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ORIGINAL ARTICLE

Historical role of manure application and its influence on soil nutrients and maize productivity in the semi-arid Ethiopian Rift Valley

Shiro Mukai (ORCID)

Abstract Maize yield dynamics generally involve temporal changes, because increasing soil organic matter through manure application influences maize yields over the longer term, while inorganic nutrient application controls shorter term yields. These temporal soil properties and yield changes have been measured with long-term experiments. In sub-Saharan Africa (SSA), long-term experiments (more than 20 years) are rare due mainly to lack of funds. Farmers in the semi-arid northern Ethiopian Rift Valley (NERV) apply manure to maize fields in the long term. The relationships between the manure application levels, nutrient supply, soil nutrient levels, maize grain yields, and above-ground plant nutrient uptake levels were investigated by field measurement, interviews with farmers, laboratory analyses, and 2-years' yield trials. The farmers applied on average 6.0 Mg ha^{-1} yr^{-1} of manure over 16.8 years on average. Significant linear or curve-linear correlations were found (1) between the annual nutrient supply and soil nutrient levels and (2) between the soil nutrient levels and maize productivities with minor exceptions. The regression equations determined from the yield trials proved 3.0 and 4.0 Mg ha^{-1} of maize yields can be expected when soil available N contents were 3.9 and 5.1 mg kg^{-1} in an ordinary rainfall year in NERV. For the farmers who apply 6.0 Mg ha^{-1} yr^{-1} manure, they are recommended to use 30 kg ha^{-1} yr^{-1} additional Urea to attain 3.0 Mg ha^{-1} maize yields. These types of assessment methods do not require much cost, and yet it can provide long-term scientific information in SSA.

Keywords Organic fertiliser · Farmyard manure · Maize productivity · Soil available nitrogen · Integrated soil fertility management

Introduction

In broader parts of Eastern and Southern Africa, cattle are the most important livestock and are kept for ploughing, milk, and manure usage (Dixon et al. 2001). These areas also suffer soil fertility decline due to high agricultural and grazing pressures (Yimer and Abdelkadir 2010). Partly because farm-level fertiliser prices in sub-Saharan Africa (SSA) are among the highest in the world, most of the farmers are constrained by a shortage of cash to use inorganic fertilisers (Morris et al. 2007). Many medium-term (over 5 years and more) soil fertility management experiments in SSA suggested that the treatments that combined inorganic and organic inputs showed the best crop yields (Kapkiyai et al. 1999; Bationo et al. 2012; Bedada et al. 2014). Given these contexts, integrated soil fertility management (ISFM), the

S. Mukai (✉)
Utsunomiya, Japan
e-mail: shiro_mukai@yahoo.co.jp

combined use of manure and inorganic fertiliser has been enhanced in SSA since the 1990s (Chivenge et al. 2011).

In the fore-mentioned parts of SSA, maize is the most or second-most important crop for smallholders. Maize yields are significantly affected by soil fertility levels, particularly N and P (Debelle et al. 2002), and the farmers often cultivate maize with manure application.

Some long-term yield experiments in SSA with treatments of different combinations and rates between manure and inorganic fertiliser application showed that maize yield dynamics involved temporal changes. For the first 6 years of a continuous maize cropping at Kabate research site (Kenya Agricultural Research Institute), application of inorganic fertilisers (60 kg N ha^{-1} yr^{-1} and 26.4 kg P ha^{-1} yr^{-1}; NP) alone increased maize yields by about 50% and out-yielded all other treatments including manure alone (applied at 10 Mg ha^{-1} yr^{-1} manure; FYM) and those combination (NP + FYM). This trend changed soon after the 6th year and NP + FYM gave higher yields than all other treatments (Kibunja et al. 2007). After the 10th to 11th years, maize yields for NP were approximately 10% lower than those for FYM, while, after 12th to 22nd years, the differences increased to approximately 15–50% (calculated based on Fig. 1 in Kibunja et al. 2007). To date, the combination use of inorganic fertilisers and manure continues to give higher yields than all the other treatments (Kibunja et al. 2007). Similar results were reported from the field experiment with goat manure application conducted in a chromic Cambisol of semi-arid Kenya (Kihanda et al. 2006). They annually applied inorganic fertilisers and manure at the same rates of N and P from 1993 to 2002 and found that sorghum grain yields initially showed the same yield levels; however, after 9 years, the yields with the inorganic fertiliser treatments declined to about 80% of those with the manure treatments. Edmeades (2003) reviewed the long-term (20–120 years) effects of manure application on soil productivity and quality across the world. Manured soils had several advantages over fertilised soils: higher contents of organic matter and P, K, Ca, and Mg in topsoils and nitrate N, Ca, and Mg in subsoils; lower bulk density; higher porosity and aggregate stability; and more numbers of microfauna (Edmeades 2003). Use of manure alone or in combination with inorganic fertilisers led to higher numbers of microbes and enhanced microbial respiration than the use of inorganic fertiliser alone, which can sustain the higher amount of soil organic carbon after 27 years period of continuous maize cultivation (Kibunja et al. 2010). Thus, increasing soil organic matter through manure application influences maize yields over the longer term, while inorganic nutrient application controls shorter-term yields. These temporal soil properties and yield changes have been measured with long-term experiments in the world including SSA.

In the semi-arid northern Ethiopian Rift Valley (NERV), farmers largely apply manure to maize fields (Fujisaka 1997). Soil quality assessment to diagnose local farmers' conception of soil fertility status (e.g., fertile or infertile fields) has been conducted across the world and SSA (Murage et al. 2000; Gray and Morant 2003), where chemical, physical, and biological properties of soils were measured to scientifically back up information obtained from interviews with the farmers. This study hypothesised that this diagnostic approach with partially using interviews with farmers and field observations helps understand maize yield dynamics characterised by a long-term manure application in NERV.

The main objectives of this study were to: (1) demonstrate a quantitative approach to assessing maize response to manure-derived nutrients on farmers' fields; (2) gain an improved understanding of the role of nutrient supply and its source on soil fertility; and (3) determine the link between soil chemical fertility and maize grain yields from farmers' fields. The results of this study can help farmers and extension personnel gain knowledge about manure application to attain their maize yield goals.

Methods

Study area and site selection

Most of the Tebo and Geldia seasonal river catchments (Fig. 1) are located in NERV. The catchment areas are categorized into the following two sub-areas in terms of major maize growing areas in Ethiopia (these two categories cover 63% of the total maize growing area in Ethiopia): mid-altitude dry (MD; 1500–1600 m above sea level, annual rainfall 800–900 mm) and mid-altitude moist (MM; similarly, 1600–1800 m,
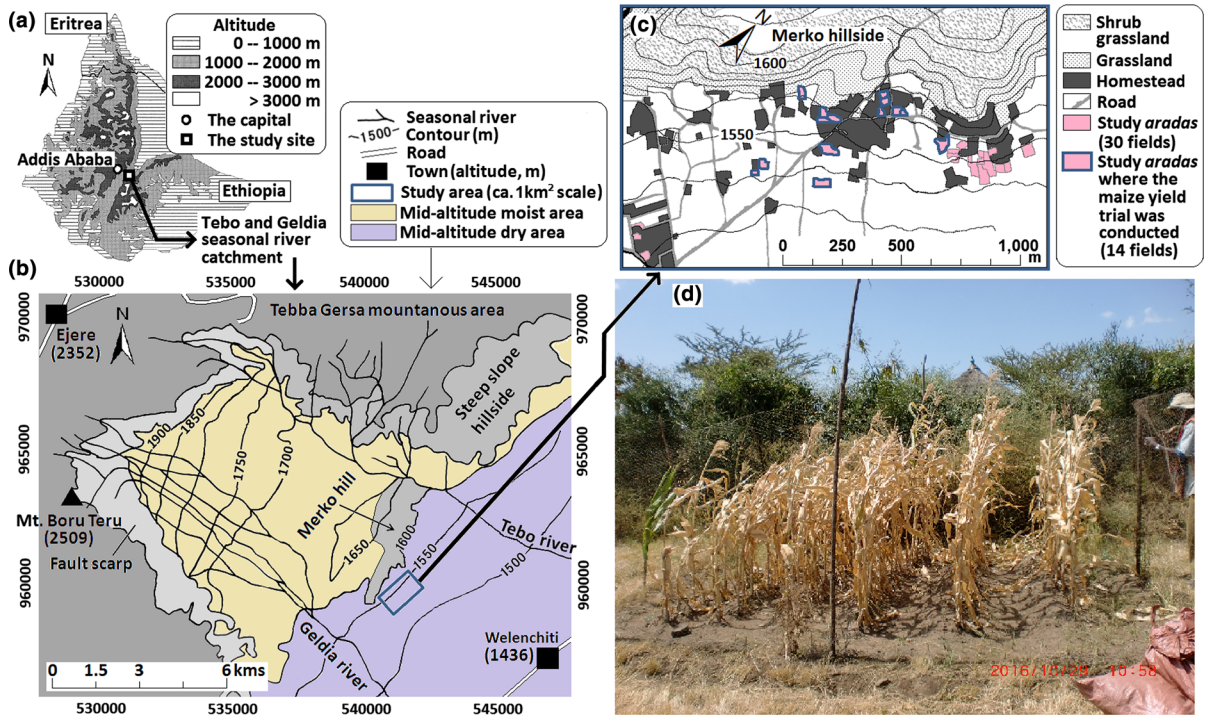
Fig. 1 **a** Location of the study area in Ethiopia, **b** Tebo and Geldia seasonal river catchments, where the study *aradas* were located in the mid-altitude dry sub-area, **c** the Calcisol area and study *aradas*, and **d** part of the maize yield experimental field in the study *arada*

800–1000 mm) sub-areas. Most households in NERV hold continuously cropped maize fields (locally referred to as *aradas*), which acquire fertility from the regular input of organic materials, such as manure or household waste. Inorganic fertiliser is rarely used for maize in NERV (Mukai 2017a). Manure (locally, *kosi*) is made from a variety of locally available organic materials, such as various types of animal dung, kitchen ash, crop residue, and livestock leftovers. These manure materials are piled up in the corners of house-yards for several months to a few years for decomposition. In most cases, farmers carry manure from manure piles to the field from May to June immediately before crop seeding and scatter it on the ground. The manure is incorporated into the soil by subsequent ploughings.

In 2012, soil surveys were conducted in the MD sub-area. Based on a preliminary auger survey, 10 pedon points were selected for a soil profile survey (Mukai 2017b). The MD sub-area was divided into four sections: the main soil components of Merko hill (Fig. 1) are: (1) underdeveloped soils, such as Regosols (Hypereutri-Calcari-Endoleptic) and Leptosols (Hypereutri-Calcari-Molli-Lithic), or rock

outcropped land; whereas: (2) Calcisols (Endopetric Calcisol and Haplic Calcisol); (3) Cambisols (Hypereutri-Fluvic); and (4) Vertisols (Hypereutri-Calcic) dominate the downslope farmlands (FAO 2006).

Correlation between manure application patterns and soil nutrient levels

This study quantitatively assessed the relationship between the annual nutrient supply levels, soil nutrient levels, and maize response to manure-derived nutrients on farmers' fields in NERV. Manure-derived nutrient supply levels were estimated from surveying farmers' manure application patterns and nutrient contents of manure through in-depth interviews with the farmers, field measurement, and laboratory analyses. Long-term manure application patterns (i.e., years of continuous use, application dose, and the frequency of application) at 30 *arada* study fields that were randomly selected from the Calcisols in the MD sub-area (Fig. 1) were carefully ascertained from the farmers who cultivated these *aradas*. It was because, since a villagisation policy was enforced in 1976, people in NERV had lived in agglomerated villages

and the Calcisols in the MD sub-area had become a representative homestead area, where most *aradas* were located.

Farmers use different types of containers to carry manure to *aradas*, such as a fertiliser sack and plastic container, by donkey or over their shoulders. After asking the farmers how many containers of manure they carried to their *aradas* and how often in a year, the container with a load of manure was weighed at the farmer's house-yard. A sample of the manure was brought to a laboratory to measure the dry matter weight. A unit dry weight of the manure in the container was multiplied by the number of containers the farmer carried at one time application to determine the farmer's application dose (Mg ha^{-1} DM). The farmer's application dose and frequency varies every year. Thus interviews and field measurement were repeated from 2011 to 2016, and these data were averaged over the farmer's continuous manure application years to obtain the best estimated manure application level (Mg ha^{-1} yr^{-1} DM) to the study *arada*.

Manure samples were collected from the 17 farmers' house-yards who cultivated these 30 *aradas*, and dry matter content, total N (the wet Kjeldahl method), total P (the vanadomolybdophosphoric acid method), and total K (the atomic absorption spectroscopy method) were analysed in a laboratory in 2016 (Peters et al. 2003). A wet triacid (HNO$_3$/HClO$_4$/H$_2$SO$_4$) digestion procedure was used for P and K. A pre-planting soil chemical test (Schröder et al. 2000) was conducted at these 30 *aradas* in 2016, because, of these 30 *aradas*, 14 *aradas* were selected as the fields for maize yield trials. The soil samples were collected in the period between ploughings (when manure was incorporated into the soil) and crop seeding.

Surface soils (from depths of 0–20 cm) were collected, and the levels of total N (the Kjeldahl method), available phosphorus (Olsen's extraction method), and exchangeable K (Mehlich 3 combined solution method) were measured in a laboratory in 2013 and 2016. Because the soils have a nature of low K level in Mehlich 3 soil test (K < 100 mg kg^{-1}; Madaras and Koubová 2015), soil test K values were corrected by using the equation proposed by Madaras and Koubová (2015). The soil and manure analyses were carried out at the Soil and Water Analysis Laboratory of Horticoop Ethiopia PLC (Debre Zeit).

Available N contents in soils, which is the sum of (1) mineralized N from both manure and soil organic matter, (2) soil mineral N, and (3) mineral fertilizer N (Soto et al. 2015), are conventionally determined by an incubation test. However, this method is complicated and requires long periods of time. It is known that the incubation analyses are strongly correlated with the total organic carbon (TOC) extracted after a hot water treatment (Curtin et al. 2006; Sano et al. 2006; Uezono et al. 2010). In this study, available N was determined using the COD (chemical oxygen demand) packtest method (PACKTEST WAK-COD with a COD measurement range between 0 and 100 mg L^{-1}, Kyoritsu Chemical-Check Lab. Corp.) (Uezono et al. 2010) after hot water extraction treatment (16 h at 80 °C) (Curtin et al. 2006). The COD packtest uses an alkaline method (COD-OH) (Kyoritsu Chemical-Check Lab. Corp. 2014) to estimate TOC (Dubber and Gray 2010).

Correlations between soil nutrient levels, maize yields, and plant nutrient uptake levels

Field experiments to assess maize grain yields and plant nutrient uptake levels in the existing manured field conditions were implemented at the 13 *aradas* in 2013 and 14 study *aradas* in 2016 (Fig. 1). These experimental fields were located within a 1 km^2 area. Soil in this 1 km^2 area is Endopetric Calcisol (Orthicalcic, Hypereutric). Soil texture is clay loam. The soil tests were conducted at the sites in 2013 and 2016.

In each of the experimental fields, 4 m × 4 m scale plots were installed with three replications (Fig. 1), and maize (Melkassa-6Q) was cultivated. Two maize seeds were placed in a 5 cm-deep planting hole dug at 25-cm intervals on the top of a ridge, which was made at 75-cm intervals. Maize seedlings were thinned at the four-leaf stage, and one seedling was left within the planting hole. Weeding was performed twice during a growing period. Maize was seeded on 3 July and harvested on 1 November in 2013, while maize was seeded on 5 July and harvested on 2 November in 2016.

At maturity, maize harvested from each plot was shelled and weighed in the field. Fresh plant biomass was determined by bundling and weighing the plants without the ears and husks. Three plants were randomly chosen from the middle two rows in each plot (9 plants for one experimental field), from which

grain and stover samples were taken. The grain and stover samples were oven-dried at 70 °C to a constant weight for dry weight measurement. The oven-dry samples were ground using a rotor mill to pass a 0.5-mm sieve for sample preparation. N, P, and K concentrations were determined in the laboratory using the wet-Kjeldahl, vanadomolybdophosphoric acid colorimetric, and atomic absorption spectroscopy methods, respectively. A wet triacid (HNO_3/$HClO_4$/H_2SO_4) digestion procedure was used for P and K. Maize and stover nutrient uptake levels were calculated by multiplying the grain and stover dry weights by the nutrient concentrations, respectively, both of which were summed to obtain above-ground plant uptake values.

A simple rainfall gauge was installed within the study area in the MD sub-area. Total rainfall during the maize growth period in the experimental years of 2013 and 2016 was 622 and 520 mm, respectively, whereas the average rainfall during the same maize growth period between 1992 and 2013 at the rainfall gauge located at Welenchiti town (Fig. 1) was 549 mm. For ranking and plotting annual rainfall data in a probability plot, the Weibull distribution was assumed. The maximum likelihood method, which had been qualified as the preferred method of parameter estimation for distribution fitting by Law and Kelton (1991), was used. For evaluating the goodness-of-fit, (1) the coefficient of determination (R^2) was calculated and (2) the Kolmogorov–Smirnov test ($\alpha = 0.05$) was applied to the cumulative density function. The software tool RAINBOW (Raes et al. 2006) was used for the analysis. RAINBOW offers a test of homogeneity which is based on the cumulative deviations from the mean. The homogeneity test showed that the rescaled cumulative deviation was far from the lines where the homogeneity is rejected with 90% probability. Thus, the rainfall data can be considered to be homogeneous. Statistical tests on goodness-of-fit indicated that (1) R^2 was 0.99 and (2) the cumulative density function was accepted with the significance level of 5%. The return periods for which the total rainfall during the maize growth period is less than the ones in 2013 and in 2016 are 4.2 years (24% probability) and 2.0 years (50% probability), respectively. Thus the year of 2016 was an ordinary rainfall year for maize cultivation.

Statistical analysis

Every bivariate correlation (1) between annual N supplies and both available N and total N contents of the 30 *arada* soils, (2) between annual P supplies and available P contents of the 30 soils, (3) between annual K supplies and exchangeable K contents of the 30 soils, and (4) between soil nutrient contents (available N, total N, available P, and exchangeable K) and both the dry weight of the maize grains and the above-ground plant uptake values was examined using Pearson's pair-wise correlation analysis. SPSS ver. 20 (IBM) was used for the statistical analyses. Non-linear regression analysis was performed by using Microsoft Excel Solver (Billo 2001). A multi-regression analysis was conducted to predict a dependent variable, the dry weight of the maize grains. The soil nutrient contents (available N, total N, available P, and exchangeable K) were selected for independent variables in the multi-regression analysis models.

Results

Farmers' manure application practices

The frequency of manure application varied widely. Of the 30 sample *aradas*, manure had been applied to 18 *aradas* annually, whereas the application was less frequent to 12 *aradas* (Table 1). As the result, the farmers applied manure once approximately 1.1 years (i.e., 0.91 times/year = 1 time/1.1 years) on average at the average application dose of 6.3 Mg ha^{-1} DM. Thus, the average actual application level was 6.0 Mg ha^{-1} yr^{-1} DM. The farmers had applied manure for 16.8 years on average. Because the average manure nutrient contents were 1.1, 0.4, and 1.4% for N, P, and K, respectively, the annual nutrient supply levels were 67 ± 54 kg ha^{-1} yr^{-1} for N, 22 ± 22 kg ha^{-1} yr^{-1} for P, and 78 ± 56 kg ha^{-1} yr^{-1} for K.

The farmers of the 14 study *aradas* (from No. 17 to No. 30 in Table 1), where maize yield experiment was conducted in 2016, applied 7.8 Mg ha^{-1} of manure on average every year (hence the average actual manure application was 7.8 Mg ha^{-1} yr^{-1}). The farmers continuously applied manure for 13.8 years on average. The average annual nutrient supply levels were 87 ± 61 kg ha^{-1} yr^{-1} for N, 29 ± 25 kg ha^{-1} yr^{-1}

Table 1 History of manure applications, manure nutrient contents, and soil nutrient contents of the study aradas (assessed in 2016; n = 30)

No.	CAY[a]	Application dose[b]	Frequency[c]	AAL[a, b]	Manure nutrient contents (%)			Annual nutrient supply (kg ha^{-1} yr^{-1})[d]			Soil nutrient contents			
					N	P	K	N	P	K	Ava. N (mg kg^{-1})	T.N. (%)	Ava.P (mg kg^{-1})	Exc.K (cmol kg^{-1})
1	15	7.0	1.00	7.0	1.1	0.3	1.7	76	20	119	3.90	0.18	8.6	0.36
2	10	3.1	0.71	2.2	1.5	0.5	2.7	34	12	61	3.12	0.26	5.6	0.30
3	30	1.4	1.00	1.4	1.2	0.2	1.5	17	2	12	2.92	0.26	7.8	0.11
4	10	1.6	0.29	0.5	1.5	0.5	2.7	7	2	12	2.49	0.22	6.8	0.18
5	9	1.3	0.75	1.0	1.7	0.4	2.1	17	4	21	2.59	0.15	3.5	0.09
6	37	14.0	1.00	14.0	1.2	0.5	1.5	163	73	205	5.75	0.39	12.9	0.72
7	37	7.7	1.00	7.7	1.2	0.5	1.5	89	40	112	4.00	0.36	9.5	0.95
8	23	7.7	0.50	3.8	1.5	0.2	1.2	57	8	45	3.34	0.24	6.9	0.45
9	40	4.4	1.00	4.4	1.7	0.5	1.5	74	22	64	3.07	0.22	15.2	0.75
10	19	4.5	1.00	4.5	0.7	0.1	0.8	31	7	36	3.35	0.23	9.3	0.82
11	19	4.1	0.75	3.0	0.8	0.2	1.0	23	7	29	2.53	0.18	6.0	0.48
12	19	4.3	0.75	3.2	0.8	0.2	1.0	25	8	31	2.88	0.18	3.3	0.48
13	17	2.5	0.75	1.9	0.8	0.2	1.0	14	5	18	3.36	0.23	5.2	0.43
14	9	4.7	0.92	4.4	0.8	0.3	0.8	48	14	70	3.88	0.26	7.7	0.66
15	9	8.5	1.00	8.5	1.2	0.3	1.9	102	29	159	4.28	0.30	17.3	1.83
16	9	3.3	0.78	2.5	1.2	0.3	1.9	31	9	48	3.59	0.14	5.9	0.61
17	18	9.4	1.00	9.4	0.7	0.3	1.0	66	28	93	3.93	0.27	13.0	0.32
18	6	12.9	1.00	12.9	0.6	0.2	1.0	77	22	128	3.59	0.24	11.4	1.22
19	4	7.3	1.00	7.3	1.1	0.3	0.7	79	22	48	3.40	0.26	12.6	1.06
20	34	7.6	1.00	7.6	1.1	0.3	0.8	81	23	57	3.49	0.26	9.8	0.79
21	8	1.4	1.00	1.4	0.9	0.4	1.0	12	6	13	2.46	0.13	3.6	0.14
22	30	3.6	1.00	3.6	1.1	0.4	1.0	40	13	36	2.98	0.16	7.6	0.50
23	7	11.9	1.00	11.9	1.7	0.4	0.8	209	47	91	5.29	0.29	17.6	0.91
24	14	3.2	1.00	3.2	1.0	0.4	2.3	33	12	75	3.81	0.27	8.5	1.18
25	13	8.2	1.00	8.2	0.8	0.5	1.6	65	44	130	4.04	0.27	10.1	1.29
26	15	16.3	1.00	16.3	1.1	0.6	1.1	179	103	186	5.90	0.36	17.3	1.85
27	15	9.5	1.00	9.5	1.4	0.3	1.5	130	29	138	4.07	0.32	12.9	0.75
28	7	2.8	1.00	2.8	1.7	0.3	1.7	48	9	48	3.21	0.22	9.7	0.43
29	10	3.4	1.00	3.4	0.8	0.3	1.7	27	9	57	3.26	0.20	7.4	0.23
30	12	11.8	1.00	11.8	1.4	0.4	1.6	169	42	191	5.09	0.33	15.8	0.55

Table 1 continued

No.	CAY[a]	Application dose[b]	Frequency[c]	AAL[a, b]	Manure nutrient contents (%)			Annual nutrient supply (kg ha^{-1} yr^{-1})[d]			Soil nutrient contents			
					N	P	K	N	P	K	Ava. N (mg kg^{-1})	T.N. (%)	Ava.P (mg kg^{-1})	Exc.K (cmol kg^{-1})
Mean	16.8	6.3	0.91	6.0	1.1	0.4	1.4	67	22	78	3.65	0.25	9.6	0.68
SD	10.2	4.1	0.17	4.3	0.3	0.1	0.6	54	22	56	0.90	0.07	4.2	0.46

[a]Continuous manure application years (CAY): the number of years over time since the commencement of manure application to the field, actual manure application level (AAL) = manure application dose × frequency

[b]Units: manure application dose = Mg ha^{-1} DM, actual manure application level = Mg ha^{-1} yr^{-1} DM

[c]Frequency (times/years): manure was applied at a rate of once every how many years (e.g., if a farmer applied manure every other year, his frequency was 1 time/2 years = 0.5)

[d]Annual nutrient supply = actual manure application level × nutrient contents of manure

for P, and 92 ± 55 kg ha^{-1} yr^{-1} for K for these 14 *aradas*.

Correlation between manure application levels and soil nutrient contents

The relationships between the annual N supply and both of the soil available N ($r = 0.90$; $p < 0.001$) and total N ($r = 0.74$; $p < 0.001$) content levels showed significantly strongly positive correlations (Fig. 2a, b). The relationship between the annual P supply and soil available P level also showed significantly strongly positive correlations ($r = 0.72$; $p < 0.001$; Fig. 2c), whereas the relationship between the annual K supply and soil exchangeable K content levels indicated significantly relatively strong correlation ($r = 0.62$; $p < 0.001$; Fig. 2d).

Correlations between soil nutrient levels, maize yields, and plant nutrient uptake levels

The average grain yield of Melkassa-6Q was 3549 and 2965 kg ha^{-1} (3.55 and 2.97 Mg ha^{-1}) in 2013 and 2016, respectively (Fig. 3). Each combination between the maize yield and soil nutrient contents of the study *aradas*, such as available N (Fig. 3a), total N Fig. 3b, and available P (Fig. 3c) exhibited significantly strong correlations ($p < 0.01$) in both 2013 and 2016; however, the relationship between the maize yield and soil exchangeable K was not significant in either 2013 or 2016 (Fig. 3d). Most of the combinations between the plant nutrient uptake and soil nutrient content values demonstrated significantly strongly positive correlations in both 2013 and 2016 ($p < 0.01$; Fig. 4a–c); however, the correlation between the soil exchangeable K and above-ground K uptake in 2013 was not significant ($p > 0.05$; Fig. 4d).

The stepwise multi-regression analyses showed that soil available N was the sole and most important independent variable that significantly explained the maize yield in both 2013 and 2016 ($p < 0.001$; Table 2).

The *arada* soils had lower available N than the recommended critical NO$_3$–N levels for maize, approximately 16–30 mg kg^{-1} (Peng et al. 2013). Significant response of maize yields up to 23–128 kg N ha^{-1} supplied by inorganic fertiliser (72 kg N ha^{-1} on average) was observed on farmers'

fields in six different locations across Ethiopia (Debelle et al. 2002). Because manure-N efficiency (the amount of mineral N fertiliser equivalent to the manure-N available to the crop grown) of farmyard cattle manure is 20–40% (Webb et al. 2009), the maximum annual N supply rate in this experiment, 209 kg ha^{-1} (field no. 23), was likely to be closer to the mean N supply rate (from inorganic fertiliser sources) to which maize yield showed a significant response, 72 kg ha^{-1}. Thus, the linear relationship observed between the soil available N and total N contents and the maize yield in this study can be the linear or curve-linear parts of the N response curve (Fig. 3a, b).

The critical level of Olsen available P in Ethiopia is 8 mg kg^{-1} (Hagdu et al. 2013; Redi et al. 2016); however, in this study, the maize yield showed a linear relationship with the soil available P content even when the soil available P values were greater than 8 mg kg^{-1} particularly in 2016 (Fig. 3c). In Hagdu et al. (2013) and Redi et al. (2016), the relationships between the different P fertilisation rates (0, 10, 20, 30, 40, 50, and 60 kg ha^{-1}) and soil available P levels exhibited significantly strong linear correlations ($r = 0.97$ and $r = 0.99$, respectively, $p < 0.001$; Fig. 2e). Heming (2008) analysed 290 fields that had typical soil types in south England where manure was applied over 3–5 years and estimated the mean

fertiliser equivalent P per 1 Mg manure supply to be 0.62 kg P Mg^{-1} yr^{-1}. This estimation and the actual manure application levels to the 30 study *aradas* in 2016 (Table 1) were used to obtain fertiliser equivalent annual P supply values, which were shown in Fig. 2e. The figure indicated that this study and Redi et al. (2016) had a similar trend in the relationship between the P supply and soil available P levels. Figure 3c exhibited that the shape of the approximate regression line in this study is more similar to the P response curve of Redi et al. (2016). Debelle et al. (2002) studied farmers' fields in six different locations across Ethiopia and obtained significant responses of maize yield to P supply levels (by inorganic fertiliser) up to 10–56 kg P ha^{-1} (28 kg P ha^{-1} on average). These 28 and 56 kg P ha^{-1} of inorganic fertiliser equivalent P supplies responded to the soil available P of 14 and 22 mg kg^{-1} in this study, respectively (Fig. 2e). Thus, the regression line representing the maize yields in response to different soil available P levels in this study is considered to be part of the linear or curve-linear parts of the P response curve observed at relatively low soil available P levels.

Among these nutrients measured, the soil available N had the highest correlation coefficients ($r = 0.87$ and $r = 0.92$) with the maize yield and N uptake levels, respectively, in 2016 (Figs. 3a and 4a). In 2013, if the outlier shown in Fig. 4 was removed, the
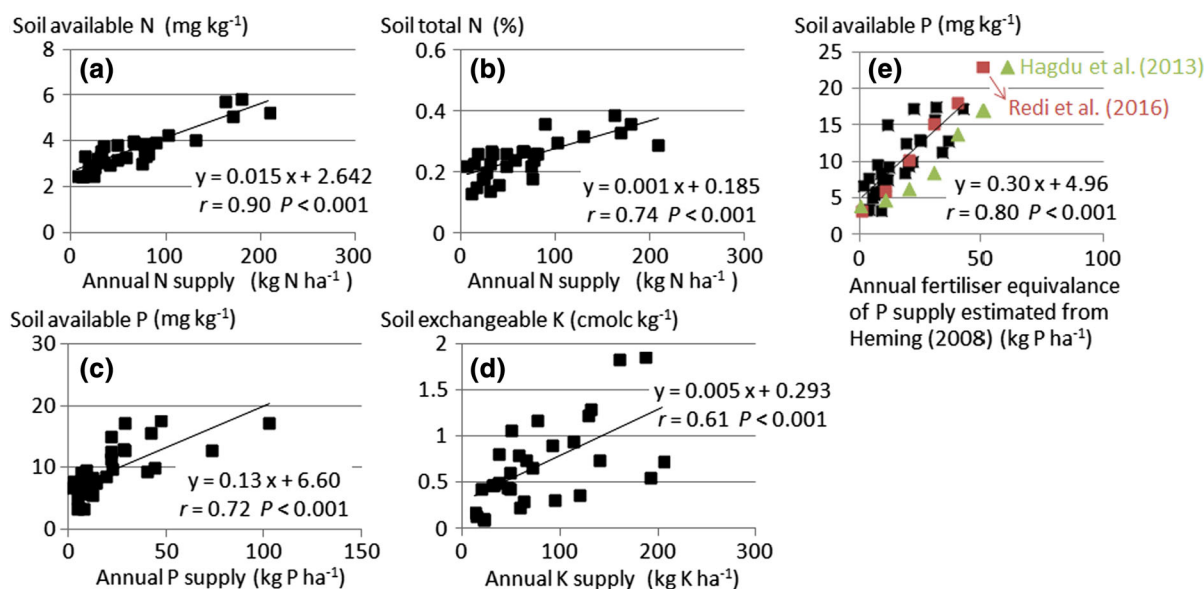
Fig. 2 Correlations between the annual nutrient supply and soil nutrient content levels in the study *aradas* ($n = 30$)
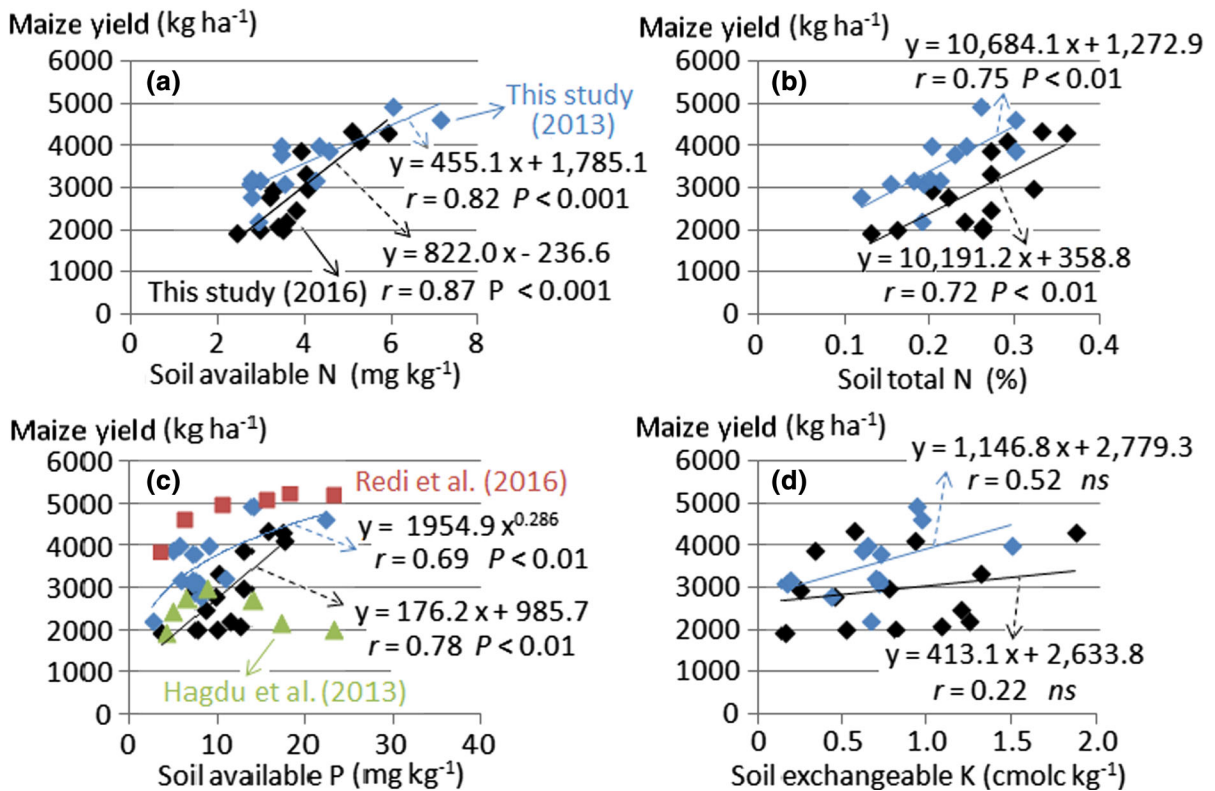
Fig. 3 Correlations between the soil nutrient contents and maize grain yields in the experimental fields ($n = 13$ in 2013 and $n = 14$ in 2016)

correlation coefficient became 0.89; the soil available N had the highest correlation coefficients with the maize yield and N uptake levels also in 2013.

Discussion

The correlations between annual manure application levels and soil nutrient contents were significantly strong or relatively strong in this study. After 11-years' manure application to clay loam soil in Alberta, Canada, Chang et al. (1991) reported that, with an increment in the application dose (0, 30, 60, and 90 Mg ha^{-1} yr^{-1}), soil NO$_3$–N (0.10, 0.29, 0.59, and 0.81 Mg ha^{-1} at 0–30 cm depth in non-irrigated condition, respectively), total N (similarly, 5.7, 7.0, 8.1, and 8.3 Mg ha^{-1}), and available P (0.07, 0.45, 0.85, and 0.96 Mg ha^{-1}) increased. After 25-years' manure application there with the same increasing rates, Hao and Chang (2002) reported that exchangeable K increased (similarly, 1.65, 3.95, 5.14, and

5.69 cmolc kg^{-1}). Although the nutrient sources are different, the analyses in this study were in agreement with the results of previous studies conducted by using inorganic fertiliser in Ethiopia; e.g., soil NO$_3$–N (Kidanu et al. 2000), total N (Habtegebrial et al. 2007), Olsen available P (Hagdu et al. 2013; Redi et al. 2016), and exchangeable K (Taddese 1999).

Based on the linear relationships between corn yields and soil nitrate concentrations, which explained 82% of the variability in the corn yields, Blackmer et al. (1989) stated that this soil nitrate test offers great potential for improving N management in the Corn Belt. Similar findings and its application on N management for maize production in the North China Plain were also shown (Cui et al. 2008; Peng et al. 2013). Considering the greatest correlations between soil available N and both the maize yield and plant nutrient uptake levels and the stepwise multi-regression analyses, available N can be considered as an optimum soil nutrient indicator for representing the maize productivity in the *arada* soils.
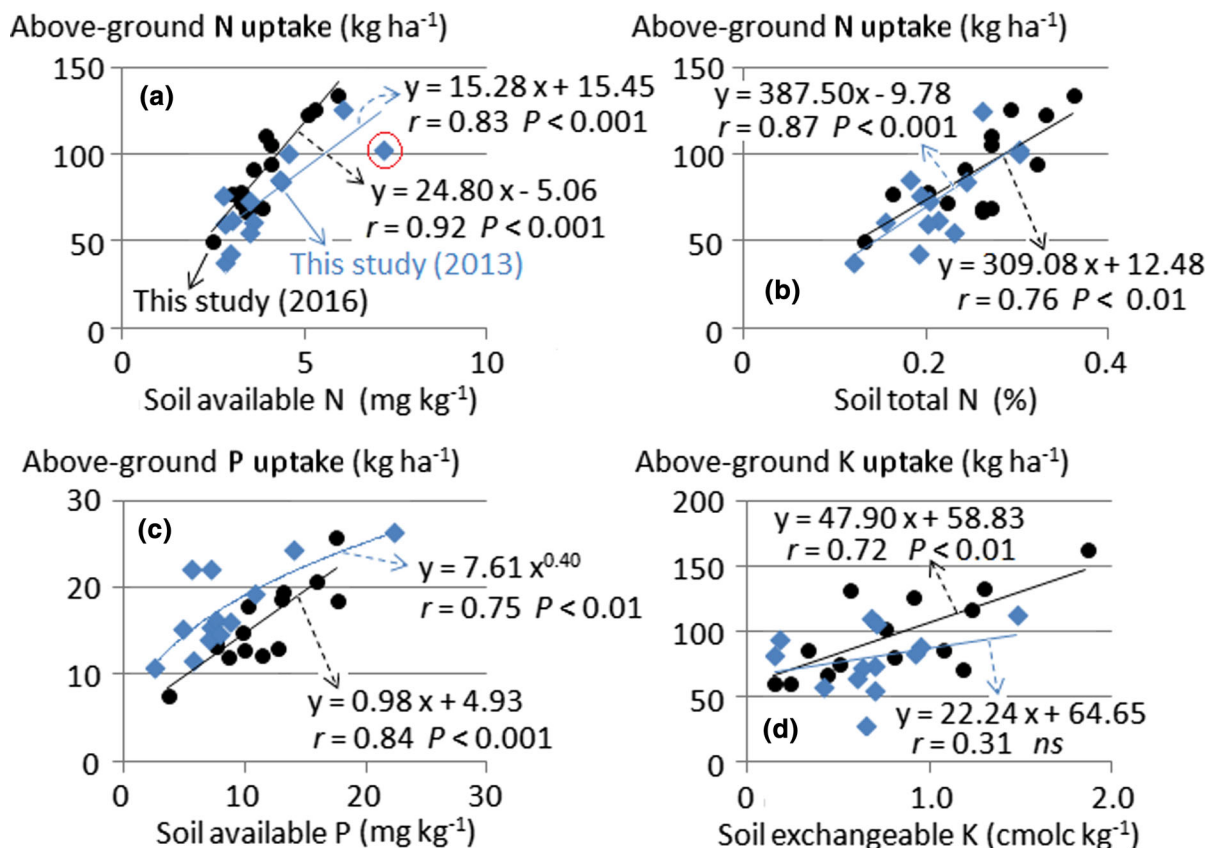
Fig. 4 Correlations between the soil nutrient contents and above-ground plant nutrient uptake values in the experimental fields ($n = 13$ in 2013 and $n = 14$ in 2016). In 2013, the linear regression equation between the N uptake (y) and soil available N (x) was $y = 22.22\ x - 8.26$; $r = 0.89$; $p < 0.001$, if the outlier surrounded by a red circle in the figure was removed. (Color figure online)

Table 2 Estimation of the best-fit models

Dependent variables	Year	Coefficients of the model[a]	p	Adjusted R square	Standard error of the estimate
Maize yield	2013	*Available N*** (456.7, 4.67, 0.82)	0.001	0.635	455.8
	2016	*Available N*** (822.2, 6.05, 1.14)	0.000	0.732	465.4

[a]Values in parentheses are unstandardized coefficients, the absolute value of *t*-statistics, and the absolute value of standardized coefficients

***$p < 0.001$

Melkassa-6Q is a drought-tolerant and early maturing variety, which was developed for low-moisture stress agro-ecological areas. It is an open-pollinated and quality protein maize variety. Grain yields in research stations and farmers' fields are 4.5–5.5 and 3.0–4.0 Mg ha^{-1}, respectively (Bogale et al. 2012). Beshir et al. (2012) conducted yield trials of quality protein maize varieties in farmers' fields with recommended management practices (e.g., fertiliser application dose, improved varieties of seeds, seeding density) from 2005 to 2010 in NERV. As a result, Melkassa-6Q recorded average yields of 3.5 Mg ha^{-1} in 2008 ($n = 16$), 4.6 Mg ha^{-1} in 2009 ($n = 19$), and 3.3 Mg ha^{-1} in 2010 ($n = 24$). Both of these Melkassa-6Q yield trials were performed at unmanured farmers' fields but with the recommended dose of fertiliser use in Ethiopia (100 kg ha^{-1} Di-Ammonium Phosphate, DAP, and 100 kg ha^{-1} Urea, equivalent to

64 kg ha^{-1} yr^{-1} of N and 46 kg ha^{-1} yr^{-1} of P in total). The linear approximation that represents the relationship between the soil available N level and maize yield (Fig. 3a) indicates that maize yields of 3.0 and 4.0 Mg ha^{-1} can be attained when the soil available N contents are 3.9 and 5.1 mg kg^{-1} in an ordinary rainfall year such as 2016 in the MD sub-area. These 3.9 and 5.1 mg kg^{-1} soil available N levels are feasible if a farmer applies 84 and 164 kg ha^{-1} yr^{-1} of manure-derived N for over ten years to a field (Fig. 2a). Because the present average manure-derived N supply level was 67 kg ha^{-1} yr^{-1} (almost equal to N fertiliser recommendation in Ethiopia, 64 kg ha^{-1} yr^{-1}), approximately an additional 14 kg ha^{-1} yr^{-1} N supply, which corresponds to 30 kg ha^{-1} yr^{-1} Urea, is needed for resource constraint farmers in manure making to attain maize yields of 3.0 Mg ha^{-1} in an ordinary rainfall year.

Most of the medium-term yield experiments with different combinations of manure and inorganic fertiliser and those intensities have been implemented at the experimental fields in research institutes in SSA. However, only a few of the long-term experiments in SSA continued for more than 20 years, making it difficult to assess longer term soil fertility dynamics. Termination of these trials has been mainly due to lack of funds to maintain the experiments (Bationo et al. 2012). This study hypothesised that a diagnostic approach partially using interviews with farmers and field observations may be applied to understand maize yield dynamics characterised by a long-term manure application in NERV. This type of assessment method does not require much cost compared with the medium- and long-term experiments in research stations; however it provides long-term scientific information in SSA.

Conclusions

A long-term manure application technique for maize cultivation in *aradas* is commonly observed in NERV. To these *aradas*, farmers apply approximately on average 6.0 Mg ha^{-1} yr^{-1} of manure over 16.8 years on average. This study proved that the annual nutrition supply levels by the long-term manure application linearly increased the nutrient contents of the *arada* soils, to which the maize yield and maize nutrient uptake linearly or curve-linearly responded because

all of the soil nutrient levels at the *aradas* were relatively lower than those critical nutrient levels for maize.

Available N can be the optimal indicative nutrient representing these relationships. Maize responses to the soil nutrients levels were linear or curve-linear, which implies that maize productivity in NERV can still increase with the additional supply of manure and inorganic fertilisers.

If a farmer applied 7.8 Mg ha^{-1} yr^{-1} of manure (the average application dose for 14 experimental fields in 2016) for over 10 years to a field, the farmer is likely to expect approximately 3.0 Mg ha^{-1} of maize yield in an ordinary rainfall year such as 2016, which was almost equivalent to the maize yield at unmanured fields but with the recommended dose of fertiliser application in NERV. However, for the sample farmers who apply on average 6.0 Mg ha^{-1} yr^{-1} of manure, they are recommended to use an additional 30 kg ha^{-1} yr^{-1} Urea to attain 3.0 Mg ha^{-1} maize yields.

This study estimated the manure-derived annual nutrient supply to the maize fields by in-depth interviews with the farmers, field measurement, and manure analyses, which was correlated with the soil analyses and maize productivities determined from yield experiments. The approach demonstrated in this study does not require much cost, and yet it can be useful to provide long-term scientific information on maize yield dynamics induced by continuous manure application to the field.

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