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Short term fallow and partitioning effects of green manures on wheat systems in East African highlands

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ABSTRACT

Soil fertility depletion is a major constraint of smallholder farming in sub-Saharan Africa. We tested the after-effects of green manures, namely vetch *(Vicia sativa* L.), lupin *(Lupinus polyphyllus* L.), and lablab (*Lablab purpureus* L.) incorporated into the soil compared to three fertilizer levels (0/0, 23/0, and 78/20 kg N/P ha^{-1}) and evaluated their effect on soil fertility status and wheat yield in acidic Nitisols of southern Ethiopia, for three consecutive years (2017–2019). The treatments were laid out in a randomized complete block design with three replications. In 2017 and 2018, green manures were sown in March and April, respectively, using short rains and incorporated into the soil during late flowering stage, either (i) the whole shoot and root biomass were plowed under, (ii) shoot biomass was transferred to non-treated plots or (iii) only the below ground root biomass was used. Wheat was sown during long rains during the same growing season a month after the incorporation of green manures. In 2019, wheat was grown on the residual plots with the application of an additional 64/20 kg N/P ha^{-1}. Results revealed that in 2017 and 2018 the application of vetch and lupin green manure resulted in grain yield advantages of 49 and 32 % and 34 and 19 %, respectively, over 0/0 and 23/0 kg N/P ha^{-1}, though it produced less grain yield compared to higher fertilizer rates. In 2019, the addition of vetch and lupin whole biomass treatments gave significantly higher wheat yield over fertilizer treatments, with yield advantages of 18–26 %. Similarly, root biomass only also produced a significantly higher yield than fertilized plots. The yield benefits from green manures were due to improved soil water content, improved P-availability, significantly increased exchangeable K, Ca, and Mg, and increased pH by about 0.5 units. The residual effect of green manures could compensate for up to 33 % of the recommended rate of 78 N kg ha^{-1}. We conclude that niche-based integration of green manures could improve yield, enhance soil carbon sequestration and sustain crop-livestock systems, whereby the above ground biomass could serve as quality livestock feed without compromising soil fertility benefits.

1. Introduction

Soil fertility decline is becoming a critical challenge to agricultural production and food security in sub-Saharan Africa, while food demand is increasing due to consistent population growth. Soil fertility depletion is predominantly caused by loss of nutrients resulting from soil erosion, lack of resources for restoration of soil fertility, and nutrient mining due to the application of low fertilizer rates (Amede et al., 2001). Because of the increasing competition for biomass for multiple uses, a significant portion of the nutrients are no longer recycled (Giller, 2001; Kirkegaard et al., 2008). Hoque et al. (2016) also noted that the depletion of soil organic matter is mainly caused by high cropping intensity, especially monocropping, increased use of nutrient demanding varieties, limited availability and use of crop residues, and limited practices of green manure-based cropping patterns. Even in a situation where farmers are applying higher rates of fertilizers in nutrient depleted soils and upslope farms of the Ethiopian highlands, the nutrient use efficiency and the return per investment is very low (Amede et al., 2020), making these degraded soils nonresponsive (Vanlauwe et al., 2007).

The integration of N-fixing food and forage legumes in cereal

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dominant farming system as green manuring has been considered as an alternative and sustainable approach for improving soil fertility and crop productivity (Agegnehu et al., 2014; Meena et al., 2018). Fast-growing, N-fixing and low lignin green manures could supply nutrients to succeeding crops (Palm et al., 2001; Vanlauwe et al., 2005), reducing the production cost due to ever-increasing prices of chemical fertilizer required to sustain crop yield (Meena et al., 2018). Moreover, the average fertilizer application rate in smallscale farms of Ethiopia was reported to be low, below 50 kg NP ha^{-1} (Haregeweyn et al., 2008) while the proportion of cropland under mineral fertilizer was estimated at 41 % of the total cultivated cropland area at the national level, which justifies the need to integrate other nutrient sources such as green manures (CSA, 2014). Hence, maintaining and improving the organic matter content of the infertile soil through green manuring appears to be a very promising intervention (Goyal et al., 1999). Various studies in Uganda with *Crotalaria* (Wortmann et al., 1994; Fischler and Wortmann, 1999) and in Benin with *Mucuna* (Versteeg et al., 1998) showed that maize grown following green manures produced a significantly higher yield than the conventional practice. The positive effect was due to increased N and P and nutrient pumping ability of legumes from deeper soil horizons (Versteeg et al., 1998; Salahin et al., 2013; Stagnari et al., 2017). Moreover, green manures offer other benefits such as providing soil cover, improving soil physical properties, soil organic matter, cation exchange capacity, microbial activity, and reduction of soil temperature (Wagger et al., 1998; Melero et al., 2006; Eichler-Löbermann et al., 2008), suppression of weed growth (Versteeg et al., 1998; Fischler and Wortmann, 1999) and long-term benefit to stabilize yields of subsequent crops (MacRae and Mehuys, 1985; Singh et al., 1991; Stopes et al., 1996; Hoque et al., 2016).

The residual effect of green manure can provide the most effective way to improve N supply for succeeding crops (Thorup-Kristensen et al., 2003). The study of N'Dayegamiye and Tran (2001) in Québec, Canada indicated that green manuring provided 15−36 kg N ha^{-1}, and this contribution accounted for 25–31 % of the total N uptake of wheat. Hoque et al. (2016) also noted that green manures exerted significant residual effects on grain and straw N concentration and total N uptake of wheat. Green manuring of poor soils also increased the quantity and quality of SOM, thereby improved the soil quality (N'Dayegamiye and Tran, 2001; Meena et al., 2018), soil water holding capacity and essential plant nutrients for the subsequent crops (Meena et al., 2018). Similarly, integrating vetch in wheat rotation in the Ethiopian highlands increased wheat grain yield by 98–202 % compared to wheat after wheat (Agegnehu and Amede, 2017). Similarly, growing wheat after legumes (e.g., lupin) produced higher grain yield and soil NO_3-N than cereal-based rotations, and reduced the N fertilizer required by 60–100 % (Tamene et al., 2017). However, the yield benefits were rarely compensated for the opportunity cost of occupying the land for a season at the expense of food crops.

The best green manure types are those that exhibit fast growth, high N-fixing, deep-rooted, efficient in capturing and recycling nutrients, and decompose easily (Stopes et al., 1996; Jama et al., 1999; Giller, 2001) and have livestock feed values. However, the success rate of adoption of green manures in Africa has been low (Sumberg, 2002) since farmers prefer food legumes over forage or/legume cover crops in that the opportunity cost is so high to allocate land and labor to green manures which otherwise could have been used to grow food crops. This is particularly challenging in the Ethiopian highlands where the average landholding per household is below one hectare, with very low productivity, to satisfy the increasing food needs of farming households. Given the high livestock density and the high feed deficit in the crop-livestock systems, there is also a strong competition for biomass between soil fertility, livestock feed, and other uses (Stopes et al., 1996; Zeleke et al., 2010). Thus, there is a need to identify the temporal and spatial needs to integrate multipurpose green manures without competing with the current cropping systems of smallholder farmers. Overall, given very high population pressure and associated severe land shortage, small scale farmers may not allocate a full season for growing green manures, but rather prefer fast-growing green manures as a short-term fallow (Amede and Taboge, 2007). The probability of integrating green manures into the system became even less when the land is relatively fertile. The potential niche available in these farming systems would be the infertile most out-fields where intercropping or legume-cereal rotation is not practiced (Amede and Taboge, 2007).

This research aimed to identify options to minimize opportunity costs and competition for land by growing green manure crops during short rainy season and incorporate the biomass into the soil before the main crop growing season starts, as farmers have slowly abandoned growing of food crops during the short seasons due to rainfall unreliability (Gummadi et al., 2018). The objectives of the study were, therefore, to 1) investigate the effects of short-term fallow of vetch, lupin, and lablab and their residual effects on succeeding wheat yield; 2) evaluate the effects of partitioning of green manures whole biomass, shoot or root alone on crop yield and soil parameters; and 3) determine the residual effects of partitioning of green manures on soil water and soil nutrient content compared to chemical fertilizers.

2. Materials and methods

2.1. Description of the study area

The experiment was conducted at Lemo district/woreda of southern Ethiopia, located at 7°58′ N latitude, 37°76′ E longitude and at an altitude of 2226 m above sea level (Fig. 1). The area is characterized by tepid sub-humid mid-highlands in which rainfall is extended from March through October, with the peak being in July and August and short dry spell in June. The long-term average total annual rainfall is 1125 mm, with an average maximum and minimum air temperatures of 25 °C and 10 °C, respectively (Fig. 2). The year 2019 had the highest while 2017 had the lowest rainfall (Fig. 2) though it was not considered as dry year for wheat production. The experiment was conducted solely under rainfall conditions. The soil type is classified as Eutric Nitisol (IUSS Working Group WRB, 2015), which are deep and moderately acidic. Composite soil samples were collected from each plot before planting the green manure crops and after harvesting of wheat in 2017, 2018 and 2019 cropping seasons at a depth of 0−20 cm using auger. The soil samples were oven-dried at 60 °C for 48 h to constant weight and analyzed for physical and chemical properties, following the standard procedures for soil analysis (Table 1). The initial soil pH, soil OC, total N, available P, and CEC were 5.2, 1.94 %, 0.17 %, 6.0 mg kg^{-1}, and 19 cmol (+) kg^{-1}, respectively.

2.2. Experimental set-up and procedures

The experimental site was selected based on farmers' feedback and targeted the farm considered as non-responsive to chemical fertilizer application. Two sets of consecutive experiments were planned: 1) establishing green manure crops, and 2) planting wheat following the incorporation of green manures. In 2017 and 2018, leguminous green manure crops were established. The treatments were short-term green manure leguminous crops, using local varieties of vetch *(Vicia sativa* L.), lupin (*Lupinus polyphyllus* L.), and lablab (*Lablab purpureus* L.). The corresponding three levels of green manure plant parts incorporated into the soil were shoot biomass only (SB), root (below ground) only (RB), and whole shoot and root biomass (SRB) of vetch (V), lupin (Lu), and lablab (La) and three fertilizer levels of 0/0, 23/0 and 78/10 kg N/P ha^{-1} (Table 1). We used three different fertilizer rates as controls to establish the amount of nutrient the green manure treatments may add to the system. These were 1) 0/0 NP is the negative control that is considered in on-station and on-farm designed experiments; 2) 23/0 kg NP/ha is used by resource poor farmers; and 3) 78/10 is the recommended NP rate for wheat production in the area.

The treatments were arranged in a randomized complete block

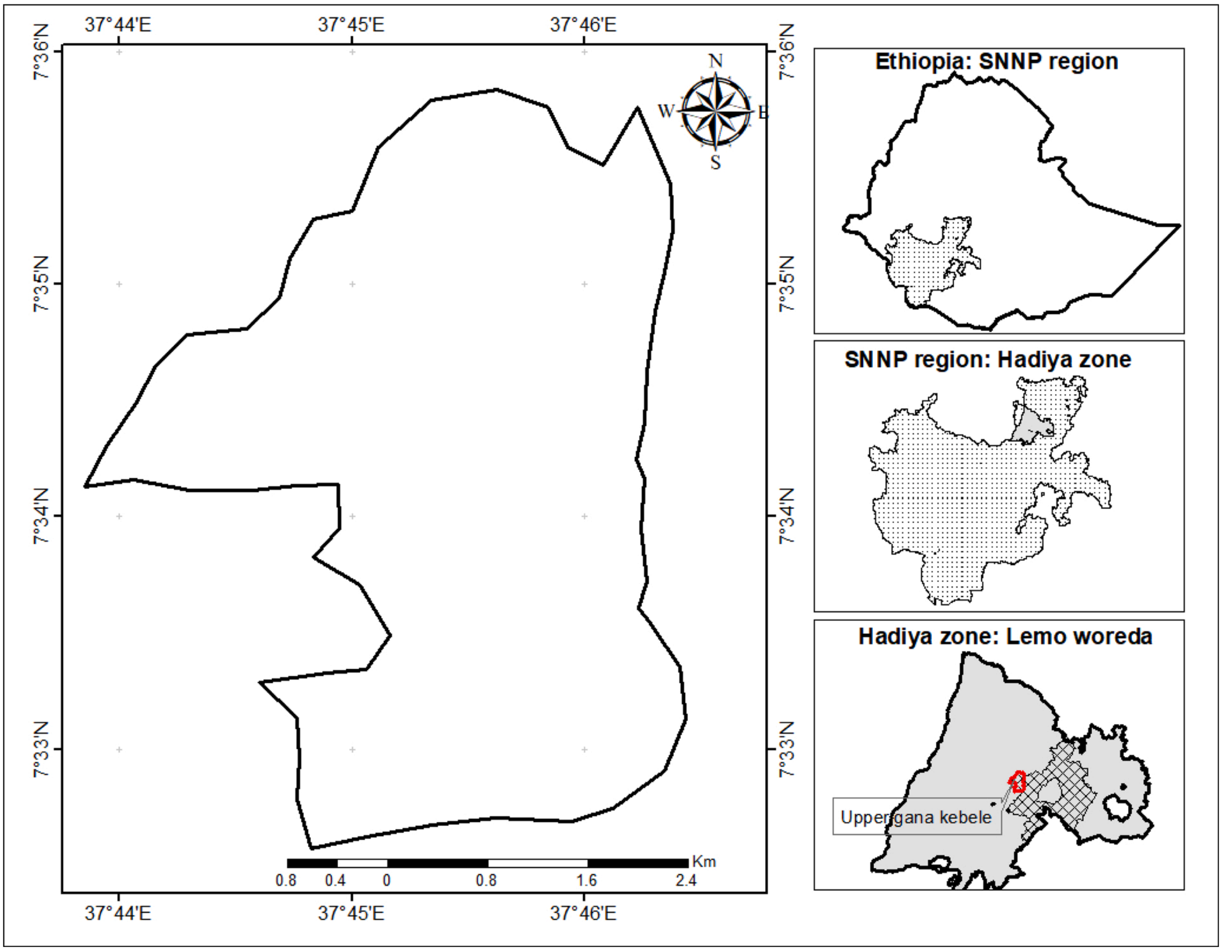


Fig. 1. Map of the study site at Lemo in the southern part of Ethiopia.

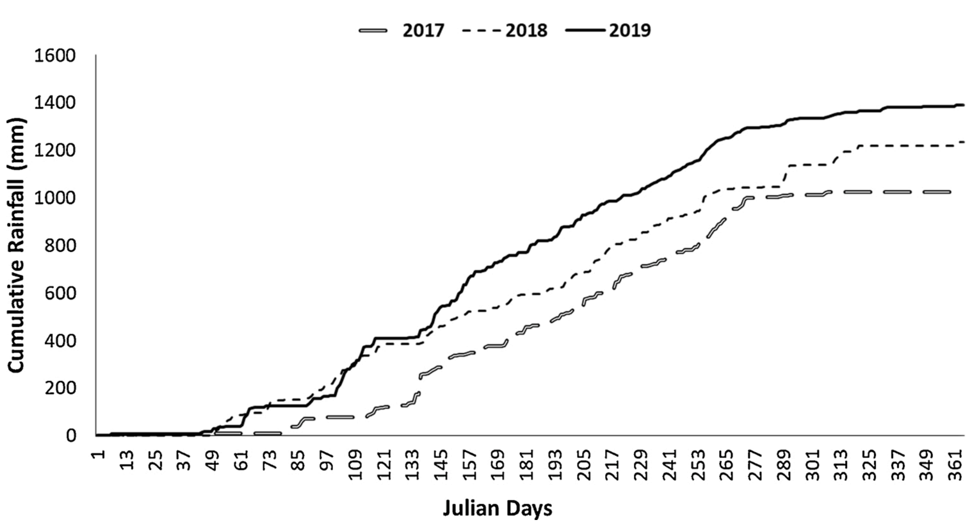


Fig. 2. Rainfall characteristics of the study sites (2017-2019).

design with three replications on a plot size of 4 m by 4 m (16 m^2). Each treatment was assigned in the same plot in all study years; (i) The shoot biomass-only treatment is a non-treated plot, which received biomass transferred from harvest of green manures grown in another plot; (ii) The root-only treatment is the source, from where the shoot was harvested and transferred to other non-treated plot; and (iii) the whole biomass plot is where the green manure was incorporated into the same plot where the legume was grown.

The field was plowed twice using a pair of oxen before planting green manures. The green manure crops of vetch, lablab, and lupin were sown at the seed rate of 25, 25, and 60 kg ha $^{-1}$, respectively on 2 May 2017, following the onset of small rains. During planting, 9/10 kg N/P ha^{-1} was applied in the form of di-ammonium phosphate (DAP) for all green manure plots, with N as a starter fertilizer. Harvesting of the green

Table 1
Soil physical and chemical properties and analytical methods, treatment combinations from three green manure crops with the corresponding levels of three levels of plant biomass parts incorporated into the soil, and three levels of inorganic fertilizers.

Soil parameters	Analytical methods	Treatment combinations	
Soil pH (H_2O)	ES ISO 10390: 2014 (1:2.5 solid to liquid ratio)		Shoot and root biomass (V-SRB)
Conductivity (EC)	ES ISO 11265: 2014 (1:5)	Vetch (V)	Shoot biomass only (V-SB)
Soil texture	Bouyoucos hydrometer method		Root biomass only (V-RB)
Organic carbon (OC)	Walkely and Black		Shoot and root biomass (Lu-SRB)
Total nitrogen (TN)	ES ISO 11261:2015 (Kjeldahl method)	Lupin (Lu)	Shoot biomass only (Lu-SB)
Phosphorus (P)	ES ISO 11263: 2015 (Bray method)		Root biomass only (Lu-RB)
Cation exchange Capacity (CEC)	Ammonium acetate (NH4OAc) extraction method		Shoot and root biomass (La-SRB)
Ammonium-nitrogen (NH_4-N) and nitrate-nitrogen (NO_3-N)	KCl extraction method	Lablab (La)	Shoot biomass only (La-SB)
Sulfur (S),	$CaCl_2$ extraction method, Mehlich-3		Root biomass only (La-RB)
Calcium (Ca), potassium (K), magnesium (Mg), sodium (Na)	Ammonium acetate extraction method, Mehlich-3		0/0 (control without fertilizer or green manure)
		Fertilizer (N/P) (kg ha^{-1})	23/0
Molybdenum (Mo), boron (B), copper (Cu), iron (Fe), manganese (Mn), and zinc (Zn)	DTPA (diethylenetriamine-pentaacetic acid) micronutrient extraction method, Mehlich-3		78/10

manure crops was done at the flowering stage on 3 July 2017, incorporated to targeted plots as per the experimental design, three weeks before planting wheat. In 2018, green manure crops were planted on 18 March and harvested on 22 June 2018 following similar procedures like that of 2017.

A wheat variety (*var. Danfe*) was planted on 18 and 26 July of 2017 and 2018 in the main rainy season under rain-fed conditions, respectively, following the incorporation of green manures and harvested on 30 and 26 November 2017 and 2018, respectively. Wheat was planted at a seed rate of 125 kg ha^{-1} using a hand drill row planting method on a net plot area of 16 m^2, with 20 rows of 4 m length and 4 m width, and 20 cm between rows. In the control plots (0/0, 11.5/0, and 39/10 kg N/P ha^{-1}), half dose of the N and full dose of P fertilizer were applied in the form of urea and DAP as basal during planting, while the remaining half of N was applied as top dressing 45 days after sowing on the same plots.

In 2019, the residual effects of green manures applied in 2018 and 2017 were evaluated on the subsequent growth and yield of wheat. Wheat was planted on 22 July 2019 and harvested on 21 November 2019. The recommended rate of 78/10 kg N/P ha^{-1} as urea and DAP was applied uniformly to all green manure treated plots, following the advice of the local extension system. Urea was applied in split, i.e., half at planting as basal application and the other half 45 days after planting as top dressing. Other agronomic practices were applied uniformly for all plots during the crop growth period as per the recommended on-farm practices. Farm operations were conducted using manual labor.

2.3. Data collection and analysis

Fresh biomass of each green manure was measured at harvest, of which 250 g samples were dried in an oven to a constant weight at 60°c, which was used to estimate the dry matter. Soil moisture content was measured under the canopy of the green manures at different growth stages at four spots per plot from each experimental plot, using a TDR 300 portable soil moisture probe (Spectrum Technologies) with a 20 cm rod size. The amount of N fixed from each green manure was computed using the dry matter yield of green manures by regression equation, $Y = 22.23DM + 10.6$; $R^2 = 0.62$; $n = 706$, adapted from Anglade et al. (2015). The amount of nitrogen in the shoot (kg N ha^{-1}) was considered as the amount of N fixed by the respective green manure crops.

The major agronomic data collected on wheat were days to emergence, days to 50 % flowering and physiological maturity, plant height, and number of productive tillers following standard procedures. The physiological maturity was considered as harvest maturity when the head was 100 % dry and ready for harvesting. Plant vigor with the scale of 1–5 (1 = very poor, 2 = poor, 3 = medium, 4 = good, and 5 = very good) was also recorded (Sloane, 1999; Mondo et al., 2013). To measure total biomass and grain yield of wheat, the entire plot was manually harvested at maturity. After threshing, the seeds were cleaned and weighed, and the moisture content was measured. Wheat stover and grain yield (adjusted to a moisture content of 12.5 %) recorded on plot basis were converted to kg ha^{-1} for statistical analysis. The data were subjected to analysis of variance using the general linear model procedure (PROC GLM) of SAS statistical package version 9.2 (SAS Institute, 2002–2010) and SAS 9.4 user's guide (SAS Institute, 2016). The total variability for each trait was quantified using the following model:

$$T_{ij} = u + R_i + G_j + R(G)_{ij} + e_{ij},$$

where T_{ij} is total observation, μ = grand mean, R_i is effect of the ith replication, Gj is the effect of the jth green manure crop, and e_{ij} is the variations due to random error. Means (12) for the effects of green manure treatments were compared using the MEANS statement with the least significant difference (LSD) test at the 5% probability level. To perform the multivariate approach of correlation and principal component analysis (PCA), the data were standardized by removing treatment mean character values, followed by dividing by the corresponding character standard deviations. Correlation coefficients (r) were then calculated among crop parameters, soil nutrient contents by the SAS CORR procedure, and the PCA was performed by the SAS PRINCOMP procedure to distinguish the treatments as a function of soil management and to determine the most important parameters to characterize them. Figures were prepared using Sigma-plot 12.

3. Results

3.1. Dry matter yield of green manures and N fixation rates

The results showed that both biomass and dry matter yields of green manures were significantly ($p < 0.01$) different between species and higher in 2018 than in 2017 cropping season (Fig. 3) partly associated with late planting in 2017 due to late onset of rains (Fig. 2). In 2017, lupin (Lu-SRB and Lu-SB) produced the highest dry matter, which was almost twice the dry matter yield of vetch and thrice that of lablab (Fig. 3). On the other hand, in 2018 cropping season, vetch (V-SRB and V-SB) produced the highest dry matter yields of 2.8 and 2.6 t ha^{-1}, followed by lupin (Lu-SRB and Lu-RB) with dry matter of 2.1 and 1.6 t ha^{-1}, respectively, within three months of growing period. The dry matter yield of lablab was highly significantly ($p < 0.01$) lower than the dry matter yield of lupin and vetch, regardless of years or treatments, which was below 0.5 t ha^{-1}.

Significant differences were also recorded in N_2 fixation among green manures. Vetch and lupin based green manures fixed more N_2

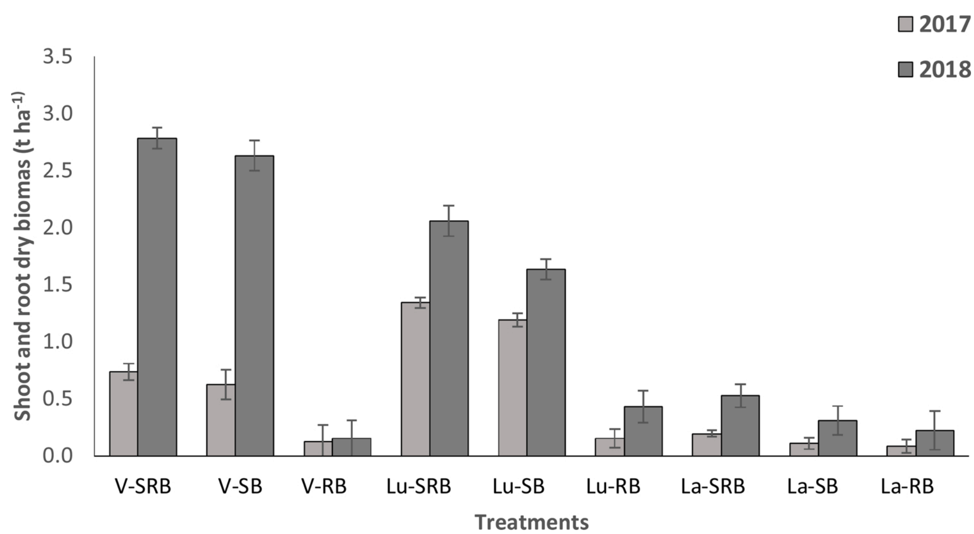


Fig. 3. Shoot, root, and shoot + root dry biomass of green manure crops at Lemo site in 2017and 2018 cropping seasons. V-SRB, V-SB, V-RB, Lu-SRB, Lu-SB, Lu-RB, La-SRB, La-SB, La-RB represent whole shoot and root biomass (SRB), shoot biomass only (SB), and root (below ground) only (RB), of Vetch (V), Lupin (Lu), and Lablab (La), respectively. Error bars represent ±1SE.

than lablab in both 2017 and 2018 cropping seasons (Fig. 3). The amounts of N_2 fixed by vetch, lupin, and lablab green manures were estimated to be 73, 58 and 21 kg ha^{-1} in 2018 and 25, 37 and 15 kg ha^{-1} in 2017, respectively, with the highest being from vetch in 2018 and lupin in 2017 (Fig. 4). Generally, the amount of N_2 fixed in 2017 was significantly lower than in 2018 due to shorter growing periods.

3.2. Effect of green manuring on wheat yield

The results showed that significant ($p < 0.01$) differences were observed in wheat yield among the different soil fertility treatments over the three cropping seasons (Table 2). In 2017 and 2018 cropping seasons, the application of N/P fertilizer at the rate of 78/10 kg N ha^{-1} (F2) had significantly higher total wheat biomass and grain yield than all the green manure and other fertilizer treatments of 23/0 kg N/P ha^{-1} (F1) and the control treatment (F0) (Table 2). However, in 2018 cropping season, all the green manure treatments produced significantly higher total biomass and grain yield of wheat compared to the application of 23/0 kg N/P ha^{-1} (F1) and F0 treatments, with the respective grain yield increments of 6–41 % and 18–53 %. Numerically higher wheat grain yields were obtained from the application of lupin and vetch based green manures, while the lowest grain yield was recorded from lablab fields in both seasons (Table 2). Significant differences in grain yield ($p < 0.05$) were observed among the application of the three green manure biomass levels (SRB, SB and RB) in both seasons (Table 2). In 2018, application of V-SRB resulted in grain yield advantages of 32 % and 49 % over F1 and F0 treatments, respectively, while Lu-SRB gave yield increments of 19 and 34 %, respectively. The addition of V-SB increased wheat grain yield by 21 and 37 % and Lu-SB treatment by 16 and 31 % over F1 and F0 treatments, respectively (Table 2). Although differences between SRB and SB treatments were not statistically significant, the combined application of shoot and root biomass of all the green manure crops resulted in higher grain yields of wheat than application of either shoot or root biomass of the corresponding green manures. Wheat total biomass and productive tillers per plant due to the application of different soil fertility treatments followed similar trends like that of wheat grain yield. In the fertilizer treatments, the increase in both grain yield and total biomass of wheat was consistent with the increase in the

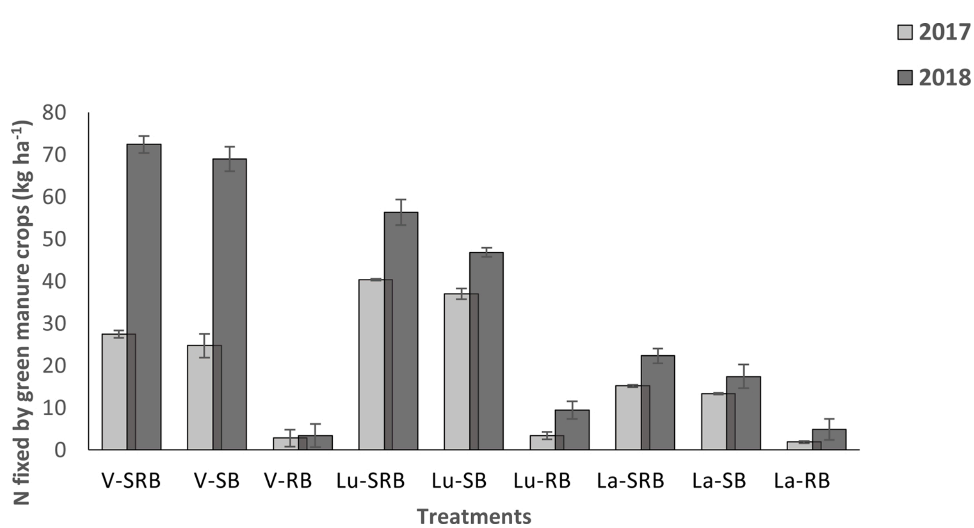
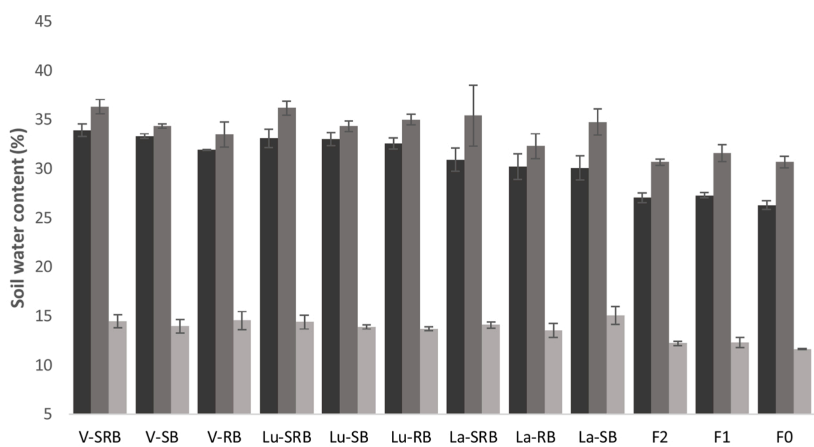


Fig. 4. Estimated nitrogen fixed by the shoot, root, and shoot plus root parts of green manure crops at Lemo site in 2017 and 2018 cropping seasons. V-SRB, V-SB, V-RB, Lu-SRB, Lu-SB, Lu-RB, La-SRB, La-SB, La-RB represents whole shoot and root biomass (SRB), shoot biomass only (SB), and root (below ground) only (RB), of Vetch (V), Lupin (Lu), and Lablab (La), respectively. Error bars represent ±1SE.

Table 2
Yield and yield components wheat as affected by the green manure crops and the levels of each green manure crops incorporated in the soil in 2017 and 2018), and the residual effects of green manures on growth and yield of wheat at Lemo site, 2017-2019.

Treatments	2017					2018					2019				
	Grain yield (t ha^{-1})	Total biomass (t ha^{-1})	HI (%)	NTPP	Plant vigor	Grain yield (t ha^{-1})	Total biomass (t ha^{-1})	HI (%)	NTPP	Plant vigor	Grain yield (t ha^{-1})	Total biomass (t ha^{-1})	HI (%)	NTPP	Plant vigor
V-SRB	1.74cd	3.73bcd	47ab	3.0	3.6ab	2.57ab	5.73a	45abc	4.0b	5.00a	4.93a	9.97a	49ab	5.6ab	4.6
V-SB	1.72cd	3.70bcd	47ab	3.0	3.6ab	2.37bc	5.17abc	45abc	3.3bc	5.00a	4.80ab	9.57ab	50a	5.0abcd	4.6
V-RB	1.53cde	3.40cde	45ab	2.6	3.3bcd	2.20cde	4.62bcd	48ab	3.0bcd	4.3ab	4.83ab	9.86a	48abc	5.6ab	4.6
Lu-SRB	1.87c	3.78bc	49a	3.0	3.6ab	2.30bcd	4.69bcd	49a	3.0bcd	5.0a	4.93a	9.83a	50a	4.6bcd	4.6
Lu-SB	1.72cd	3.53cdef	49a	3.0	3.6ab	2.23bcd	4.63bcd	48ab	3.0bcd	4.3ab	4.87ab	8.93abc	49ab	5.3abc	4.5
Lu-RB	1.45cde	3.18cde	46ab	2.6	3.3abc	2.16cde	4.51bcd	48ab	2.6cd	4.3ab	4.67bc	9.87a	47bc	6.0a	4.6
La-SRB	1.33de	2.76def	48a	2.6	3.0abc	2.13cde	4.23cde	50a	2.3cd	4.0bc	4.63bc	9.10b	51a	5.0abcd	4.6
La-SB	1.34de	2.74ef	48a	2.0	2.6bc	2.03cdef	3.83def	49a	2.3cd	4.3ab	4.63bc	9.20b	50a	4.3cd	4.6
La-RB	1.23de	2.68ef	45ab	2.0	2.3bc	1.97def	4.70bcd	48ab	2.3cd	4.0bc	4.50c	8.80bc	51a	5.oabcd	4.5
F2	3.03a	6.23a	49a	4.0	4.3a	2.73a	5.63a	47abc	5.3a	5.00a	4.17d	8.79bc	46bc	5.3abc	4.6
F1	2.40b	4.60b	48a	3.3	3.3abc	1.93ef	3.50ef	43bc	2.3cd	4.0bc	4.13de	8.89abc	46bc	4.3dc	4.3
F0	1.13e	2.37f	42b	2.0	2.0c	1.73f	3.40f	42c	2.0d	3.33c	3.90e	8.71c	43c	4.0d	4.3
p level	**	**	*	ns	*	**	**	*	**	*	*	**	*	*	ns
LSD (0.05)	0.46	1.02	5.8	1.9	1.5	0.33	0.97	5.3	1.1	0.89	0.26	0.62	4.2	1.1	0.58
CV (%)	15.78	16.63	7.3	40.02	27.37	8.78	12.82	6.7	21.71	11.70	3.33	4.93	5.3	12.38	7.36

Note: Significant at *$p \leq 0.05$, **$p \leq 0.01$; ns: not significant. NTPP: Number of tillers per plant; V: Vetch, Lu: Lupin, La: Lablab, SB: Shoot biomass, RB: Root biomass, SR: Shoot and root biomass, F2, F1 and F0: 78/10, 23/0, and 0/0 kg N/P ha^{-1}, respectively. Within a column, means followed with different letters are significantly different at $p < 0.05$. LSD: least significant difference; CV: coefficient of variation.



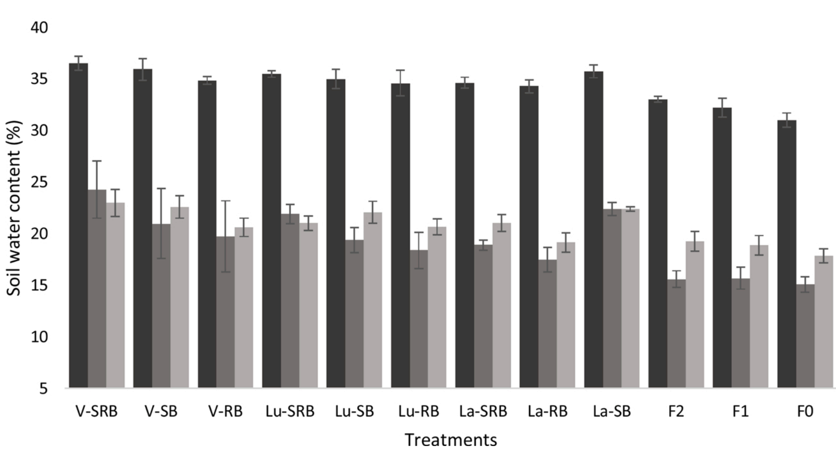


Fig. 5. Volumetric soil water content (SWC) as influenced by different soil fertility treatments at different growth stages of wheat in 2017 and 2018 cropping seasons. SWC at planting ■, growth ■, and maturity ■ stage in 2017 (**Top**), and SWC at planting ■, grain-filling ■, and maturity ■ stage in 2018 (**Bottom**).

V-SRB, V-SB, V-RB, Lu-SRB, Lu-SB, Lu-RB, La-SRB, La-SB, La-RB represents whole shoot and root biomass (SRB), shoot biomass only (SB), and root (below ground) only (RB), of Vetch (V), lupin (Lu), and Lablab (La), respectively. F2, F1, and F0 represent 78/10, 23/0, and 0/0 kg N/P ha^{-1}, respectively. Error bars represent ±1SE.

fertilizer rates across years. In both 2017 and 2018 cropping seasons, the highest number of fertile tillers were obtained from the F2 treatment, followed by vetch and lupin green manures, although the difference was not statistically significant.

3.3. The residual effect of different green manures on wheat yield

In 2019 cropping season, the residual effect of green manure significantly ($p < 0.01$) improved productive tillers per plant, total biomass and grain yield of wheat (Table 2). Despite application of same fertilizer rate on all plots in 2019, the results clearly revealed that all the residues of green manure crops gave significantly ($p < 0.01$) higher grain yield compared to the fertilizer treatments. The performance of both vetch and lupin based green manures on wheat yield was superior to lablab based green manure. The highest mean wheat grain yield of 4.93 t ha^{-1} was obtained from the application of vetch and lupin shoot and root biomass (SRB), followed by the yield of 4.87 t ha^{-1} from the addition of lupin shoot biomass only (Lu-SB). Interestingly, wheat grown on RB produced significantly ($p < 0.05$) higher grain yield than the highest fertilizer treatment (F2). Moreover, even those plots treated by low biomass producing lablab gave significantly higher grain yields of wheat than all the fertilizer treatments alone, despite lower yield of wheat in the first season. The trend observed in total wheat biomass was like that of grain yield (Table 2). In contrast, application of fertilizer alone exhibited significantly lower yields of wheat than green manure treatments. Vetch and lupin based green manures (SRB) resulted in grain yield increments of 17, 20, and 26 % over the F2, F1 and F0 treatments (Table 2).

The number of productive tillers per wheat significantly ($p < 0.05$) differed among different green manure and fertilizer treatments across years (Tables 2), ranging between 2–6. In 2019 cropping season, the number of fertile tillers responded significantly to the residual effects of green manures. Lupin and vetch based green manures recorded the highest number of fertile tillers (6) per plant, while the lowest number of fertile tillers per plant was recorded from the F0 treatment.

3.4. Effect of green manure crops on soil physicochemical properties

The incorporation of green manures highly significantly ($p < 0.01$) improved soil water content at planting (SWCP) and at grain filing stage (SWCGF) in both cropping seasons (Fig. 5). The year 2017 was drier than 2018 and the onset of rain in 2017 was delayed by a month (Fig. 2), and the difference in rainfall amount and distribution among the three seasons was reflected in soil water content too. The average soil water contents at planting in 2017 and 2018 were 34 and 37 %, while at grain filling stage the amounts were 14 and 23 %, respectively. During wheat planting, all green manure treated plots retained significantly higher SWCP than the fertilizer treated plots, regardless of years. In both years, vetch and lupin based green manure treated plots had significantly higher ($p < 0.01$) soil water content (SWC) than fertilizer treated plots. The plots which received whole biomass of vetch and lupin had significantly ($p < 0.05$) greater SWC than plots treated by root biomass only. Interestingly, plots with root biomass treatment only also exhibited significantly ($p < 0.01$) higher SWC than the fertilizer treatments (Fig. 5).

The experimental site had a clay dominant soil texture and moderately acidic in reaction with pH values ranging from 5.3-5.8 in 2018 and 5.2-5.4 in 2019 cropping seasons. Soil analysis after green manure application showed significant ($p < 0.05$) differences among treatments in soil pH in 2018 and in soil organic carbon (SOC) in 2018 and 2019 cropping seasons. In 2018, the application of vetch and lupin green manures increased soil pH by about 0.5 units compared to the F2 treatment (Table 3). Application of V-SRB and V-SB green manures resulted in significantly ($p < 0.05$) higher pH values compared to the fertilizer treatments, but statistically significant difference was not observed among V-SRB, V-SB, V-RB, Lu-SRB, and La-SRB treatments. The soils are generally rich in SOC content, with 2.1–3.6 % (Table 3). Green manure treated plots were significantly ($p < 0.05$) higher in SOC content in 2018 than in 2019 cropping season. Plots treated by vetch and lupin had significantly higher SOC content than fertilizer treated plots in both cropping seasons, while plots treated with SRB gave significantly ($p < 0.05$) higher SOC in 2018 season (Table 3). In 2018, the soil OC contents at a depth of 20 cm following V-SRB, Lu-SRB, L-SRB, F2, and F0 after harvesting wheat were about 68.2, 79.2, 63.8, 52.8, and 46.2 t ha^{-1}, respectively, with the increase in OC ranging from 19 to 71.4% compared to F0 and 4.2 to 50 % compared to the F2 treatment. While in 2019, soil OC contents with same depth following the residual effect of V-SRB, Lu-SRB, L-SRB, F2, and F0 after harvesting wheat were about 61.6, 63.8, 61.6, 50.6, and 48.4 t ha^{-1}, respectively, with the OC content increases of 13.6–31.8 % compared to the F0 and 8.7–26.1 % compared to the F2 treatment (Table 3).

Green manure treated plots also resulted in significantly ($p < 0.05$) higher total N than fertilizer treated plots, regardless of years (Table 3), with Lu-SRB, V-SRB and La-SRB treatments recycled the highest N (0.30 %) concentration. In contrast, the lowest total N (0.18 %) was recorded from the F0 treatments. The concentration of NH_4-N in the soil was

Table 3
Effects of green manure crops on soil chemical properties of the experimental site after harvesting wheat in 2018 and 2019.

Treatment combinations	pH-H_2O		SOC (%)		Total N (%)		Av. P mg kg^{-1}		NH_4-N		NO_3-N		S	
	2018	2019	2018	2019	2018	2019	2018	2019	2018	2019	2018	2019	2018	2019
V-SRB	5.8a	5.4	3.1ab	2.8a	0.27ab	0.22a	7.3ab	8.6ab	10.5ab	6.6b	0.63a	0.87ab	30.8a	21.9abc
V-SB	5.8a	5.3	2.9abc	2.7ab	0.24abc	0.21ab	6.9b	7.8abc	9.7ab	4.2ab	0.43bcd	0.73ab	24.3abc	21.4abc
V-RB	5.7ab	5.3	2.6bc	2.6abc	0.21bc	0.20ab	6.7b	8.3abc	10.2ab	4.8bcd	0.43bcd	0.80ab	23.8abc	20.1bc
Lu-SRB	5.6abc	5.4	3.6a	2.9a	0.21bc	0.21ab	9.7a	9.0a	11.5a	10.4a	0.50abc	0.83ab	29.7a	24.1ab
Lu-SB	5.5bcd	5.4	2.6bc	2.6abc	0.20bc	0.19b	7.0b	6.5abc	10.5ab	4.2bcd	0.40bcd	0.70ab	24.2abc	24.0ab
Lu-RB	5.5bcd	5.3	2.5bc	2.7ab	0.19c	0.19b	6.9b	7.1ab	8.4b	5.8bc	0.33cd	0.80ab	25.6abc	22.1abc
La-SRB	5.7ab	5.4	2.9abc	2.8a	0.29a	0.22a	7.8ab	9.0a	7.9abc	6.2b	0.53ab	1.0a	26.8abc	25.6a
La-SB	5.6abc	5.4	2.5bc	2.6abc	0.22bc	0.21ab	7.2b	6.5abc	7.5abc	5.2bcd	0.43bcd	0.8ab	23.2ab	21.5abc
La-RB	5.5bcd	5.3	2.7abc	2.5bc	0.19c	0.22a	6.5b	6.2abc	6.1bcd	5.8bc	0.37bcd	0.8ab	24.1abc	21.7abc
F2	5.3d	5.2	2.4bc	2.3b	0.19c	0.20ab	6.4b	6.1abc	4.6cd	3.8cd	0.27d	0.7ab	27.3ab	23.9ab
F1	5.5bcd	5.3	2.4bc	2.3b	0.22bc	0.20ab	6.5b	6.1abc	5.0cd	3.4cd	0.33cd	0.67ab	19.7c	20.8bc
F0	5.4cd	5.2	2.1c	2.2c	0.18c	0.21ab	5.9b	6.0bc	4.0d	2.8d	0.27d	0.53b	18.9c	19.4c
p value	*	ns	*	*	**	*	*	*	**	**	*	*	**	*
LSD (0.05)	0.20	0.40	0.84	0.54	0.07	0.02	2.5	2.9	2.7	2.5	0.17	0.36	8.8	4.6
CV (%)	2.0	4.4	18.4	12.9	18.0	7.9	20.8	24.5	25.8	29.6	25.1	27.8	22.3	12.0

Note: Significant at *$p \leq 0.05$, **$p \leq 0.01$; ns: not significant. V: Vetch, Lu: Lupin, La: Lablab, SB: Shoot biomass, RB: Root biomass, SR: Shoot and root biomass, F2, F1 and F0: 78/10, 23/0, and 0/0 kg N/P ha^{-1}, respectively. Within a column, means followed with different letters are significantly different at $p < 0.05$. LSD: least significant difference; CV: coefficient of variation.

significantly ($p < 0.005$) higher in green manure treated plots than the fertilizer plots, which was higher in 2018 than in 2019 cropping season (Table 3). Similarly, the soil NO_3-N concentrations were significantly higher in green manures treated plots than fertilizer treated plots. In general, V-SRB and Lu-SRB green manures resulted in significantly ($p < 0.05$) greater concentrations of NO_3-N compared to the SB and RB of Lablab (Table 3). Although the Bray soil P was generally low (Horneck et al., 2011), significant ($p < 0.05$) differences were observed for soil P concentration among the treatments in both seasons that ranged between 5.9-9.7 mg kg^{-1} in 2018 and 5.4–10.7 mg kg^{-1} in 2019 cropping season. Lu-SRB and La-SRB treated plots had significantly higher P than all the other treatments, although the benefit diminished in 2019 (Table 3).

Soil sulfur ($CaCl_2$-S) concentration ranged between 18.9–30.8 mg kg^{-1} in 2018 and 19.4–25.6 mg kg^{-1} in 2019 cropping season. Thus, based on the sufficiency range of S (Horneck et al., 2011), the soil $CaCl_2$-S concentrations were high in both seasons (Table 3). The combined application of shoot and root biomass in all green manures resulted in significantly higher concentrations of soil S compared to inorganic fertilizer treatments alone, though its concentration decreased in 2019 like that of total N, available Bray soil P, exchangeable NH4OAc-K and Mg.

Similarly, a significant ($p < 0.05$) difference was observed in soil K concentration among the treatments, the highest being from the V-SRB treated plots (Table 4), though the difference in NH4OAc-K among the different treatments diminished in 2019. All green manure treated plots had significantly higher soil NH4OAc-Mg concentrations than fertilizer treated plots in both 2018 and 2019 cropping seasons. Soil Mg concentration was high (Mehlich-3) in both seasons, which ranged between ~200−270 mg kg^{-1} in 2018 and ~209−258 mg kg^{-1} in 2019 cropping season (Table 4). Application of V-SRB and La-SRB resulted in significantly ($p < 0.05$) higher concentration of soil Mg than fertilizer treatments in both seasons (Table 4). Soil exchangeable NH4OAc-Ca was also significantly ($p < 0.05$) improved by the green manure treatments, but the concentration of Ca in the soil was significantly ($p < 0.005$) higher in 2019 than in 2018 cropping season. Compared to previously suggested values (Heckman, 2006), the concentration of Ca in the soil was high (Mehlich-3 test method) in both seasons that ranged between about 1327−1808 mg kg^{-1} in 2018 and 1662−2001 mg kg^{-1} in 2019 cropping season. Among green manure treatments, V-SRB and Lu-SRB treated plots gave higher concentration of soil Ca than other treatments both in 2018 and 2019 cropping season (Table 4).

The cation exchange capacity (NH4OAc-CEC) and exchangeable cations of the soil responded significantly ($p < 0.05$) to the application of Lu-SRB and La-SRB treatments compared to F2, F1, and F0 treatments (Table 4). Compared to previously suggested values (Spargo et al., 2013), the CEC of the soil was high in both seasons, ranging between 19.5 and 36.8 meq/100 g soil with an average concentration of 23.9 and 23.2 meq100 g^{-1} soil in 2018 and 2019 cropping season, respectively.

Application of green manures considerably improved the concentrations of boron (DTPA-B), zinc (DTPA-Zn), manganese (DTPA-Mn), and molybdenum (DTPA-Mo) in the soil, but their effect was not significant on soil copper (DTPA-Cu) and iron (DTPA-Fe) concentrations in both seasons. The soil B concentration was significantly ($p < 0.05$) higher in 2019 than in 2018 cropping seasons. Green manure treated plots had significantly ($p < 0.05$) higher concentrations of Zn (7.1 and 5.0 mg kg^{-1}) and B (0.46 and 0.79 mg kg^{-1}) in 2018 and 2019 cropping season, respectively than the control treatment. Similarly, V-SRB and Lu-SRB treated plots gave higher concentrations of Zn and B in both cropping seasons (Table 5). According to soil Zn and B sufficiency range (McKenzie, 1992), the concentration of Zn in the soil was high that ranged between 3.2–7.3 mg kg^{-1} in 2018 and 3.8–5.2 mg kg^{-1} in 2019 cropping season, while soil B concentration showed medium level in both seasons. Green manure treatments also resulted in significantly ($p < 0.05$) higher soil Mn than fertilizer treatments. Application of V-SRB gave the highest soil Mn concentrations (293 and 273 mg kg^{-1}) in 2018 and 2019 cropping seasons, respectively. Compared to the values reported by Horneck et al. (2011), soil Mn and Fe concentrations in all treatments were very high (Table 5).

Wheat grain yield was positively and significantly correlated with total biomass, productive tillers per plant, soil water content, soil pH, soil N, NH4OAc-K, Ca, and Mg concentrations ($r = 0.88$, 0.60, 0.97, 0.91, 0.68, 0.55, 0.78, 0.72, and 0.67, respectively) (Table 6). Soil pH was strongly and significantly correlated with exchangeable Ca, Mg, K, N, and B concentrations, SWCP and SWCGF (r = 0.95, 0.74, 0.70, 0.77, 0.80, 0.71, and 0.75, respectively) (Table 6).

The principal component analysis (PCA) revealed that the first three principal components (PC1, PC2, and PC3) accounted for ~76 % of the total variation of the treatments, of which 50 % was contributed by PC1 (Table 7). The first eigenvector had similar weights almost in all the characters. Thus, most characters in PC1 individually contributed comparable effects (0.116–0.273) to the total variation of the treatments (Table 7). The second eigenvector had negative loadings on most of the variables, including grain yield, total biomass, SWC, and SOC, but positive loadings on Ca, Mg, CEC, Zn, and boron. Each vector corresponds to one of the analysis variables and is proportional to its component

Table 4
Effects of green manure crops on selected soil chemical properties of the experimental site after harvesting wheat in 2018 and 2019.

Treatments	Exch. K mg kg^{-1}		Exch. Na		Exch. Ca		Exch. Mg		CEC (cmol kg^{-1})	
	2018	2019	2018	2019	2018	2019	2018	2019	2018	2019
V-SRB	493a	443	24.4a	23.1	1808a	1968a	270a	248ab	25.3b	22.6 ab
V-SB	423abc	437	15.8b	21.0	1721ab	1888abc	238b	250ab	23.1b	22.6 ab
V-RB	385cd	380	17.6ab	21.2	1595abcd	1777abc	239b	233abc	23.6b	23.0 ab
Lu-SRB	475ab	410	19.7ab	21.1	1521abcd	1827abc	252ab	258a	27.0ab	24.2 ab
Lu-SB	392bcd	382	19.8ab	19.9	1471bcd	1662c	244ab	242abc	23.0b	24.0 ab
Lu-RB	386cd	410	17.6ab	20.1	1327d	1674abc	235b	247ab	24.1b	22.7 ab
La-SRB	418abc	442	22.7ab	23.6	1670abc	1941ab	246ab	256ab	36.8a	25.9a
La-SB	402bcd	386	18.9ab	22.8	1575abcd	1869abc	234b	230abc	22.3b	24.9ab
La-RB	381cd	386	17.3ab	21.5	1416cd	2001a	233b	233abc	21.6b	25.5ab
F2	326d	360	21.5ab	20.7	1360d	1691bc	200c	209c	20.7b	21.3ab
F1	369cd	356	23.8ab	20.5	1510bcd	1749abc	224bc	221bc	20.1b	21.2 ab
F0	346cd	355	25.3a	20.1	1511bcd	1860abc	236b	226abc	19.5b	20.3b
p value	*	ns	*	ns	*	*	**	*	*	*
LSD (0.05)	84.5	107.1	8.4	4.2	290.9	259.5	30.7	36.8	10.81	5.5
CV (%)	12.2	15.6	24.1	11.6	10.9	8.2	7.5	8.9	26.1	13.7

Note: Significant at $^*p \leq 0.05$, $^{**}p \leq 0.01$, ns: not significant. V: Vetch, Lu: Lupin, La: Lablab, SB: Shoot biomass, RB: Root biomass, SRB: Shoot and root biomass, F2, F1, and F0: 78/10, 23/0, and 0/0 kg N/P ha^{-1}, respectively. Within a column, means followed with different letters are significantly different at $p < 0.05$. LSD: least significant difference; CV: coefficient of variation.

Table 5
Effects of green manure crops on selected soil chemical properties of the experimental site after harvesting wheat in 2018 and 2019.

Treatments	Zn		B		Cu		Mo		Fe		Mn	
	mg kg^{-1}											
	2018	2019	2018	2019	2018	2019	2018	2019	2018	2019	2018	2019
V-SRB	7.3a	5.0a	0.60a	0.90	0.90a	1.53	0.23a	0.63	181	201	293a	273a
V-SB	5.3abc	4.7ab	0.57a	0.87	0.87ab	1.57	0.20b	0.60	176	199	290ab	269ab
V-RB	4.2bc	4.1ab	0.47abc	0.83	0.83ab	1.50	0.20b	0.60	175	199	266ab	256ab
Lu-SRB	6.4ab	4.3ab	0.57ab	0.90	0.90a	1.57	0.20b	0.60	174	197	267ab	268ab
Lu-SB	4.9abc	3.9b	0.53abc	0.80	0.80ab	1.53	0.20b	0.60	170	193	264ab	254ab
Lu-RB	4.9abc	3.8b	0.53abc	0.80	0.80ab	1.50	0.20b	0.60	164	194	272ab	245ab
La-SRB	6.3ab	5.1a	0.57ab	0.83	0.83ab	1.57	0.20b	0.63	175	194	291ab	264ab
La-SB	4.2bc	4.8ab	0.53abc	0.77	0.77b	1.60	0.20b	0.60	165	192	239b	261ab
La-RB	4.4bc	4.2ab	0.50abc	0.83	0.83ab	1.53	0.20b	0.60	167	190	257b	261ab
F2	3.2c	4.3ab	0.40c	0.77	0.77b	1.53	0.20b	0.60	174	197	252b	267ab
F1	3.7c	4.3ab	0.47abc	0.77	0.77b	1.53	0.20b	0.60	180	194	241b	239b
F0	4.2bc	4.6ab	0.43bc	0.80	0.80ab	1.57	0.20b	0.60	176	204	263ab	253ab
p value	**	*	*	ns	ns	ns	*	ns	ns	ns	*	*
LSD (0.05)	2.3	1.0	0.14	0.12	0.14	0.16	0.02	0.04	27.4	21.2	34.3	31.2
CV (%)	27.4	13.7	16.0	8.7	9.8	6.1	8.2	4.0	9.4	6.4	12.0	7.1

Note: Significant at $^*p \le 0.05$, $^{**}p \le 0.01$, ns: not significant. V: vetch, Lu: lupin, La: lablab, SB: shoot biomass, RB: Root biomass, SRB: shoot and root biomass, F2, F1, and F0: 78/10, 23/0, and 0/0 kg N/P ha^{-1}, respectively. Within a column, means followed with different letters are significantly different at $p < 0.05$. LSD: least significant difference; CV: coefficient of variation.

loading. For instance, the bi-plot of PC1 and PC2 showed that the variables F2 and V-SB load heavily on the first component, while the variables V-RB, Lu-SB, Lu-RB, La-SB, and La-RB load heavily on the second component (Fig. 6).

4. Discussion

4.1. Differential effects of green manures on crop productivity

Decline in soil fertility and application of low amounts of fertilizer are major production constraints in the tropical agroecosystems, partly associated with poor nutrient recycling, adamant soil erosion, increasing soil acidity and severe nutrient mining (Haileslassie et al., 2005; Agegnehu and Amede, 2017). In this study, growing different green manures as precursor crops in-between the major rainy seasons, using short rains, showed positive but differential effects on the growth and productivity of wheat.

Our results confirmed earlier report (Tamene et al., 2017; People et al., 2001; Meena et al., 2018) that green manuring could partly substitute chemical fertilizers. The residual effect of green manures compensated for up to 33 % of N obtained from the highest N fertilizer rate of 78 kg N ha^{-1} (Fig. 4). The effect of green manures was much more pronounced in 2019 than in 2018, which could be explained by the cumulative effects of green manures overtime in conditioning these acidic soils through increased availability of cations (Tables 4 and 5) as also reflected in changes in CEC and soil pH. Previous studies have also shown that either green manure alone or combined with inorganic fertilizer can stimulate the subsequent crop growth, yield, and soil nutrient levels (Dabin et al., 2016; Couëdel et al., 2018; Yang et al., 2018) as it was demonstrated with wheat following green manuring with red and white clover (Stopes et al., 1996; Wivstad, 1998). Although the critical SOC concentration for optimal yield response to mineral N fertilizers in tropical soils is not well established, Musinguzi et al. (2016) reported that fields with >1.2 % SOC registered the highest fertilizer agronomic efficiency (AE) and grain yield, with 1.9–2.2 % SOC suggested to be optimal. Similarly, as presented in Table 2, application of fertilizer F2 gave significantly higher grain yield compared to F0 treatments, despite the high soil organic carbon (2.1 %). This could be partly explained by change in soil acidity, whereby green manures increased soil pH by about 0.5 units (Table 3), which enhanced P availability and reflected in crop yield.

Our results also clearly indicated that the higher biomass of vetch and lupin corresponded to higher wheat yield compared to lablab across the three years (Table 6), implying differential N supply of different legumes (Peoples et al., 2001; Mendonça et al., 2017). For instance, lupin and vetch were capable of fixing N up to 150 and 116 kg N ha^{-1} yr^{-1}, respectively while lablab fixed 37 kg N ha^{-1} yr^{-1}. The higher the dry biomass yield of the green manure the higher the N_2 fixed by them (Peoples et al., 2001), indicating a strong positive relationship between the biomass produced and the N_2-fixed by the green manure crops. According to Meena et al. (2018), many legume species which have been used for green manuring have shown high N accumulation rate of 80–100 kg ha^{-1} in duration of 45–60 days of crop growth. But the low yield of lablab is not common (Meena et al., 2018), possibly caused by the acidic environment and short growth duration for lablab.

One reason why adoption of green manures in small scale farming is limited was due to the high opportunity cost of green manures (Sumberg, 2002) associated with high cost of land and labor to grow green manures which otherwise could have been used to grow feed or food crops. Our results showed that it is possible to minimize trade-offs and maintain crop yield (Table 2) and soil fertility (Tables 3 and 4) by growing green manures as short-term fallows without competing for the main growing season, but also by partitioning the biomass to different uses. Aboveground biomass could be used for livestock feed or biomass transfer to other plots while it was possible growing wheat on the residual belowground root biomass (RB) without compromising significant yield benefits (Table 2). In East Africa, where the short rains became unreliable for crop production (Gummadi et al., 2018) it would be advisable to introduce fast-growing green manures as short-term fallows in between main growing seasons. This would not only improve crop productivity but also enhance sustainability by reducing erosion effects, improving carbon sequestration and increasing biomass for multiple uses.

4.2. Contribution of green manures to physicochemical soil characteristics

Green manures could improve productivity through the recovery of lost nutrients by their deeper roots (Couëdel et al., 2018; Smith and Chalk, 2018), improving soil organic matter content and nutrient status (Johnston et al., 2005; Moghaddam et al., 2011; Agegnehu et al., 2014), providing additional N to succeeding crops, and reducing disease incidence and weed populations (Kirkegaard et al., 2008; Harker et al., 2009; Turkington et al., 2012). The atmospheric N_2 fixed by these legumes increased soil N level (Fig. 4) and soil organic matter (Table 3), implying that nutrients become available to subsequent crops as the residues decompose (Diaz-Ambrona and Mínguez, 2001; Yang et al.,

Table 6
Correlation coefficients among plant parameters, soil water content, soil and plant nutrient contents.

Parameters	Mn	B	Zn	CEC	Mg	Ca	K	P	N	OC	pH	SWCGF	SWCP	PV	TPP	TB	GY
GY	0.57*	0.78**	0.65**	0.53*	0.67**	0.72**	0.78**	0.50*	0.55*	0.72**	0.68**	0.91**	0.97***	0.70**	0.60*	0.88***	
TB	0.51*	0.78**	0.63*	0.44^{ns}	0.61*	0.51*	0.73**	0.39^{ns}	0.58*	0.73**	0.52*	0.88***	0.89***	0.57*	0.65*		
TPP	0.51*	0.31^{ns}	0.36^{ns}	0.31^{ns}	0.23^{ns}	0.45^{ns}	0.51*	0.26^{ns}	0.52*	0.54*	0.33^{ns}	0.61*	0.63*	0.55*			
PV	0.49^{ns}	0.58**	0.38^{ns}	0.43^{ns}	0.27^{ns}	0.52*	0.63*	0.53*	0.60*	0.55*	0.36^{ns}	0.63*	0.64*				
SWCP	0.67**	0.83**	0.72**	0.44^{ns}	0.73**	0.75**	0.77**	0.48^{ns}	0.39^{ns}	0.69**	0.71**	0.88***					
SWCGF	0.60*	0.79**	0.69**	0.65**	0.70**	0.79**	0.78**	0.68**	0.54*	0.75**	0.75**						
pH	0.74**	0.80**	0.71**	0.52*	0.74**	0.95***	0.70**	0.53*	0.77**	0.60*							
OC	0.59*	0.76**	0.80**	0.55**	0.65**	0.60*	0.91***	0.59*	0.59*								
N	0.76**	0.68**	0.69**	0.75**	0.55*	0.80**	0.60*	0.74**									
P	0.58*	0.65**	0.68**	0.98***	0.48^{ns}	0.54*	0.57*										
K	0.63*	0.83**	0.87***	0.61*	0.74**	0.78**											
Ca	0.78**	0.83**	0.75**	0.64*	0.71**												
Mg	0.57*	0.83**	0.89**	0.57*													
CEC	0.63*	0.61*	0.68**														
Zn	0.74**	0.88***															
B	0.71*																

Note: GY: grain yield, TB: total biomass, TPP: number of tillers per plant, PV: plant vigor, SWCP and SWCGF: soil water content at planting and grain filling stage, respectively. *$p < 0.05$, **$p < 0.01$, ***$p < 0.001$, ns: not significant.

2018). The fast soil organic carbon build-up due to green manures, which seems unattainable in short period, may satisfy at least 50 % of the minimum sufficiency level of soil OC. Our interpretation is that once you attain a minimum SOC (2.1 % in F0), further build up could be much faster.

The benefit from the belowground biomass could be associated with increased soil carbon conditioning, increased soil N (Table 3), and increased soil cations (Table 4). Smith and Chalk (2018) reported that high mineral N remained in the root zone which was assimilated by the subsequent crops.

Yield increment in wheat due to vetch and lupin treatment could be also explained by improved soil water retention due to improved soil organic matter content during the grain filling stage (Fig. 5), reduced soil pH (Table 3), increased availability of macro- and micronutrients (Tables 4 and 5) and the gradual release of N through the conversion of NH_4-N to NO_3-N from the residues of green manures which may have supplied nutrients throughout the growth period of the succeeding wheat crop. According to Marx et al. (1996), the concentration of plant available NH_4-N and NO_3-N in green manure was higher than fertilizer treatments, though it was generally low (less than 11 mg kg^{-1}) and highly variable between treatments and cropping seasons.

Soil N level can be improved with increased level of soil organic matter (Meena et al., 2018). However, the mineral composition and N content of legumes may vary considerably depending on the species, crop growth duration, and growth condition (Schulz et al., 1999; Verma et al., 2015). Ammonium-nitrogen usually does not accumulate in the soil, as soil temperature and moisture conditions suitable for plant growth also are ideal for conversion of NH_4-N to NO_3-N. Ammonium-nitrogen concentration of 2–10 mg kg^{-1} are typical (Horneck et al., 2011), agreeing with the results of this study. Soil NH_4-N levels above 10 mg kg^{-1} may occur in cold or extremely wet soils.

The fertility status of the experimental soil was sub-optimal for wheat production, with initial pH and CEC of 5.2 and 19 cmol kg^{-1}, respectively. In most cases, soils with pH less than 5.5 are deficient in available P and exchangeable cations. In such soils, P becomes unavailable to the crop and the proportion of P fertilizer that could be available to the crop becomes inadequate (Marschner, 2011), unless ameliorated with organic and/or liming inputs. One of the major effects of these legumes was by significantly increasing soil pH ($p < 0.05$) compared to chemical fertilizers or non-treated plots (Table 3). This could be partly explained by pumping of leached cations to the root zones, and increased CEC in all green manure treated plots (Table 4), as also reported by others (Hoque et al., 2016; Couëdel et al., 2018). Interestingly, the effect was more pronounced in SRB treated plots, although application of root biomass alone had a significant effect on soil exchangeable cations.

Exchangeable cations (NH4OAc-K, Mg, and Ca), cation exchange capacity (NH4OAc-CEC), and some micronutrients (such as DTPA-Mo, Zn, and Mn) of the soil were substantially improved due to green manuring, suggesting the contribution of nutrients to the soil and improvement in the nutrient retention capacity of the soil. The increment in CEC due to application of green manures ranged from 0.9 to 5.6 cmol/kg compared to the negative control (F0) (Table 4). The soil OC and CEC could further increase if the practice continues because the recalcitrant part of OC as humic material will increase due to the application of green manures which will in turn contribute to increase in soil OC, CEC and nitrogen content.

The increase in wheat yield in 2019 grown after green manuring may have been closely associated with increased availability of macro- and micronutrients, including Bray-P, N, K, Ca, Mg, and DTPA-B. Likewise, Salahin et al. (2013) have shown that green manure crops could be a significant source of total N, Bray-P, $CaCl_2$-S, NH4OAc-K, Ca, and Mg, DTPA-Zn, B, Cu, and Fe to the succeeding crop.

The residual effect of green manure treatments surpassed the effect of fertilizer treatments on total biomass and grain yield of wheat in 2018 and 2019 (Table 2). On the other hand, nutrient concentrations of the

Table 7
Percentage, cumulative variances and eigenvectors on the first four principal components (PC1-7) for 17 characters in 12 treatments.

Parameter	Prin1	Prin2	Prin3	Prin4	Prin5	Prin6	Prin7
Eigenvalue	11.57	3.68	2.20	1.70	1.47	0.81	0.63
%variance	50.32	15.99	9.55	7.37	6.40	3.51	2.74
Cumulative	50.32	66.31	75.86	83.23	89.63	93.14	95.88
Character	*Eigenvectors*						
GY	0.241324	−0.263149	0.013978	0.041059	−0.111705	0.013057	−0.064120
TB	0.214603	−0.250211	0.168229	0.120084	−0.004715	0.358543	0.027222
TPP	0.155601	−0.191379	−0.042008	0.456174	0.054193	0.022517	0.566906
PV	0.182631	−0.203320	−0.211558	0.260949	0.220399	−0.130347	−0.383036
SWC	0.249964	−0.236442	0.063998	0.019434	−0.146749	0.012971	0.114862
pH	0.246256	0.050578	−0.153644	−0.128212	−0.350051	0.035049	−0.009584
SOC	0.242779	−0.085069	0.077749	0.002498	0.129686	0.269324	−0.295901
N	0.224437	0.240268	−0.267076	−0.118944	0.063021	−0.062644	−0.066951
P	0.206167	−0.007299	−0.197837	−0.262768	0.436102	−0.078626	0.105322
K	0.272834	−0.019439	0.110982	0.112062	0.046214	−0.018005	−0.293966
Ca	0.263552	0.050885	−0.153800	0.007699	−0.259291	−0.196998	0.021664
Mg	0.240125	0.043980	0.249091	−0.217343	−0.155944	−0.050271	0.115502
CEC	0.200083	0.031144	−0.222052	−0.252961	0.415071	−0.009321	0.290135
Zn	0.271777	0.073068	0.178227	−0.134293	0.087982	0.006782	0.087893
Cu	0.115473	0.377113	−0.207708	−0.045284	−0.316178	−0.241417	0.034975
B	0.268481	−0.061083	0.034619	−0.191821	−0.052301	−0.151137	−0.148174
Mn	0.242184	0.072634	−0.162638	0.015742	−0.054879	0.256686	0.317076

Note: GY: grain yield, TB: total biomass, TPP: tillers per plant, PV: plant vigor, SWC: soil water content, SOC: soil organic carbon, CEC, cation exchange capacity.

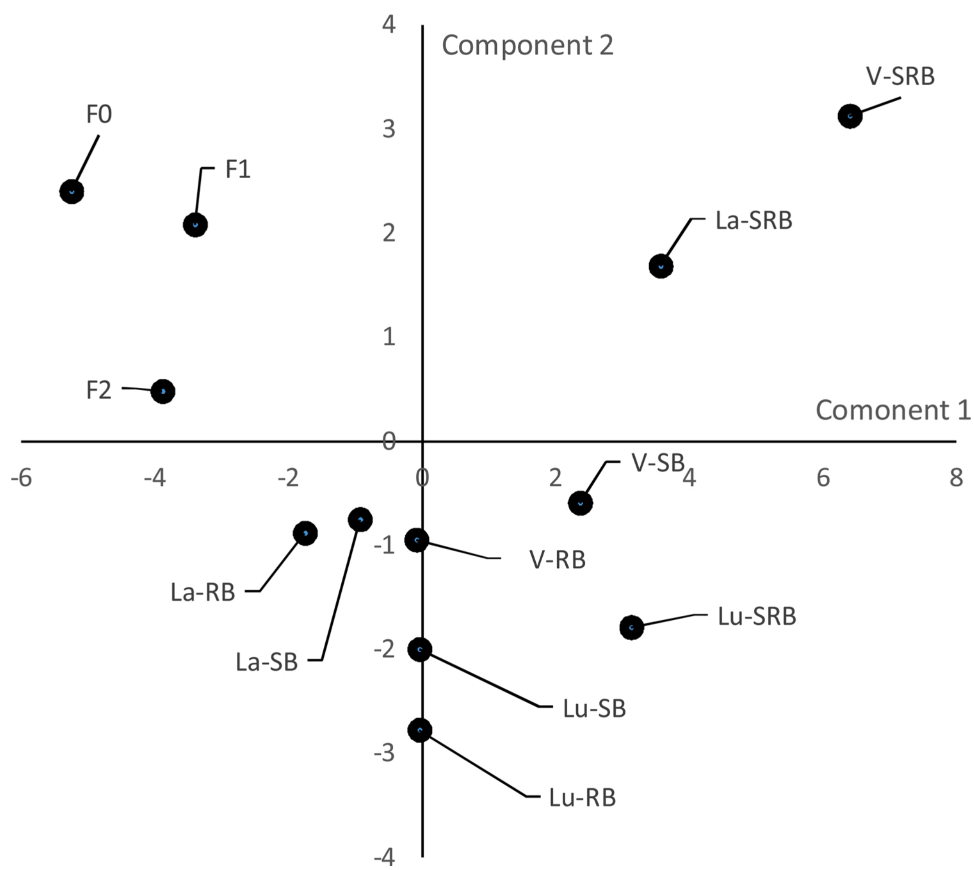


Fig. 6. Plot of principal component one and principal component two in 12 treatments. V-SRB, V-SB, V-RB, Lu-SRB, Lu-SB, Lu-RB, La-SRB, La-SB, La-RB represents whole shoot and root biomass (SRB), shoot biomass only (SB), root (below ground) only (RB), of vetch (V), lupin (Lu), and lablab (La), respectively. F2, F1, and F0: 78/10, 23/0, and 0/0 kg N/P ha^{-1}, respectively.

experimental soil amended by green manures showed a decrease in soil nutrients after the harvest of the second crop in 2019 (Table 3), indicating that the turnover of soil organic matter in green manures is short-lived unless crop fields are alternately covered by green manure crops every two or three years. Higher correlations of yield with SWC and soil nutrient contents and amending the soil with green manures facilitated the availability of nutrients in this study. Previous studies reported positive linear correlations between crop yield, SWC, and soil chemical properties (pH, N, K, P, Ca, Mg, and CEC) as a result of application of different soil fertility treatments (Jagadamma et al., 2008; Agegnehu et al., 2014).

The PCA indicated that the first three components (PC1-PC3) provided a reasonable summary of the data, accounting for ~76 % of the total variance, whereby it explained most of the variation in the entire dataset. It is usually believed that characters with larger absolute values closer to unity within the first principal component influence the clustering more than those with lower absolute values closer to zero (Jolliffe, 2002). In this study, however, almost all characters in the first eigenvector individually contributed similar effects to the total variation of the treatments, suggesting that the first component is primarily a measure of the whole characters. Thus, the differentiation of the treatments into different clusters was rather dictated by the cumulative effects of several characters. Likewise, Sena et al. (2002) compared conventionally managed plots that intensively utilized chemical fertilizers with non-disturbed forest areas and alternatively managed plots using PCA to show the effects of alternative soil amendments.

5. Conclusions

We conclude that integration of green manures is possible with minimum land opportunity cost, by integrating fast growing, N-fixing legumes in between the main growing seasons. Short term fallows would improve soil fertility and productivity of subsequent crops, while reducing fertilizer costs and improving soil fertility through soil conditioning and adding substantial amount of nutrients. For instance, the residual effects of vetch and lupin improved soil fertility status while producing higher or equivalent yields compared to higher rates of inorganic fertilizers (78/10 kg N/P ha^{-1}), thereby substantially reducing wheat production costs.

While the incorporation of whole biomass of green manure legumes is recommended, our results showed that using either the shoot biomass or the root residue would have positive effects on the subsequent wheat crop, particularly when it is supplemented by application of chemical fertilizers. The use of the root biomass for soil amendment and the shoot biomass for feed will be particularly relevant in crop-livestock systems where the competition for biomass between different uses is intense. However, it calls for further research to establish the supplementary N fertilizer required with the green manure crops and the rotation cycle for green manures after wheat over longer periods. Moreover, the socio-economic aspect of this research should be considered in future research to evaluate the economic and social benefits of green manures in sustainable crop production systems. To conclude, at least two years of application of vetch or lupin based green manure alternately followed by one-year fertilization with the recommended dose of inorganic fertilizer may enhance the soil fertility and sustain crop productivity overtime.

Authors' statement

This manuscript has solely been submitted to Field Crop Research.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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