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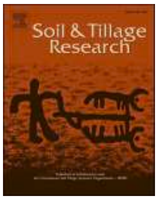

Effect of integrated soil fertility management on hydrophysical soil properties and irrigated wheat production in the upper Blue Nile Basin, Ethiopia

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ABSTRACT

In Ethiopia, soil fertility problem caused by acidity substantially limits agricultural productivity, necessitating sustainable integrated nutrient management. This study assessed the effect of combined application of lime, manure and inorganic fertilizer on selected hydrophysical properties of an acid clay Nitisols in the Koga irrigation scheme, Ethiopia. Five levels of integrated soil fertility management treatments were tested for four consecutive cropping seasons: (i) 0.86 t ha^{-1} lime combined with 3 t ha^{-1} manure and full−dose inorganic (urea and NPS−B) fertilizer (L3); (ii) 1.15 t ha^{-1} lime combined with 3 t ha^{-1} manure and full−dose inorganic fertilizer (L2); (iii) 1.43 t ha^{-1} lime combined with 3 t ha^{-1} manure and full−dose inorganic fertilizer (L1); (iv) 3 t ha^{-1} manure combined with full−dose inorganic fertilizer (M); and (v) full−dose inorganic fertilizer alone (C) as a control. Undisturbed soil samples were collected at 0–10 and 10–20 cm soil depths and analyzed to determine saturated hydraulic conductivity (Ks), soil−water retention characteristics, total porosity and bulk density. Disturbed soil samples were collected at the same depths to analyze soil organic carbon and texture. Infiltration capacity measurements and visual evaluation of soil structural quality were done in the field. Significantly higher ($P < 0.05$) soil organic carbon was found at L1, L2, L3 and M compared with C. The application of L1, L2, L3 and M reduced bulk density compared with the C. The amount of water retained at field capacity (FC) was significantly ($P < 0.05$) affected by the treatments in the order of L1 > L2 > M > L3 > and C for both soil depths 0–10 and 10–20 cm. The Ks under plots treated with L1 was 64% and 37% higher than that of C for the 0–10 and 10–20 soil depths, respectively. Significantly ($P < 0.05$) higher infiltration capacity was found at L1 (0.007 cm min^{-1}) followed by L2, L3 and M (0.006 cm min^{-1}, 0.006 cm min^{-1}, and 0.005 cm min^{-1}) compared with C (0.004 cm min^{-1}), respectively. Good soil structural quality (Sq) score was identified in L1, L2, L3 and M, whereas in C poor Sq score was found. As compared with C, grain yield was improved by 69% at L1, 59% at L2, 53% at L3, and 44% at M during 2018 and by 70% at L1, 58% at L2, 55% at L3 and 46% at M in 2019. In conclusion, the application of organic manure combined with lime and inorganic fertilizer enhanced the infiltration rate, water holding capacity and grain yield more than the inorganic fertilizer application alone. There was also a significant effect of liming as such, with the highest doses showing the best results.

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1. Introduction

Soil acidity considerably limits agricultural productivity (Getachew et al., 2017, 2019). In Ethiopia, ~43% of the cultivated land is affected by soil acidity (Ameyu, 2019; Taye et al., 2020), 27% of which is moderately to weakly acidic with a pH value of 5.5–6.7, while the remaining 16% is strongly acidic with a pH of 4.1–5.5. In the northwest, central and southwestern Ethiopian highlands, wheat, maize, faba bean, barley and teff are commonly planted (Haile and Boke, 2011). But, productivity is declining because of soil acidity-induced fertility problems (Gurmessa, 2020; Agegnehu et al., 2014).

Soil acidity can be managed with mineral fertilizers, lime, compost and manure, used as acid soil management elements (Abate et al., 2013; Getachew et al., 2019; Gurmessa, 2020). Abewa et al. (2013), Agegnehu et al. (2014) and Chimdi et al. (2012) also identified that in Ethiopia particularly, liming and applying organic fertilizers are commonly accepted strategies.

Integrated soil fertility management (ISFM) studies in Sub-Saharan Africa suggested that the combined use of inorganic and organic inputs significantly improved crop yields (Bedada, 2015). The addition of organic residues to acid soils is potentially an attainable low-input strategy for raising soil pH, decreasing concentrations of phytotoxic Al_{mono} and decreasing lime requirements (Mokolobate and Haynes, 2002). A previous study also found that apart from providing nutrients, the use of farmyard manure (FYM) improves the physical, chemical, hydraulic and microbial properties of the soil (Lupwayi et al., 2000).

Liming of soil can be used to increase soil pH and can enhance the benefits provided by inorganic fertilizers (Chimdi et al., 2012). Studies have found that the application of lime increases soil pH and can improve crop yields (Getachew et al., 2017). Abate et al. (2013) also found that lime application rate reduces exchangeable acidity and available micronutrients but increases cation exchange capacity, soil organic matter and available phosphorus. Additionally, studies have found liming can improve soil aggregate stability and infiltration rate (Haynes and Naidu, 1998). After six months of liming in a field experiment, Roth (1992) reported an enhanced soil aggregation, and improved aggregate stability and infiltration capacity in South America. Saha et al. (2010) also found that combing manure and lime application with inorganic fertilizers (lime and NPK) improves soil physical properties and organic carbon.

It is believed that liming and manuring combined with inorganic fertilizer could improve the hydrophysical soil properties (Haynes and Naidu, 1998). Yet, scientific studies about the effect of liming and manuring on soil hydrophysical attributes are very scarce. Liming and manuring studies are commonly limited to soil chemical attributes. For Nitisols in particular, which are known for their stable soil structure, fair water-holding capacity and good infiltration (WRB, 2015), there are no researches on how they respond, when acid, to liming in combination with manuring in terms of their hydrophysical properties. To bridge these knowledge gaps, the effect of combined application of lime at different rates, manure and inorganic fertilizer on hydrophysical properties of an acidic Nitisol was investigated. Hence, the objective of this study was to evaluate the role of ISFM including applications of lime and manure on hydrophysical soil properties and wheat grain yield

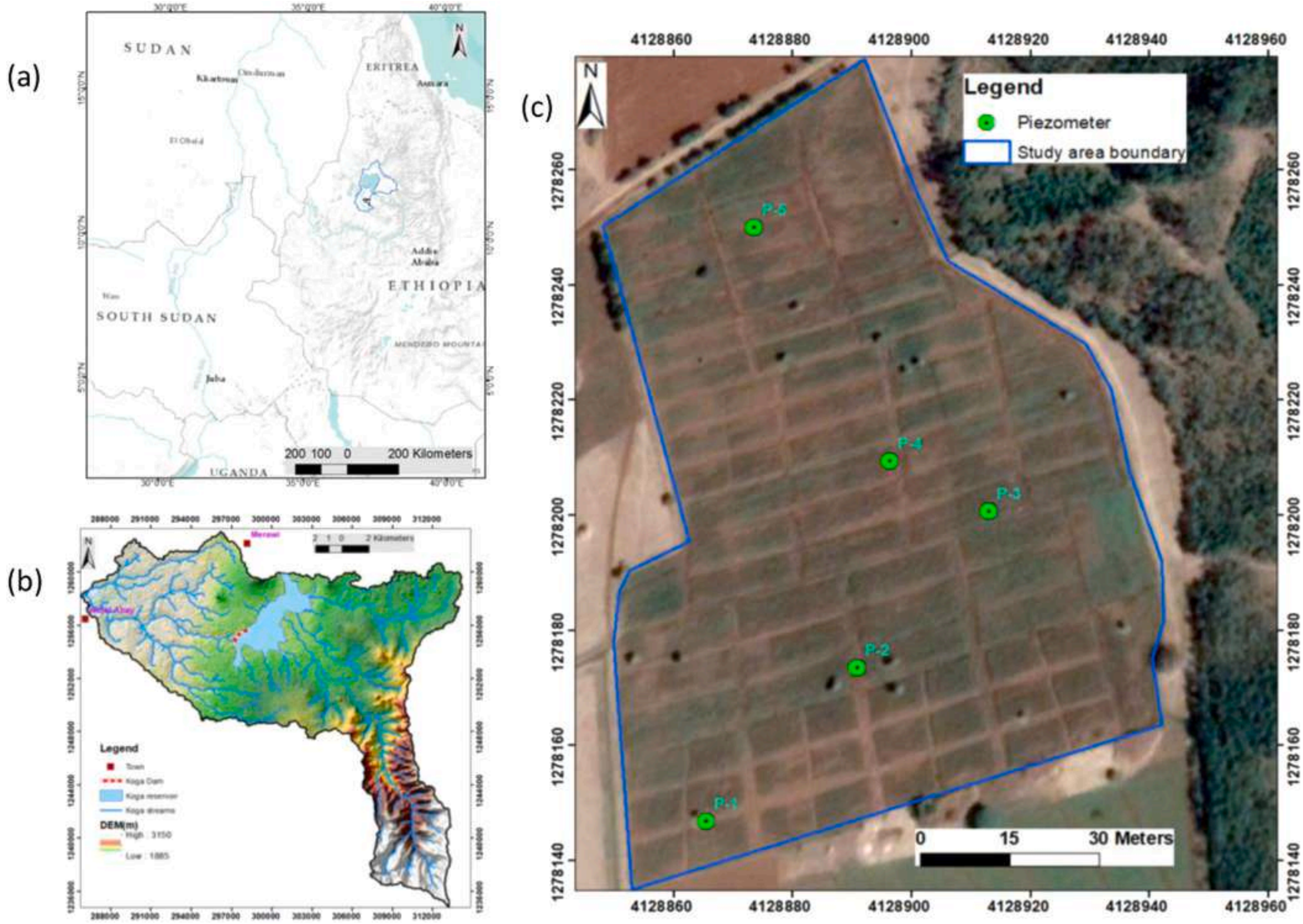

Fig. 1. Map of Ethiopia (a), map of Koga watershed (b), and experimental site at Ambomesk (c), p − 1 to p − 5 show piezometers installed to measure groundwater depth at the experimental plot.

compared with the use of inorganic fertilizer alone.

2. Materials and methods

2.1. Description of the study area

The study was conducted in the Koga irrigation scheme, located south of Lake Tana, in the upper Blue Nile basin (Fig. 1). The scheme began in 2010 with a dam volume of 83 million cubic meters, through its 1750 ha reservoir. It provides irrigation to nearly 5828 ha from a planned total of 7004 ha in the dry season for about 10,356 beneficiaries (Haileslassie et al., 2016). The average annual rainfall, mean air temperature and reference evapotranspiration are 1528 mm, 24 °C, and 3.9 mm, respectively (Fig. 2).

The basic physical and chemical soil properties of the Koga irrigation scheme are displayed in Table 1. According to our baseline survey data analysis, the soils in Koga are classified as clay Nitisols (WRB, 2015). They are very low in sand content (< 30 g kg^{-1}) and very high in clay content (> 700 g kg^{-1}), with little variation between the topsoil (0–20 cm) and the shallow subsoil (20–40 cm). The bulk density increases with increasing soil depth. The mean soil pH (H_2O) was 5.14. Also, a high value of exchangeable acidity was found. The SAR values at 0–20 and 20–40 cm soil depths were 0.15 and 0.16, respectively, while, ECe was 0.91 dS cm^{-1} for both soil depths. The EC of the irrigation water was 0.90 dS cm^{-1}.

2.2. Experimental set-up and procedures

2.2.1. Experimental design

Experiments were carried out under deficit and full irrigation at Ambomesk, in the Koga irrigation scheme (Fig. 1c) for four consecutive irrigated seasons with two cropping intensities (2018–2019). Here, only full irrigation results are reported. The annual cropping sequence was wheat (*Triticum aestivum* L.) - maize (*Zea mays* L). Here, only wheat results are reported. During the irrigation season from October to May, wheat and maize are dominantly planted in Koga, while in the rainy season from June to September, farmers mainly grow maize. To exactly apply farmers' practices such as ploughing, furrow preparations, weed and pest control, and to compare their practices with our experiments, ten model farmers were involved during the experiments (five per year). One farmer was selected as a coordinator and contact person with the researcher. Trainings were given to the participating farmers on the main concepts and application of lime ($CaCO_3$) and manure combined with inorganic fertilizer.

Integrated soil fertility management (ISFM) treatments with three levels of lime, fixed level of manure and inorganic fertilizer were arranged in a randomized complete block design with three replications. The ISFM treatments were (i) 0.86 t ha^{-1} lime (60% of the lime requirement) combined with 3 t ha^{-1} manure and full dose inorganic fertilizer (L3); (ii) 1.15 t ha^{-1} lime (80% of lime requirement) combined with 3 t ha^{-1} manure and full dose inorganic fertilizer (L2); (iii) 1.43 t ha^{-1} lime (100% of lime requirement) combined with 3 t ha^{-1} manure and full dose inorganic fertilizer (L1); (iv) 3 t ha^{-1} manure combined with full dose inorganic fertilizers (M); and (v) full dose inorganic fertilizer (C) as a control (see Table 2). These treatments were selected based on the following reasons: (i) our baseline survey results and previous findings revealed that the soil is strongly acidic; (ii) manure is locally available for farmers without any cost; (iii) lime is made available by the regional government to farmers at very low cost (US$ 209.2 per ton), and (iv) lime and manure application are the widely suggested acidic soil management practices. Each experimental plot measured 8 m width × 30 m length. The individual plots were separated from each other by a 2 m not-tilled buffer on all sides.

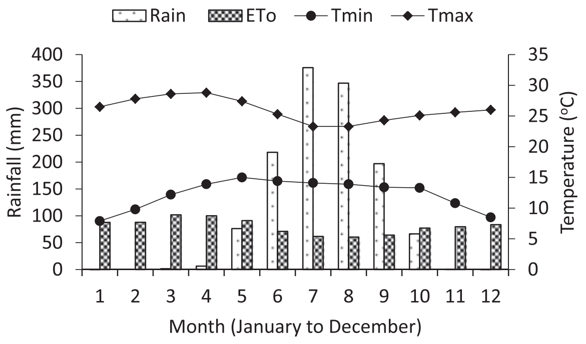

Fig. 2. Long-term mean monthly rainfall (RF), reference evapotranspiration (ETo, mm) and temperature (°C) (NMSA, 1987–2019).

Table 1
Physical and chemical properties of representative soils before treatment application.

Soil depth (cm)	0 – 20	20 – 40
Sand (g kg^{-1})	26 (1.2)	19 (0.9)
Silt (g kg^{-1})	253 (14)	259 (15)
Clay (g kg^{-1})	720 (46)	722 (47)
Textural class (USDA)	Clay	Clay
Bulk density (Mg m^{-3})	1.32 (0.24)	1.38 (0.31)
Exch. Al^{3+} (meq/100 g of soil)	0.64 (0.01)	0.96 (0.02)
Exch. H^+ (meq/100 g of soil)	0.32 (0.00)	0.32 (0.00)
Exch. acidity (meq/100 g of soil)	0.96 (0.01)	1.28 (0.22)
pH (H_2O)1:2.5	5.25 (0.51)	5.04 (0.46)
pH (KCl)1:2.5	4.04 (0.42)	4.1 (0.44)
ECe (dS/cm)1:2.5	0.91 (0.00)	0.91 (0.00)
Exch. Na (meq/100 g of soil)	0.3 (0.00)	0.3 (0.00)
Exch. K (meq/100 g of soil)	0.4 (0.00)	0.3 (0.00)
Exch. Ca (meq/100 g of soil)	4.4 (0.21)	4.3 (0.20)
Exch. Mg (meq/100 g of soil)	3.5 (0.18)	3.1 (0.16)
Sum of Cations (meq/100 g of soil)	8.6 (1.22)	8 (1.20)
Sodium Adsorption Ratio (SAR)	0.15 (0.00)	0.16 (0.00)
Organic carbon (g kg^{-1})	20.3 (3.52)	17.8 (2.43)
Nitrogen (%)	0.23 (0.00)	0.2 (0.00)
Available P (mgP_2O_5/kg soil)	55 (4.61)	53 (4.48)
Available K (mgK_2O/kg soil)	192.3 (6.74)	184.1 (6.62)
$CaCO_3$ (g kg^{-1})	Nil	Nil

Note: Standard deviations are presented in parenthesis (±). The methods used are described in section 2.3.2.

2.2.2. Integrated Soil Fertility Management

2.2.2.1. Manure management. The total nitrogen (TN), organic carbon (OC) and available phosphorus (av. P) content of the fresh manure were 34.4 g kg^{-1} TN, 350 g kg^{-1} OC and 134 av. P (ppm), respectively. Manure was given in 3 t ha^{-1} dose for all treatments except the control. The amount of manure was determined based on its local availability and soil acidity level.

The manure was evenly spread manually by broadcasting. After broadcasting, it was well mixed with the soil under dry soil conditions by traditional tillage operations with ox-driven *Maresha* ard plough about 10–15 cm depth (Fig. 3b) on the same dates by the farmers (Asmamaw et al., 2012; Temesgen et al., 2012).

Table 2
ISFM soil management practices at Ambomesk, Koga irrigation scheme.

Treatment	Lime	Organic fertilizer	Inorganic fertilizer	
	(t ha^{-1})	manure (t ha^{-1})	Urea (kg ha^{-1})	NPS-B (kg ha^{-1})
L1	1.43	3	183	120
L2	1.15	3	183	120
L3	0.86	3	183	120
M	0	3	183	120
C	0	0	183	120

NPS-B is Nitrogen, Phosphorus, Sulphur, and Boron, 0 indicates no organic input

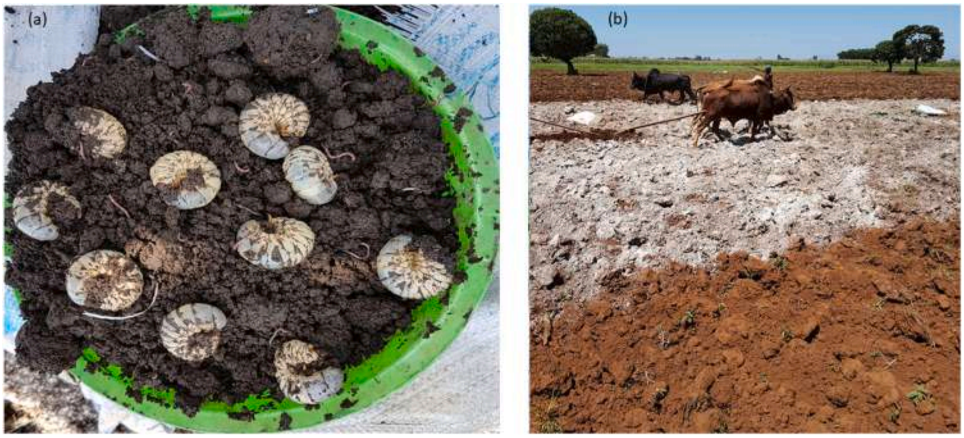

Fig. 3. Prepared manure enriched with earthworms (the thinnest and pink like) and white worms (that facilitate decomposition process) (a) and lime incorporation using oxen-driven *Maresha* ard plough (b) photos by Asmamaw (2018).

2.2.2.2. Lime and inorganic fertilizer management. The lime was incorporated within 10–15 cm soil depth on the same date as spreading the manure (Fig. 3b). The lime requirement ($CaCO_3$) was calculated based on the Ethiopian Institute of Agricultural Research (EIAR) recommendation (Getachew et al., 2019). The calculation considers soil pH, depth of tillage, level of exchangeable acidity and bulk density of the soil.

In all treatments, a full dose of urea (183 kg ha^{-1}) was applied. The dose of inorganic fertilizer was determined based on the Amhara Region Agricultural Research Institute recommendation (ARARI, 2014). The urea application was done in a split: 1/3 was applied during sowing and the remaining 2/3 was applied at the tillering stage of wheat. The full dose of NPS-B (120 kg ha^{-1}) containing 18.9% Nitrogen, 37.7% Phosphorus, 6.95% Sulphur and 0.1% Boron was applied once, during the sowing date.

2.3. Soil sampling and analysis

2.3.1. Soil sampling

Samples were collected after four seasons of treatments application (i.e two seasons of wheat and two seasons of maize cropping). The undisturbed soil core samples were taken from 0 to 5, 5–10, 10–15 and 15–20 cm depth at each plot (in three replicates per treatment) using stainless steel cylinders (inner diameter of 4.95 cm and a height of 5.1 cm) and covered with plastic lids to protect them during transport. But, for the 0–10 cm depth, an average of 0–5 cm and 5–10 cm core and for the 10–20 cm depth, an average of 10–15 and 15–20 cm core from each treatment was reported for this study.

The undisturbed soil samples were taken to determine the bulk density, porosity, soil water retention curve and saturated hydraulic conductivity. The composite soil samples were collected to analyze soil organic carbon and texture. The water content during sampling was approximately at field capacity.

2.3.2. Lab analysis

Soil pH and EC were determined on the composite samples in 1:2.5 soil−water suspensions using a pH meter and conductivity meter, respectively. The measured EC on 1:2.5 was converted to ECe using an equation as described by Slavich and Petterson (1993). The exchangeable acidity was extracted using the KCl method. The sample was percolated with a nonbuffered 1 mol (KCl) L^{-1} solution which enables the extraction of exchangeable acidity (H^+ and Al^{3+}). Texture analysis was done following standard sieving and a hydrometer (Kettler et al., 2001). Soil organic carbon (SOC) content was determined by the wet digestion method (Walkley and Black, 1934). Available nitrogen was determined by the Kjeldahl wet digestion and distillation technique (Olsen and Sommers, 1982). The available phosphorus content was analyzed using the Olsen method. Exchangeable cations (Ca, Mg, K and Na) were extracted using the Mehlich-3 procedure (Olsen and Sommers, 1982). The contents in the extracts were determined by flame photometry and atomic absorption spectrophotometry (Chapman, 1965).

The constant-head method was used to measure saturated hydraulic conductivity (*Ks*) in a closed permeameter (Eijkelkamp Soil & Water, Giesbeek, the Netherlands) and a constant water head was obtained by creating a difference in water pressure on both sides of the saturated soil sample so that water was passing upwards through the soil sample. The flow was measured until a constant water flux was observed and *Ks* was determined using Darcy's equation:

$$Ks = \frac{QL}{Ad} \tag{1}$$

where Q is the outflow through the soil core ($cm^3\ h^{-1}$), L is the length of the soil core (cm), A is the surface area of the soil core (cm^2), and d is the applied hydraulic head (cm H_2O).

Soil water retention characteristic curves were determined using the sandbox method supplemented by a set of pressure chambers as described by Cornelis et al. (2005). For lower matric potentials of − 10 hPa, − 30 hPa, − 50 hPa, − 70 hPa and − 100 hPa, the sandbox apparatus (Eijkelkamp Soil & Water) was used. The undisturbed samples were partitioned into three sub-samples for soil water content determination at a lower matric potential of − 340 hPa, − 1000 hPa and − 15,000 hPa using the pressure chambers (Soilmoisture Equipment, Santa Barbara CA, USA). Water content at field capacity was then measured at − 100 hPa, matric porosity at − 10 hPa and permanent wilting point at − 15,000 hPa, while soil bulk density was determined at − 100 hPa during the retention curve analysis (Reynolds et al., 2007).

In addition to the measured soil physical properties, macroporosity, MacPor ($m^3\ m^{-3}$) and soil air capacity, AC ($m^3\ m^{-3}$) were estimated from the soil water retention curve following the procedures described by Reynolds et al. (2007). Sorptivity (*S*) was estimated from the field infiltration test using an equation described by Philip (1957).

2.4. Infiltration field measurement

The infiltration capacity was determined in the field using a double-ring infiltrometer (Eijkelkamp Soil & Water, Giesbeek, the Netherlands). The inner and outer rings had a diameter of 30 and 60 cm respectively, with a 25 cm height. The rings were driven 5 cm into the soil with a sledgehammer after placing the rings with the cutting edges facing down on the soil surface. Water was filled to 10 cm above the soil surface. The rings were refilled to the 10 cm head level each time when the head approached 5 cm above the soil surface. Readings of water level were taken at 5, 10, 15, 20, 25, 30, 35, 40, 50, 60, 70, and 80 min for calculation of infiltration rate and cumulative infiltration. All measurements were done under moist soil and crack-free locations. A hook gauge was fitted in the inner cylinder to measure the infiltration rate. The test continued until the drop in water level was equal over an equal time interval, indicating that steady-state flow reached (80 min). The measurements were carried out on all plots (in three replicates per treatment). The basic steady-state infiltration capacity (cm min^{-1}) and cumulative infiltration (cm) were estimated using Phillip's models (Phillip, 1957):

$$i(t) = \frac{1}{2}St^{\frac{1}{2}} + K \tag{2}$$

$$I(t) = St^{\frac{1}{2}} + Kt \tag{3}$$

where i is the final infiltration rate, I is the cumulative infiltration, S is the sorptivity (cm min$^{-1/2}$), t is the time of infiltration, and K is a parameter with the dimension of the saturated hydraulic conductivity (cm min^{-1}) and is equal to transmissivity (cm min^{-1}).

2.5. *Visual evaluation of soil structure (VESS)*

Three locations were selected from each treatment for visual soil evaluation and examination following the Visual Evaluation of Soil structure approach (Guimarães et al., 2011). Flat-faced spade nearly 20 cm wide, 22–25 cm long, VESS chart, tarp, measuring tape, small knife and smartphone were used. During the evaluations, the soil was slightly moist so that a block of soil was dug out without altering the structure. The blocks of soil were graded on a scale from 1 to 5 where 1 signifies the best condition and 5 denotes poor condition. The score was given based on related factors such as visibility of macroporosity (availability of large wormholes), aggregate type and size, presence of roots, simplicity of extracting soil blocks using a spade and the breakage of large aggregates into small fragments (Pulido Moncada et al., 2014). Soils with scores of 1–3 have an 'acceptable' condition of soil structure, whereas those with scores of 4–5 have a 'limiting' condition and need changing management strategies (Cornelis et al., 2019).

2.6. *Grain yield*

The wheat grain yield data was collected at harvesting time from a sample area of 2 m × 3 m in each plot with three replicates. Samples were collected from the middle rows to avoid border effects. The harvested crop was sun-dried and threshed separately using wooden sticks and finally, the grain was separated, cleaned, and weighed to record the grain yield. Grain yield was measured as the weight of harvested grain and adjusted to 13.5% standard moisture content for wheat, and then converted to t h^{-1} (Meskelu et al., 2017).

2.7. *Statistical analyses*

Statistical analysis and graphics were done in R software, version 3.4.2. (R Core Team, 2020). Statistical differences were tested using a two-way analysis of variance (ANOVA) following the General Linear Model (GLM) procedure. Fisher's LSD (the least significance difference) test was used for mean separation when the analysis of variance showed statistically significant differences ($P < 0.05$) between the parameters. The residual normal distribution and homoscedasticity of the data were tested before these analyses.

3. Results and discussion

3.1. *Treatments effect on soil physical and chemical properties*

Soil organic carbon (SOC) was significantly lower ($p < 0.05$) at C than at L1, L2, L3 and M in both soil depths (Table 3). In comparison with C, 125%, 124%, 123% and 127% higher SOC was found at L1, L2, L3 and M for the 0–10 cm soil depth, respectively. Similarly, for the 10–20 cm soil depth, 124%, 107%, 107% and 124% SOC improvement was found at L1, L2, L3 and M, respectively, compared with C. Adding manure combined with inorganic fertilizers increased soil organic carbon content but lime application caused small increases compared to manure application on soil organic carbon. Studies confirmed that the combined use of inorganic fertilizer, lime and manure increased SOC contents through enhancing carbon sequestration mostly because it increases biomass and hence residue returns (Auler et al., 2017).

Soil bulk density (BD) was significantly lower ($p < 0.05$) under L1, L2, L3 and M than at C (Table 3) in both soil depths. The BD under L1, L2, L3 and M was reduced by 20%, 13%, 8.0% and 10% for the 0–10 cm soil depth and by 13%, 7.5%, 8.3% and 8.3% for the 10–20 cm soil depth, respectively, compared with C. The lower BD found at lime and manure treated plots compared with the control (C), possibly due to the addition of organic matter through increased biomass (roots and residue returns) and from the direct application of organic manure. Similarly, Haynes and Naidu (1998) found reduced BD because of the combined use of lime, fertilizer and manure.

The application of full dose lime (L1) increased the soil pH by 3%, 8%, 9% and 13% compared with L2, L3, M and C, respectively. The exchangeable acidity was affected by the magnitude of the lime doses and manuring compared with C. The application of L1 improved exchangeable acidity compared with L2, L3, M and C by 16%, 22%, 30% and 71% for the 0–10 cm and 15%, 18%, 30% and 70% for the 10–20 cm soil depths, respectively. Manuring also enhanced exchangeable acidity

Table 3

Mean values of basic soil properties and soil quality indicators with standard deviation in parenthesis (±) for top 0–10 and 10–20 cm soil depths under different IFSM practices after two years (see Table 1 the respective values at the start of the experiment).

Treatment	Soil Depth (cm)	SOC (g kg^{-1})	BD (Mg m^{3})	TP (m^{3} m^{-3})	pH	Exc. Acidity (meq/100 g of soil)	FC (m^{3} m^{-3})	PWP (m^{3} m^{-3})	PAWC (m^{3} m^{-3})	AC (m^{3} m^{-3})	MacPor (mm)
L1	0–10	30(0.2)^{Aa}	1.02(0.02)^{Aa}	0.61(0)^{Aa}	6 (0.06)^{Aa}	0.32(0)^{Aa}	0.40(0.01)^{Aa}	0.27(0)^{Aa}	0.13(0)^{Aa}	0.21 (0)^{Aa}	0.11(0)^{Aa}
	10–20	30(0.2)^{Aa}	1.16(0.01)^{Bb}	0.56(0)^{Bb}	6(0.04)^{Aa}	0.33(0)^{Aa}	0.38(0.01)^{Ab}	0.25(0.02)^{Bb}	0.13(0)^{Aa}	0.19(0)^{Aa}	0.08(0)^{Aa}
L2	0–10	30(0.2)^{Aa}	1.11(0.01)^{Bb}	0.60(0)^{Aa}	5.8(0.06)^{Bb}	0.38(0)^{Bb}	0.39(0.0)^{Ae}	0.26(0)^{Aa}	0.13(0)^{Aa}	0.16(0)^{Aa}	0.08(0)^{Aa}
	10–20	29(0.1)^{Aa}	1.23 (0.02)^{Cc}	0.55(0)^{Cc}	5.9(0.05)^{Bb}	0.39(0)^{Bb}	0.36(0.01)^{Cd}	0.24(0.02)^{Cc}	0.12(0)^{Ba}	0.15(0)^{Aa}	0.07(0)^{Aa}
L3	0–10	30(0.2)^{Aa}	1.17(0.04)^{Bb}	0.59(0)^{Aa}	5. 6(0.07)^{Cc}	0.41(0)^{Cc}	0.37(0.0)^{Bc}	0.25(0.0)^{Bb}	0.12(0)^{Ab}	0.16(0)^{Aa}	0.07(0)^{Aa}
	10–20	29(0.1)^{Aa}	1.22(0.01)^{Cc}	0.55(0)^{Cb}	5.5(0.07)^{Cc}	0.40(0)^{Cc}	0.35(0.01)^{Cd}	0.23(0.02)^{Cc}	0.12(0)^{Ab}	0.13(0)^{Bb}	0.06(0)^{Aa}
M	0–10	31(0.3)^{Aa}	1.14 (0.01)^{Bb}	0.61(0)^{Aa}	5.4(0.03)^{Dd}	0.46(0)^{Dd}	0.37(0.0)^{Ba}	0.26(0.02)^{Aa}	0.13(0)^{Aa}	0.13(0)^{Bb}	0.06(0)^{Aa}
	10–20	30(0.2)^{Aa}	1.22(0.03)^{Cc}	0.56(0)^{Ab}	5.5(0.02)^{Dd}	0.47(0)^{Dd}	0.36(0.01)^{Cd}	0.25(0.02)^{Bb}	0.12(0)^{Ab}	0.12(0)^{Bb}	0.05(0)^{Aa}
C	0–10	14(0.0)^{Bb}	1.27(0.02)^{Cc}	0.57(0)^{Bb}	5.2(0.04)^{Ee}	1.12(0)^{Ee}	0.35(0.01)^{Cc}	0.24(0.01)^{Bb}	0.11(0)^{Bb}	0.13(0)^{Bb}	0.05(0)^{Aa}
	10–20	14(0.0)^{Bb}	1.33(0.02)^{Dd}	0.54(0)^{Cc}	5.1(0.03)^{Ee}	1.11(0)^{Ee}	0.34(0.01)^{Cc}	0.23(0)^{Cc}	0.11(0)^{Bb}	0.11(0)^{Bb}	0.04(0)^{Aa}

Note: SOC = soil organic carbon, BD = bulk density, TP = total porosity, pH = a measurement of the degree to which water is acidic or basic and it ranges from 0 (strongly acidic) to 14 (strongly basic), Exc. = exchangeable acidity, *FC* = soil water content at field capacity, *PWP* = soil water content at permanent wilting point, *PAWC* = plant available water capacity, *AC* = soil air capacity and MacPor = soil macroporosity. Values in a column followed by the same capital letters (for soil depth) and small letters (for treatments) are not significantly different ($P < 0.05$). For L1, L2, L3, M and C, see Table 2.

compared with the control (C) by 60% and 58% for the 0–10 and 10–20 cm soil layers, respectively.

The improved soil management practices had no significant effect on macroporosity but soil air capacity was slightly affected by liming compared with manure and C under both soil depths (Table 3). Air capacity (AC) values ranged between 0.21 m^3 m^{-3} under the highest lime treatment (L1) and 0.11 m^3 m^{-3} under the control plots. In this study, L1, L2, L3, M and C (0–10 cm depth) showed good soil physical conditions (MacPor $\geq$ 0.05 m^3 m^{-3}) but at 10–20 cm soil depth, C revealed poor soil physical conditions (MacPor = 0.04 m^3 m^{-3}). This study confirms that liming integrated with organic and inorganic sources enhanced AC and total porosity. In agreement with this study, findings noted that combined use of lime, manure and inorganic fertilizers on clay soil improved total porosity (Haynes and Naidu, 1998).

3.2. Soil water retention

The amount of water retained at field capacity (*FC*) was significantly ($p < 0.05$) higher under L1, L2, L3 and M as compared with C both for the 0–10 and 10–20 cm soil depths (Table 3). The water content at *FC* for the 0–10 cm soil depth at L1 which had the highest lime dose was increased by 2.5%, 7.5%, 7.5% and 12.5% compared with L2, L3, M and C, respectively. Also, for the 0–10 cm soil depth, L1, L2, L3 and M improved the water content at *FC* by 12.5%, 11.3%, 5.4% and 5.4%, respectively, compared with C. Similarly, for the 10–20 cm soil depth, the water content at *FC* at L1, L2, L3 and M was improved by 5.3%, 8%, 5.3% and 11%, respectively, compared with C.

Higher permanent wilting point (*PWP*) was found at L1, L2, L3 and M compared with C in both soil depths ($p < 0.05$; Table 3). In comparison with L1, the water content at *PWP* at L2, L3 and M for the 0–10 cm soil depth reduced by 3.7%, 7.4% and 3.7%, respectively. Likewise, for the 10–20 cm soil depth, water content at *PWP* at L1 was improved by 4% and 8%, respectively, compared with L2 and L3. Because of M application, the water content at *PWP* for the 0–10 cm and 10–20 cm soil depths was enhanced by 8.3% and 8.7%, respectively, compared with C. Also, L1, L2 and M improved the plant available water capacity (*PAWC*) by 8% compared with L3 for the 0–10 cm soil depth (Table 3). Relatively higher *PAWC* values were found from L1, L2, L3 and M for both soil depths than at C. But, since the treatments increased both the water content at *FC* and *PWP*, the effect on *PAWC* was small (Table 3).

At L1, higher water retention was found compared with L2, L3 and M from both soil depths (Fig. 4a & b). As expected, L2 revealed a higher value between pF 1–1.5 than L3, M and C for the 0–10 cm soil depth. Considerably lower water retention was observed across all pF ranges at C in both soil depths.

The combined use of liming with manure and inorganic fertilizer further improves the soil's aggregate that can absorb and retain more water during rainfall events or irrigation and hence, can be taken up by plants during dry spells (Hillel, 1998). It should be noted, however, that this does not necessarily result in a substantial increase in plant-available water capacity, given that also the water content at *PWP* increases with lime and manure application. Similarly, due to liming, water content at *FC, PWP, PAWC* and *RWC* were increased in studies by Farhadi et al. (2018) and Ferreira et al. (2019).

3.3. Saturated hydraulic conductivity

The effect of L1, L2, L3, M and C on saturated hydraulic conductivity (*Ks)* of the soil was significant ($p < 0.05$; Fig. 5) in both soil depths. The *Ks* under L1, L2, L3 and M was increased by 64%, 61%, 44% and 38% for the 0–10 cm soil depth and by 37%, 51%, 35% and 11% for the 10–20 cm soil depth in comparison with C. The *Ks* obtained from the treatments with lime L1, L2 and L3 increased by 19%, 17% and 4.6% for the 0–10 cm soil depth and by 24%, 37% and 21.6% for the 10–20 cm soil depth, as compared with M without lime. This indicated that liming combined with manuring ameliorate soil structure, increasing the stability of clay assemblages and improving macroporosity by adding organic matter as a binding agent for soil particles, which enhances the *Ks*. The combined use of manure with inorganic fertilizer also significantly improved the *Ks* over the control (Chakraborty et al., 2010). This could be caused by better crop root growth (residue return) and more microbial activities.

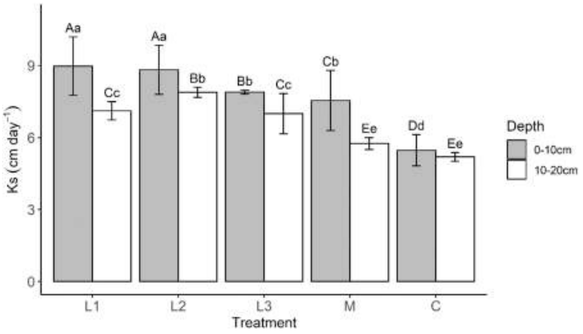

Fig. 5. Saturated hydraulic conductivities obtained with the constant-head laboratory permeameter as affected by the treatments. Bars indicated with the same capital letters are not significantly different between the treatments under the same soil depth, while bars indicated with the same small letters are not significantly different ($p < 0.05$) between 0 and 10 cm and 10–20 cm soil depth. For L1, L2, L3, M and C, see Table 2.

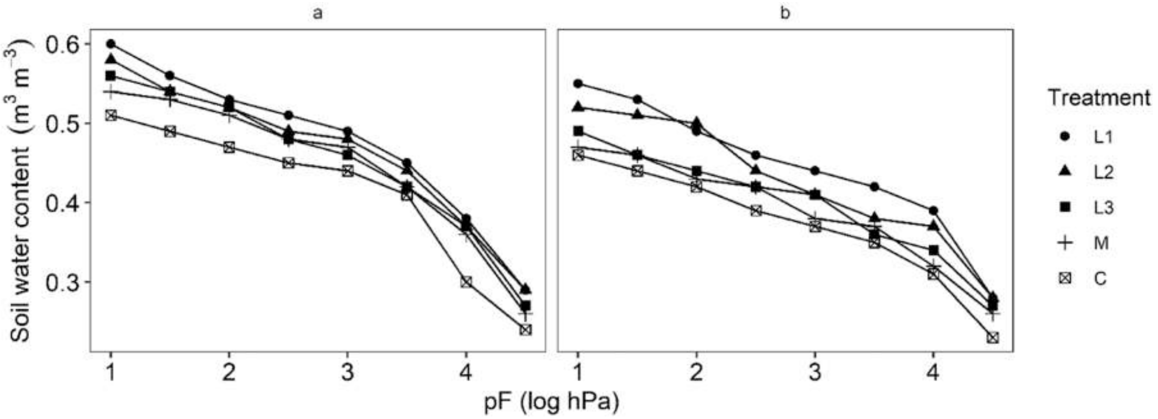

Fig. 4. Soil water retention curve (SWRC) as affected by ISFM practices at 0–10 cm (a) and 10–20 cm soil depth (b). SWRC showed the relationship between the soil water content and pressure heads. These curves showed how soil water holding capacity changes at different suction. For L1, L2, L3, M and C, see Table 2.

3.4. Infiltration

The infiltration rate and cumulative infiltration were significantly higher ($p < 0.05$) at L1, L2, L3 and M than at C (Fig. 6a & b). A higher rate of final (steady-state) infiltration was found after 80 min at L1 (0.007 cm min^{-1} ± 0) followed by L2 (0.006 cm min^{-1} ± 0), L3 (0.006 cm min^{-1} ± 0), M (0.005 cm min^{-1} ± 0) and C (0.004 cm min^{-1} ± 0). Compared with L2, L3 and M, a significantly higher ($p < 0.05$) final infiltration rate was found at L1. The use of L1 increased the final infiltration rate by 14.3%, 14.3%, 28.6% and 43% compared with L2, L3, M and C, respectively. But, the infiltration rate found at L2 was alike with L3. The final infiltration rate increased significantly with increasing the dose of lime (i.e. from a lower dose, L3 to full dose, L1). Similar to the infiltration rate, the cumulative infiltration at L1 was improved by 7%, 10%, 10% and 14.3% in comparison with L2, L3, M and C, respectively. However, the cumulative infiltration found at L2 was comparable with L3.

The significantly higher final infiltration rate found at L1, L2, L3 and M compared with C may be because liming and manuring improves soil physical properties, increases microbial activities and reduces Mn^{2+} and Al^{3+} toxicity, which ultimately enhances infiltration. In line with this finding, Haynes and Naidu (1998) reported improved infiltration capacity from the combined use of lime, manure and inorganic fertilizer. In other words, liming combined with manuring reduced ponding of water and runoff, particularly important under high-intensity rainfall conditions (Hillel, 1998).

3.5. Sorptivity

The highest sorptivity was found from a higher lime dose (L1) and reduced with decreasing lime doses (i.e. from a higher dose (L2) to a lower dose (L3), compared with the control (C) (Fig. 7). The application of L1 improved sorptivity by 5.0%, 10%, 11% and 15% compared with L2, L3, M and C, respectively. Yet, the sorptivity found at L3 was comparable with M, especially after 25 min of water pouring into the soil. The sorptivity result followed a comparable trend with infiltration rate, indicating that liming and manuring enhanced the soil organic matter, which in turn influenced soil hydraulic properties. This implies that the addition of manure combined with liming and inorganic sources improves soils water movement.

3.6. VESS structural quality (Sq) scores

The overall (0–20 cm) VESS structural quality (Sq) scores ranged from 1.6 (L1) to 3.8 (C), indicating a variation from good to poor soil Sq among the ISFM treatments (Fig. 8). When the liming dose increased, overall VESS Sq scores showed a significant decrease from Sq = 2.2 in L3 to Sq = 1.9 in L2 and then to Sq = 1.6 in L1, indicating an improvement of soil structural quality. Manuring (M) as such, also decreased overall VESS Sq score with Sq = 2.4, indicating improved Sq, compared with C (Sq = 3.8) which was beyond the threshold of poor quality as suggested by Ball et al. (2007). As observed with soil hydraulic properties, porosity and organic carbon results, the Sq score confirmed that liming and manure practices improved soil Sq as compared with C. The significant correlation attained between VESS Sq and SOC could be explained by liming and manuring, which improves soil structure. Liming indirectly improves soil structure through increasing biomass and residue returns, which enhances soil structure. Yet, manuring can directly improve soil structure by adding organic matter as a binding agent for soil particles.

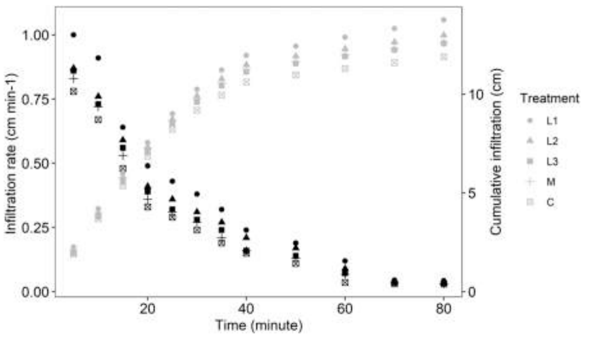

Fig. 6. Infiltration rates as affected by soil management practices (bold symbols) and cumulative infiltration curve (gray symbols) obtained from 15 measurements with double ring infiltrometer at Ambomesk, Koga irrigation scheme. For L1, L2, L3, M and C, see Table 2.

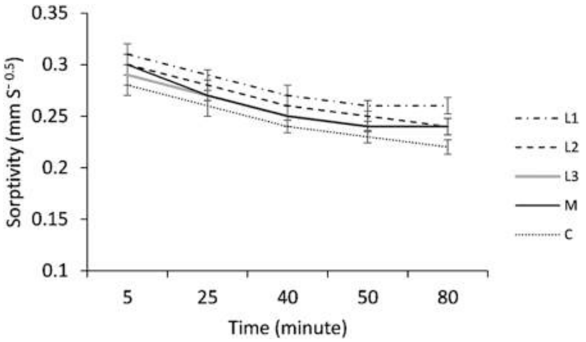

Fig. 7. Sorptivity as a function of time or soil water content under different soil management practices. At the initial stage of field test infiltration, the sorptivity increases, indicating unsaturated flow in which hydraulic gradient is determined mainly by matrix potential. The sorptivity values estimated at steady state (80 min) field test infiltration decreases in all treatments. For L1, L2, L3, M and C, see Table 2.

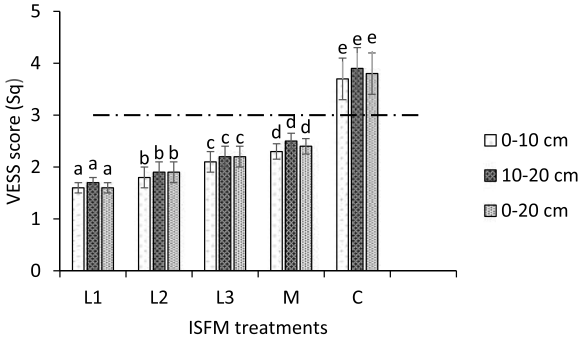

Fig. 8. VESS scores (Sq) for 0–10 cm, 10–20 cm, and overall Sq for total layer (0–20 cm) at L1, L2, L3, M and C. The dashed line indicated the VESS score (Sq = 3.0) considered as a threshold for suitable root growth. Evaluations were done at fifteen representative locations i.e. three samples at each treatment (L1, L2, L3, M and C).

The overall VESS Sq scores exhibited good correlations with all individual soil physical properties (see Annex). The SOC (r = 0.59–0.81), BD (r = 0.60–0.78), Ks (r = 0.61–0.86), AC (r = 0.65–0.88), MacPOR (r = 0.66–0.77), sorptivity (r = 0.61–0.82), and grain yield (r = 0.63–0.88) showed significant positive correlations. This indicates that the use of VESS techniques (spade test) is viable for Nitisols. Likewise, Cornelis et al. (2019) stated that VESS performed very well for assessing soil structural quality of highly weathered tropical soils in Uganda.

3.7. Wheat grain yield

The ISFM application considerably ($p < 0.05$) affected wheat grain yield (Fig. 9). As compared with C, grain yield was improved by 69% at L1, 59% at L2, 53% at L3, and 44% at M during 2018 and by 70% at L1, 58% at L2, 55% at L3 and 46% at M in 2019. Also, L2 improved the grain

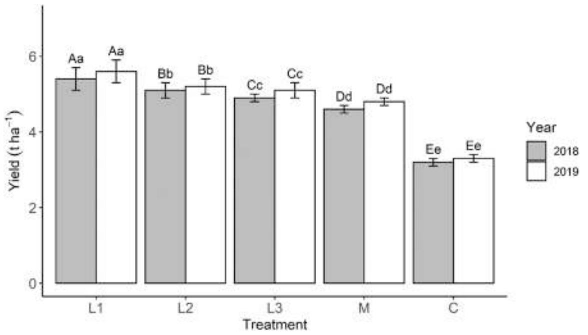

Fig. 9. Wheat grain yield under ISFM and full irrigation (100% ETc) application in 2018 and 2019. Bars indicated with the same capital letters are not significantly different ($p > 0.05$) between the treatments, while bars indicated with the same small letters are not significantly ($p > 0.05$) different between the study years. For L1, L2, L3, M and C, see Table 2.

yield by 4% at L3, and 11% at M in 2018 and 2% at L3 and 8% at M in 2019. But, at the same treatment, the grain yield was decreased by 6% and 8% compared with L1 in 2018 and 2019, respectively. An increasing grain yield was found with increasing lime doses (i.e. L3 to L1) and manuring compared with only inorganic fertilizer application (C). The lowest grain yield found at C could be attributed to the presence of strong soil acidity. In line with our finding, Yebo (2015) reported a substantially declined crop production due to the direct and indirect effects of soil acidity. Soil acidity inhibits the growth of primary and lateral root apexes, reduces fine roots branching, and suppresses root hair development (Abate et al., 2013). Manuring increased grain yield compared with the control is probably due to improvements in organic matter, reduced bulk density and enhanced water holding capacity, which enhances grain yield. The long-term application of liming increases crop yields, organic matter returns, soil organic matter content and thus soil aggregation (Abate et al., 2013; Asmare and Markku, 2016). The enhancement in physical soil properties and increased wheat yield is due to the increased soil organic carbon directly from manure use and indirectly from the increase in biomass (roots and residues returns) as a result of liming.

4. Conclusion

The effect of liming combined with manure and inorganic fertilizer on bulk density, soil water retention, saturated hydraulic conductivity, infiltration capacity, soil structural quality and wheat yield was studied. This study found that increasing lime application rate in combination with manure application increased soil pH, soil organic carbon, saturated hydraulic conductivity, porosity, infiltration rate, water retention, sorptivity and wheat yield but reduced soil bulk density. Adding manure combined with inorganic fertilizers also considerably improved the soil water holding capacity, soil structure, infiltration capacity and saturated hydraulic conductivity compared with the use of inorganic fertilizers alone. We noted that adding manure combined with inorganic fertilizer is important, but adding lime at different rates additionally improves hydrophysical soil attributes of clay-dominated Nitisols and wheat yield over just manure application. The possible reasons for the improvement in soil physical properties and wheat yield are the increased soil organic carbon directly from manure application and indirectly from the increase in biomass due to lime application. The findings of this study can be used as management techniques by farmers to combat soil acidity, improve crop yields and soil physical quality. Combining lime application with manure can improve the resiliency of soils in changing climates and sustain long-term crop yields.

Declaration of Competing Interest

This is to confirm that we have no conflict of interest.

Acknowledgment

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Appendix 1. Pearson correlation between soil structural quality (Sq) and basic soil properties and soil quality indicators under different IFSM practices

Treatments	Correlation	R	P − value
L1	SOC vs Sq	0.76	0.003
L2	SOC vs Sq	0.66	0.012
L3	SOC vs Sq	0.81	0.000
M	SOC vs Sq	0.59	0.000
C	SOC vs Sq	0.70	0.004
L1	BD vs Sq	0.75	0.010
L2	BD vs Sq	0.60	0.030
L3	BD vs Sq	0.76	0.010
M	BD vs Sq	0.68	0.020
C	BD vs Sq	0.78	0.020
L1	AC vs Sq	0.65	0.012
L2	AC vs Sq	0.80	0.031
L3	AC vs Sq	0.76	0.014
M	AC vs Sq	0.88	0.022
C	AC vs Sq	0.68	0.021
L1	MacPor vs Sq	0.66	0.011
L2	MacPor vs Sq	0.77	0.021
L3	MacPor vs Sq	0.60	0.022
M	MacPor vs Sq	0.69	0.001
C	MacPor vs Sq	0.75	0.021
L1	Ks vs Sq	0.86	0.001
L2	Ks vs Sq	0.81	0.000
L3	Ks vs Sq	0.74	0.000

(*continued on next page*)

(*continued*)

Treatments	Correlation	R	P − value
M	Ks vs Sq	0.65	0.002
C	Ks vs Sq	0.61	0.004
L1	S vs Sq	0.61	0.050
L2	S vs Sq	0.73	0.001
L3	S vs Sq	0.82	0.000
M	S vs Sq	0.75	0.011
C	S vs Sq	0.67	0.002
L1	Yield vs Sq	0.63	0.022
L2	Yield vs Sq	0.72	0.012
L3	Yield vs Sq	0.84	0.031
M	Yield vs Sq	0.88	0.022
C	Yield vs Sq	0.87	0.021

Note: Sq = soil structural quality, S= sorptivity, Ks = saturated hydraulic conductivity, MacPor = macroporosity, AC = air capacity, BD = bulk density, SOC = soil organic carbon

References

Abate, E., Hussein, S., Laing, M., Mengistu, F., 2013. Aluminum tolerance in cereals: a potential component of integrated acid soils management in Ethiopia. Ethiop. J. Nat. Resour. 13 (January), 43–66.

Abewa, A., Yitaferu, B., G.Selassie, Y., Tadele Amare, T., 2013. The role of biochar on acid soil reclamation and yield of teff (Eragrostis tef [Zucc] Trotter) in Northwestern Ethiopia. J. Agric. Sci. 6 (1), 1–12. https://doi.org/10.5539/jas.v6n1p1.

Agegnehu, G., vanbeek, C., Bird, M.I., 2014. Influence of integrated soil fertility management in wheat and tef productivity and soil chemical properties in the highland tropical environment. J. Soil Sci. Plant Nutr. 14 (3), 532–545. https://doi.org/10.4067/s0718-95162014005000042.

Ameyu, T., 2019. A review on the potential effect of lime on soil properties and crop productivity improvements. J. Environ. Earth Sci. 9 (2), 17–23. https://doi.org/10.7176/jees/9-2-03.

Asmamaw, D.K., Leye, M.T., Mohammed, A.A., 2012. Effect of winged subsoiler and traditional tillage integrated with fanya juu on selected soil physico-chemical and soil water properties in the Northwestern Highlands of Ethiopia. East Afr. J. Sci. 6 (2), 105–116.

Asmare, M., Markku, Y.H., 2016. Effects of applications of lime, wood ash, manure and mineral P fertilizer on the inorganic P fractions and other selected soil chemical properties on acid soil of Farta District, Northwestern highland of Ethiopia. Afr. J. Agric. Res. 11 (2), 87–99. https://doi.org/10.5897/ajar2015.9632.

Auler, A.C., Pires, L.F., Caires, E.F., 2017. Surface and incorporated liming effects on clay dispersion, water availability, and aeration capacity of a dystrudept soil. Bragantia 76 (3), 433–446. https://doi.org/10.1590/1678-4499.290.

Ball, B.C., Batey, T., Munkholm, L.J., 2007. Field assessment of soil structural quality - a development of the Peerlkamp test. Soil Use Manag. 23 (4), 329–337. https://doi.org/10.1111/j.1475-2743.2007.00102.x.

Bedada, W. (2015). Compost and Fertilizer - Alternatives or Complementary ? Management Feasibility and Long-Term Effects on Soil Fertility in an Ethiopian Village.

Chakraborty, D., Garg, R.N., Tomar, R.K., Dwivedi, B.S., Aggarwal, P., Singh, R., Behera, U.K., Thangasamy, A., Singh, D., 2010. Soil physical quality as influenced by long-term application of fertilizers and manure under maize-wheat system. Soil Sci. 175 (3), 128–136. https://doi.org/10.1097/SS.0b013e3181d53bd7.

Chapman, H.D. (1965). Methods of Soil Analysis: Part 2 Chemical and Microbiological Properties, 9.2. In *agronmonogr* (Issue 01 January). https://doi.org/https://doi.org/10.2134/agronmonogr9.2.c6.

Chimdi, A., Gebrekidan, H., Kibret, K., Tadesse, A., 2012. Effects of liming on acidity-related chemical properties of soils of different land use systems in Western Oromia. Ethiop. World J. Agric. Sci. 8 (6), 560–567. https://doi.org/10.5829/idosi.wjas.2012.8.6.1686.

Cornelis, W.M., Akodi, D., Komutunga, E., Agaba, C., Ahumuza, E., Oratungye, K., 2019. Exploring visual soil evaluation and examination methods on highly-weathered tropical soil. Soil Tillage Res. 195 (July), 104360 https://doi.org/10.1016/j.still.2019.104360.

Cornelis, W.M., Khlosi, M., Hartmann, R., Van Meirvenne, M., De Vos, B., 2005. Comparison of unimodal analytical expressions for the soil-water retention curve. Soil Sci. Soc. Am. J. 69 (6), 1902–1911. https://doi.org/10.2136/sssaj2004.0238.

Farhadi, M., Pla, C., & Valdes-abellan, J. (2018). Improving hydraulic properties of sandy soil with lime powder addition. *20*, 12195.

Ferreira, T.R., Pires, L.F., Auler, A.C., Brinatti, A.M., Ogunwole, J.O., 2019. Water retention curve to analyze soil structure changes due to liming. An. Da Acad. Bras. De. Cienc. 91 (3), 1–12. https://doi.org/10.1590/0001-3765201920180528.

Getachew, A., Temesgen, D., Tolessa, D., Ayalew, A., Geremew, T., Chelot, Y., 2017. Effect of lime and phosphorus fertilizer on acid soil properties and barley grain yield at Bedi in Western Ethiopia. Afr. J. Agric. Res. 12 (40), 3005–3012. https://doi.org/10.5897/ajar2017.12562.

Getachew A., Chilot Y., andTeklu E. (2019). Soil Acidity Management. In Soil Acidity Management. Ethiopian Institute of Agricultural Research (EIAR). Addis Ababa, Ethiopia.

Guimarães, R.M.L., Ball, B.C., Tormena, C.A., 2011. Improvements in the visual evaluation of soil structure. Soil Use Manag. 27 (3), 395–403. https://doi.org/10.1111/j.1475-2743.2011.00354.x.

Gurmessa, B., 2020. Soil acidity challenges and the significance of liming and organic amendments in tropical agricultural lands with reference to Ethiopia. Environ., Dev. Sustain. 0123456789. https://doi.org/10.1007/s10668-020-00615-2.

Haile, W., & Boke, S. (2011). On-Farm Verification of Lime and NPK Fertilizers Effects on the Tuber Yield of Irish Potato (Solanum tuberosum) on Some Acidic Soils of Southern Ethiopia. *4*(1), 283–288.

Haileslassie, A., Hagos, F., Agide, Z., Tesema, E., Hoekstra, D., & Langan, S. (2016). Institutions for irrigation water management in Ethiopia: Assessing diversity and service delivery. 31.

Haynes, R.J., Naidu, R., 1998. Influence of lime, fertilizer and manure applications on soil organic matter. Nutr. Cycl. Agroecosystems 51 (123), 123–137. http://link.springer.com/article/10.1023/A:1009738307837.

Hillel, D. (1998). *Introduction to Environmental Soil Physics - 1st Edition*. Academic Press. Retrieved March 20, 2021, from https://www.elsevier.com/books/introduction-to-environmental-soil-physics/hillel/978–0-12–348655-4.

Kettler, T.A., Doran, J.W., Gilbert, T.L., 2001. Simplified method for soil particle-size determination to accompany soil-quality analyses. Soil Sci. Soc. Am. J. 65 (3), 849–852. https://doi.org/10.2136/sssaj2001.653849x.

Lupwayi, N.Z., Girma, M., Haque, I., 2000. Plant nutrient contents of cattle manures from small-scale farms and experimental stations in the Ethiopian highlands. Agric., Ecosyst. Environ. 78 (1), 57–63. https://doi.org/10.1016/S0167-8809(99)00113-9.

Meskelu, E., Woldemichael, A., Hordofa, T., 2017. Effect of moisture stress on yield and water use efficiency of irrigated wheat (Triticum aestivum L.) at Melkassa. Ethiopia 5 (March), 90–97. https://doi.org/10.14662/ARJASR2016.055.

Mokolobate, M.S., Haynes, R.J., 2002. Comparative liming effect of four organic residues applied to an acid soil. Biol. Fertil. Soils 35 (2), 79–85. https://doi.org/10.1007/s00374-001-0439-z.

Olsen, S.R., Sommers, L.E.S., 1982. Phosphorus. In: Page, A.L. (Ed.), Methods of Soil Analysis Part 2 Chemical and Microbiological Properties. American Society of Agronomy and Soil Science Society of America, *Madison*.

Phillip, J.R., 1957. Theory of Infiltration: 4. Sorpitivity and Alrebric infiltration equations. Soil Sci. 84 (3), 257–264. https://doi.org/10.4067/S0718-16202014000200013.

Pulido Moncada, M., Helwig Penning, L., Timm, L.C., Gabriels, D., Cornelis, W.M., 2014. Visual examinations and soil physical and hydraulic properties for assessing soil structural quality of soils with contrasting textures and land uses. Soil Tillage Res. 140, 20–28. https://doi.org/10.1016/j.still.2014.02.009.

R Core Team, 2020. A language and environment for statistical computing. R foundation for statistical computing, Vienna, Austria (August). J. Nat. Sci. Res.. https://doi.org/10.7176/jnsr/10-5-01.

Reynolds, W.D., Drury, C.F., Yang, X.M., Fox, C.A., Tan, C.S., Zhang, T.Q., 2007. Land management effects on the near-surface physical quality of a clay loam soil. Soil Tillage Res. 96 (1–2), 316–330. https://doi.org/10.1016/j.still.2007.07.003.

Roth, C.H. (1992). Soil sealing and crusting in tropical South America. In *In: M.E. Sumner and B.A. Stewart (Editors)*, *Soil crusting, chemical and physical-processes*, (pp. 267–300).

Saha, R., Mishra, V.K., Majumdar, B., Laxminarayana, K., Ghosh, P.K., 2010. Effect of integrated nutrient management on soil physical properties and crop productivity under a Maize (Zea mays)-mustard (Brassica campestris) cropping sequence in acidic soils of Northeast India. Commun. Soil Sci. Plant Anal. 41 (18), 2187–2200. https://doi.org/10.1080/00103624.2010.504799.

Slavich, P.G., Petterson, G.H., 1993. Estimating the electrical conductivity of saturated paste extracts from 1:5 soil: Water suspensions and texture. Aust. J. Soil Res. 31 (1), 73. https://doi.org/10.1071/SR9930073.

Taye, G., Bedadi, B., & Wogi, L. (2020). Comparison of Lime Requirement Determination Methods to Amend Acidic Nitisols in Central Highlands of Ethiopia. *30*(1), 35–48.

Temesgen, M., Uhlenbrook, S., Simane, B., Van Der Zaag, P., Mohamed, Y., Wenninger, J., Savenije, H.H.G., 2012. Impacts of conservation tillage on the hydrological and agronomic performance of fanya juus in the upper Blue Nile (Abbay) river basin. Hydrol. Earth Syst. Sci. 16 (12), 4725–4735. https://doi.org/10.5194/hess-16-4725-2012.

Walkley, A., Black, I.A., 1934. An examination of the degtjareff method for determining soil organic matter, and a proposed modification of the chromic acid titration method. Soil Sci. 37 (1), 29–38. https://doi.org/10.1097/00010694-193401000-00003.

WRB. (2015). World Reference Base for Soil Resources 2014: International soil classification systems for naming soils and creating legends for soil maps (Update 2015). In Food and Agriculture Organization of the United Nations. http://www.fao.org/soils-portal/soil-survey/soil-classification/world-reference-base/en/.

Yebo, B., 2015. Integrated soil fertility management for better crop production in Ethiopia. Int. J. Soil Sci. Vol. 10 (Issue 1), 1–16. https://doi.org/10.3923/ijss.2015.1.16.