1d). The highest values of TC and TN were observed in 'Weina-Dega' (WD) in both farm typologies, while the lowest TC was found in fields of D ($p < 0.01$) (Figure 1a). In 'High-Dega' (HD), higher TC and higher TN contents in K were found in fields of wealthy compared with less wealthy farmers ($p < 0.01$) (Figure 1a,b). Agro-ecological zone influenced soil pH and P_{av} ($p < 0.001$) (Figure 1c,e), where lowest values were observed in WD. No effect of farm typology was found for pH and P_{av} ($p > 0.05$) (Figure 1c,e).

Three dominant relative peak areas representing SOC functional groups were identified and used as proxies for SOC quality: (a) 2,930 cm^{-1} (C-H- aliphatic groups), (b) 1,620 cm^{-1} (C = C- aromatic groups) and (c) 1,159 cm^{-1} (C-O poly-alcoholic and ether group) (Figure 2a–c The relative peak areas of these SOC functional groups and the SOC stability index, calculated as the ratio of aromatic to aliphatic area (peak 1,620 cm^{-1} to 2,930 cm^{-1}), varied across agro-ecological zones and farmers resource endowment, with respective interaction effects ($p < 0.05$) (Figure 2a–d). The highest (5.5%) and lowest (3.1%) peaks at 2,930 cm^{-1} were noted on fields of poor farmers in K and D, respectively. Similarly, fields of wealthy farmers had a larger peak area at 2,930 cm^{-1} than those of poor farmers in D ($p < 0.05$) (Figure 2a). In contrast, the highest (95.2%) and lowest (91.9%) values of relative peak area at 1,620 cm^{-1} peak were found in fields of poor farmers in D and K, respectively ($p < 0.05$) (Figure 2b). The highest relative peak area of 1,159 cm^{-1} was observed in K fields of both farm typologies, while the lowest was found in HD ($p < 0.01$) (Figure 2c). The highest and lowest SOC stability indices were calculated for fields of poor farmers in D and K, respectively ($p < 0.001$) (Figure 2d). In D, a larger index was noted in fields of poor compared with wealthy farmers ($p < 0.05$). Furthermore, significant positive correlations of pH and TOC with C-H aliphatic SOC (pH: $r^2 = 0.39$; TOC: $r^2 = 0.51$) were found, while negative relationships were calculated for C = C aromatic SOC (pH: $r^2 = -0.39$; TOC: $r^2 = -0.47$) ($p < 0.001$) (data not shown). Correlations between the stability index and TOC ($r^2 = -0.45$) and TN ($r^2 = -0.24$) ($p < 0.001$) were negative, while no correlation was found for soil pH.

3.2 | Farmers' indigenous knowledge

Farmers' indigenous knowledge on soil fertility agreed with 75% (eight out of 12 soil fertility indicators) of scientifically generated soil fertility indicators across agro-ecological zones (Tables 2 and 3). Soil colour as a soil fertility indicator for farmers suggested that black and brown soils were considered as fertile, while red soils were assessed to be less fertile soils. This was confirmed by laboratory analysis, that is black and brown soils had generally higher TC, TN, P_{av} and pH than the red soils, except soil pH at HD (Table 2). The capability of farmers' indigenous knowledge to identify fertile and less fertile soils was further verified by a higher relative peak area of 1,159 cm^{-1} in less fertile fields; a similar trend was noted for the SOC stability index ($p < 0.01$) (Table 3).

4 | DISCUSSION

4.1 | Inter-related effect of agro-ecological zones and farmers' resource endowment on soil fertility

It was a key finding that the soil fertility status in the study region was determined by an inter-related effect of farmers' resource endowment (farm typology) and agro-ecological zone. This effect was most pronounced between the wealthy and poor farms located in the lowland (K) and highland (HD)

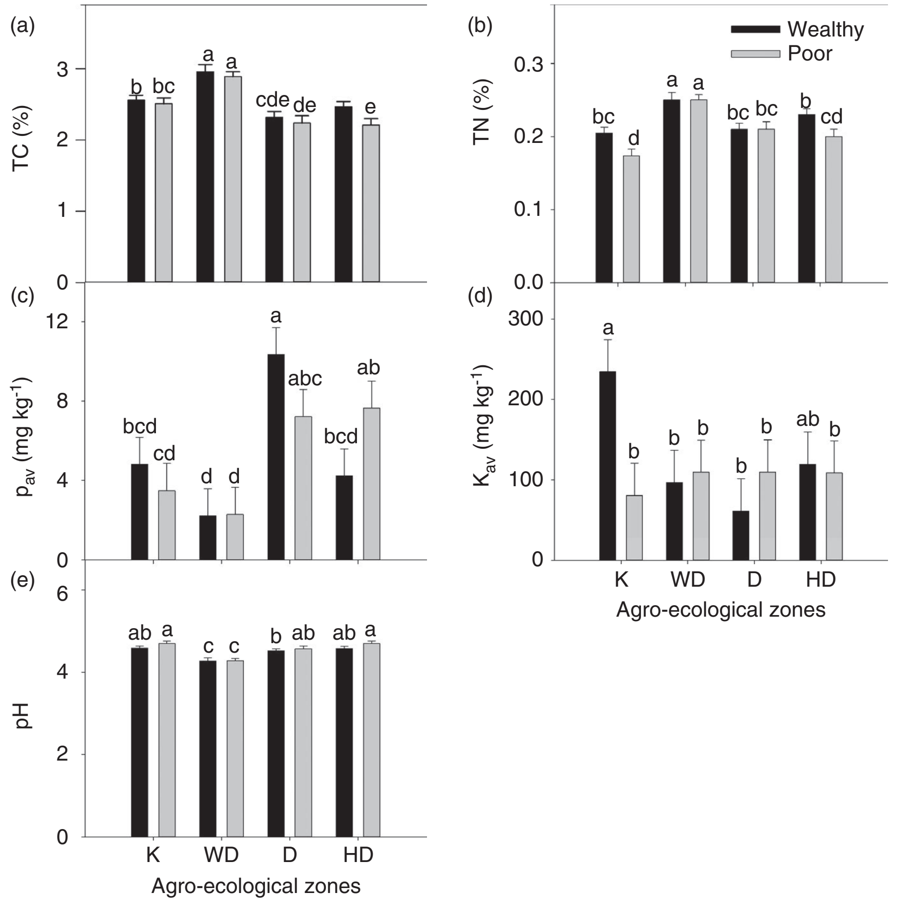

FIGURE 1 Soil chemical properties (a = total carbon [TC] [%]; b = total nitrogen [TN] [%]; c = available phosphorus [P_{av}] [mg kg^{-1}], d = available potassium [K_{av}] [mg kg^{-1}]; e = soil pH) obtained from soils of fields of wealthy and poor farmers' fields across the four agro-ecological zones (K [Kola], WD [Weina-Dega], D [Dega], HD [High-Dega]). $N = 215$ for TC, TN and pH while 96 for (P_{av}) and (K_{av}). Bars with different letters on top of standard error indicate significant differences at $p < 0.05$

agro-ecological zones, as explained by higher TN, SOC and K_{av} in fields of wealthy farms. The farm typologies in the midlands (WD) took an intermediate position, with no clear distinction in the soil fertility status with respect to agro-ecological zone. This finding is in line with Nyamangara et al. (2011) and Masvaya et al. (2010) who observed higher TN, SOC, P_{av} and cation exchange capacity (CEC) in wealthy than poor farmers' fields in two different agro-ecological zones in Zimbabwe.

The effect of resource endowment in the lowlands was explained by the better soil nutrient status (e.g., TN, K_{av}) in the fields of wealthy compared with poor farmers. It is a main advantage of wealthy farms to have a higher soil fertility status, as a result of extended fallowing, organic residue burning and higher livestock numbers (Corbeels et al., 2000; Tian et al., 2005; Haileslassie et al., 2006). These interventions provide sufficient resources to replenish the soil nutrient pool (Cobo et al., 2010; Haileslassie et al., 2007). With this, wealthy farmers also compensate the accelerated decomposition of organic resources by higher temperatures in the lowlands that generally increases the soil nutrient pool (Coûteaux et al., 2002) Even though poor farmers have a higher livestock density and may potentially provide more manure per area of land; these farmers commonly use livestock manure for cooking fuel rather than applying it to fields for fertilization purposes. The use of manure as fuel is essential for poor farmers as they do not have extra land to cultivate biomass for firewood production, unlike wealthy farmers.

Apart from the obvious differences in the soil nutrient status in the lowlands, no clear effect of resource endowment on TC content and SOC quality was observed. This was explained with the fast decomposition of active SOC pools, which was, irrespective of the soil fertility management strategy of wealthy farmers, responsible for the pronounced nutrient release. Even though there was no difference between both farm typologies, a higher TC content was found in the warmer lowlands and mild midlands than in the colder highlands (Coûteaux et al., 2001; Du et al., 2014; Tian et al., 2016). This increased TC content might have resulted from maize-dominated cropping practices in the lowlands and midlands, where the low biochemical quality (high C/N ratio, lignin and polyphenol content) of respective crop residues enhanced the SOC pool (Wang et al., 2015). Irrespective of the typology classes in the low and medium altitude agro-ecological zones, it has been shown that the conversion of C derived from crop residues, such as maize, to SOC is generally lower in fields of poor farmers than those of wealthy farmers due to higher fertilization (Wang et al., 2015). This high potential of C stabilization was corroborated by the presence of recalcitrant

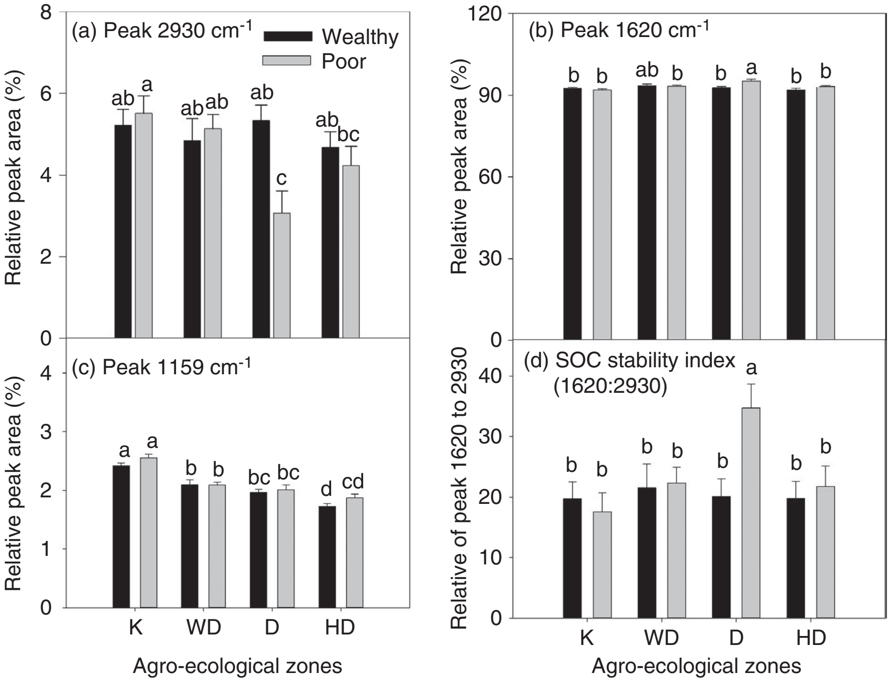

FIGURE 2 MidDRIFTS relative peak areas ([a] 2,930 cm^{-1}, [b] 1,620 cm^{-1}, [c] 1,159 cm^{-1}) and ratio of 1,620:2,930 (d) obtained from soils of fields of wealthy and poor farmers' fields across the four agro-ecological zones (K [Kola], WD [Weina-Dega], D [Dega], HD [High-Dega]). $N = 107$; Bars with different letters on top of standard error indicate significant differences at $p < 0.05$

TABLE 2 Selected soil fertility indicators (TC, total carbon; TN, total nitrogen; P_{av}, available phosphorus, pH, soil pH) in relation to different soil colours (red, less fertile; black and brown; fertile) across agro-ecological zones. Stand errors are given in brackets. $N = 24$

Agro-ecological zone	Soil colour	TC [%]	TN [%]	P_{av} [mg kg^{-1}]	Soil pH
Kola (K)	Red	2.89 (0.08)	0.21 (0.01)	4.19^{b} (1.25)	4.75^{b} (0.07)
	Black	2.72 (0.25)	0.18 (0.03)	15.83^{a} (5.64)	5.13^{a} (0.09)
	P-level	ns	ns	*	*
Weina-Dega (WD)	Red	3.00^{b} (0.05)	0.25 (0.03)	1.09^{b} (0.32)	4.12^{b} (0.16)
	Black	3.17^{a} (0.08)	0.28 (0.02)	5.65^{a} (0.91)	4.21^{ab} (0.13
	Brown	3.21^{a} (0.28)	0.28 (0.04)	5.18^{a} (2.8)	4.51^{a} (0.41)
	P-level	*	Ns	**	*
High-Dega (HD)	Red	2.60^{b} (0.45)	0.23^{b} (0.01)	10.33 (6.98)	4.74^{a} (0.29)
	Brown	2.97^{a} (0.41)	0.27^{a}(0.01)	9.44 (7.28)	4.46^{b} (0.37)
	P-level	*	*	ns	*

Significance levels: ns, not significant at $p < 0.05$; *$p < 0.05$; **$p < 0.01$.

SOC pools (i.e., C-O poly-alcoholic and ether groups). In the highlands, in contrast to the low- and midlands, there was a distinct difference in TC content, which was higher in the fields of the wealthier farmers. This was substantiated by the option of wealthy farmers to combine organic and inorganic fertilizer inputs, leading to an increase of C-H aliphatic SOC functional groups, but a decrease of C = C aromatic SOC functional groups. Accordingly, this management option created a higher SOC stability index (i.e., peak area ratio of 1,620:2,930) in the fields of poor farmers.

The application of inorganic fertilizer resulted most likely in greater plant biomass production, providing additional inputs to accelerate the decomposition rate of roots and plant residues to produce more labile SOC pools (Blair et al., 2006). In contrast to the findings in the fields of wealthy farmers, pronounced C = C aromatic SOC functional groups along with a higher SOC stability index were found in the soils of poor farmers in the highland agro-ecological zone, indicating fewer organic inputs. Similar results were given by Demyan et al. (2012), who found in plots of the Bad Lauchstädt long-term field experiment (Germany) treated with both chemical and organic fertilizers for more than 100 years higher C-H aliphatic SOC groups than in plots receiving only farmyard manure. The higher labile SOC pool with a lower SOC stability index may be an indicator for high soil fertility as compared to higher C = C aromatic and high stability index. In contrast, C = C aromatic pools were shown to increase soil C stabilization (Haynes, 2005). It is acknowledged that the labile SOC pool can benefit important soil functions, including soil aggregate formation and nutrient supply as well as serve

TABLE 3 Relative peak areas and stability index as indicators of soil organic carbon (SOC) quality with regard to farmers' perception of fertile and less fertile fields

SOC quality indicators	Fertile	Less fertile	P level
Peak 2,930 cm^{-1}	4.95 (0.22)	4.55 (0.22)	ns
Peak 1,620 cm^{-1}	92.88 (0.26)	93.18 (0.26)	ns
Peak 1,159 cm^{-1}	2.03 (0.03)	2.15 (0.03)	**
SOC stability index (1,620:2,930)	19.68 (1.57)	24.72 (1.57)	**

Note: Standard errors are given in brackets, $N = 107$. SOC quality indicators: Peak 2,930 cm^{-1}, aliphatic C-H; Peak 1,620 cm^{-1}, aromatic C = C; Peak 1,159 cm^{-1}, C-O poly-alcoholic and ether groups of SOC functional groups. Significance levels: ns, not significant at $p < 0.05$; *$p < 0.05$; **$p < 0.01$.

as essential microbial energy source (Ghani et al., 2003; Haynes, 2005; Kunlanit et al., 2020; Maia et al., 2007).

4.2 | Farmers' perception of soil fertility across agro-ecological zones and farm typologies

This study confirmed the capability of farmers' indigenous knowledge to define the soil fertility status, a capacity not influenced by either agro-ecological zone or farm typology. The identification of soil fertility status based on farmers' indigenous knowledge is often in close agreement with soil chemical properties analysed in the laboratory (Huynh et al., 2020). Irrespective of their wealth status and geographic location, farmers confirmed their capacity to assess soil fertility variability using indigenous knowledge accumulated through generations of experience and consistent exchange through socio-cultural events (e.g., weddings and funerals) between lowland and highlands (Leta et al., 2018). Such knowledge transfer across agro-ecological zones may have been responsible for the common farmer perception that red soils are less fertile than black and brown soils.

Farmers describe and classify their soils using a holistic approach and use relatively homogeneous soil classification indicators across agro-ecologies (Laekemariam et al., 2017). Accordingly, farmers have been using soil colour, soil texture, soil depth, topography and drainage, as well as crop performance as criteria to categorize their land into fertile and less fertile fields (Belachew & Abera, 2010; Corbeels et al., 2000; Karltun et al., 2013; Yeshaneh, 2015). In the low and midlands, a higher variability between fertile and less fertile fields was observed for soil pH and P_{av}. Farmers considered red soils as less fertile and used this as an indicator for soil acidity (soil pH) (Laekemariam et al., 2017). The low P_{av} values might have been a result of P fixation in acidic soils (Agumas et al., 2014). On the contrary, black soils were interpreted as fertile with high SOC and P_{av} contents (Moody et al., 2008). Similarly, we detected higher TC and P_{av} values in black than in red soils in the midlands and lowlands, respectively. Higher P_{av} values in black than in red soils may have resulted from higher organic P cycling favoured by higher SOC and soil moisture content (Corbeels et al., 2000; Moritsuka et al., 2014). This might indicate that organic matter and soil mineralogy are the most important soil properties that govern soil colour (Poppiel et al., 2020).

No difference between farm typologies was observed with respect to the identification of fertile and less fertile fields based on indigenous knowledge (Table S2), a likely result of the informal communication channels among social institutions: for example 'iddir' (indigenous and local self-help association), 'debo' (collective labour support group) and 'dado' (reciprocal labour sharing arrangement among farmers) (Leta et al., 2018). Even though farmers are generally limited to explain on a scientific basis why such differences in soil fertility exist, both wealthy and poor farmers have comparable indigenous knowledge to identify fertile and less fertile fields.

Indigenous knowledge is generally used by farmers to design management strategies for site-specific soil fertility problems. Farmers in the lowlands, for example, fallow, burn organic residues and apply higher farmyard manure on fields perceived as fertile. Similarly, farmers in the highlands invest more inorganic fertilizer on their fertile fields than on those with lower fertility. This corroborates the fact that farmers are aware of the soil fertility status, whereby their indigenous knowledge can guide site-adapted ISFM interventions (Tittonell, Vanlauwe, Leffelaar, Shepherd, et al., 2005).

5 | CONCLUSIONS

This study verified that inter-related rather than individual effects of agro-ecological zones and farmers' resource endowment (farm typology) must be considered to explain soil fertility variability of smallholder farms across regions and wealth classes. Accordingly, it was inferred that prospective ISFM strategies must be niche-based, considering such contrasting but inter-related agro-ecological zones and farm typologies to reduce the inherent depletion of soil fertility across smallholder farms in the study region of Ethiopia. Moreover, across agro-ecological zones, farmers identified fertile and less fertile fields based on their indigenous knowledge, which was corroborated by the laboratory-based soil fertility survey. Hence, farmers' indigenous knowledge was verified as a valuable proxy for this local soil fertility survey.

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DATA AVAILABILITY STATEMENT

Research data are not shared.

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SUPPORTING INFORMATION

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

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