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SOIL & CROP SCIENCES | RESEARCH ARTICLE

Crop rotation and organic matter application restore soil health and productivity of degraded highland crop farms in northwest Ethiopia

Getachew Alemayehu^{1*}, Agegnehu Shibabaw², Enyew Adgo², Folkard Asch³ and Bernhard Freyer⁴

Abstract: Potentials of pragmatic crop rotation practices and organic matter applications for restoration of soil health and productivity of degraded highland crop fields were studied for three rotation phases from 2013 to 2015 in northwest Ethiopia. Factorial combinations of five crop rotations ($R1^+$ = bread wheat–clover–potato, $R2^+$ = clover–bread wheat undersowing lupine–potato, $R3^+$ = potato–clover–bread wheat, $R4^+$ = bread wheat undersowing lupine–potato undersowing lupine–bread wheat, and $R5^+$ = lupine–potato undersowing lupine–bread wheat) and four manure application rates [$M1$ = control/ 0tha^{-1} manure, $M2$ = 2.5 tha^{-1} sesbania green manure (SGM), $M3$ = 5 tha^{-1} fresh cattle manure (FCM), and $M4$ = 2.5 tha^{-1} SGM + 5 tha^{-1} FCM] were laid out in randomized complete block design (RCBD) with four replications. Plus sign (+) with crop rotation indicated that crop residues and green manure of legumes at 50% flowering were incorporated into the soil. The results showed that soil properties and productivity of crops were markedly improved with three-year interventions of crop rotation and manure application. As

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PUBLIC INTEREST STATEMENT

Soil degradation and fertility depletion in the cultivated land of Ethiopian highlands is severe due to mainly complete removal of crop residues, and abandoning of crop rotation and organic matter application. Consequently, crop productivity and its response to chemical fertilizers have been declining consistently. Researchers, extension workers and farmers, on the other hand, don't realize well about these phenomena. Hence, a field experiment was conducted for three years in the cultivated of northwest Ethiopian highlands to assess the potentials of crop rotation and manure application for restoring soil health and crop productivity. Results of the study showed that sound crop rotation and organic matter application even at moderate rates improved markedly the soil health and crop productivity steadily. Therefore, researchers and extension workers advise farmers strongly to apply sound crop rotation and organic matter to their crop fields so as to restore the soil health and enhance crop productivity sustainably.

compared to that of the initial before starting the experiment, soil bulk density, pH, CEC, and contents of organic carbon, total nitrogen, available phosphorous, and exchangeable potassium were improved on average by about 23%, 18%, 67%, 89%, 150%, 89%, and 44%, respectively, with R1⁺M4 treatment combination in three-year period. Similarly, compared to that of 2013, productivity of bread wheat and potato increased on average by about 446% and 540% in 2015 with R3M4 and R1M4, respectively.

Subjects: Agriculture & Environmental Sciences; Agriculture; Crop Science

Keywords: cattle manure; crop residues; crop rotation; green manure; crop productivity; soil degradation

1. Introduction

Before the advent of using chemical fertilizers for crop production, sound crop rotation practices, and farm yard manure applications were the only ways of replenishing soil fertility of cultivated crop fields in Ethiopian highlands, where smallholder crop-livestock mixed farming is the main economic sector ever since the time of immemorial (Ketema & Bauer, 2011). For the last three decades, however, using nitrogen (N) and phosphorous (P) inorganic chemical fertilizers has been considered by Ethiopian Government as the primary strategy of alleviating soil fertility deficiency problem and of boosting crop productivity and production in the country (Tamene et al., 2017). At the expense of sound crop rotation practices and farm yard manure applications, the scale and extent of using these two NP chemical fertilizers for crop production have been indeed increased tremendously in the country especially in the highlands (Tamene et al., 2017).

Initially when the crop fields were containing sufficient soil organic matter, applications of NP chemical fertilizers to major cereal crops gave better yields to farmers, and thereby applications of NP chemical fertilizers have been passively accepted by Ethiopian farmers as better means of increasing soil productivity (Shibabaw et al., 2017, 2018; Tamene et al., 2017). On the contrary to increase the use of NP chemical fertilizers in the country, using sound crop rotation practices and farm yard manure applications, which had been adopted long as well-established nutrient and land management practices undertaken by Ethiopian smallholder farmers for centuries have been abandoned gradually (Shibabaw et al., 2017, 2018). Applications of NP chemical fertilizers to crop fields would not be considered as ill practice, indeed. But rather, their exclusive usage for long time without complementary applications of organic matter as that of being practiced currently by Ethiopian farmers results in aggravating soil erosion and degradation of physical, chemical and biological properties of soils (Shibabaw et al., 2018, 2017), and declining of crop responses even to the applied NP chemical fertilizers (Tamene et al., 2017), whose prices have been increased ever and their purchasing costs are becoming big burdens to resource poor smallholder farmers, and eventually reduction of soil productivity.

Several research reports underline the importance of organic inputs including compost, farm-yard, and green manure in restoring problematic soils. According to Karazija et al. (2015), farmyard manure (FYM) enables to modifying the physical, chemical and biological properties of the soil of cultivated lands into the better ones which are of more suitable to crop production. Physically, it functions well in enhancing aggregation and stability, and thereby improving soil structure, porosity, and water-holding capacity, as well as, reducing soil bulk density (Mutegi, 2012). In turn, stability of aggregates prevents surface sealing and soil erosion, improves water infiltration, and enhances water-holding capacity (Martínez et al., 2013). Soil porosity is important for root proliferation, gas exchange, and water retention and movement. Moreover, FYM improves the retention of plant nutrients and increases the soil biodiversity (Lal, 2009).

The chemical properties of the soil are the second important characters that are improved by application of organic matter including farmyard manure. Organic inputs including manure and

compost check soil pH and improve electrical conductivity (EC) and nutrient supply of the soil. Organic inputs also enhance cation exchange capacity (CEC) particularly in sandy soils and reduce Al toxicity and P-fixation in strongly acidic soils with oxide mineralogy (Negassa et al., 2007). Contrary to inorganic chemical fertilizers that supply only a few plant nutrients mainly NP in Ethiopian case, organic inputs constitute all essential plant mineral nutrients, although their available nutrient contents are low and they are released slowly. To meet the large requirements of plants for macronutrients mainly NP with only organic inputs, application of huge quantity of organic inputs per unit area is hence required as compared to inorganic chemical fertilizers.

Unless their sources are limited and their transportation and uniform application to crop fields are cumbersome, organic inputs can be used as fertilizers for enhancing the productivity of soils. According to Karazija et al. (2015), application of farmyard manure at 40 t/ha significantly increased the tuber yield of potato (40 t/ha) by four folds over the yield (10.5 t/ha) of unfertilized control. Similarly, Ali & Al-Juthery, 2015 reported that application of well-prepared organic fertilizer at the optimal rate of 20 t/ha gave an equivalent tuber yield of potato produced with 100% mineral fertilizers. In addition, Sayed et al. (2014) indicated that organic production of potato using 23.8 t/ha of compost could be an alternative to the conventional production with commercial inorganic fertilizers without significant reduction in yield and quality. Furthermore, Zha et al. (2015) reported that long-term organic manure fertilization at the rate of 10 t/ha attributed to elevating wheat grain yield to 4.58 t/ha as compared to 2.02 t/ha grain yield obtained from unfertilized control. Similarly, Der et al. (2012) showed that organic manure increased grain yield of wheat by 23.2% over that of unfertilized treatment. Besides, Muhammad and Anwar (2008) showed that application of organic manure increased the wheat yield by 105% over the control. All other growth parameters such as plant height, number of tillers, spike length, straw yield, grain yield, and thousand grain weight of wheat grown after incorporation of manure into the soil were statistically different from that of the control (Muhammad & Anwar, 2008).

Sound crop rotation plays also a great role in amending soil health and productivity. According to Eugenija et al. (2014), the greatest tuber yield of potato obtained after clover than barley rotation system. Similarly, Malihe et al. (2015) found that potato plants grown in plots following common vetch and faba bean produced 12.7% and 15.0% more tuber yield, respectively, over that of potato grown after winter wheat. Stefano et al. (2010) indicated that clover green manure and farmyard manure substantially increased the total yield of potato by 22.5% and 25.1%, respectively, over the untreated control. In addition, the effect of including legume in the rotation system on improving wheat yield is quite tremendous. According to Talgre et al. (2009), the yield of spring wheat on wheat to wheat rotation system was only 2.12 t/ha but an extra yield of 1.45 t/ha was recorded after *Lucerne* as a preceding crop. Similarly, Garofalo et al. (2009) reported that the yield increment of wheat following faba bean was above 12% but this effect went up to 135% in drier years. In line with these reports, Ndayegamiye et al. (2015) demonstrated that legumes have significantly increased yields of wheat by 35%. Ali et al. (2015) showed that legumes as preceding crop had significantly elevated grain yield (5.1 t/ha) compared to wheat-wheat (3.18 t/ha) cropping systems. Furthermore, Hayat and Ali (2010) demonstrated that legumes certainly increased the biomass and grain yield of succeeding wheat by 18% over nonlegume sorghum.

Agronomists and soil fertility scientists strongly advise to use inorganic chemical fertilizers with the integration of organic matter applications (Tamene et al., 2017). On top of its great role in improving physical, chemical and biological properties of soils, the presence of sufficient organic matter in the soil enhances not only the uptake efficiency of the applied chemical fertilizers by crop plants, but it also increases also the response of crops productivity to the applied chemical fertilizers (Tamene et al., 2017). During application of NP chemical fertilizers, the presence of sufficient organic matter in the soil is essential for supplying of the remaining essential mineral nutrients to the growing crop plants at required levels through its mineralization. As indicated above, application of NP chemical fertilizers alone for long without applying organic inputs would eventually be ended up with the declining of crops productivity responses to the applied NP chemical fertilizers (Tamene et al., 2017), while the soil

humus might continuously be degraded and reached the lower level of mineralization to supply other essential mineral nutrients inadequately to the growing crop plants.

Soil degradation is one of the main causes of increasing food insecurity in Sub-Saharan Africa including Ethiopia (FAO, 2015). This is often due to continuous cultivation, a low replenishing rate of organic matter, mono-cropping, and ineffective use of mineral fertilizer (FAO, 2015). For the Ethiopian highlands, Meseret et al. (2015) showed that continuous cultivation leads to nutrient depletion, high bulk density, low soil pH, and reduced soil organic carbon. Habtamu et al. (2014) confirmed that over-relying on chemical soil fertilizer and continuous cropping negatively impacted the physico-chemical properties of cultivated soil that is in turn resulting in low levels of N, P, S, cation exchange rate (CEC), and soil porosity. Yihnew (2015) reported low levels of soil pH, nitrogen, and available phosphorus in the highlands of Awi Zone. He reported also critically low levels of nitrogen, organic matter, CEC, and available phosphorus in most cropping areas of northwest Ethiopia.

Meanwhile, multiple organic matter sources are widely available in the highlands of Awi Zone, northwest Ethiopia (Shibabaw et al., 2017, 2018). Dung from higher animals including cattle, sheep, horse, donkey, and mule, and litter from chicken are available in the area with significant quantity. Crop residues and shrubs of green manure (tree lucerne, clover, and sesbania) are also found in a measurable amount (Shibabaw et al., 2017, 2018). As indicated above, however, farmers have abandoned to apply these organic materials to their crop soils since they started to use NP commercial chemical fertilizers (Shibabaw et al., 2017, 2018). Furthermore, continuous cereal cropping systems are dominating in the area without integration of legume crops in the rotation system (Shibabaw et al., 2017, 2018). Abandoning of using sound crop rotation practices and organic inputs in the crop farms of Ethiopian highlands has been resulting in deteriorating the physicochemical properties of cultivated lands and their productivity (Shibabaw et al., 2017, 2018). Hence, there is an urgent need for redirecting the current trends of inorganic soil fertility management systems to integrated organic and inorganic soil fertility management systems in the crop farms of northwest Ethiopian highlands. This entails indeed concrete evidences, but hitherto there is no consolidated information available about the effect of crop rotation practices and organic inputs on physicochemical properties and productivity of crop soils in the study area. Therefore, the main objective of the present study was to assess the potentials of crop rotation practices and organic inputs for restoration of soil health and productivity of degraded highland crop farms in northwest Ethiopia.

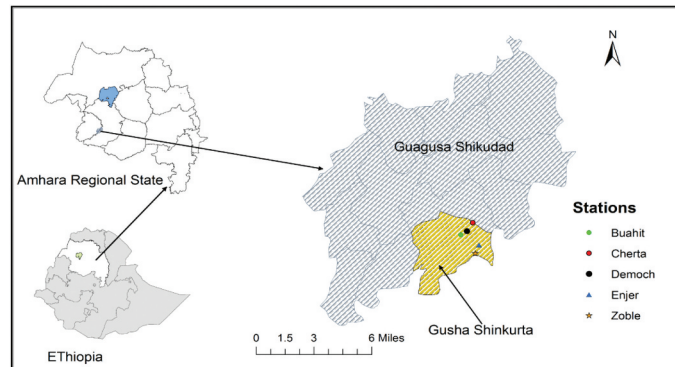
2. Materials and methods

2.1. Description of the study area

The study was conducted both at station and on-farm testing sites for three consecutive years from 2013 to 2015 in Gusha Shinkurta rural village of Guagusa Shikudad district, Awi zone, northwest Ethiopian highlands (Figure 1). Geographically, the study area is located between 11°92' and 11°91' N latitude, and 28°61' and 28°87' E longitude. The altitude of experimental sites ranges from 2451 to 2537 meters above sea level with a slope of 2.6%–3.7%. Climate of the study area is cool humid with annual average night and day temperatures of 10.2°C and 22.4°C, respectively, and mean total annual rainfall of 2492 mm. Rainfall distribution of the area is somewhat mono-modal and the rainy season extends from March to the end of November, peak in July and August.

According to Yihenew (2002), the dominant soil type of the study area is Acrisol. Soil laboratory analysis results of the present study obtained from soil samples collected just before starting the experiment showed that the texture of experimental soils both on-station and on-farms was clay loam with average bulk density of 1.37 g cm⁻³, pH (H₂O) of 5.19, CEC of 15.6 cmol(+)kg⁻¹, organic carbon content of 1.26%, total nitrogen of 0.12%, available phosphorous of 8.64 ppm, and exchangeable potassium of 0.68 cmol(+)kg⁻¹ (see the details in Table 2 in results and discussion part).

Figure 1. Location map of the study sites in Gusha Shinkurta rural village, Guagusa Shikudad district, Amhara region, north-west Ethiopian highlands (Democh was station testing site, while Buahit, Cherta, Enter and Zoble were on-farm testing sites).



Farming system of the study area is characterized by small-scale mixed farming of both crops and livestock under the same management unit. Potato, bread wheat, barley, maize, field pea, and faba bean are the dominant crops grown in the area and they are accounted for about 90% of the cultivated area. Husbandries of cattle, sheep, horse, mule, and poultry are dominantly carried out in the study area.

2.2. Experimental treatments, design and procedures

Five crop rotation practices ($R1^+$ = bread wheat–clover–potato, $R2^+$ = clover–bread wheat undersowing lupine–potato, $R3^+$ = potato–clover–bread wheat, $R4^+$ = bread wheat undersowing lupine–potato undersowing lupine–bread wheat, and $R5^+$ = lupine–potato undersowing lupine–bread wheat) combined with four manure applications [$M1$ = control at 0 t ha^{-1} manure, $M2$ = 2.5 t ha^{-1} sesbania green manure (SGM), $M3$ = 5 t ha^{-1} fresh cattle manure (FCM), and $M4$ = 2.5 t ha^{-1} SGM + 5 t ha^{-1} FCM] were laid out in randomized complete block design (RCBD) with four replications. The on-station experiment at Democh Farmers' Training Center (Figure 1) was considered as mother trial, where all four experimental replications (blocks) were found at the same site, while the on-farm experiment at Buahit, Cherta, Enter and Zoble (Figure 1) was carried out with the concept of baby trials whereby the four replications were separately done at four different farmers' crop fields, and each farmer's crop field was considered as a single replication (a block) and a baby trial. Plus sign (+) added with crop rotation treatments showed the incorporation of crop residue and/or green manure of preceding crops into the soil of experimental plots. Five different crop rotations were devised in three rotation phases in 2013, 2014, and 2015 (Table 1), and hence years

Table 1. Three phases of crop rotations used for the experiment in three consecutive years from 2013 to 2015

R	1st rotation phase (2013)	2nd rotation phase (2014)	3rd rotation phase (2015)
R1	Bread wheat	Clover	Potato
R2	Clover	Bread wheat US lupine	Potato
R3	Potato	Clover	Bread wheat
R4	Bread wheat US lupine	Potato US lupine	Bread wheat
R5	Lupine	Potato US lupine	Bread Wheat

R, rotation; US, under sowing; years 2013, 2014, and 2015 represented 1st, 2nd, and 3rd consecutive rotation phases, respectively; crop rotation in different years was done on the same fixed plots, for instance, in the first rotation (R1), plots occupied with bread wheat in 2013 were occupied with clover and potato in 2014 and 2015, respectively.

are representing the rotation phases and they wouldn't be considered as source of variation. Since the main concern of this research was abandoning of crop rotation and organic matter application in the cultivated land of the study area, the sole bread wheat and potato without manure application (R1M1 and R3M1) in 2013 were considered as the controls and baselines of bread wheat and potato productions, respectively.

Gross size of experimental plots was 3 m*3 m (9 m²). Adjacent plots within blocks were separated with 0.5 m wide paths, while the distance between blocks was 1.0 m apart. As per treatments, manure was uniformly surface broadcasted and incorporated within 20 cm soil depth two weeks before planting. Potato tuber seeds of "Belete" variety were planted with a spacing of 70 cm between rows and 30 cm within rows. Bread wheat seeds of "Tay" variety were also drilled in 20 cm distant rows at the recommended seeding rate of 150 kg ha⁻¹. Seeds of the most adaptive Ethiopian clover (*Trifolium decorum*) were drilled in 20 cm distant rows at the seeding rate of 3 kg ha⁻¹. As pure stand, seeds of white lupine (*Lupinus album*) were planted in rows at the spacing of 40 cm*10 cm. In undersowing treatments, lupine seeds were planted between rows of potato at 50% flowering and between every two rows of bread wheat at tillering growth stage at 10 cm spacing between plants. Beyond experimental treatments, all other agronomic practices were applied to experimental plots equally as per their respective recommendations used for experimental crops in the study area.

2.3. Soil sampling and analysis

Soil sampling and analysis was carried out two times, first initially before starting the experiment in 2013, and second finally after the completion of the experiment in 2015. Initially before starting the experiment in 2013, soil samples at on-station (mother trial site) and on-farm testing sites (baby trial sites) were collected randomly in cress-cross fashion of the whole plot at a plow depth of 0–20 cm using an augur and composited separately by taking equal amount of soil from collected samples. Finally, after the completion of the experiment in 2015, soil sampling and compositing was rather done at each experimental plot basis following the same procedures used for samples collected initially before starting the experiment. In both cases, composited soil samples were air dried and crushed with motorized grinder and sieved with a 2 mm diameter screen sieve for further laboratory analysis of important soil physicochemical properties.

Particle size distribution of composited soil samples was determined using the hydrometer method (Bouyoucos, 1962; Gee & Bauder, 1986), while oil pH was measured using a digital pH meter in a 1:2.5 soil-water suspension. Cation exchange capacity (CEC) was determined by titration method using ammonium acetate (Chapman, 1965). Organic carbon (OC) was determined by wet digestion using the Walkley and Black method (Heanes, 1984). Total N was determined by micro-Kjeldahl digestion method (Black & Alison, 1965; Bremner & Mulvaney, 1982). Available phosphorus was determined calorimetrically using the Olsen's method (Olsen & Cole, 1954). Exchangeable potassium was determined by flame photometer as described by McLean (1965). Undisturbed soil samples were also taken to measure bulk density using soil core method (Blake & Hartge, 1986). Percentile changes of soil properties from the initial before starting the experiment in 2013 to the final after harvesting of crops in 2015 were computed with the following formula:

$$\Delta P(\%) = \frac{fP - iP}{iP} * 100$$

Where ΔP (%) was a change/improvement of a soil property (P) in percentile, and fP and iP were the final and initial values of a soil property, respectively.

2.4. Crop yield data collection

Since bread wheat (*Triticum aestivum*) and potato (*Solanum tuberosum*) are the most dominant crops grown in the study area, on top of soil health, the present study was targeted at assessing the potential of crop rotation and manure application for enhancing the productivity of bread

wheat and potato. Grain and tuber yield productivity of bread wheat and potato, respectively, were taken as the main experimental variables. At about 14% moisture content of grains, bread wheat plants in the net plot areas were harvested manually and subjected to sun drying for about a week, and threshed separately in tight sacks. Clean grains were recovered from straw and debris through manual sifting and winnowing, and weighed with sensitive electrical balance. Grain yields obtained from the net plot areas were adjusted to 12.5% moisture content and converted to hectare basis and put in ton per hectare. Similarly, as leaves turned yellow and started withering, potato plants in the net plot areas were manually harvested with the help of forked hoes. Recovered potato tubers in the net plot areas were manually cleaned from soil and weighed with sensitive electrical balance and converted to hectare basis.

2.5. Data analysis

The collected data of soil properties (both primary and derived data), as well as grain and tuber yields of bread wheat and potato from on-station and on-farm testing sites were primarily subjected to Bartlett homogeneity test and the results showed no significant difference between on-station and on-farms for all variables. After verification of homogeneity between on-station and on-farms for the study variables, the data were further subjected to combined analysis of variance (ANOVA) using the general linear model (GLM) procedures of SAS version 9.4 (Statistical Analysis System Institute [SAS], 2013). Whenever the ANOVA results showed significant difference between treatments for a variable, further mean separation was done using the least significant difference (LSD) test. Since years (2013–2015) were representing the consecutive phases of crop rotation on the fixed plots, they were not considered as source of variation, and productivity progresses of bread wheat and potato along different phases of crop rotation were compared to their controls or baselines. To minimize the cumbersomeness of presenting all results, average results over sites combination are presented in both cases of soil properties and crop yield productivities. Since presenting the results of a single variable with source(s) of variation in a table is not attractive, results of grain and potato yield productivity as influenced by crop rotation and manure application are presented in bar graphs.

3. Results and discussion

3.1. Soil properties as affected by crop rotation and manure application

Initial soil analysis results showed that the soils of experimental sites were low in organic carbon, total nitrogen, available phosphorous, and exchangeable potassium contents with moderately acidic pH and moderate CEC (Table 2). Their bulk density was also compacted with 1.37 g cm^{-3} . Similar to the present results, Yihnew (2015), Shibabaw et al. (2017, 2018) reported also low soil organic carbon, total nitrogen, and available phosphorous contents in the crop fields of Awi Zone in northwest Ethiopian highlands. Slightly different from the present results, Yihnew (2015) reported even low levels of soil pH and CEC in the present study area. High bulk density and low levels of most chemical properties of experimental soils verified the severity of soil degradation in the crop farms of northwest Ethiopian highlands that would likely be associated with improper soil management (Habtamu et al., 2014). This was also supported by Shibabaw et al. (2017, 2018) who reported that since they start to use NP commercial inorganic fertilizers, farmers in the present study area have abandoned to apply organic inputs and sound crop rotation practices to their crop fields.

After three consecutive years of applying crop rotation practices and manure inputs, very considerable improvements were observed on physicochemical properties of experimental soils (Tables 3 and 4). Compared to that of the initial status of soil properties before starting the experiment (Table 2), interaction of crop rotation and manure application interventions in three consecutive rotation phases resulted in improving the bulk density (BD), pH, cation exchange capacity (CEC), and organic carbon (OC), total nitrogen (TN), available phosphorous (AP), and exchangeable potassium (EK) contents of the experimental soils on average by 3.65–22.63%, 3.80–17.87%, 20.91–66.82%, and 14.29–88.89%, 8.33–150.00%, 25.08–88.87%, and 1.47–44.12%,

Table 2. Physicochemical properties of the experimental soils before starting the experiment in 2013 in Awi highlands, northwest Ethiopia

Soil properties	On-station	On-farms	Mean	Category
Bulk density (g cm ⁻³)	1.36	1.37	1.37	Compacted@
pH (H ₂ O)	5.36	5.15	5.19	Moderately acidic#
CEC (cmol(+) kg ⁻¹)	16.10	15.52	15.64	Moderate*
Organic carbon (%)	1.30	1.25	1.26	Low*
Total nitrogen (%)	0.13	0.11	0.12	Low*
Available P (ppm)	9.54	8.64	9.09	Low*
Exc. K (cmol(+) kg ⁻¹)	0.68	0.67	0.68	Low*
Particle distribution				
Sand (%)	27.00	29.50	29.00	
Silt (%)	35.00	34.25	34.40	
Clay (%)	38.00	36.25	36.60	
Textural class	Clay loam	Clay loam	Clay loam	

CEC = cation exchange capacity; P = phosphorus; K = potassium; ppm = part per million; pH = potential of hydrogen; @Blake and Hartge (1986), Panda (2010), and Landon (1991).

Table 3. Average soil properties over sites combination after three-year interventions of crop rotation and manure application in 2015 in Awi highlands, northwest Ethiopia

Treatment		Soil properties						
a) Rotation (R)		BD	pH	CEC	SOC	TN	AP	EK
R1		1.16	5.92	23.24 ^a	2.06 ^a	0.23 ^a	15.40 ^a	0.87 ^a
R2		1.19	5.87	22.89 ^a	2.02 ^a	0.21 ^b	15.36 ^a	0.85 ^{ab}
R3		1.20	5.83	21.68 ^{bc}	1.82 ^b	0.20 ^{bc}	14.34 ^b	0.79 ^{bc}
R4		1.23	5.75	21.24 ^c	1.72 ^b	0.18 ^d	13.94 ^b	0.74 ^c
R5		1.21	5.80	21.50 ^{bc}	1.77 ^b	0.19 ^{cd}	14.19 ^b	0.78 ^c
P-value		ns	ns	*	*	*	*	*
SE±		0.02	0.07	0.43	0.04	0.01	0.29	0.02
b) Manure (M)								
M1		1.29 ^a	5.54 ^c	19.66 ^c	1.52 ^d	0.14 ^d	12.40 ^c	0.73 ^c
M2		1.23 ^b	5.78 ^b	21.49 ^b	1.82 ^c	0.17 ^c	14.53 ^b	0.77 ^{bc}
M3		1.18 ^b	5.94 ^{ab}	22.43 ^b	1.99 ^b	0.23 ^b	14.96 ^b	0.81 ^b
M4		1.10 ^c	6.08 ^a	24.87 ^a	2.19 ^a	0.26 ^a	16.70 ^a	0.91 ^a
P-value		**	**	**	**	**	**	**
SE±		0.02	0.06	0.38	0.03	0.01	0.26	0.02
c) Interaction								
R	M							
R1	M1	1.25 ^{abcd}	5.61 ^{efghi}	20.77 ^{hij}	1.59 ^{ghi}	0.16 ^{gh}	13.43 ^{gh}	0.79 ^{efghi}
	M2	1.19 ^{cd}	5.81 ^{bcdefgh}	22.49 ^{cdefgh}	2.04 ^c	0.20 ^{ef}	14.98 ^{cdef}	0.83 ^{cdefgh}
	M3	1.15 ^{feghi}	6.07 ^{abc}	23.61 ^{bcdef}	2.22 ^{abc}	0.25 ^{bc}	16.04 ^{abc}	0.89 ^{bcd}
	M4	1.06 ⁱ	6.20 ^a	26.09 ^a	2.38 ^a	0.30 ^a	17.16 ^a	0.98 ^a
R2	M1	1.28 ^{abcd}	5.56 ^{fghi}	20.37 ^{ij}	1.55 ^{ghi}	0.15 ^{hi}	13.23 ^{gh}	0.77 ^{fghijk}
	M2	1.21 ^{bcd}	5.80 ^{bcdefgh}	22.36 ^{defgh}	2.16 ^{bc}	0.18 ^{fg}	15.99 ^{abcd}	0.81 ^{defgh}
	M3	1.18 ^{degh}	6.00 ^{abcd}	23.31 ^{cdefg}	2.04 ^c	0.24 ^{cd}	15.25 ^{bcde}	0.86 ^{bcde}

(Continued)

Treatment		Soil properties						
	M4	1.08 ^{hi}	6.11 ^{ab}	25.53 ^{ab}	2.33 ^{ab}	0.27 ^b	16.98 ^a	0.94 ^{ab}
R3	M1	1.29 ^{abc}	5.51 ^{hi}	19.17 ^j	1.52 ^{ghi}	0.15 ^{hi}	12.22 ^{hi}	0.71 ^{ijk}
	M2	1.23 ^{abcdfe}	5.79 ^{bcdefgh}	20.89 ^{hij}	1.67 ^{fg}	0.17 ^{gh}	13.90 ^{ef}	0.75 ^{ghijk}
	M3	1.18 ^{degh}	5.90 ^{abcde}	22.14 ^{efghi}	1.94 ^{de}	0.22 ^{de}	14.59 ^{defg}	0.78 ^{efghij}
	M4	1.10 ^{ghi}	6.10 ^{ab}	24.52 ^{abc}	2.13 ^c	0.26 ^{bc}	16.64 ^{ab}	0.90 ^{abc}
R4	M1	1.32 ^a	5.46 ⁱ	18.91 ^j	1.44 ⁱ	0.13 ⁱ	11.37 ^h	0.69 ^k
	M2	1.27 ^{abcd}	5.72 ^{defghi}	20.83 ^{hij}	1.58 ^{ghi}	0.15 ^{hi}	13.76 ^{fg}	0.70 ^{jk}
	M3	1.20 ^{bcdfe}	5.84 ^{bcdefg}	21.28 ^{ghi}	1.83 ^{ef}	0.20 ^{ef}	14.35 ^{efg}	0.74 ^{hijk}
	M4	1.14 ^{efghi}	5.99 ^{abcd}	23.93 ^{bcde}	2.04 ^{cd}	0.24 ^{cd}	16.26 ^{abc}	0.84 ^{cdef}
R5	M1	1.30 ^{ab}	5.54 ^{ghi}	19.06 ^j	1.48 ^{hi}	0.13 ⁱ	11.73 ⁱ	0.69 ^k
	M2	1.24 ^{abcdfe}	5.76 ^{cdefghi}	20.86 ^{hij}	1.65 ^{fgh}	0.16 ^{gh}	14.00 ^{efg}	0.74 ^{hijk}
	M3	1.19 ^{cdfeg}	5.87 ^{bcdef}	21.81 ^{fghi}	1.90 ^{de}	0.22 ^{de}	14.55 ^{efg}	0.77 ^{fghijk}
	M4	1.11 ^{ghi}	6.02 ^{abcd}	24.27 ^{abcd}	2.06 ^{cd}	0.25 ^{bc}	16.46 ^{ab}	0.90 ^{abc}
P-value		**	*	**	**	**	**	**
SE±		0.04	0.13	0.86	0.07	0.01	0.57	0.03
CV (%)		6.62	4.48	7.78	7.94	7.75	7.82	8.64

BD = bulk density (g cm⁻³); pH (H₂O) = potential of hydrogen in water suspension; CEC = cation exchange capacity (cmol(+) kg⁻¹); OC = organic carbon (%); TN = total nitrogen (%); AP = available phosphorous (ppm); EK = exchangeable potassium (cmol(+) kg⁻¹); R1 = bread wheat-clover-potato; R2 = clover-bread wheat undersowing lupine-potato; R3 = potato-clover-bread wheat; R4 = bread wheat undersowing lupine-potato undersowing lupine-bread wheat; R5 = lupine-potato undersowing lupine-bread wheat; *In the first and second cropping seasons, crop residues of wheat and potato after harvesting were incorporated into the soil, while the biomass of clover and lupine was chopped and incorporated into the soil at their 50% flowering; M1 = control at 0tha⁻¹ manure; M2 = 2.5tha⁻¹ sesbania green manure (SGM); M3 = 5tha⁻¹ fresh cattle manure (FCM); M4 = 2.5tha⁻¹ SGM + 5tha⁻¹ FCM; P = probability; **highly significant at P < 0.01; *significant at P < 0.05; ns = not significant at P ≥ 0.05; SE = standard error; CV = coefficient of variation; means in a column followed with the same letter are not significantly different at P ≥ 0.05.

Table 4. Average percentile changes of soil properties over sites combination after three-year interventions of crop rotation and manure application in 2015 compared to the initial before starting the experiments in 2013 in Awi highlands, northwest Ethiopia

Treatment	Mean percentile changes of soil properties						
a) Rotation (R)	BD	pH	CEC	SOC	TN	AP	EK
R1+	-15.15 ^a	12.60 ^a	48.59 ^a	63.29 ^a	89.58 ^a	69.44 ^a	28.31 ^a
R2+	-13.32 ^{ab}	11.55 ^{ab}	46.37 ^a	60.32 ^{ab}	75.00 ^{ab}	69.00 ^a	24.26 ^{ab}
R3+	-12.41 ^{ab}	10.74 ^{ab}	38.62 ^b	44.05 ^{ab}	66.67 ^{ab}	57.73 ^b	15.44 ^{bc}
R4+	-10.04 ^b	9.36 ^b	35.79 ^b	36.71 ^b	50.00 ^b	53.30 ^b	9.19 ^c
R5+	-11.68 ^{ab}	10.22 ^{ab}	37.47 ^b	40.67 ^{ab}	58.33 ^{ab}	56.05 ^b	13.97 ^{bc}
P-value	*	*	*	*	*	*	*
SE±	0.21	0.12	0.80	0.97	1.32	1.19	0.39
b) Manure (M)							
M1	-5.99 ^c	5.25 ^c	25.68 ^b	20.32 ^c	20.00 ^b	36.37 ^b	7.35 ^c
M2	-10.36 ^{bc}	9.81 ^b	37.38 ^b	44.44 ^{bc}	43.33 ^b	59.80 ^{ab}	12.65 ^{bc}
M3	-13.87 ^b	12.85 ^a	43.41 ^{ab}	57.62 ^{ab}	88.33 ^a	64.53 ^{ab}	18.82 ^b
M4	-19.85 ^a	15.67 ^a	59.00 ^a	73.65 ^a	120.00 ^a	83.72 ^a	34.12 ^a
P-value	**	**	**	**	**	**	**
SE±	0.19	0.11	0.72	0.87	1.18	1.07	0.35

(Continued)

Table 4. (Continued)

Treatment		Mean percentile changes of soil properties						
c) Interaction								
R	M							
R1+	M1	−8.76 ^{efgh}	6.65 ^{ghij}	32.80 ^{ab}	26.19 ^{cde}	33.33 ^{ef}	47.74 ^{abc}	16.18 ^{cdefgh}
	M2	−13.14 ^{abcd} efgh	10.46 ^{bcdefghi}	43.80 ^{ab}	61.90 ^{abcd}	66.67 ^{bcdef}	64.80 ^{abc}	22.06 ^{bcdefg}
	M3	−16.06 ^{abcdef}	15.40 ^{abcd}	50.96 ^{ab}	76.19 ^{ab}	108.33 ^{abc}	76.46 ^{abc}	30.88 ^{abcd}
	M4	−22.63 ^a	17.87 ^a	66.82 ^a	88.89 ^a	150.00 ^a	88.78 ^a	44.12 ^a
R2+	M1	−6.57 ^{fgh}	5.70 ^{ghij}	30.24 ^{ab}	23.02 ^{de}	25.00 ^{ef}	45.54 ^{abc}	13.24 ^{defgh}
	M2	−11.68 ^{bcd} efgh	10.27 ^{bcdefghi}	42.97 ^{ab}	71.43 ^{abc}	50.00 ^{cdef}	75.91 ^{abc}	19.12 ^{bcdefgh}
	M3	−13.87 ^{abc} defg	14.07 ^{abcde}	49.04 ^{ab}	61.90 ^{abcd}	100.00 ^{abcd}	67.77 ^{abc}	26.47 ^{abcde}
	M4	−21.17 ^{ab}	16.16 ^{ab}	63.24 ^a	84.92 ^a	125.00 ^{ab}	86.80 ^{ab}	38.24 ^{ab}
R3+	M1	−5.84 ^{gh}	4.75 ^{ij}	22.57 ^b	20.63 ^{de}	25.00 ^{ef}	34.43 ^{abc}	4.41 ^{fgh}
	M2	−10.22 ^{cdefgh}	10.08 ^{cdefghi}	33.57 ^{ab}	32.54 ^{bcde}	41.67 ^{def}	52.92 ^{abc}	10.29 ^{efgh}
	M3	−13.87 ^{abc} defg	12.17 ^{abcdef}	41.56 ^{ab}	53.97 ^{abcde}	83.33 ^{bcde}	60.51 ^{abc}	14.71 ^{defgh}
	M4	−19.71 ^{abc}	15.97 ^{abc}	56.78 ^{ab}	69.05 ^{abc}	116.67 ^{ab}	83.06 ^{abc}	32.35 ^{abcd}
R4+	M1	−3.65 ^h	3.80 ⁱ	20.91 ^b	14.29 ^e	8.33 ^f	25.08 ^c	1.47 ^h
	M2	−7.30 ^{efgh}	8.75 ^{efghij}	33.18 ^{ab}	25.40 ^{cde}	25.00 ^{ef}	51.38 ^{abc}	2.94 ^{gh}
	M3	−12.41 ^{bc} defgh	11.03 ^{bcdefgh}	36.06 ^{ab}	45.24 ^{abcde}	66.67 ^{bcdef}	57.87 ^{abc}	8.82 ^{efgh}
	M4	−16.79 ^{abcde}	13.88 ^{abcde}	53.01 ^{ab}	61.90 ^{abcd}	100.00 ^{abcd}	78.88 ^{abc}	23.53 ^{bcdef}
R5+	M1	−5.11 ^{gh}	5.32 ^{hij}	21.87 ^b	17.46 ^{de}	8.33 ^f	29.04 ^{bc}	1.47 ^h
	M2	−9.49 ^{defgh}	9.51 ^{defghij}	33.38 ^{ab}	30.95 ^{bcde}	33.33 ^{ef}	54.02 ^{abc}	8.82 ^{efgh}
	M3	−13.14 ^{abc} defgh	11.60 ^{bcdefg}	39.45 ^{ab}	50.79 ^{abcde}	83.33 ^{bcde}	60.07 ^{abc}	13.24 ^{defgh}
	M4	−18.98 ^{abcd}	14.45 ^{abcde}	55.18 ^{ab}	63.49 ^{abcd}	108.33 ^{abc}	81.08 ^{abc}	32.35 ^{abcd}
P-value		**	**	**	**	**	**	**
SE±		0.41	0.24	1.61	1.95	2.63	2.39	0.79
CV (%)		6.62	4.48	7.78	7.94	7.75	7.82	8.64

BD = bulk density (g cm^{−3}); pH (H₂O) = potential of hydrogen in water suspension; CEC = cation exchange capacity (cmol(+) kg^{−1}); OC = organic carbon (%); TN = total nitrogen (%); AP = available phosphorous (ppm); EK = exchangeable potassium (cmol(+) kg^{−1}); R1 = bread wheat–clover–potato; R2 = clover–bread wheat undersowing lupine–potato; R3 = potato–clover–bread wheat; R4 = bread wheat undersowing lupine–potato undersowing lupine–bread wheat; R5 = lupine–potato undersowing lupine–bread wheat; *In the first and second cropping seasons, crop residues of wheat and potato after harvesting were incorporated into the soil, while the biomass of clover and lupine was chopped and incorporated into the soil at their 50% flowering; M1 = control at 0 tha^{−1} manure; M2 = 2.5 tha^{−1} sesbania green manure (SGM); M3 = 5 tha^{−1} fresh cattle manure (FCM); M4 = 2.5 tha^{−1} SGM + 5tha^{−1} FCM; P = probability; **highly significant at P < 0.01; *significant at P < 0.05; ns = not significant at P ≥ 0.05; SE = standard error; CV = coefficient of variation; means in a column followed with the same letter are not significantly different at P ≥ 0.05.

respectively (Table 4). The extent of improvements due to the interaction of crop rotations and manure applications was higher in total nitrogen, available phosphorous, organic carbon, and CEC than that of bulk density and pH. The highest improvements in all soil properties were recorded with the combination of bread wheat–clover–potato rotation (R1) and application of 2.5 tha^{−1} sesbania green manure + 5 tha^{−1} fresh cattle manure application (M4). In most physicochemical properties of soils, on the other hand, the lowest improvements were observed with the

combination of bread wheat undersowing lupine–potato undersowing lupine–bread wheat (R4) and the control without manure application (M1). Under each crop rotation system, improvements of soil properties increased with the increase of the applied manure rates (Tables 3 and 4). In the control without manure application (M1), improvements of soil properties were recorded due to crop residues and/or green manure of preceding crop(s) incorporated into the soil as part of crop rotation systems. Differences between rotations (without manure application) in the improvement of soil properties would indeed be associated with their differential effects on quality and quantity of crop residues and/or green manure of the preceding crop(s) incorporated into the soil of experimental plots. Marked improvements in the soil properties of the experimental soils with crop rotation and manure application interventions would further be associated with enhanced soil organic matter as the result of cumulative direct and residual effects of manure application as treatment and incorporation of crop residues and/or green manure of preceding crop(s) into the soil as part of crop rotations. In agreement with the present results, several workers reported also that application of organic inputs and/or crop rotation with the inclusion of legumes had have marked improving effects on physicochemical properties of crop soils (Karazija et al., 2015; Kuz & Mina, 2011; Lal, 2009; Martínez et al., 2013; Mutegi, 2012; Perez et al., 2013; Tamos et al., 2015).

Except bulk density and pH, other soil properties were significantly ($P < 0.05$) affected by different crop rotations (Table 3). Although the magnitude of improvements varied on the soil properties (Table 4), the highest percentile improvements in all soil properties were observed with the crop rotation of bread wheat–clover–potato (R1), while the lowest improvements were observed with the rotation of bread wheat undersowing lupine–potato undersowing lupine–bread wheat (R4). With different crop rotations, lesser improvements of 10.04–15.15% and 9.36–12.60% were relatively recorded in bulk density and pH, respectively (Table 4). On the other hand, higher improvements of 50.00–89.58%, 53.30–69.44%, 36.71–63.29% and 35.79–48.59% were observed in total nitrogen (TN), available phosphorous (AP) and organic carbon (OC) contents, and CEC, respectively, with application of different crop rotations. The improving effects of crop rotations on soil TN, AP, OC, CEC and K^+ were shown in similar trends of $R1 > R2 > R3 > R5 > R4$ (Table 4) and these might be related to their differences in kind and amount of crop residues and/or legume green manure that were incorporated into the soil in the first and second cropping years. In harmony to the present results, several researchers reported that integrating crop rotation with legume crops improved most soil properties much better than monocroppings (Meseret et al., 2015; Muthoni & Kabira, 2010; Perez et al., 2013; Yusuf et al., 2009).

The impact of manure treatments on the improvement of soil properties was more distinctive than that of crop rotations. Average percentile improvements in all soil properties increased with the increase of manure application rated (Table 4). The highest improvements in all soil properties were recorded with the application of 2.5 ton ha^{-1} sesbania green manure + 5 ton ha^{-1} fresh cattle manure (M4), while the lowest improvements were recorded with the control without manure application (M1). On average, applications of manure in ascending order of 2.5 ton ha^{-1} sesbania green manure (M2), 5 ton ha^{-1} fresh cattle manure (M3), and 2.5 ton ha^{-1} sesbania green manure + 5 ton ha^{-1} fresh cattle manure (M4) attributed to improve BD, pH, CEC, OC, TN, AP and EK of experimental soils by 5.99–19.85%, 5.25–15.67%, 25.68–59.00%, 20.32–73.65%, 20.00–120.00%, 36.37–83.72%, and 7.35–34.12%, respectively (Table 4). The control without manure application rendered even to improve BD, pH, CEC, OC, TN, AP, and EK of experimental soils by 5.99%, 5.25, 25.68%, 20.32%, 20.00%, 36.37%, and 7.35%, respectively. As indicated above, crop residues and/or green manure of preceding crop(s) incorporated into the soil in the first and second cropping years would most likely be contributed for the improvements of soil properties in the control without manure application. Their contribution was not only limited to the control without manure application (M1), they were also complementing other manure treatments (M2, M3, and M4) to have more impact on the improvement of soil properties. Without crop residues and green manure incorporated into the soil in the first and second cropping years, the impact of manure treatments alone on the improvement of soil properties would be much lesser than the present results. Similar to the present results, Kuz and Mina (2011) observed that fertilization with farmyard manure led to an increase in cation exchange capacity, pH, and organic

carbon level of the soil. Tamos et al. (2015) reported also that long-term compost-amended soils showed significant improvements in organic carbon content, CEC, and pH more than unfertilized soils with compost and those fertilized with inorganic fertilizers. Karazija et al. (2015) indicated also that regular farmyard manure application can play a great role in improving the physical, chemical, and biological properties of the soil of cultivated lands.

3.2. Productivity of crops as affected by crop rotation and manure application

3.2.1. Grain productivity of bread wheat (*Triticum aestivum*)

Grain yield productivity of bread wheat was highly significantly ($P < 0.001$) affected by crop rotations and manure treatments, and by their interactions (Figures 2–4). Main and interaction effects of crop rotations and manure treatments on the productivity of bread wheat increased in ascending order from the first cropping year (2013) to the second (2014) and the third (2015) cropping years. After three years from 2013 to 2015, interaction of R4 with M1, M2, M3, and M4 attributed to increase grain yield of bread wheat by 65%, 112%, 139%, and 116%, respectively (Figure 2). Such significant increment of grain yield of bread wheat with the same treatments in the succeeding cropping years would likely be associated with the cumulative direct and residual effects of the applied manure treatments, and crop residues and legume green manure incorporated into the soil in the first and second cropping years. Across all three years, grain yield of bread wheat in different crop rotation systems increased with the increase of manure rates (Figure 2). In the first cropping year (2013), the interaction of R4 with manure treatments gave better grain yield of bread wheat than the interaction of R1 with manure treatments. In the third cropping year (2015), the interaction of R3 with manure treatments gave the highest grain yield of bread wheat as compared to the interactions of R5 and R4 with manure treatments (Figure 2). The highest grain yield of bread wheat (4.48 t ha^{-1}) was recorded in 2015 with the interaction of R3 and M4 followed by the interaction of R5 and M4 (3.88 t ha^{-1}). Similarly, the response of grain yield of bread wheat to the control without manure application in potato–clover–bread wheat rotation (R3) was better than in lupine–potato undersowing lupine–bread wheat rotation (R5), and bread wheat undersowing lupine–potato undersowing lupine–bread wheat rotation (R4). Although they didn't see the interaction effect of crop rotation and manure/compost application on wheat productivity, in agreement with the present results, several researchers observed also significant improvement of wheat productivity after the rotation of legume crops (Ali et al., 2015; Babulicova, 2016; Garofalo et al., 2009; Hayat & Ali, 2010; Ndayegamiye et al., 2015; Talgre et al., 2009) and with the application of manure and/or compost (Der et al., 2013; Moharana et al., 2012; Muhammad & Anwar, 2008; Ram et al., 2014; Zha et al., 2015).

Figure 2. Average grain productivity of bread wheat over sites combination as influenced by interaction of crop rotation and manure application in three rotation phases (2013–2015) in northwest Ethiopian highlands (bars followed with the same letters are not significantly different at $P \geq 0.05$).

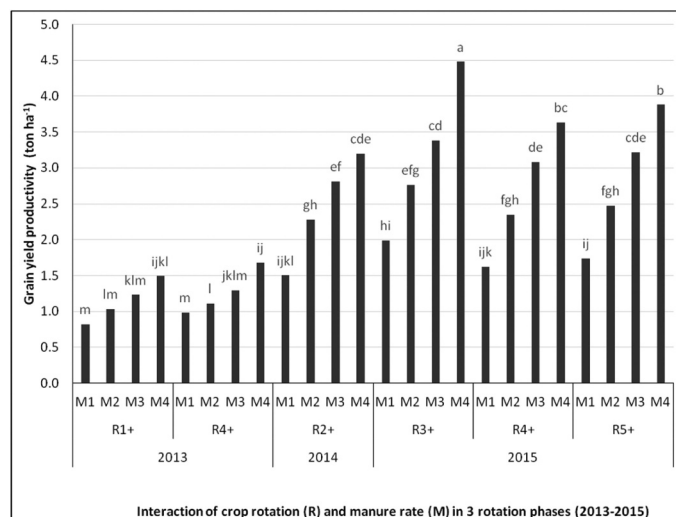


Figure 3. Average grain productivity of bread wheat over sites combination as influenced by crop rotation in three consecutive rotation phases (2013–2015) in northwest Ethiopian highlands (bars followed with the same letters are not significantly different at $P \geq 0.05$).

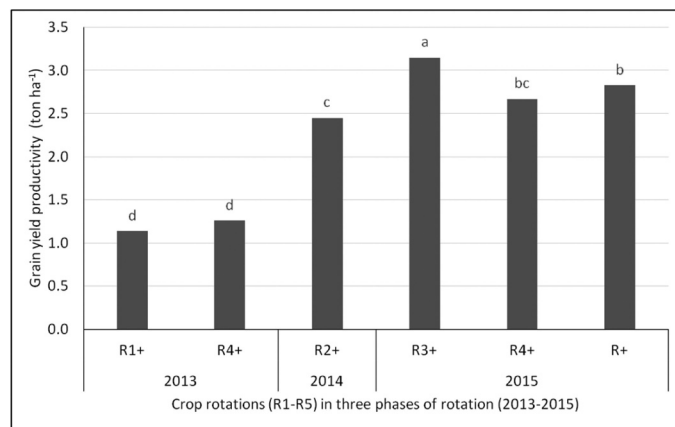
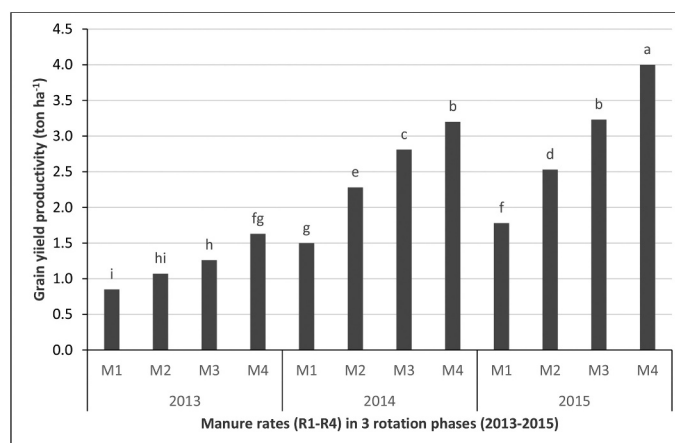


Figure 4. Average grain productivity of bread wheat over sites combination as influenced by manure application in three consecutive rotation phases (2013–2015) in northwest Ethiopian highlands (bars followed with the same letters are not significantly different at $P \geq 0.05$).



Marked increment of grain yield productivity of bread wheat due to crop rotations was also observed as the progress of the cropping years from 2013 to 2015 (Figure 3). Besides, the differences between crop rotations for grain yield productivity of bread wheat became distinct as the progress of the cropping years. In the first cropping year (2013), there was no significant ($P \geq 0.05$) difference between R1 and R4 for grain yield of bread wheat. As compared to that of R4 and R1 in 2013, however, grain yield of bread wheat leaped by 94%–115% in 2014 with R2. This significant increment in 2014 with R2 was largely due to clover green manure incorporated in the first cropping year. The maximum grain yield of bread wheat (3.15 t ha^{-1}) in 2015 was recorded with R3, which was higher than that of R1 in 2013 by 176% (Figure 3). Differences between R3, R4, and R5 for grain yield productivity of bread wheat in 2015 might largely due to their differences in kind and amount of crop residues and legume green manure incorporated into soil in the first and second cropping years. In line with the present results, Zaghoul (2010) reported that organic residues resulted in increasing the grain productivity of wheat significantly. Several workers observed also significantly higher grain yields of wheat after the preceding of legume crops than that of cereal crops (Ali et al., 2015; Babulicova, 2016; Hayat & Ali, 2010; Ndayegamiye et al., 2015).

Similar to that of crop rotations, effect of manure treatments on productivity of bread wheat grain was increased also very significantly with the progress of the cropping years from 2013 to 2014 and 2015 (Figure 4). In each cropping year, grain yield of bread wheat significantly increased with the increase of manure rates from M1 to M4 (Figure 4). Across the years, there was no significant difference between M4 and M1 in 2013 and 2014, respectively, for bread wheat

productivity. Grain yield productivity of bread wheat in 2014 with M4 was also similar with that of M3 in 2015. These results clearly indicated that incorporation of crop residues and legume green manure into the soil in the preceding cropping seasons had comparable effect on bread wheat productivity as that of newly applied manure treatments in some extent. Marked increment of bread wheat productivity with manure treatments in the progress of the cropping years revealed noticeably that applied manure as treatments, and crop residues and legume green manure incorporated into the soil in the preceding cropping seasons had significant residual additive effect on boosting grain productivity of bread wheat with newly applied manure treatments. In harmony with the present results, Ram et al. (2014) reported that organic manures and biofertilizers had substantial direct, residual, and cumulative effects on improving grain yield productivity and quality of wheat. Moharana et al. (2012) and Zha et al. (2015) reported also that long-term applications of organic manures attributed to increase the grain productivity of wheat steadily year after year.

3.2.2. Tuber productivity of potato (*Solanum tubersum*)

Similar to that of bread wheat, main and interaction effects of crop rotations and manure applications on the productivity of potato tuber yield increased more significantly with the progress of the cropping seasons than their differences between treatments within the same cropping year (Figures 5–7). Productivity of potato tuber yield across the interaction of crop rotations and manure treatments increased significantly over rotation phases (Figure 5). It was increased with the increase of manure in the same rotation system, but its peak increment with the maximum manure treatment in one rotation system switched down back bottom in the control without manure application in another rotation system (Figure 5). As compared to the interaction of R3 with the highest manure level (M4) in 2013, the interaction of R5 and R1 with M4 in 2014 and 2015 attributed to increase the productivity of potato tuber yield by 70% and 141%, respectively. Similarly, the interaction of R1 and R5 with the control without manure application (M1) in 2014 and 2015 attributed to increase the productivity of potato tuber yield by 100% and 179%, respectively, compared to that of R3 interaction with M1 in 2013. In 2014, the interaction effect of R4 with manure treatments on potato productivity was similar to that of R5 interaction with manure treatments. In 2015, responses of potato productivity to the interaction of R1 with M1 and M4 were significantly different from that of R2 interaction with M1 and M4 (Figure 5). Steadily increase of tuber yield productivity of potato over years would likely be associated with residual and cumulative effects of manure and crop residues. In harmony with the present results, Manoj et al. (2013) showed that long-term organic treatments either

Figure 5. Average tuber productivity of potato over sites combination as influenced by interaction of crop rotation and manure application for three rotation phases (2013–2015) in northwest Ethiopian highlands (bars followed with the same letters are not significantly different at $P \geq 0.05$).

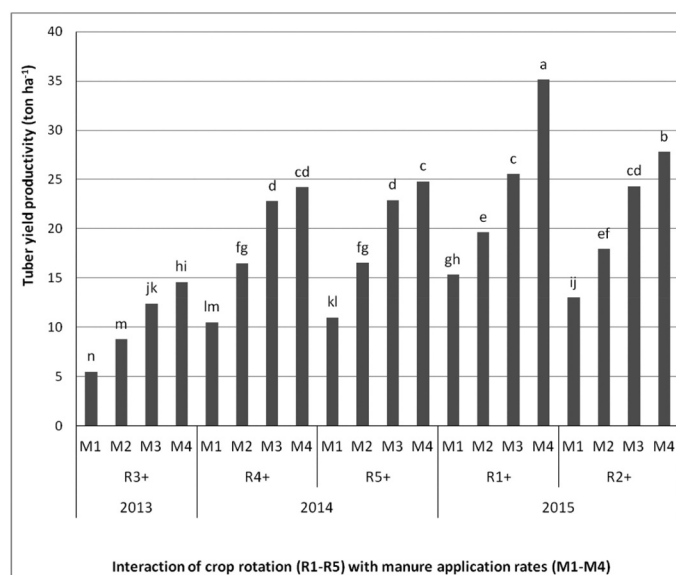


Figure 6. Average tuber productivity of potato over sites combination as influenced by crop rotation in three consecutive rotation phases (2013–2015) in northwest Ethiopian highlands (bars followed with the same letters are not significantly different at $P \geq 0.05$).

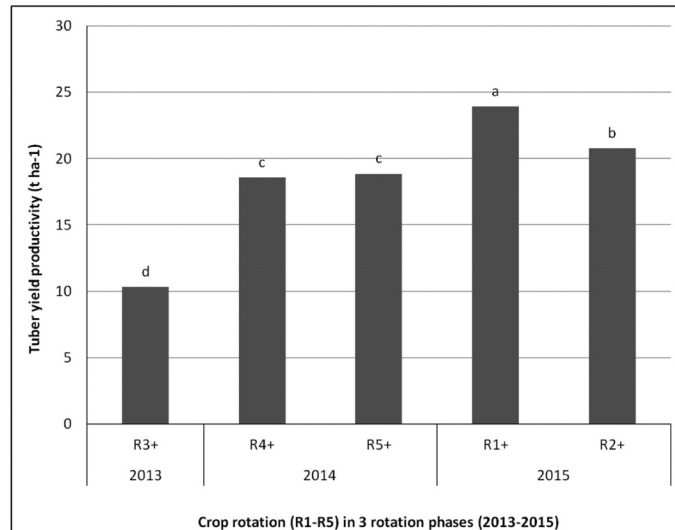
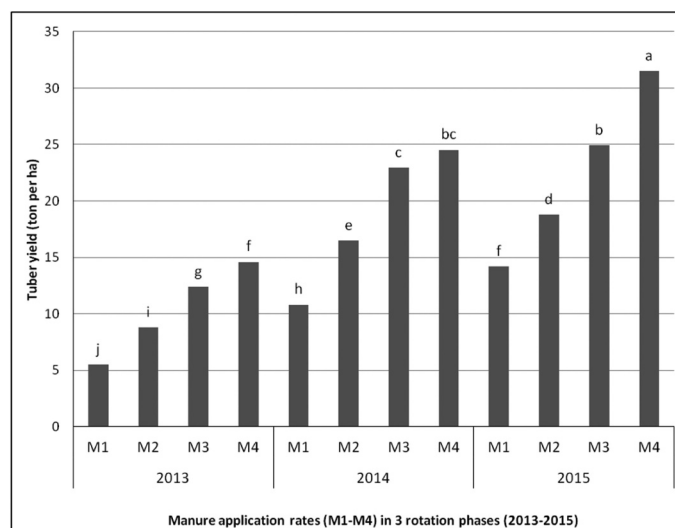


Figure 7. Average tuber productivity of potato over sites combination as influenced by manure application in three consecutive rotation phases (2013–2015) in northwest Ethiopian highlands (bars followed with the same letters are not significantly different at $P \geq 0.05$).



from preceding crops or farm yard manure improved tuber yield productivity of potato steadily over years. Amber et al. (2010) reported also that tuber yield of potato was significantly increased year after year through applications of composted dairy manure and proper crop rotation system.

Similar to that of the interaction between crop rotation and manure application, improving effect of crop rotations on the productivity of potato tuber yield was also pronounced much with the progress of the cropping years from 2013 to 2015 (Figure 6). The highest potato tuber yield of 23.91 t ha^{-1} was recorded in the third experimental year of 2015 from bread wheat-clover-potato rotation system (R1), while the lowest potato tuber yield of 10.32 t ha^{-1} was recorded in the first experimental year of 2013 from potato-clover-bread wheat rotation system (R3). Response of potato productivity to R4 and R5 in 2014 was not significant ($P \geq 0.05$), but it was significant in response to R1 and R2 in 2015 (Figure 6). This higher productivity of potato with R1 than with R2 in 2015 might be associated with their differences for quality and amount of crop residues and legume green manure that were incorporated into the soil in the cropping seasons of 2013 and 2014. Residual and cumulative effects of crop residues and legume green manure

attributed to the steadily increase of potato productivity over years with different crop rotation systems. In line with the present results, Ndayegamiye et al. (2017) reported that crop residues of cereals and legume green manure had great improvement effect on the productivity of potato grown as succeeding crop compared to that of potato monoculture. Eugenija et al. (2014) and Stefano et al. (2010) observed also that significantly higher tuber yields of potato were obtained after clover than barley and winter wheat rotations, respectively.

Response of potato productivity to manure treatments was so clear and distinctive, and it was significantly increased with the increase of the manure rates (Figure 7). Similar to that of crop rotations, effect of manure treatments on potato productivity was concomitantly increased also with the progress of the cropping years from 2013 to 2014 and 2015 (Figure 7). Response of potato productivity to the highest rate of manure application (M4) in 2014 and 2015 increased by 68% and 116%, respectively, compared to that of 2013. As compared to that of 2013, similarly, the response of potato productivity to the control without manure application (M1) in 2014 and in 2015 increased by 97% and 158%, respectively. As explained above, applied manure as treatments, and crop residues and legume green manure incorporated into the soil in the first and second cropping seasons would have residual additive effect with newly applied manure treatments on potato productivity, which was more than that of manure treatment effects *per se* within the same cropping season. In agreement with the present results, several workers reported also that productivity of potato tuber yield significantly increased with the increase of organic inputs (Ali & Al-Juthery, 2015; Amber et al., 2010; Amir et al., 2012; Karazija et al., 2015; Najm et al., 2013; Sayed et al., 2014). Amir et al. (2012) argued that the productivity of potato tuber yield was increased by increasing the rates of farm yard manure, but supplement of farm yard manure above 20.9 t ha⁻¹ with commercial inorganic nitrogen fertilizer didn't increase the productivity of potato tuber yield.

4. Conclusion

Results of the present study clearly demonstrated that application of sound crop rotation practices and organic inputs (manure and crop residues) had great potentials for the restoration of soil health and productivity of degraded highland crop farms in northwest Ethiopia. In three year period (2013–2015), sound crop rotation practices and manure applications attributed to improve soil bulk density, pH, CEC, organic carbon, total nitrogen, available phosphorous, and exchangeable potassium on average up to 23%, 18%, 67%, 89%, 150%, 89%, and 44%, respectively. Similarly, the combination of these practices rendered to improve the productivity of potato and bread wheat on average up to 540% and 446%, respectively. In both soil properties and crops productivity, improvements increased with the increase of the applied manure rates. Incorporating crop residues and legume green manure into the soil had also significant additive effects to enhance the improvement effects of manure applications on both soil properties and crops productivity. Total shifting from applying inorganic fertilizers to limited organic inputs alone would temporarily however penalize farmers with lower crops productivity. Until the maximum productivity of crop soils attained with applications of sound crop rotation practices and organic inputs, thus, it is recommended to integrate crop rotation practices and organic inputs with commercial inorganic soil fertilizers for minimizing crop yield penalties happening in the first few years of applying limited organic inputs alone in any sound crop rotation systems.

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References

- Ali, N. S., & Al-Juthery, H. W. (2015). The combined effect of different fertilizer sources and irrigation method on potato and water productivities under Iraqi conditions of agriculture. *International Journal of Recent Scientific Research*, 6, 556–557.
- Ali, W., Jan, A., & Abbas, A. (2015). Residual effect of preceding legumes and nitrogen levels on subsequent maize. *International Journal of Agronomy and Agricultural Research*, 7, 78–85.
- Amber, D., Olsen, L., & Anna, M. (2010). Residual effects of fresh and composted dairy manure application on potato tuber yield. *American Journal of Potato Research*, 88, 324–332.
- Amir, A., Mohammad, R., Haj, S., Faezeh, F., Mohammad, T., & Alireza, R. (2012). Effect of integrated nutrient management of nitrogen fertilizer and cattle manure on leaf chlorophyll and tuber yield of potato. *Communications in Soil Science and Plant Analysis*, 43(6), 912–923. <https://doi.org/10.1080/00103624.2012.653027>
- Babulicova, M. (2016). Enhancing of winter wheat productivity by the introduction of field pea into crop rotation. *Agriculture Journal of Science*, 62, 101–110.
- Black, C., & Alison, L. (1965). *Methods of soil analysis, soils effect of variations in digestion conditions and inorganic soil constituents*. Agronomy monograph.
- Blake, G. R., & Hartge, K. H. (1986). Bulk density. In A. Klute (Ed.), *Methods of soil analysis. Agronomy no. 9, part 1: Physical and mineralogical methods* (2nd ed., pp. 364–367). American Society of Agronomy (ASA), Soil Science Society of America (SSSA).
- Bouyoucos, A. (1962). Hydrometer method improved for making particle size analyses of Soils 1. *Agronomy Journal*, 54(5), 464–465. <https://doi.org/10.2134/agronj1962.00021962005400050028x>
- Bremner, J. M., & Mulvaney, C. S. (1982). Nitrogen total. In A. L. Page (Ed.), *Methods of soil analysis. Agronomy no. 9, part 2: Chemical and microbiological properties* (2nd ed., pp. 595–624). American Society of Agronomy (ASA).
- Chapman, D. D. (1965). Determination of exchangeable Ca, Mg, K, Na, Mn and effective cation exchange capacity in soil. In C. A. Black (Ed.), *Methods of soil analysis. Agronomy no. 9, part 2* (pp. 902–904). American Society of Agronomy (ASA).
- Der, T., Ozturk, A., Bulut, S., Yildiz, N., Murat, M., & Lu, K. (2012). Effects of organic manures and non-chemical weed control on wheat : Plant growth and grain yield. *Journal of Agricultural Sciences*, 3, 9–20.
- Eugenija, B., Almantas, R., Rita, A., Audrius, K., Zita, M., Danuta, R., Jelena, T., & Liudmila, T. (2014). Effects of ecological farming systems: Five year crop rotations on crop productivity and properties of haplic luvisol. *Journal of Food, Agriculture and Environment*, 4, 1137–1142.
- FAO. (2015). *Status of the world's soil resources: Main report, Food and Agriculture Organization (FAO) of the United Nations and intergovernmental technical panel on soils*.
- Garofalo, P., Paolo, E., & Rinaldi, M. (2009). Durum wheat in rotation with faba bean: Long-term simulation case study. *Crop & Pasture Science*, 60(3), 240–250. <https://doi.org/10.1071/CP08208>
- Gee, G. W., & Bauder, J. W. (1986). Particle-size analysis. In A. Klute (Ed.), *Methods of soil analysis. Agronomy no. 9, Part 1: Physical and mineralogical methods* (2nd ed., pp. 383–411). American Society of Agronomy (ASA), Soil Science Society of America (SSSA).
- Habtamu, A., Heluf, G., Bobe, B., & Enyew, A. (2014). Fertility status of soils under different land uses at Wujiraba watershed, northwestern highlands of Ethiopia. *Agriculture, Forestry and Fisheries*, 3(5), 410–419. <https://doi.org/10.11648/j.aff.20140305.24>
- Hayat, R., & Ali, S. (2010). Nitrogen fixation of legumes and yield of wheat under legumes-wheat rotation in pothwar. *Pakistan Journal of Botany*, 42(4), 2317–2326.
- Heanes, D. L. (1984). Determination of total organic C in soils by an improved chromic acid digestion and spectrophotometric procedure. *Communications in Soil Science Plant Analysis*, 15(10), 1191–1213. <https://doi.org/10.1080/00103628409367551>
- Hernández, D., Fernández, J. M., Plaza, C., & Polo, A. (2007). Water-soluble organic matter and biological activity of a degraded soil amended with pig slurry. *Science of the Total Environment*, 307(1–2), 101–103. <https://doi.org/10.1016/j.scitotenv.2007.01.020>
- Karadzija, T., Cosic, T., Lazarevic, B., Horvat, T., Petek, M., Palcic, I., & Jerbic, N. (2015). Effect of organic fertilizers on soil chemical properties on vineyard calcareous soil. *Agriculturae Conspectus Scientificus*, 80, 79–84.
- Ketema, M., & Bauer, S. (2011). Determinants of manure and fertilizer applications in eastern highlands of Ethiopia. *Quarterly Journal of International Agriculture*, 50, 237–252.
- Kowaljaw, E., & Mazzarino, M. (2007). Soil restoration in semiarid patagonia: Chemical and biological response to different compost quality. *Soil Biology and Biochemistry*, 39(7), 1580–1588. <https://doi.org/10.1016/j.soilbio.2007.01.008>
- Kuz, G., & Mina, B. (2011). Effect of organic manures on agronomic and economic performance of garden pea and on soil properties. *Indian Journal of Agricultural Sciences*, 81, 236–239.
- Lal, R. (2009). Challenges and opportunities in soil organic matter research. *European Journal of Soil Science*, 60(2), 158–169. <https://doi.org/10.1111/j.1365-2389.2008.01114.x>
- Landon, J. R. (1991). *Booker tropical soil manual: A hand book for soil survey and agricultural land evaluation in the tropics and subtropics*. Longman Scientific and Technical Essex.
- Malihe, M., Mohammad, F., Alireza, K., Mohsen, N., & Mehdi, T. (2015). Farmyard manure application of potato with three level of nitrogen fertilizer. *International Journal of Farming and Allied Sciences*, 4, 536–540.
- Mando, A., Ouattara, B., Sédogo, M., Stroosnijder, L., Ouattara, K., Brussaard, L., & Vanlauwe, B. (2005). Long-term effect of tillage and manure application on soil organic fractions and crop performance under Sudano-Sahelian conditions.

- Soil and Tillage Research*, 80(1–2), 95–101. <https://doi.org/10.1016/j.still.2004.03.002>
- Manoj, K., Baishya, L., Ghosh, M., & Ghosh, V. (2013). Effects of organic manures, chemical fertilizers and bio-fertilizers on growth and productivity of rain fed potato in the eastern himalayas. *Journal of Plant Nutrition and Agriculture*, 36(7), 1065–1082. <https://doi.org/10.1080/01904167.2013.770021>
- Martínez, J., Lazcano, C., Christensen, T. H., Munoz, P., Rieradevall, J., Møller, J., Antón, A., & Boldrin, A. (2013). Compost benefits for agriculture evaluated by life cycle assessment. A review. *Agronomy for Sustainable Development*, 33(4), 721–732. <https://doi.org/10.1007/s13593-013-0148-7>
- McLean, E. (1965). Exchangeable aluminum. In *Methods of soil analysis. Part 2: Chemical and microbiological properties* (pp. 849–886). American Society of Agronomy (ASA), Soil Science Society of America (SSSA).
- Meseret, M., Addis, K., & Eyasu, M. (2015). Assessing the physico-chemical properties of soil under different land use types. *Ethiopia Agriculture and Environment and Toxicology*, 5, 55–62.
- Moharana, P., Sharma, B., Biswas, D., Dwivedi, B., & Singh, R. (2012). Long-term effect of nutrient management on soil fertility and soil organic carbon pools under a 6-year-old pearl millet-wheat cropping system in an inceptisol of subtropical India. *Field Crops Research*, 136, 32–41. <https://doi.org/10.1016/j.fcr.2012.07.002>
- Muhammad, I., & Anwar, H. (2008). Response of wheat growth and yield to various levels of compost and organic manure. *Pakistan Journal of Biotechnology*, 40, 2135–2141.
- Mutegi, E. M. (2012). Complementary effects of organic and mineral fertilizers on maize production in the smallholder farms of Meru South district of Kenya. *Agricultural Sciences*, 3(2), 221–229. <https://doi.org/10.4236/as.2012.32026>
- Muthoni, J., & Kabira, J. (2010). Effects of crop rotation on soil macronutrient content and pH in potato producing areas in kenya : Case study of KARI Tigoni station. *Journal of Soil Science and Environmental Management*, 1, 227–233.
- Najm, A., Reza, M., Seyed, H., & Darzi, M. (2013). Influence of nitrogen fertilizer and cattle manure on the vegetative growth and tuber production of potato. *International Journal of Agriculture and Crop Sciences*, 5, 147–154.
- Ndayegamiye, A., Nyiraneza, J., Grenier, M., Bipfubusa, M., & Drapeau, A. (2017). The benefits of crop rotation including cereals and green manures on potato yield and nitrogen nutrition and soil properties. *Advanced Crop Science*, 5, 279–291.
- Ndayegamiye, A., Whalen, J. K., Tremblay, G., Nyiraneza, J., Grenier, M., Drapeau, A., & Bipfubusa, M. (2015). The benefits of legume crops on corn and wheat yield, nitrogen nutrition and soil properties improvement. *Agronomy Journal*, 107(5), 1653–1665. <https://doi.org/10.2134/agronj14.0416>
- Negassa, W., Getaneh, F., Deressa, A., & Dinsa, B. (2007). Integrated use of organic and inorganic fertilizers for maize production. *International Journal of Agricultural Sciences*, 30, 20–30.
- Olsen, S., & Cole, C. (1954). *Estimation of available phosphorus in soils by extraction with sodium bicarbonate*. USDA.
- Panda, S. C. (2010). *Agronomy. Agrobios (India)*.
- Perez, C., Arzeno, J. L., Huidobro, J., Conforto, C., Grumberg, B., Bending, G. D., Meriles, J. M., Vargas-Gil, S., & Hilton, S. (2013). The effect of crop sequences on soil microbial, chemical and physical indicators and its relationship with soybean sudden death syndrome. *Spanish Journal of Agricultural Research*, 12(1), 252–264. <https://doi.org/10.5424/sjar/20141214654>
- Ram, M., Davari, M., & Sharma, S. (2014). Direct, residual and cumulative effects of organic manures and biofertilizers on yields, NPK uptake, grain quality and economics of wheat under organic farming of rice-wheat cropping system. *Journal of Organic Systems*, 9, 16–30.
- Statistical Analysis System Institute (SAS). (2013). *SAS/AF® 9-4 procedure guide* (2nd ed.). SAS Institute.
- Sayed, F., Hassien, A., Muhamed, M., & Ahimed, A. (2014). Growth, yield and nutrient concentration of potato plants. *American-Eurasian Journal of Agriculture and Environmental Science*, 7, 36–43.
- Shibabaw, A., Alemayehu, G., Adigo, E., Ash, F., & Freyer, B. (2018). Effects of organic manure and crop rotation system on potato (*Solanum tuberosum* L.) tuber yield in the highlands of Awi zone. *Ethiopian Journal of Science and Technology*, 11(1), 1–18. <https://doi.org/10.4314/ejst.v11i1.1>
- Shibabaw, A., Alemayehu, G., Adigo, E., Germer, J., Ash, F., & Freyer, B. (2017). Growth and biomass yield response of clover (*Trifolium decorum*) to preceding crop and organic treatment in the highlands of Awi administrative zone, Ethiopia. *Ethiopian Journal of Science and Technology*, 10(3), 151–164. <https://doi.org/10.4314/ejst.v10i3.1>
- Stefano, C., Corrado, C., Daniele, A., Paolo, B., & Fite, M. (2010). Interactions between green manure and amendment type and rate: Effects on organic potato and soil mineral nitrogen dynamic. *Journal of Food, Agriculture and Environment*, 8, 537–543.
- Talgre, L., Lauringson, E., Roostalu, H., & Astover, A. (2009). The effects of green manures on yields and yield quality of spring wheat. *Agronomy Research Journal*, 7, 125–132.
- Tamene, L., Amede, T., Kihara, J., Tibebe, D., & Schulz, S. (2017). *A review of soil fertility management and crop response to fertilizer application in Ethiopia: Towards development of site- and context-specific fertilizer recommendation* (CIAT Publication No. 443).
- Tamos, D., Elsen, H., & Vandendriessche, R. (2015). Impact of long term compost amendment on soil fertility, soil organic matter distribution and nitrogen mineralization. *International symposium on organic matter management and compost use in horticulture*, Murcia, Spain.
- Yihenew, G. (2002). Selected chemical and physical characteristics of soils of Adet Agricultural Research Center and its testing sites. *Ethiopia Journal of Natural Resource*, 4, 203–206.
- Yihnew, G. (2015). The effects of land use types, management practices and slope classes on selected soil physico-chemical properties in Zikre watershed, Awi zone. *Environmental Systems Research*, 5, 0–6.
- Yusuf, A., Abaidoo, R., Iwuafor, E., Olufajo, E., & Sanginga, N. (2009). Rotation effects of grain legumes and fallow on maize yield and chemical properties of an alfisol in the Nigerian savanna. *Agriculture, Ecosystems and Environment Journal*, 129(1–3), 325–331. <https://doi.org/10.1016/j.agee.2008.10.007>
- Zaghloul, M. (2010). Response of wheat to different rates and ratios of organic residues on yield and chemical composition under two types of soil. *Journal of American Science*, 6, 858–864.
- Zha, Y., Wu, X., Gong, F., Xu, M., Zhang, H., & Chen, L. C. D. (2015). Long-term organic and inorganic fertilizations enhanced basic soil productivity in a fluvo-aquic soil. *Journal of Integrative Agriculture*, 14(12), 2477–2489. [https://doi.org/10.1016/S2095-3119\(15\)61191-1](https://doi.org/10.1016/S2095-3119(15)61191-1)



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