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Recovery of Soil Health and Crop Productivity of Degraded Cultivated Land of Northwest Ethiopian Highlands

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*በአብዘኛው የኢትጵያ ከፍተኛ ቦታዎች በከፍተኛ የአፈር መሸርሸርና የለምነት መሟጠጥ ምክንያት የሚታረሰው መሬት ጤንነቱ በጣም የተጎዳ ከመሆኑም ባሻገር ምርታማነቱን ዝቅተኛ እንዲሆን አድረጎታል፡፡ በመሆኑም ሰብልን አፈራርቆ መዝራትና የተፈጥሮ የአፈር ማዳበሪያ መጨመር በሰብል አፈር ጤናማነትና ምርታማነት ማገገም ላይ ያላቸውን ፋይዳ ለማወቅ እንደ አውሮፓዊያን **ዘመን** አቆጣጠር ከ2013 እስከ 2015 ዓ.ም ለሶስት ተከታታይ ዓመታት በሰሜን ምዕራብ ከፍተኛ ቦታዎች ውስጥ በሚገኝ በተጎዳ የሰብል አፈር ላይ የመስክ ጥናት ተካሂኳደል፡፡ ሙከራውም በአምስት የሰብል አፈራረቆ መዝራትና አራት የተፈጥሮ ማዳበሪያ መጠን ጥምርታዎችን በራንደማይዝድ ኮምፕሊት ብሎክ ዲዛይን (RCBD) የተባለ ቴክኒክ በመጠቀም በአራት ድግግሞሽ ተሰርቷል:: በተከታታይ ለሶስት ዓመታት ትክክለኛ ሰብልን አፈራርቆ መዝራትና የተፈጥሮ ማዳበሪያ በመጨመር የሰብል ምርታማነትን እስከ 1230 በመቶና የአፈር ባህሪያትን ከ20 እስከ 154 በመቶ እንዲሸሻል አድርጓል:: የዳቦ ስንዴ-የነጭ ዋጅማ-ድንች ፍርቅርቆሽ ከ75 ኩንታል በሄክታር የተፈጥሮ ማዳባሪያ ጥምርታ ከፍተኛ መሸሻል አሳይቷል፡፡ ስለዚህ ትክክለኛ የሰብል ፍርቅርቆሽና የተፈጥሮ ማዳበሪያ መጠቀም በከፍተና ቦታዎች ውስጥ የሚገኘውን የተጎዳ የሰብል አፈር ለምነትና ምርታማነት በከፍተና ደረጃ ማገገምና ማሻሻል እንደሚቻል የሙከራው ውጤት ያመላከታል፡፡*

Abstract

Severe soil degradation and fertility depletion have resulted in poor soil health and low crop productivity in the cultivated land of most Ethiopian highlands. Thus, a three-year experiment from 2013 to 2015 was conducted to assess the potential of crop rotation and organic matter application for recovery of the soil health and crop productivity of cultivated land in northwest Ethiopian highlands. Factorial combinations of five crop rotations [bread wheat–clover–potato ($R1^+$); clover–bread wheat undersowing lupine–potato ($R2^+$); potato–clover–bread wheat ($R3^+$); bread wheat undersowing lupine–potato undersowing lupine–bread wheat ($R4^+$); and lupine–potato undersowing lupine–bread wheat ($R5^+$)] and four manure application rates [control without manure (M1); 2.5 t ha^{-1} sesbania green manure SGM (M2); 5 t ha^{-1} fresh cattle manure FCM (M3); and 2.5 t ha^{-1} SGM + 5 t ha^{-1} FCM (M4)] were laid out in randomized complete block design with four replications at on-station and on-farm testing sites. Interaction of crop rotation and *manure application significantly improved the soil properties and crop productivity of the experimental plots. Combined applications of crop rotation and manure in a three-year period resulted in the improvement of crop productivity up to 13 folds, as well as of bulk density, pH, CEC, and contents of organic carbon, total nitrogen, available phosphorous, and exchangeable potassium of the experimental soils up to 25, 20, 67, 92, 154, 96 and 54 percent, respectively, compared to their baseline records. These highest improvements of physicochemical soil properties and crop productivity were mainly recorded from the interaction of $R1^+$ and M4. The results clearly showed that long-term sound crop rotation and organic matter application have a great potential for recovering the soil health and crop productivity of degraded cultivated land in Ethiopian highlands.*

Keywords: Equivalent yield; Fertility depletion; Manure application; Soil degradation; Soil properties; Sustainable fertility management

Introduction

Ethiopian highlands account for about 90% of crop production of the country, although they cover only 44% portion of the total surface area of the country (Teklu, 2005). Most cultivated lands of Ethiopian highlands are however literally sick owing to severe soil degradation and fertility depletion (Agegnehu *et al*., 2017, 2018). Soil degradation and fertility depletion are further noted as a fundamental cause for poor soil health and low crop productivity of cultivated lands in the highlands of the country (Mulualem and Yebo, 2015). A continuous exploitative cropping system, severe soil erosion, high nutrient mining mainly due to suboptimal fertilizer application, and poor soil fertilization efficiency are the main causes for soil degradation and poor productivity in Ethiopian highlands (Tamene *et al*., 2017).

Apart from traditional exploitative farming with complete removal of crop residues mainly for animal feed and local energy source, abandoning of crop rotation and organic matter application by farmers has also been claimed as the major primary cause for the degradation of Ethiopian crop soils especially in the highlands (Getachew *et al*., 2020). Using chemical fertilizers has been over popularized for more than four decades in the country and misled farmers wrongly to abandon crop rotation and organic matter applications (Agegnehu *et al*., 2018). Using inorganic fertilizers for crop production wouldn't indeed be considered as malpractice, but rather their exclusive usage for a long time without complementary application of organic matter would be the main shortcoming of using inorganic fertilizers by Ethiopian farmers (Getachew *et al*., 2020). Unlike organic fertilizers, chemical/inorganic fertilizers constitute a limited number of essential plant nutrients (only N and P in the Ethiopian case) and don't play a great role in improving the physical, chemical, and biological properties of crop soils (Goda, 2019). Habtamu *et al*. (2014) reported that over-relying on chemical fertilizer without the complement of organic input and continuous cereal cropping practice negatively impacted the productivity and physicochemical properties of cultivated soil in the northwest highlands of Ethiopia.

Long-term organic soil fertility management and sound crop rotation practices have been recommended for many years to resolve the challenges of poor-quality soils and their low crop productivity setbacks in various parts of the world (Fondere *et al*., 2015; Karažija *et al*., 2015; Moharana *et al.*, 2012). Since time immemorial before the start of using chemical fertilizers, farmyard manure applications and sound crop rotation practices were the only means of replenishing soil fertility of cultivated crop fields in Ethiopian highlands (Ketema and Bauer, 2011). According to Agegnehu *et al*. (2017), the most universal methods of sustainable soil fertilization are using crop rotations, cover cropping, maintaining crop residues, and relying on organic soil fertility amendments such as the use of animal and green manures. Moharana *et al.* (2012) noted that organic manure unquestionably sustains crop production and maintains soil quality, and it should hence be involved in the nutrient management of intensive cropping systems. Sound crop rotation practices have also been reported to play a great role in amending soil health and crop productivity (Waźniak and Kawecka-Radomka, 2016; Waźniak, 2019).

Before the start of using chemical fertilizers as stereotypical solutions for enhancing soil productivity, pragmatic crop rotation practices and farmyard manure applications were used for improving the health and productivity of crop soils in Ethiopian highlands (Ketema and Bauer, 2011; Tamene *et al.*, 2017). Despite the fact that multiple organic matter sources are widely available and sound crop rotation experiences are still traceable in the present study area of northwest Ethiopian highlands, farmers are however currently abandoning neither crop rotation practices nor organic matter applications owing to their misunderstanding on solely use of chemical fertilizers without supplementing organic fertilizers (Agegnehu *et al.*, 2017, 2018; Getachew *et al*., 2020). On the other hand, as indicated above, most crop soils of Ethiopian highlands are severely degraded and ended up with poor soil health and low crop productivity (Tamene *et al.,* 2017). There is hence an urgent need for recovering the soil health for sustainable crop production and productivity in Ethiopian highlands. Therefore, the main objective of the present study was to assess the extent of recovering the soil health and improving crop productivity of degraded cultivated land of northwest Ethiopian highlands through crop rotation and organic matter application.

Materials and Methods

Description of the study site

The study was carried out during the main rainy/cropping seasons in three consecutive years from 2013 to 2015 in one of the northwest Ethiopian highlands in Gusha Shinkurta rural village of Guagusa Shikudad district, Awi Zone. Geographically, the experimental site is located at 11°92' N latitude and 28°61' E longitude. The altitude of the experimental site is 2451 meters above sea level with a slope of 3.2 percent.

The weather data collected during the three-year experimental period from 2013 to 2015 showed that the study area was found as 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 (Figure 1). Rainfall distribution of the area was unimodal and the rainy season extended from May to October, but it reaches a peak in July. The dry season with a rainfall of less than 100 mm per month occurred from November to April. The maximum temperature started to decrease with the start of the main rainy season and reached the lowest below 20^0C in July and August when most days were covered with rainfall and heavy clouds. Following the cessation of the main rainfall and the decline of precipitation both in amount and distribution, the minimum temperature during the night decreased critically and became below 10^0C starting from October to February, in which a slight night frost occurred frequently. The minimum temperature rose above 10^0C in March when a shower of rainfall started and reached a maximum of 13.2 ^{o}C in April.

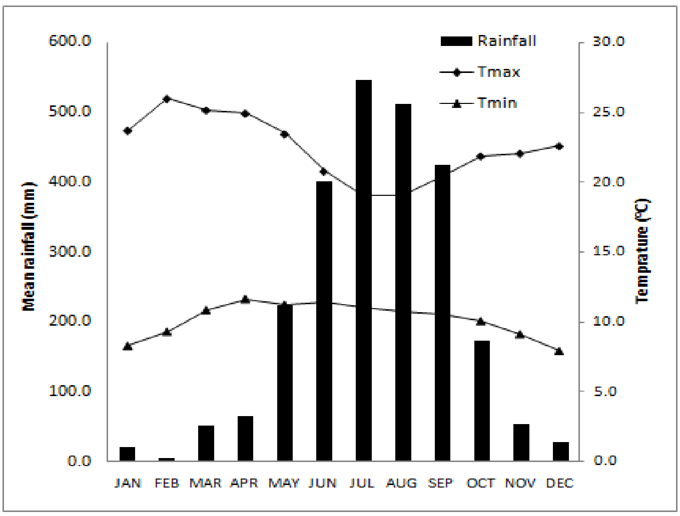

Figure 1. Average monthly rainfall, and minimum and maximum temperatures of the experimental sites during three years study period from 2013 to 2015 (Tmax = maximum temperature, Tmin = minimum temperature)

The soil of the study site is highly weathered and degraded Acrisol (Yihenew, 2015). The agricultural system of the area is small scale rainfed traditional mixed farming, where both crops and livestock are under the same unit of management, on average less than a hectare of landholding size per household. Bread wheat, barley, and potato are the dominant crops grown in the area. Faba bean, field pea, and lupine are also grown as subsidiary crops, although their area of production has been declining steadily due to the high population and disease pressures, and thereby giving priority to highly productive and profitable crops of bread wheat, and potato.

Experimental treatments, design, and procedures

At both on-station and on-farm testing sites, factorial combinations of five crop rotation practices: (1) bread wheat–clover–potato (R1+), (2) Clover–bread wheat undersowing lupine–potato (R2+), (3) Potato–clover–bread wheat (R3+), (4) Bread wheat undersowing lupine–potato undersowing lupine–bread wheat (R4+), (5) Lupine–potato undersowing lupine–bread wheat (R5+); and four manure application rates vis. (1) control without manure (M1), (2) 2.5 t ha^{-1} sesbania green manure SGM (M2), (3) 5 t ha^{-1} fresh cattle manure FCM (M3), and (4) 2.5 t ha^{-1} SGM + 5 t ha^{-1} FCM (M4) were laid out in randomized complete block design with four replications. The mother trial, where all four experimental replications (blocks) were found at the same site, was conducted at the on-station site, while the baby trials were conducted at on-farm sites that were located within a 5 km radius of the on-station site (mother trial). In baby trials, the four replications of the experiment 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. Five different crop rotations were devised in three rotation phases in 2013, 2014, and 2015 (Table 1), and all kinds of rotations were started on plots that were used for growing the same crop (bread wheat) in the immediate preceding cropping year of 2012 to avoid the differential residual effects of precursor crops. 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.

The Gross and net areas of the experimental plots were 3 m*3 m (9 m^2) and 2.6 m*2.6 m (6.76 m^2) with a distance of 0.5 m and 1 m between adjacent plots and replications, respectively. Since the same plots were used for three rotation phases in 22013, 014, and 215, randomization of treatments to the plots was done in the first rotation phase in 2013. As per treatments and design, fresh manure inputs (cattle manure and sesbania green manure after chopping up into 2-3 cm size) were uniformly surface broadcasted and incorporated in 20 cm soil depth two weeks before planting to minimize their negative effects on the emergence and seedling growth of newly planted crops. Improved varieties of bread wheat '*Tay*' and potato '*Belete*' as well as the most adaptive Ethiopian clover (*Trifolium decorum*) and local white lupine (*Lupinus album*) were used as test crops for crop rotation systems. Bread wheat seeds were drilled in 20 cm row spacing at the recommended seeding rate of 150 kg/ha in the first to the second weeks of July depending on the rainfall conditions. Similarly, seeds of Ethiopian clover were also drilled in 20 cm row spacing at the seeding rate of 3 kg/ha. As a pure stand, seeds of white lupine were planted in 40 cm inter-row and 10 cm intra-row spacing. 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 with 10 cm intra-row spacing in both cases.

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

Rotation system	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; bread wheat appeared six times in five rotation schemes in three years period; 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.

Clover and lupine plants at their 50% flowering were chopped up into 2-3 cm size and incorporated into the soil at 20 cm soil depth. After harvesting and threshing, crop residues of bread wheat were also chopped up into 2-3 cm size and incorporated into the soil manually. The amount of manure and average above-ground biomass of crop residues and/or green manure of preceding crops incorporated into the soil of experimental plots in three rotation phases are presented in Table 2. Other than the 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.

Soil sampling and analysis

Soil sampling and analysis were carried out two times, first initially before starting the experiment in 2013, and second finally after the completion of the experiment in 2015. At the beginning before starting the experiment in 2013, five soil samples at each testing site were collected randomly in a crisscross fashion of the whole plot at a plow depth of 0-20 cm using an augur and composited by taking an equal amount of soil from collected samples. Finally, after the completion of the experiment in 2015, soil sampling and compositing were rather done at each experimental plot basis following the same procedures used for samples collected initially before starting the experiment. In both cases, composite soil samples were air-dried and crushed with a motorized grinder and sieved with a 2 mm diameter screen sieve for further laboratory analysis.

Prepared composite soil samples were analyzed further at the soil laboratory of Adet Agricultural Research Center for determination of soil texture, pH, CEC, and contents of soil organic carbon (SOC), total nitrogen (TN), available phosphorous (AP), and exchangeable potassium (K^+). Particle size distribution (soil texture) was determined by the hydrometer method (Gee and Bauder, 1986), while soil pH was measured using a digital pH meter in a 1:2.5 soil-water suspension (Panda, 2010). Organic carbon (OC) was determined by wet digestion Walkley and Black method (Heanes, 1984). Determination of total N was carried out through the micro-Kjeldahl digestion method (Bremner and Mulvaney, 1982). Available phosphorus was determined by calorimetrically using Olsen's method (Olsen and Cole, 1954). Exchangeable potassium was determined by flame photometer as described by McLean (1965), while CEC was determined using the titration method (FAO, 2008).

Table 2. Average above-ground biomass of the preceding crop green manure/residue, and manure as treatment incorporated into experimental plots in three rotation phases

Trt combination			1st phase (2013)	2nd phase (2014)				3rd phase (2015)			
R	M	TC	Manure (ton ha^{-1})	Preceding crop			Manure (ton ha^{-1})	Preceding crop			Manure (ton ha^{-1})
				CB	LB	WB		CB	LB	WB	
R1$^+$	M1	T1	-	-	-	1.23	-	3.14	-	-	-
	M2	T2	2.50	-	-	1.51	2.50	4.46	-	-	2.50
	M3	T3	5.00	-	-	1.73	5.00	4.60	-	-	5.00
	M4	T4	7.50	-	-	2.62	7.50	5.76	-	-	7.50
R2$^+$	M1	T5	-	0.	-	-	-	-	0.79	1.37	-
	M2	T6	2.50	0.	-	-	2.50	-	0.85	2.80	2.50
	M3	T7	5.00	1.	-	-	5.00	-	1.15	4.45	5.00
	M4	T8	7.50	1.	-	-	7.50	-	1.29	5.13	7.50
R3$^+$	M1	T9	-	-	-	-	-	2.96	-	-	-
	M2	T10	2.50	-	-	-	2.50	3.47	-	-	2.50
	M3	T11	5.00	-	-	-	5.00	4.76	-	-	5.00
	M4	T12	7.50	-	-	-	7.50	5.42	-	-	7.50
R4$^+$	M1	T13	-	-	1.18	0.74	-	-	0.89	-	-
	M2	T14	2.50	-	1.31	0.91	2.50	-	1.18	-	2.50
	M3	T15	5.00	-	1.64	1.13	5.00	-	1.63	-	5.00
	M4	T16	7.50	-	2.07	1.42	7.50	-	2.24	-	7.50
R5$^+$	M1	T17	-	-	2.06	-	-	-	1.18	-	-
	M2	T18	2.50	-	2.23	-	2.50	-	1.24	-	2.50
	M3	T19	5.00	-	2.70	-	5.00	-	1.79	-	5.00
	M4	T20	7.50	-	3.15	-	7.50	-	2.27	-	7.50

For soil bulk density determination, three independent undisturbed core soil samples were taken randomly at each selected testing site before starting the experiment in 2013 and at each experimental plot after the completion of the experiment in 2015. Core soil samples were further oven-dried at 105°C for 24 hours and their bulk density was measured using the soil core method (Blake and Hartge, 1986). Percentile change/improvement of each soil variable (property) after three-year interventions of crop rotation and manure application was computed with Equation 1:

$$\Delta P(\%) = \frac{(fp-ip)}{ip} * 100 \qquad \text{Eq. (1)}$$

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

Manure and crop residue sampling and analysis

Before incorporating into the soil, collected cattle manure and chopped sesbania, clover and lupine green manure, and wheat crop residue were thoroughly mixed up separately and a five kg composite sample from each organic input was taken for further laboratory analysis. Composite samples of cattle manure and sesbania green manure were prepared by randomly taking and mixing up several samples from the mass, while composite samples of wheat crop residue and green manure of clover and lupine were prepared by taking an equal amount of samples randomly from the experimental plots.

Composited samples of the organic inputs were further oven-dried at 65^0C until a constant weight was attained. Their dry matter contents were estimated as the ratio of sample weights after and before oven drying and expressed in percentile. Oven-dried samples were then crushed and sieved for further analysis for organic carbon, total nitrogen, available phosphorous, and exchangeable potassium contents in the soil laboratory of Adet Agricultural Research Center. Organic carbon and total nitrogen contents of manure and crop residue samples were determined by DEGTJAREFF method (Walkley and Black, 1954) and the micro-Kjeldahl digestion method (N'Dayegamiye *et al*., 2015), respectively. Available phosphorous and exchangeable potassium contents of organic input samples were determined by the mass spectrophotometric method (Jackson, 1958). Average dry matter and macronutrients contents of the organic inputs determined for three years are presented in Table 3.

Table 3. Average dry matter and macronutrient contents of cattle manure and above-ground biomass of the preceding crop residue/green manure incorporated into the soil of experimental plots

Organic source (input)		DM (%)	Nutrient content				C:N ratio
			C (%)	N (%)	P (%)	K (%)	
Manure as treatment	Sesbania green manure	19.78	36.78	2.42	0.72	0.91	15.20:1
	Cattle manure	18.12	16.31	1.20	0.65	1.10	13.59:1
Preceding crop residue/green manure	Clover green manure	17.06	30.88	2.17	0.43	0.89	14.23:1
	Lupine green manure	16.23	28.97	1.95	0.31	0.88	14.86:1
	Wheat crop residue	90.41	52.06	0.32	0.03	0.76	162.69:1

DM, dry matter content; C, carbon; N, nitrogen; P, phosphorous; K, potassium. Samples of sesbania and cattle manure applied each year were taken for dry matter and macronutrient analysis. Similarly, an equal amount of biomass of the preceding crop residue/green manure was taken from similar treatment plots and composited for analysis of dry matter and macronutrient contents following their respective standard methods and procedures.

Crop yields data collection and equivalent yield estimation

Bread wheat, potato, clover, and lupine were the main crops rotated one after another. Weight of dry grain (adjusted to 12.5% moisture content), fresh clean marketable tuber (≥50 g), and above-ground fresh biomass at 50% flowering harvested from a net plot area and converted into hectare basis (ton/ha) was considered as yield of bread wheat, potato, and clover and lupine, respectively. Since yields of the experimental crops were different, it was not possible to compare their productivity at different treatment combinations in different rotation phases (2013-2015). Hence, it was necessary to convert yields of potato marketable tuber, and clover and lupine biomass into bread wheat grain equivalent yields using Equation 2:

$$BWGEY = PMTY\left(\frac{Price\ of\ PMT}{Price\ of\ BWG}\right), = CBY\left(\frac{Price\ of\ CB}{Price\ of\ BWG}\right), or = LBY\left(\frac{Price\ of\ LB}{Price\ of\ BWG}\right) \quad \text{Eq. (2)}$$

Where; BWGEY = bread wheat grain equivalent yield (t/ha), PMTY = potato marketable tuber yield (t/ha), CBY = clover biomass yield (t/ha), LBY = lupine biomass yield (t/ha), PMT = potato marketable tuber, BWG = bread wheat grain, CB = clover biomass, LB = lupine biomass.

Farmgate prices of the crops used for estimating the equivalent yields are presented in Table 4.

Table 4: Farmgate prices of bread wheat grain, potato marketable tuber, and clover and lupine biomass used for estimating the equivalent grain yield of bread wheat in the three rotation phases

Rotation phase (RP)	Price per ton in Ethiopian Birr			
	Bread wheat grain	Potato marketable tuber	Clover biomass	Lupine biomass
1st RP (2013)	8000	1500	6500	3500
2nd RP (2014)	12000	2000	6700	-
3rd RP (2015)	16000	2500	-	-

Bread wheat grain and potato marketable tuber for human consumption, while clover and lupine biomass for animal feed.

Data analysis

Soil laboratory analysis data of chemical and physical soil properties of the composite soil samples taken before the start of the experiment were compared against their respective critical levels (see rating references in Table 5). Whereas, soil data collected after the completion of the experiments, as well as crop yield data collected in each rotation phase, were subjected to analysis of variance (ANOVA) using general linear model (GLM) procedures of SAS version 9.4 (SAS Institute, 2013). Since values for the error mean square of the on-station and on-farm trials were homogeneous, the data were not combined over trial sites (Gomez and Gomez, 1984). Whenever the ANOVA result showed a significant difference between treatments for an experimental variable, further mean separation was done using the Tukey test at a probability level of 5% using the same statistical software.

Results and Discussion

Initial soil status

Results of the soil analysis for pre-planting soil samples taken before starting the experiment at both on-station and on-farm testing sites are presented in Table 5. Lab analysis results of pH, BD, CEC, OC, TN, AP, and K^+ status of the experimental soil before starting the experiment were rated according to Panda (2010), Blake and Hartge (1986), Landon (1991), Charman and Roper (2007), Havlin *et al*. (1999), Tekaign *et al*. (1991) and Metson (1961), respectively, while the texture of the soil was classified according to Brady and Weil (2017). The results showed that the texture of experimental soils both at on-station and on-farm testing sites was clay loam. The bulk density of the experimental soils before the experiment was high and classified as compact physically. The pH of the experimental soils was low and grouped as acidic. Furthermore, the soils of both testing sites were containing low organic carbon, total nitrogen, available phosphorous, and exchangeable potassium, while the cation exchange capacity (CEC) of the soils was rated as moderate. All physicochemical properties of experimental soils at on-station testing sites were slightly better than at on-farm testing sites.

High bulk density and low chemical properties of the experimental soils initially before starting the interventions of crop rotation and manure application indicated that the soil health of the cultivated land of the study area was poor generally. Problems of physicochemical properties of soils were also interrelated to each other. Similar to the present results, Yihenew (2015) and Agegnehu *et al*. (2017, 2018) reported also high soil bulk density (BD), and low pH, cation exchange capacity (CEC), soil organic carbon (SOC), total nitrogen (TN), available phosphorous (AP) and exchangeable potassium (K^+) in the cultivated land of the present study area in Awi highlands of northwest Ethiopian. High bulk density and low levels of chemical properties of the experimental soils verified the severity of soil degradation in the cultivated land of northwest Ethiopian highlands. Lower soil physicochemical properties at on-farm testing sites than at station testing site indicated that the severity of soil degradation in farmers' crop fields was higher than in research trial sites.

Table 5. The initial status of physicochemical properties of the experimental soils before starting the experiment in 2013 in northwest Ethiopian highlands

Soil properties	On-station	On-farm	Rating category	Rating reference
Bulk density (g/cm)	1.36	1.37	Compact	Blake and Hartge (1986)
pH (H_2O)	5.36	5.15	Acidic	Panda (2010)
CEC (cmol(+)/kg)	16.10	15.52	Moderate	Landon (1991)
Organic carbon (%)	1.30	1.25	Low	Charman and Roper (2007)
Total nitrogen (%)	0.13	0.11	Low	Havlin *et al*. (1999)
Available P (ppm)	9. 54	8.64	Very low	Tekalign *et al*. (1991)
Exchangeable K	0.68	0.67	Low	Metson (1961)
Particle distribution				Bouyoucos (1962)
Sand (%)	27.00	29.50		
Silt (%)	35.00	34.25		
Clay (%)	38.00	36.25		
Textural class	*Clay loam*	*Clay loam*		Brady and Weil (2017)

CEC, cation exchange capacity; P, phosphorus; K, potassium; ppm, part per million; pH, the potential of hydrogen. These results were also used as a baseline for computing the percentile changes/improvements of soil properties after three-year interventions of crop rotation and manure application.

High bulk density and low levels of chemical properties would largely be associated with serious degradation of soil organic matter as the result of exploitative farming with complete removal of crop residues, as well as of abandoning crop rotation and organic matter application into crop cultivated land of the study area (Agegnehu *et al*., 2017, 2018; Getachew *et al*., 2020; Habitamu *et al*. 2014). The low organic carbon content of the soils indicated poor replenishment of soil organic matter that led further to serious degradation of soil organic matter in continuously cultivated land of the study area, which was historically covered with forest before. Apart from improper soil management, a low level of soil organic matter could negatively affect the physical, chemical, and biological properties of crop soils, and thereby render eventually for low crop productivity (Goda, 2019; Tamene *et al*., 2017).

High bulk density of the experimental soils before the intervention of crop rotation and organic matter application revealed the deterioration of their physical properties particularly soil structure (Bezuayehu *et al*., 2003; Taye and Yifru, 2010). High bulk density was the reflection of the compact structure of the experimental soils, which might largely be associated with soil organic matter degradation. Compact soil structure would likely be manifested with less aggregation and stability of the structure of experimental soils, which might further attribute to increased soil erosion, reduce water holding capacity, deprive soil aeration and water infiltration, limit biological and enzyme activities, impede crop root penetration and proliferation, and thereby contribute for low crop productivity (Bezuayehu *et al*., 2003; Habtamu *et al*., 2014; Mulualem and Yebo, 2015).

High rainfall in the area coupled with high soil degradation might contribute to leaching cations and increasing soil acidity in the cultivated land of the study area (Agegnehu *et al*., 2017, 2018; Yihenew, 2015). According to the report of EATA (2013), soil degradation for long period in high rainfall areas of Ethiopian highlands leads to acidification of crop soils and approximately 41% of the total farmland of the country especially in the highlands is acidic. In acidic soils with low pH, there would be the reduction of soil microbial and enzymatic activities (Bohme *et al.,* 2005; Corstanje *et al.,* 2007), the fixation of soil-plant nutrients such as P, Mo, and Ca making them unavailable to plants (Yohanis, 1992), and the enhancement of solubility and availability of Fe, Cu, Mn, and Al up to the level of toxicity to crop plants (Negassa *et al.*,2007). In agreement with the present results of the experimental soils containing low NPK, Mulualem and Yebo (2015) also noted the low level of macronutrients in high rainfall areas of Ethiopian highlands as the result of continuous exploitative cropping system, high nutrient mining, severe soil erosion, and poor soil fertility management.

Soil health recovery with the treatments

Physical soil property recovery

Soil bulk density in the present study was considered as an important indicator for soil physical property and it was significantly (P<0.05) influenced by the interaction effect of crop rotation and manure application in a three-year period from 2013 to 2015 (Table 6). Bulk density and its percentile change of experimental soils decreased significantly (P<0.05) by the interaction effect of crop rotation and manure application rates. As compared to the initial BD status before starting the experiment, the interaction of crop rotation and manure application in a three-year period attributed to improving BD of experimental soils significantly by up to 25% (Table 6).

Table 6. BD and its percentile change of experimental soils after three-year crop rotation and manure application (2013-2015) in cultivated land of northwest Ethiopian highlands

Treatment combination		On-station testing site		On-farm testing sites	
Rotation (R)	Manure (M)	BD	∆BD	BD	∆BD
$R1^+$	M1	1.22^{abcde}	-10.29^{abcde}	1.27^{abcd}	-7.30^{abcd}
	M2	1.17^{bcdef}	-13.97^{bcdef}	1.21^{bcdef}	-11.68^{bcdef}
	M3	1.13^{efgh}	-16.91^{efgh}	1.18^{defg}	-13.87^{defg}
	M4	1.02^{i}	-25.00^{i}	1.09^{g}	-20.44^{g}
$R2^+$	M1	1.24^{abcd}	-8.82^{abcd}	1.31^{abc}	-4.38^{abc}
	M2	1.18^{bcde}	-13.24^{bcde}	1.23^{abcde}	-10.22^{abcde}
	M3	1.16^{cdef}	-14.71^{cdef}	1.20^{cdefg}	-12.41^{cdefg}
	M4	1.04^{hi}	-23.53^{hi}	1.11^{fg}	-18.98^{fg}
$R3^+$	M1	1.26^{abc}	-7.35^{abc}	1.32^{ab}	-3.65^{ab}
	M2	1.18^{bcde}	-13.24^{bcde}	1.27^{abcd}	-7.30^{abcd}
	M3	1.14^{defgh}	-16.18^{defgh}	1.22^{bcdef}	-10.95^{bcdef}
	M4	1.05^{ghi}	-22.79^{ghi}	1.14^{efg}	-16.79^{efg}
$R4^+$	M1	1.29^{a}	-5.15^{a}	1.34^{a}	-2.19^{a}
	M2	1.24^{abcd}	-8.82^{abcd}	1.30^{abc}	-5.11^{abc}
	M3	1.16^{cdef}	-14.71^{cdef}	1.24^{abcde}	-9.49^{abcde}
	M4	1.12^{efghi}	-17.65^{efghi}	1.15^{efg}	-16.06^{efg}
$R5^+$	M1	1.27^{ab}	-6.62^{ab}	1.32^{ab}	-3.65^{ab}
	M2	1.20^{abcde}	-11.76^{abcde}	1.28^{abcd}	-6.57^{abcd}
	M3	1.15^{defg}	-15.44^{defg}	1.22^{bcdef}	-10.95^{bcdef}
	M4	1.07^{fghi}	-21.32^{fghi}	1.14^{efg}	-16.79^{efg}
Sig. difference		*	*	*	*
SE±		0.04	2.94	0.04	2.95
CV(%)		6.19	NA	6.98	NA

∆(%), percentile change after crop harvest in 2015 compared to its initial status just before starting the experiment in 2013; *significant at P<0.05; means followed with the same letters are not significantly different at P≥0.05; NA, not applicable.

The highest reduction in soil bulk density (-25%) was recorded by the interaction of $R1^+$ and M4 ($R1^+$M4) at the on-station testing site, while the lowest reduction in bulk density (only -2.19%) was recorded by the interaction of $R4^+$ and M1 ($R4^+$M1) at on-farm testing sites. Across all crop rotation systems, soil bulk density decreased markedly with the increase of manure application rates, and the lowest bulk density was recorded at the highest manure application rate (7.5 ton ha^{-1}). Among crop rotations, $R1^+$ followed by $R2^+$ attributed to the highest soil bulk density reduction, while $R4^+$ attributed to the lowest soil bulk density reduction. Whereas, $R3^+$ and $R5^+$ had a comparable effect on soil bulk density reduction after $R1^+$ and $R2^+$.

Chemical soil properties recovery

Chemical properties of the experimental soils including pH, CEC, and contents of organic carbon (OC), total nitrogen (TN), available phosphorous (AP) and exchangeable potassium (K^+) were also significantly (P<0.05) influenced by three-year interventions with crop rotation and manure application positively (Table 7). After three-year interventions with crop rotation and manure application, pH, CEC, OC, TN, AP, and K^+ of the experimental soils improved up to 20, 67, 92, 154, 96, and 54 percent, respectively, compared to their initial status (Table 8). In all cases, the highest and lowest improvements were recorded at the combinations of $R1^+M4$ and $R4^+M1$, respectively.

In all crop rotation systems, the chemical properties (pH, CEC, OC, TN, AP, and K^+) of the experimental soils increased consistently with the increase of manure application rates from 0 to 7.5 ton/ha (Tables 7). Like that of bulk density, crop rotations had also a similar trend of influence on all chemical properties in the order of $R1^+ > R2^+ > R3^+ \approx R5^+ > R4^+$. The interaction of different crop rotation systems with the control without manure application resulted even in the improvement of pH, CEC, OC, TN, AP, and K^+ of the experimental soils up to 7, 34, 29, 36, 49, and 22 percent, respectively (Table 8). Overall improvement effect of three-year crop rotation and manure application on physicochemical properties of experimental soils at the on-station testing site was better than at on-farm testing sites.

Table 7. Chemical properties of experimental soils after three-year crop rotation and manure application from 2013 to 2015 in cultivated land of northwest Ethiopian highlands

Treatment combination		On-station testing site						On-farm testing sites					
Rotation	Manure	pH	CEC	OC	TN	AP	K^+	pH	CEC	OC	TN	AP	K^+
$R1^+$	M1	5.72^{abcd}	21.56^{efg}	1.67^{gh}	0.17^{ij}	14.00^{gh}	0.83^{cdefg}	5.50^{defg}	19.98^{efg}	1.51^{g}	0.15^{hi}	12.85^{efg}	0.74^{efgh}
	M2	5.94^{abcd}	24.55^{bcd}	2.24^{bc}	0.21^{gh}	15.60^{bcdef}	0.88^{bcde}	5.68^{bcdefg}	20.43^{e}	1.84^{cdef}	0.18^{fg}	14.35^{cde}	0.78^{cdef}
	M3	6.09^{abcd}	25.62^{ab}	2.37^{ab}	0.26^{c}	16.98^{ab}	0.93^{abcd}	6.05^{ab}	21.60^{bcd}	2.07^{ab}	0.24^{bc}	15.10^{bc}	0.85^{abc}
	M4	6.23^{a}	26.90^{a}	2.50^{a}	0.33^{a}	17.35^{a}	1.05^{a}	6.17^{a}	25.28^{a}	2.26^{a}	0.27^{a}	16.96^{a}	0.91^{a}
$R2^+$	M1	5.67^{bcd}	21.43^{efg}	1.65^{gh}	0.15^{jk}	13.88^{gh}	0.81^{defgh}	5.45^{efg}	19.28^{efg}	1.45^{gh}	0.14^{ij}	12.58^{fgh}	0.72^{fgh}
	M2	5.86^{abcd}	24.32^{bcd}	2.23^{bcd}	0.19^{hi}	15.13^{defg}	0.86^{bcdef}	5.75^{bcdef}	20.39^{e}	1.84^{cdef}	0.17^{gh}	14.08cdef	0.75^{efgh}
	M3	6.04^{abcd}	25.34^{ab}	2.26^{bc}	0.24^{def}	15.96^{abcde}	0.92^{bcd}	5.93^{abc}	21.27^{cde}	2.05^{abc}	0.23^{cd}	14.53^{cd}	0.80^{bcde}
	M4	6.17^{ab}	26.41^{ab}	2.49^{a}	0.29^{b}	17.13^{ab}	1.01^{a}	6.05^{ab}	24.65^{ab}	2.17^{ab}	0.25^{abc}	16.84^{a}	0.87^{abc}
$R3^+$	M1	5.60^{cd}	20.38^{fg}	1.63^{gh}	0.15^{jk}	12.80^{hi}	0.72^{gh}	5.42^{fg}	17.95^{fg}	1.40^{gh}	0.14^{ij}	11.63^{ghi}	0.70^{gh}
	M2	5.82^{abcd}	21.56^{efg}	1.84^{fg}	0.17^{ij}	14.33^{fgh}	0.75^{fgh}	5.75^{bcdef}	20.22^{ef}	1.49^{gh}	0.16^{ghi}	13.46^{def}	0.74^{efgh}
	M3	5.95^{abcd}	23.03^{cde}	2.06^{cde}	0.23^{efg}	14.94^{defg}	0.79^{efgh}	5.85^{abcd}	21.24^{de}	1.82^{def}	0.21^{de}	14.24^{cde}	0.77^{defg}
	M4	6.14^{abc}	24.83^{abc}	2.20^{bcd}	0.27^{bc}	16.90^{ab}	0.96^{ab}	6.05^{ab}	24.20^{ab}	2.06^{ab}	0.24^{bc}	16.37^{ab}	0.83^{bcd}
$R4^+$	M1	5.58^{d}	20.03^{g}	1.60^{h}	0.14^{k}	11.98^{i}	0.69^{h}	5.33^{g}	17.80^{g}	1.28^{h}	0.12^{j}	10.75^{i}	0.68^{h}
	M2	5.81^{abcd}	21.47^{efg}	1.72^{gh}	0.15^{jk}	14.12^{fgh}	0.71^{gh}	5.63^{cdefg}	20.18^{efg}	1.44^{gh}	0.14^{ij}	13.40^{def}	0.69^{h}
	M3	5.87^{abcd}	21.62^{efg}	1.97^{ef}	0.22^{fg}	14.60^{efg}	0.75^{fgh}	5.80^{abcdef}	20.93^{e}	1.68^{f}	0.18^{fg}	14.09^{cdef}	0.72^{fgh}
	M4	6.12^{abcd}	24.20^{bcd}	2.10^{cde}	0.25^{cde}	16.40^{abcd}	0.88^{bcde}	5.85^{abcd}	23.65^{abc}	1.98^{bcde}	0.23^{cd}	16.11^{ab}	0.80^{bcde}
$R5^+$	M1	5.65^{bcd}	20.33^{fg}	1.62^{h}	0.14^{k}	12.33^{i}	0.70^{h}	5.42^{fg}	17.87^{fg}	1.34^{gh}	0.12^{j}	11.12^{hi}	0.68^{h}
	M2	5.82^{abcd}	21.54^{efg}	1.81^{fgh}	0.16^{jk}	14.20^{fgh}	0.74^{fgh}	5.70^{bcdefg}	20.23^{ef}	1.48^{gh}	0.15^{hi}	13.80^{cdef}	0.73^{efgh}
	M3	5.91^{abcd}	22.56^{def}	2.02^{def}	0.23^{efg}	14.86^{defg}	0.78^{efgh}	5.82^{abcde}	21.06^{e}	1.78^{ef}	0.20^{ef}	14.23^{cde}	0.75^{efgh}
	M4	6.13^{abcd}	24.65^{abcd}	2.12^{cde}	0.26^{c}	16.50^{ab}	0.95^{abc}	5.90^{abc}	23.88^{ab}	2.00^{bcd}	0.24^{bc}	16.41^{ab}	0.84^{abcd}
Sig. difference		*	**	**	*	**	**	*	**	**	*	**	**
SE±		0.20	0.84	0.08	0.01	0.57	0.05	0.14	0.88	0.08	0.01	0.57	0.03
CV%		4.01	7.25	7.73	8.10	7.54	10.77	4.94	8.36	8.63	7.46	8.04	6.99

**Highly significant at $P<0.01$; *significant at $P<0.05$; means in a column followed with the same letter are not significantly different at $P\geq0.05$.

Table 8. Percentile changes of chemical properties of experimental soils after three-year crop rotation and manure application in 2015 compared to the initial status before starting the experiment in 2013

Treatment combination		On-station testing site						On-farm testing sites					
Rotation	Manure	∆pH	∆CEC	∆OC	∆TN	∆AP	∆K^{+}	∆pH	∆CEC	∆OC	∆TN	∆AP	∆K^{+}
R1^{+}	M1	6.72^{abcd}	33.91^{efg}	28.46^{gh}	30.77^{ij}	46.75^{gh}	22.06^{cdefg}	6.80^{defg}	28.74^{efg}	20.80^{g}	36.36^{ji}	48.73^{efg}	10.45^{efgh}
	M2	10.82^{abcde}	52.48^{bcd}	72.31^{bc}	61.54^{gh}	63.52^{bcdef}	29.41^{bcde}	10.29^{bcdefg}	31.64^{e}	47.20^{cdef}	63.64^{fg}	66.09^{cde}	16.42^{cdef}
	M3	13.62^{abcd}	59.13^{ab}	82.31^{ab}	100.00^{c}	77.99^{ab}	36.7^{6abcd}	17.48^{ab}	39.18^{bcd}	65.60^{ab}	118.18^{bc}	74.77^{bc}	26.87^{abc}
	M4	16.23^{a}	67.08^{a}	92.31^{a}	153.85^{a}	81.87^{a}	54.41a	19.81^{a}	62.89^{a}	80.80^{a}	145.45^{a}	96.30^{a}	35.82^{a}
R2^{+}	M1	5.78^{bcd}	33.11^{efg}	26.92^{gh}	15.38^{jk}	45.49^{gh}	19.12^{defgh}	5.83^{efg}	24.23^{efg}	16.00^{gh}	27.27^{ij}	45.60^{fgh}	7.46^{fgh}
	M2	9.33^{abcd}	51.06^{bcd}	71.54^{bcd}	46.15^{hi}	58.60^{defg}	26.47^{bcdef}	11.65^{bcdef}	31.38^{e}	47.20^{cdef}	54.55^{gh}	62.96^{cdef}	11.94^{efgh}
	M3	12.69^{abcd}	57.39^{ab}	73.85^{bc}	84.62^{def}	67.30^{abcde}	35.29^{bcd}	15.15^{abc}	37.05^{cde}	64.00^{ab}	109.09^{cd}	68.17^{cd}	19.40^{bcde}
	M4	15.11^{ab}	64.04^{ab}	91.54^{a}	123.08^{b}	79.56^{ab}	48.53^{a}	17.48^{ab}	58.83^{ab}	73.60^{ab}	127.27^{abc}	94.91^{a}	29.85^{abc}
R3^{+}	M1	4.48^{cd}	26.58^{fg}	25.38^{gh}	15.38^{jk}	34.17^{hi}	5.88^{gh}	5.24^{fg}	15.66^{fg}	12.00^{gh}	27.27^{ij}	34.61^{ghi}	4.48^{gh}
	M2	8.58^{abcd}	33.91^{efg}	41.54^{fg}	30.77^{ij}	50.21^{fgh}	10.29^{fgh}	11.65^{bcdef}	30.28^{ef}	19.20^{gh}	45.45^{ghi}	55.79^{ef}	10.45^{efgh}
	M3	11.01^{abcd}	43.04^{cde}	58.46^{cde}	76.92^{efg}	56.60^{defg}	16.18^{efgh}	13.59^{abcd}	36.86^{de}	45.60^{def}	90.91^{de}	64.81^{cde}	14.93^{defg}
	M4	14.55^{abc}	54.22^{ab}	69.23^{bcd}	107.69^{bc}	77.15^{ab}	41.18^{ab}	17.48^{ab}	55.93^{ab}	64.80^{ab}	118.18^{bc}	89.47^{ab}	23.88^{bcd}
R4^{+}	M1	4.10^{d}	24.41^{g}	23.08^{h}	7.69^{k}	25.58^{i}	1.47^{h}	3.50^{g}	14.69^{g}	2.40^{h}	9.09^{j}	24.42^{i}	1.49^{h}
	M2	8.40^{abcd}	33.35^{efg}	32.31^{gh}	15.38^{jk}	48.01^{fgh}	4.41^{gh}	9.32^{cdefg}	30.03^{efg}	15.20^{gh}	27.27^{ij}	55.09^{def}	2.99^{h}
	M3	9.51^{abcd}	34.29^{efg}	51.54^{ef}	69.23^{fg}	53.04^{efg}	10.29^{fgh}	12.62^{abcdef}	34.86^{e}	34.40^{f}	63.64^{fg}	63.08^{cdef}	7.46^{fgh}
	M4	14.18^{abcd}	50.31^{bcd}	61.54^{cde}	92.31^{cde}	71.91^{abcd}	29.41^{bcde}	13.59^{abcd}	52.38^{abc}	58.40^{bcde}	109.09^{cd}	86.46^{ab}	19.40^{bcde}
R5^{+}	M1	5.41^{bcd}	26.27^{fg}	24.62^{h}	7.69^{k}	29.25^{i}	2.94^{h}	5.24^{fg}	15.14^{fg}	7.20^{gh}	9.09^{j}	28.70^{hi}	1.49^{h}
	M2	8.58^{abcd}	33.79^{efg}	39.23^{fgh}	23.08^{jk}	48.85^{fgh}	8.82^{fgh}	10.68^{bcdefg}	30.35^{ef}	18.40^{gh}	36.36^{hi}	59.72^{cdef}	8.96^{efgh}
	M3	10.26^{abcd}	40.12^{def}	55.38^{def}	76.92^{efg}	55.77^{defg}	14.71^{efgh}	13.01^{abcde}	35.70^{e}	42.40^{ef}	81.82^{ef}	64.70^{cde}	11.94^{efgh}
	M4	14.37^{abcd}	53.11^{abcd}	63.08^{cde}	100.00^{c}	72.96^{ab}	39.71^{abc}	14.56^{abc}	53.87^{ab}	60.00^{bcd}	118.18^{bc}	89.93^{ab}	25.37^{abcd}
Sig. difference		*	**	**	*	**	**	*	**	**	*	**	**
SE±		3.81	5.42	6.57	5.67	5.95	6.49	3.00	4.54	6.16	6.68	6.90	3.85

**Highly significant at *P*<0.01; *significant at *P*<0.05; means in a column followed with the same letter are not significantly different at *P*≥0.05.

Marked improvements of physical and chemical properties of the experimental soils after three-year interventions with crop rotation and manure application showed that the soil health of the cultivated land of the study area could significantly be recovered through regular application of organic matter and sound crop rotation practices. In agreement with the present results, many workers in different years and countries reported that crop rotation and/or organic matter application improved soil bulk density, pH, CEC, and contents of soil organic carbon, total nitrogen, available phosphorous, and exchangeable potassium of cultivated land at various magnitudes (Karazija *et al*., 2015; Moharana *et al*., 2012; Perez *et al*., 2014; Waźniak, 2019). Similar to the results of the present study, several authors also reported that the improvement of physicochemical properties of cultivated land soils was invariably increased with the increase of organic matter application rates (De Clercq *et al*., 2015; Fonderer *et al*., 2015; Ram *et al*., 2014). In line with the results of the current study, Yusuf *et al*. (2009) and Perez *et al*. (2014) also reported that cereal-legume rotation improved soil physicochemical properties of cultivated land better than cereal-cereal or legume-legume cropping.

The significant improvements of soil physicochemical properties (BD, pH, CEC, and content of OC, TN, AP, and K^+) through regular crop rotation and manure application for three years might be associated with the cumulative direct and residual effects of manure application as treatment and incorporation of crop residues and/or green manure into the soil as part of crop rotation in the three-years period. In harmony with the present results, Moharana *et al*. (2012) and Ram *et al*. (2014) noted that, unlike most inorganic soil fertilizers, organic fertilizers do have a residual effect for several years and a series of residual effects added forward under regular annual application of organic inputs. Cumulative direct and residual effects of manure application and incorporation of crop residues and/or green manure on the improvements of soil physicochemical properties might also be dependent upon quality and quantity of manure and crop residues and/or green manure of the preceding crops. This was confirmed with the improvements of soil property as the increase of manure application rates, as well as with the differential improvement effects of different crop rotation systems on soil properties. Differences among crop rotation systems for the improvements of physical and chemical properties of experimental soils were likely due to their differences in quality and quantity of crop residues and/or green manure of the preceding crops incorporated into the soil. The highest improvement of soil properties was recorded in bread wheat-clover-potato rotation ($R1^+$). This might be associated with the highest total biomass of crop residues and/or green manure of the preceding crops incorporated into the soil in a three-year period in this $R1^+$

crop rotation system. Better levels of soil physicochemical properties at the on-station testing site than at on-farm testing sites initially before starting the experiment, as well as after three-year interventions of crop rotation and manure application indicated also an additive nature of physicochemical properties of soils.

Combination of manure application as treatment and incorporation of crop residues and/green manure into the soil as part of crop rotation resulted in more significant soil property improvement than either one of them separately, while manure and crop residues and/or green manure of the preceding crops would have an additive effect on the improvement of soil physicochemical properties. Cumulative direct and residual effects of regular manure application and incorporation of crop residues and/or green manure of the preceding crops for three consecutive years might have contributed to enhanced organic matter content of the experimental soils. Similarly, Moharana *et al*. (2012) also reported that the long-term application of organic fertilizers resulted in the accumulation of organic matter in crop soils. This accumulated and enhanced soil organic matter would further be accounted for the improvement of soil BD, pH, CEC, and contents of OC, TN, AP, and K^+ of degraded cultivated land of the study area.

Improvement responses of physical and chemical properties of the experimental soils to three-years manure application and incorporation of crop residues and/or green manure of preceding crops were quite different, but showed similar trends across treatment combinations in the order of TN>SOC>AP>CEC>K^+>BD>pH. Several workers reported also similar results to the present study (Fonderer *et al*., 2015; Perez *et al*., 2014; Waźniak and Kawecka-Radomka, 2016). Significant reduction of soil bulk density of the experimental soils after three-year interventions of crop rotation and manure application indicated the improvement of the physical properties of the cultivated land of the study area. This physical soil property improvement could be associated with the enhancement of aggregation and stability of soil structure as the result of soil organic matter accumulation in three-year regular crop rotation and manure application (Martínez *et al.,* 2013; Mutegi, 2012). Well aggregated soil structure would in turn increase soil porosity that is important for root and soil microbes proliferation, aeration, water retention, and movement, and further, stability of soil aggregates also prevents surface sealing, minimizes soil erosion, and eases tillage practices (Bezuayehu *et al*., 2003; Martínez *et al*., 2013; Taye and Yifru, 2010). Improvement of these physical properties of experimental soils might eventually have contributed a lot to the improvement of crop productivity.

Similarly, the significant improvement in soil pH of experimental soils after three-year crop rotation and manure application might be associated with the enriched soil organic matter, which could play a great role in improving cation exchange capacity and enhancing cations that might be released from its mineralization. More than its direct effect on improving the soil pH, enhanced soil organic matter might rather play a great role in binding toxic elements like Cu, Mn, and Al in highly acidic soils and thereby enhancing soil biological activities, as well as crop diversity and productivity (Golla, 2019; Tamene *et al*., 2017). The increase of organic matter in acidic soils is also important for reducing the fixation of nutrients like phosphorous primarily through binding the fixing materials mainly Fe- and Al-oxides (Golla, 2019). Negassa *et al*. (2007) earlier indicated that high soil organic matter checks soil pH and reduces Al toxicity and P-fixation in acidic soils.

Highly significant -increase in CEC of the experimental soils after three-years crop rotation and manure application might also be due to the enhancement of soil organic matter content as the result of cumulative direct and residual effects of regular crop rotation and manure application for three years. Since soil organic matter (humus) is part of negatively charged soil colloidal materials that account for cation exchange (Brady and Weil, 2017), enhanced soil organic matter might directly attribute to improving the cation exchange capacity of experimental soils. As CEC is essential for retaining and storing exchangeable soil mineral nutrients, the observed significant increase of CEC in the present study indicated the significant fertility improvement of the experimental soils with three-year crop rotation and manure application. Discernible improvements of TN, AP, and K^+ of the experimental soils also indicated the enhancement of soil-plant nutrients in the cultivated land of the study area with regular manure application and incorporation of crop residues and/or green manure of the preceding crops. The release of plant nutrients through mineralization of organic matter might increase proportionally with the increase of soil organic matter.

Crop productivity recovery with the treatments

At both on-station and on-farm testing sites, productivities of bread wheat, potato, clover, and/or lupine as influenced by crop rotation and/or manure application in three different rotation phases (2013-2015) are presented in Tables 9, 10, and 11, respectively. Since farmers in the study area have currently been given high priority to produce bread wheat and potato, rotation schemes were designed to appear bread wheat, and potato in all three different rotation phases from 2013 to 2015. On the other hand, lupine as the sole crop appeared only in the first rotation phase of 2013, while clover appeared in the first and second rotation phases of 2013 and 2014. Although the effects of crop rotation and/or manure application on productivities of experimental crops were significant ($P<0.05$), the least productivities were recorded in the first rotation phase of 2013 (Tables 9, 10, and

11). As the progress of rotation phases from 2013 to 2015, the productivities of experimental crops increased highly significantly (P<0.01) by crop rotation and manure application. In all three rotation phases, crop productivities at the on-station trial site were better than at on-farm trial sites.

The least crop productivities in the first rotation phase (2013) reflected indirectly the severity of soil degradation and fertility depletion in the study area. These results indicated further low crop productivity responses to crop rotation and manure application in degraded soils. Significant productivity differences in 2013 might largely be associated with manure application rates. But, the effect of crop rotation on crop productivities in 2013 was not significantly visible, indicating to trace the direct effect of manure application in the first rotation phase. In the first rotation phase, productivities of lupine were much higher than clover, revealing a better response of lupine to the degraded soils, as well as to manure application in degraded soils than clover. In the second and third rotation phases, direct and residual effects of manure treatments and crop residues/green manure of preceding crops accumulated further (Ram *et al.*, 2014) to result marked increase in crop productivities with the progress of rotation phases in 2014 and 2015.

Table 9: Grain, marketable tuber, and biomass yields of bread wheat, potato, and clover and lupine as influenced by crop rotation and manure application in the first rotation phase of 2013

Treatment combination		On-station testing site				On-farm testing sites			
Crop rotation	Manure	BWGY	PMTY	CBY	LBY	BWGY	PMTY	CBY	LBY
R1+	M1	0.95f	-	-	-	0.69e	-	-	-
	M2	1.07e	-	-	-	0.99d	-	-	-
	M3	1.24cd	-	-	-	1.21c	-	-	-
	M4	1.61b	-	-	-	1.45b	-	-	-
R2+	M1	-	-	0.72c	-	-	-	0.49d	-
	M2	-	-	1.04b	-	-	-	0.86c	-
	M3	-	-	1.15a	-	-	-	1.01b	-
	M4	-	-	1.22a	-	-	-	1.14a	-
R3+	M1	-	6.14d	-	-	-	5.49d	-	-
	M2	-	8.78c	-	-	-	8.37c	-	-
	M3	-	10.97b	-	-	-	9.81b	-	-
	M4	-	14.68a	-	-	-	14.09a	-	-
R4+	M1	0.96f	-	-	-	0.80e	-	-	-
	M2	1.14de	-	-	-	1.09d	-	-	-
	M3	1.32c	-	-	-	1.26c	-	-	-
	M4	1.85a	-	-	-	1.63a	-	-	-
R5+	M1	-	-	-	2.23d	-	-	-	1.77d
	M2	-	-	-	2.45c	-	-	-	2.01c
	M3	-	-	-	2.86b	-	-	-	2.54b
	M4	-	-	-	3.42a	-	-	-	2.88a
Sig. difference		*	*	*	*	*	*	*	*
SE±		0.04	0.33	0.02	0.04	0.03	0.26	0.02	0.04
CV(%)		5.68	6.45	3.89	2.92	6.13	5.58	5.41	3.80

BWGY, bread wheat grain yield (t ha^{-1}); PMTY, potato marketable tuber yield (t ha^{-1}); CBY, clover biomass yield (t ha^{-1}); LBY, lupine biomass yield (t ha^{-1}); means in a column followed with the same letter are not significantly different at $P \geq 0.05$.

Table 10: Grain, marketable tuber and biomass yields of bread wheat, potato, and clover as influenced by crop rotation and manure application in the second rotation phase of 2014

Treatment combination		On-station testing site			On-farm testing sites		
Crop rotation	Manure	BWGY	PMTY	CBY	BWGY	PMTY	CBY
R1+	M1	-	-	3.26^{d}	-	-	3.02^{e}
	M2	-	-	4.35^{c}	-	-	4.29^{c}
	M3	-	-	4.96^{b}	-	-	4.78^{b}
	M4	-	-	5.89^{a}	-	-	5.63^{a}
R2+	M1	1.54^{d}	-	-	1.46^{d}	-	-
	M2	2.52^{c}	-	-	2.04^{c}	-	-
	M3	2.97^{b}	-	-	2.65^{b}	-	-
	M4	3.22^{a}	-	-	3.18^{a}	-	-
R3+	M1	-	-	3.12^{d}	-	-	2.80^{e}
	M2	-	-	3.61^{c}	-	-	3.33^{d}
	M3	-	-	4.72^{b}	-	-	4.38^{bc}
	M4	-	-	5.57^{a}	-	-	5.25^{a}
R4+	M1	-	9.42^{d}	-	-	8.21^{d}	-
	M2	-	14.86^{c}	-	-	14.33^{c}	-
	M3	-	21.64^{b}	-	-	20.78^{b}	-
	M4	-	24.39^{a}	-	-	23.62^{a}	-
R5+	M1	-	9.73^{d}	-	-	8.92^{d}	-
	M2	-	15.01^{c}	-	-	14.43^{c}	-
	M3	-	21.30^{b}	-	-	20.37^{b}	-
	M4	-	24.28^{a}	-	-	23.04^{a}	-
Sig. difference		**	**	**	**	**	**
SE±		0.05	0.61	0.08	0.10	0.66	0.10
CV(%)		3.56	6.90	3.65	8.28	7.87	4.59

Means in a column followed with the same letter are not significantly different at $P \geq 0.05$.

Table 11: Grain and marketable tuber yields of bread wheat and potato as influenced by crop rotation and manure application in the third rotation phase of 2015

Treatment combination		On-station testing site		On-farm testing sites	
Crop rotation	Manure	BWGY	PMTY	BWGY	PMTY
R1+	M1	-	13.52^{ef}	-	12.71^{de}
	M2	-	18.67^{d}	-	16.55^{d}
	M3	-	23.92^{bc}	-	23.19^{bc}
	M4	-	34.02^{a}	-	32.54^{a}
R2+	M1	-	10.90^{f}	-	10.77^{e}
	M2	-	16.64^{de}	-	15.09^{d}
	M3	-	22.97^{c}	-	21.72^{c}
	M4	-	26.51^{bc}	-	25.28^{bc}
R3+	M1	1.97^{gh}	-	2.01^{fg}	-
	M2	2.65^{ef}	-	2.77^{cde}	-
	M3	3.61^{cd}	-	3.15^{bc}	-
	M4	4.83^{a}	-	4.14^{a}	-
R4+	M1	1.71^{h}	-	1.53^{h}	-
	M2	2.33^{fg}	-	2.37^{ef}	-
	M3	3.26^{de}	-	2.91^{cd}	-
	M4	3.87^{bc}	-	3.39^{b}	-
R5+	M1	1.89g		1.60^{gh}	
	M2	2.38^{fg}		2.55^{de}	
	M3	3.41^{cd}		3.03^{bc}	
	M4	4.28^{b}		3.47^{b}	
Sig. difference		**	**	**	**
SE±		0.15	0.92	0.14	0.90
CV(%)		9.74	8.77	10.02	9.11

Means in a column followed with the same letter are not significantly different at $P \geq 0.05$.

For proper comparison of productivity responses to the treatments, it was necessary to have a common productivity variable for all experimental crops. Hence, the productivity of experimental crops was converted into bread wheat equivalent yield and its results are presented in Table 12. Bread wheat equivalent yield was significantly ($P<0.05$) influenced by the interaction of crop rotation and manure application at both on-station and on-farm testing sites. Similar to productivities of experimental crops, at both on-station and on-farm testing sites, the effect of crop rotation and manure application on equivalent grain yield of bread wheat was highly significantly ($P<0.01$) pronounced as the progress of rotation phases from 2013 to 2015.

Crop rotation and manure application for three consecutive years (2013-2015) attributed to increasing the productivity of equivalent grain yield of bread wheat up to 13.3 folds (1230%). The highest equivalent grain yield of bread wheat (5.32 ton ha^{-1}) was recorded with R1^{+}M4 in 2015 at the on-station testing site, while the lowest equivalent grain yield of bread wheat (0.4 ton ha^{-1}) was recorded with R2^{+}M1 in 2013 at on-farm testing sites (Table 12). In all rotation phases (2013-2015), the overall productivity of bread wheat equivalent grain was also superior at the on-station testing site than at on-farm testing sites.

Table 12. Equivalent grain yield of bread wheat as influenced by crop rotation and manure application in degraded cultivated land of northwest Ethiopian highland

Treatment combination		On-station testing site			On-farm testing sites		
Crop rotation	Manure	2013	2014	2015	2013	2014	2015
R1^{+}	M1	0.95^{ij}	1.82^{ij}	2.11^{ijk}	0.69k	1.69h^{ij}	1.99^{jk}
	M2	1.07^{ghi}	2.43^{gh}	2.92^{fgh}	0.99^{fghi}	2.40^{fg}	2.59^{hi}
	M3	1.24^{ef}	2.77^{efg}	3.74^{cde}	1.21^{e}	2.67^{ef}	3.62^{de}
	M4	1.61^{d}	3.29^{bcd}	5.32^{a}	1.45^{d}	3.14^{cd}	5.08^{a}
R2^{+}	M1	0.59^{k}	1.54^{j}	1.70^{k}	0.40^{l}	1.46^{j}	1.68^{k}
	M2	0.85^{j}	2.52^{gh}	2.60^{hi}	0.70^{k}	2.04^{gh}	2.36^{ij}
	M3	0.93^{ij}	2.97^{def}	3.59^{de}	0.82^{ijk}	2.65^{ef}	3.39^{efg}
	M4	0.99^{ghij}	3.22^{bc}	4.14^{cd}	0.93^{ghij}	3.18^{cd}	3.95^{cd}
R3^{+}	M1	1.15^{fg}	1.74^{ij}	1.97^{jk}	1.03^{fgh}	1.56^{ij}	2.01^{jk}
	M2	1.65^{d}	2.02^{hi}	2.65^{ghi}	1.57^{cd}	1.86^{hi}	2.77^{hi}
	M3	2.06^{b}	2.64^{fgh}	3.61^{de}	1.84^{b}	2.45^{f}	3.15^{efg}
	M4	2.75^{a}	3.11^{cde}	4.83^{ab}	2.64^{a}	2.93^{de}	4.14^{bc}
R4^{+}	M1	0.96^{ij}	1.57^{j}	1.71^{k}	0.80^{jk}	1.37^{j}	1.53^{k}
	M2	1.14^{fgh}	2.48^{g}	2.33^{ij}	1.09^{efg}	2.39^{fg}	2.37^{ij}
	M3	1.32^{e}	3.61^{b}	3.26^{efg}	1.26^{e}	3.46^{bc}	2.91^{gh}
	M4	1.85^{c}	4.07^{a}	3.87^{cde}	1.63^{c}	3.94^{a}	3.39^{efg}
R5^{+}	M1	0.98^{hij}	1.62^{ij}	1.89^{jk}	0.77^{jk}	1.49^{ij}	1.60^{k}
	M2	1.07^{ghi}	2.50^{gh}	2.38^{hij}	0.88^{hij}	2.41^{fg}	2.55^{hi}
	M3	1.25^{ef}	3.55^{bc}	3.41^{ef}	1.11^{ef}	3.40^{c}	3.03^{fgh}
	M4	1.50^{d}	4.05^{a}	4.28^{bc}	1.26^{e}	3.84^{ab}	3.47^{def}
Sig. difference		*	**	**	*	**	**
SE±		0.06	0.16	0.22	0.06	0.14	0.17
CV(%)		9.16	12.03	14.25	10.77	11.28	12.11

Means in a column followed with the same letter are not significantly different at $P \geq 0.05$.

Across all crop rotation systems, equivalent grain productivity of bread wheat increased with the increase of manure application rates from the control without manure (M1) to 7.5 ton ha^{-1} manure (M4). The influence of crop rotation on equivalent grain productivity of bread wheat varied however upon experimental crops and rotation phases. Instead of crop rotation, manure application in the first rotation phase (2013) seemed solely influence the equivalent grain productivity of bread wheat. At both testing sites, the least equivalent grain yields of bread wheat in the first rotation phase (2013) were recorded with clover in the combination of $R2^{+}$ and manure application rates of M1 to M4 (Table 12). Clover responses to the interaction of crop rotation and manure application increased however highly significantly in the second rotation phase of 2014. In the first and second rotation phases (2013-2014), compared with that of other experimental crops, higher equivalent grain yields of bread wheat were recorded with potatoes at higher rates of manure application (Table 12).

Like that of soil properties, a highly significant increase of bread wheat equivalent yield with the progress of crop rotation and manure application from 2013 to 2015 also indicated that the crop productivity of the cultivated land of Ethiopian highlands would markedly be recovered through regular application of organic matter input(s) and sound crop rotation systems. This huge productivity increase of bread wheat equivalent grain yield through regular crop rotation and manure application might be associated with the progressive additive improvements of physical, chemical, and biological properties of experimental soils as the result of cumulative direct and residual effects of manure application and incorporation of crop residues and/or green manure of preceding crops. Similar crop productivity improvements through organic matter application and/or crop rotation were also reported by several workers (Ali *et al*., 2015; Malihe *et al*., 2015; N'dayegamiye *et al*., 2017; Waźniak, 2019). In all three crop rotation phases, the better crop productivities at the on-station testing site than at on-farm testing sites might also be associated with the betterment of physical, chemical, and biological soil properties of the former testing site more than that of the latter testing sites owing to the additivity of soil property levels before and after crop rotation and manure application interventions (Moharana *et al*., 2012; Ram *et al*. 2014).

In the early rotation phases, a higher equivalent grain yield of bread wheat in potato than that of bread wheat, lupine, and clover indicated better productivity response of potato to crop rotation and organic matter application in degraded cultivated land of the study area. On the contrary, the lowest equivalent grain yield of bread wheat in clover in the first crop rotation phase revealed the poor response of clover to organic matter application in degraded cultivated land of Ethiopian highlands. In agreement to Habtamu *et al*. (2014) and Tamene *et al*. (2017), the lowest crop productivities in the control without organic matter application in the first rotation phase of the present study showed indirectly also the severity of soil health degradation in the cultivated land of the study area. Agegnehu *et al*. (2017, 2018) and Getachew *et al*. (2020) claimed that this serious soil health degradation and low crop productivity in the cultivated land of Ethiopian highlands has largely been due to continuous cropping with inorganic commercial fertilizers alone for long period without supplementing any organic fertilizers.

Apart from constituting one or two nutrients (N and P in the Ethiopian case), inorganic fertilizers don't have an improving effect on physical, biological, and most chemical soil properties directly (Moharana *et al*., 2012). On the contrary, organic fertilizers do have a significant improving effect on physical, chemical, and biological soil properties, as well as constitute almost all essential plant nutrients, although they release nutrients slowly and contain low nutrients per unit mass unlike that of inorganic fertilizers (Brady and Weil, 2017). Application of inorganic fertilizers alone to crop fields without supplementing organic fertilizers for long period like in the present study area may hence be resulted in severe soil organic matter depletion up to the lowest critical level that unable to maintain desirable soil properties and to supply the required amount of other essential nutrients for optimal growth and development of crop plants (Agegnehu *et al*., 2017, 2018; Goda, 2019). Under this condition, productivity responses of crops to applied inorganic fertilizers would have been declining further and there is, therefore, an urgent need to supplement inorganic soil fertilizers with organic fertilizers regularly for sustainable improvement of soil health and crop productivity in the cultivated land of Ethiopian highlands. Recommending organic fertilizers solely without supplementing inorganic fertilizers for attaining the maximum productivity potentials of crops couldn't also be plausible for the study area where organic matter sources are not as such plenty enough for meeting the required optimum rates of sole organic matter fertilization, which are so huge normally above 20 ton ha^{-1} for most crops. Since organic fertilizers applied at low to moderate rates like in the present study wouldn't able to supply the required amount of macronutrients such as NPK per unit time for optimal growth and development of crop plants at least in the early phases of their regular applications, they should hence be supplemented with inorganic fertilizers for getting desirable productivity of crops.

Conclusion

The results of the present study showed clearly the great potentials of regular sound crop rotation with the inclusion of legumes like clover and organic matter application even at moderate rates for marked recovery of the soil health and crop productivity in the degraded cultivated land of Ethiopian highlands. Incorporation of crop residues and/or green manure of preceding crops as part of crop rotation system complemented the recovery effect of manure application on soil health and crop productivity more pronounced than applying either one of them separately. Productivity recovery of bread wheat equivalent grain through regular crop rotation and manure application was highly significantly increased with the progress of rotation phases as the result of cumulative direct and residual effects of the organic inputs in the progress of crop years. At least in the early phases of regular application of organic inputs at low to moderate rates may not be able to supply the required amount of macronutrients per unit time for optimal growth and development of crop plants, and hence supplementing of organic inputs with inorganic fertilizers should be necessary for getting desirable productivity of crops in the present study area. The present study didn't indeed include inorganic fertilizers and it is, therefore, important to study further the potentials of regular crop rotation and organic application with supplementing inorganic fertilizers for recovering the soil health and crop productivity of degraded cultivated land of Ethiopian highlands.

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