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Research article

Dry matter production, nitrogen yield and estimation of nitrogen fixation of legumes on vertisols of the Ethiopian highlands

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ABSTRACT

Traditional land management techniques on vertisols frequently lead to soil fertility loss and land degradation. The objective of this study was to evaluate the impact of improved land preparation methods on the dry biomass and nitrogen (N) content of two legume species grown under two phosphorus fertilizer applications. The experimental design employed for these experiments was a randomized complete block design, with six treatments and four replications. Land preparation methods and phosphorus application significantly ($P < 0.05$) increased biomass production and N content in legumes. Over years and land preparation methods, vetch N accumulation was superior ($P < 0.05$) to clover and teff (Eragrostis teff). Such a large amount of N accumulation may have a positive contribution to subsequent crops when incorporated into the soil. Land preparation methods and years influenced soil mineral N accumulation, particularly under legumes. The N balance values indicated that it differed among species, land preparation methods, and P treatments over the year. The N balance of vetch +P ranged from 67.1 to 185.9 kg N ha^{-1} over years and land preparation methods, whereas the comparable figure for vetch−P was 40.3–141.9 kg N ha^{-1}. Similarly, the N balance in clover-P ranged from 13.0 to 67.2 kg N ha^{-1}, and in clover +P from 13.8 to 98.6 kg N ha^{-1}. Teff's N balance has never exceeded 35 kg ha^{-1} over the years.

1. Introduction

Black clay soils, or vertisols, are clay-rich soils that shrink and swell with changes in moisture content. Vertisols cover approximately 335 million hectares worldwide, and about 200 million hectares of these soils are in the tropics. Vertisols are important agricultural soils found in the world's major agro-climatic zones (FAO, 2015). Crop production on vertisols is constrained by their texture, shrinking, and swelling properties related to unfavorable soil-moisture relationships. In Africa, the largest vertisol areas are in the Sudan, Chad, and Ethiopia, cultivated by subsistence-oriented smallholder farmers. Due to their physical limitations for land preparation and difficulty in cultivation, resource-poor farmers leave the land fallow during the long rainy season and opt to grow food crops on residual moisture after the cessation of the long rainy season due to fear of waterlogging. In dry periods, deep, wide cracks open, while in a wet state, the soil becomes sticky and plastic (Srivastava et al., 1989). The shrink-swell properties of vertisols pose severe restrictions on land preparation for traditional farming practices. This practice exposes the land to land degradation and soil and water erosion and does not allow for the use of the full potential of the crop-growing season (Elias et al., 2022).

In the highlands of Ethiopia, vertisols cover around 7.3 million hectares of land, cultivated under unpredictable, high seasonal and annual rainfall variability (Seid et al., 2020; Li, 2014; Bewket, 2009). The soils are considered fertile, but their physical characteristics and high and intense rainfall make them prone to land degradation and soil and water erosion, restricting their crop production potential. These soils are sensitive to an excess or shortage of rain, which causes severe limitations to land preparation and crop management under traditional farming practices. The range of soil moisture in which vertisols become suitable for tillage operations is very narrow (Manik et al., 2019; Society, 2016). Naturally, vertisols are soils with high clay contents, and the physical properties change based on soil moisture fluctuation. When wet, vertisols become waterlogged, sticky, and plastic, and when dry, the soils become hard and cloddy, restricting farm operations and lowering crop production (Gebreselassie et al., 2015; Berry et al., 2003).

Farmers have developed several traditional practices to overcome the waterlogging constraints on vertisols. These practices are ridges and

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furrows, opening shallow drainage furrows across the slope, hand-made broad bed and furrows (BBF), guie (soil burning), planting of teff on waterlogged soils, and growing crops on residual moisture after the end of the long rainy season. Guie is a unique traditional practice of burning sods of heavy clay soils to bring the soil aggregates together and enhance the drainage system. The system brings fallow land into cultivation (Mertens et al., 2015; Astatke et al., 2002; Sertsu and Sánchez, 1978). The other practice widely used by smallholder farmers on vertisols is planting crops on residual soil moisture after the withdrawal of the long rains. Sowing crops on residual moisture after the long rains exposes the crops to thermal drought and frost damage (Society, 2016); Erkossa et al., 2014). From the perspective of protecting soil resources, the methods are not sustainable because each of these practices has its own drawbacks to the environmental sustainability of the resources. Teff is Ethiopia's only food crop that grows in moderately waterlogged soil conditions and performs well under warm temperatures at mid-altitude (Chanyalew et al., 2019).

Realizing the potential and capacity of vertisols to produce more food than the traditional system, the Ethiopian Institute of Agricultural Research, along with national and international agricultural research institutions, has made efforts to increase the productivity of the soil through improved technologies. In a food-deficit country like Ethiopia, putting the vast vertisols areas under cultivation means attaining food self-sufficiency. Several researchers have also confirmed that removal of excess water from the farmland and addition of fertilizer on vertisols can boost crop productivity (Lebay et al., 2021; Hamilton et al., 2000; Mekonen et al., 2013; Tekalign et al., 1993).

The research has developed a range of improved technologies, such as the construction of BBF by a broad bed and furrow maker (BBM) to drain the excess water from the field, improved crop varieties, optimum fertilizer application, and early planting. A broad bed and furrow maker (BBM) is an implement that creates beds that are 80 cm wide, 20 cm deep, and 40 cm wide, with furrows alternating between the two beds. A broad bed and furrow maker (BBM) is a tool that makes beds that are 80 cm wide, 20 cm deep, and 40 cm wide, with furrows between them. It is a covered metal sheet attached to a local plow, which scoops soil to the center to form a bed (Hamilton et al., 2000; Astatke et al., 2002). The construction of an improved BBF allowed farmers to plant early by removing the waterlogging condition rather than leaving the land fallow and planting on residual moisture after the cessation of the long rainy season. Early planting reduced soil and water erosion that would have occurred due to a lack of vegetative cover on the farmland. In addition to draining the excess water, N and P management are equally essential for crop production on vertisols (Mamo et al., 2002; Mamo and Haque, 1987), because the soils have a long history of cultivation without applying the optimum amount of inorganic fertilizer, climate-induced land degradation, and mismanagement of agricultural lands. Most Ethiopian soils are deficient in major plant nutrients, and fertilizer consumption per unit of land is the lowest in sub-Saharan Africa (Jayne and Rashid, 2013). Lack of purchasing power by farmers, unavailability and distribution problems Food crops depend on native soil fertility for their nutrition (Haileslassie et al., 200; Haileslassie et al., 2005). The use of crop residues and manure is minimal due to their use as livestock feed and to fulfill household energy requirements, respectively (Vanlauwe et al., 2015; Tittonell et al., 2008).

For such a farming system, it is critical to developing a crop production system that is affordable, cost-effective, and environmentally friendly (Bado et al., 2018; Giller, 2005). Integration of legumes into the farming system may solve the fertility problem while improving the drainage system will maximize crop production on vertisols. Farmers cultivate legumes as an essential component of their cropping system, typically as a break crop or on residual moisture. Commonly, grain legumes grow on vertisols and are uprooted at maturity, leaving little nitrogen for succeeding crops (Huss-Danell et al., 2007). Forage legumes may provide N input into the system, but farmers rarely grow forage legumes. It is essential to design more sustainable agricultural production practices based on an appropriate level of technology (Reckling et al., 2016). The current study tried to explore the biomass production potential, nitrogen concentration, and nitrogen accumulation of selected legumes on vertisols under drained conditions. Vetch and clover are the legumes employed in this research. Therefore, vetch and clover were used in these experiments. Vetch can tolerate wet soil, while clover tolerates it to a certain extent (Striker and Colmer, 2017a,b; Pampana et al., 2018). So far, there is no information regarding their use to improve the soil fertility conditions.

Growing crops early at the start of the rainy season instead of the fallow period has many agronomic and environmental benefits. Integration of legumes in the cropping systems benefits farm-level resource optimization and protects the soil from erosion and runoff. The rationale for growing a forage legume as a long-season crop is that it could take the place of fallow in the traditional system provided the net benefit exceeds the latter. The rationale for growing forage legumes during the primary rainy season by improving the drainage system is that it could take the place of fallow to protect ground cover to minimize soil and water erosion during high-intensity rainfall. Legume-derived N is an alternative source of fertilizer that can maintain the productivity of crops and reduce the use of mineral fertilizers, which is economically and environmentally advisable. The objective of this study was, therefore, to assess the dry biomass and nitrogen content of legumes under drained vertisol conditions with two levels of P application during the long rainy season. An article on the assessment of incorporated legume residues in the soil for subsequent wheat crop production is under preparation.

2. Methodology

2.1. Study site description

The field experiment was carried out for two years in a row (2018 and 2019) in the Holeta Agricultural Research Center (9°02′12″N and 38°29′00″E, and at an elevation of 2400 m above sea level), 35 km west of Addis Ababa, Ethiopia. The soil of the study site is typically pellic vertisol, found in the highland-humid agro-ecology, poorly aerated, and waterlogged for a prolonged period. The soil exhibits impeded drainage due to high clay content (>30%) in the upper soil profile and qualify for the classification of the World Reference Base, Update 2015, of the third edition (Soil and Reports, 2015; Elias, 2019). The soil is developed on alluvium and colluvium deposits from higher slopes with weathered rocks of volcanic origin (Elias, 2019). The study area represents a tropical climate, having two distinct rainfall regimes and a dry period. A graph showing rainfall and temperature for the study site during the experimental periods is shown in Figure 1.

2.2. Land preparation methods and treatment arrangement

In the 2018 and 2019 cropping seasons, two experiments were established each year on BBF and camber-bed land preparation methods. Vetch (*Vicia villosa*, *Varia* (Host) Corb.), clover (*Trifolium quartinianum* A. Rich), and a cereal crop, teff, were sown on both land preparation methods in RCBD fashion with four replications. A tractor-mounted mouldboard plow digs camber beds of 50-cm-deep drainage ditches and piles soil in the center. Camber beds can have a width of 4–9 m (in the present study, 6 m) with a concave raised bed, the top of which is about 50–60 cm above the bottom of the furrow. The camber bed needs maintenance every three to four years and can last several years. Vetch, clover, and teff were planted in both years, on both land preparation methods, with and without P fertilizer in the form of triple superphosphate administered at 0 and 18 kg ha^{-1} for legumes and 0 and 26 kg ha^{-1} for teff. The test crops were applied with urea fertilizer at a rate of 46 kg ha^{-1}. In 2018 and 2019, the treatments had four and three replications, respectively.

The plot size of BBF was 12 m long and 11 m wide (i.e., nine beds), while the plots on camber beds were 6 m wide and 18 m long. In the last week of June, legumes were sown at a seed rate of 25 and 15 kg ha^{-1} for vetch and clover, respectively. During the last week of June, legumes

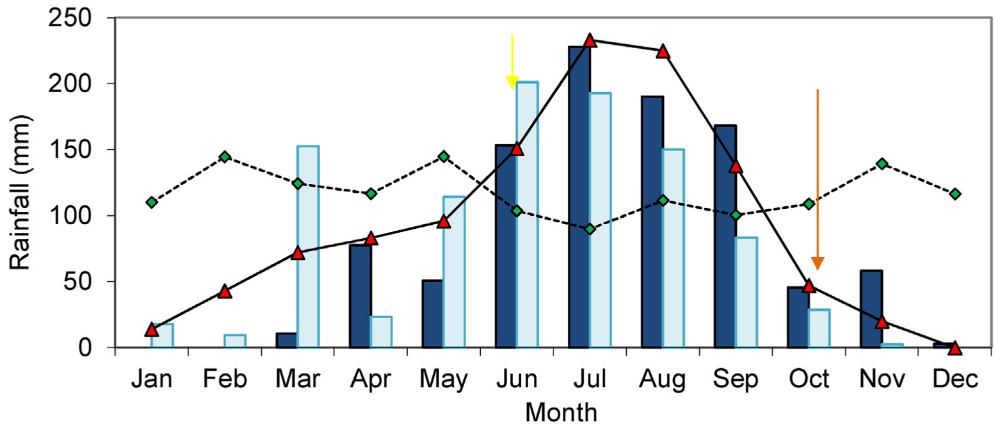

Figure 1. Monthly average rainfall at Holeta in 2018 (blue bars) and 2019 (light bars) and the average long-term (1982–2020) rainfall (red triangles and fully drawn lines). The broken line with green diamonds represents the calculated potential evapotranspiration (Penman-Monteith). The short arrow (June) shows the planting time of Expts I, II, III, and IV, while the long arrow (October) represents the planting time of crops on residual moisture.

were broadcast at 25 and 15 kg ha^{-1} rates for vetch and clover, respectively. Teff was sown at a seed rate of 30 kg ha^{-1} on June 12 for the 2018 experiment and June 15 for the 2019 experiment. Teff was used as a test crop in the study to assess dry biomass and nitrogen accumulation in comparison to legumes. Details of the treatments used in the experiments are shown in Table 1.

In the year 2019, the same experiments were conducted on both land preparation methods, with codes Exp III and IV on BBF and camber, respectively. +P and –P denotes crops applied with and without phosphorus fertilizer, respectively.

2.3. Soil sampling and analysis

The soil and plant nutrition laboratory at the Holeta Agricultural Research Centre conducted the physicochemical properties of soil samples collected from the experimental fields. The soil samples collected from 0–20, 20–40, and 20–60 cm soil layers from both land preparation methods were ground to pass a 2 mm sieve before determining the parameters indicated in Table 1. Soil samples collected to determine soil mineral N (ammonium nitrate and nitrate nitrogen) were immediately taken to the laboratory and kept in the refrigerator until the analysis was done (Bremner and Keeney, 1965).

2.4. Plant sampling and analysis

In Experiments I–IV, the main plots of legumes and teff crops were cut at ground level at maturity from an area of 25 m^2 of BBF of both land preparation methods between 8 and 13 December and sub-sampled to determine the fresh weight, dry weight, and N concentration. Subsamples of about 200 g were oven dried at 70 °C for 24 h. The oven-dried plant materials were ground to pass through a 2 mm mesh and further sub-sampled and analyzed for total N content by the Kjeldahl method (Kirk, 1950). The N uptake and concentration were determined from the dry biomass of the crops under investigation. For calculation purposes, the dry biomass produced and the N accumulated were converted to kg ha^{-1}.

2.5. Calculations of N balance and atmospheric N input

To measure the increase in N in the plant-soil (0–40 cm) system between planting and crop harvest, the net N balance was determined (Sainju, 2017). The N balance was explained as follows: -

$$\text{Net N balance} = (\text{crop N content at harvest} + \text{residual soil mineral N at harvest}) - (\text{initial soil mineral N} + \text{added fertilizer N} \quad (1)$$

Other N sources and sinks were not measured. The difference in N-balance between legumes and teff provides an estimate of the N input into the soil-plant system from fixation. Data from the teff+P treatment was used in these calculations, as crop N content in teff+P was always higher than in teff−P. Therefore, the N content in Teff+P was the best estimator of the amount of N that could be derived from the soil. The amount of N fixed by legumes was estimated by the N-difference method, using teff as a reference crop, such that-

$$\text{N fixed} = \text{N legumes} - \text{N teff} \quad (2)$$

where N is the total amount of nitrogen in legumes and the reference crop teff in the above-ground biomass.

2.6. Statistical analysis

An analysis of variance was done using the Statistical Analysis System computer package (IBM SPSS Statistics for Windows, Version 25.0) to determine the main treatment effects and their interactions on biomass, nitrogen concentration, and N accumulation. The main effects and interactions were determined using the Turkey LSD analysis of SPSS. At $P < 0.05$, differences were considered significant for all statistical tests.

3. Results

3.1. Soil properties and weather conditions

The soil was clayey in texture, having 66% clay at 0–60 cm depth with strong vertic properties. The physical and chemical characteristics showed a pH of 5.6, a total N content of 0.8%, 1.13% organic matter

Table 1. Summary of treatment description.

Year	Land preparation methods	Treatments	Treatment description	Fertilizer (kg ha^{-1})	
				Urea	TSP
2018	BBF (Exp I)	Vetch−P	Vetch without P	46	18
		Vetch+P	Vetch with P	46	18
		Clover−P	Clover without P	46	18
		Clover+P	Clover with P	46	18
		Teff−P	Teff without P	46	26
		Teff+P	Teff with P	46	26
	Camber bed (Exp II)	Vetch−P	Vetch without P	46	18
		Vetch+P	Vetchwith P	46	18
		Clover−P	Clover without P	46	18
		Clover+P	Clover with P	46	18
		Teff−P	Teff without P	46	26
		Teff+P	Teff with P	46	26

content, and P (Bray II) of 8.1 mg kg^{-1}. The pH of the soil increases as total N and organic matter decrease with depth. The P status is low in the top 0–60 cm but tends to increase with depth (Table 2). Generally, the soil showed lower plant-available nutrients, which is the characteristic of vertisols in the highlands of Ethiopia.

The rainfall of the study area is bio-modal, having two peaks in a year, namely the long (June–September) and the short rainy season (February May). The short-rainy season rainfall is less in quantity and erratic and has no agronomic importance. The dry period extends from October to January. The long-term (39 years) mean rain was 1126 mm, showing considerable annual and seasonal variations. The mean long-term rainfall for the long-rainy season was 768.2 mm in 2018 and 509 mm in 2019, showing both years had lower rain than the long-term annual mean (Figure 1). The mean potential evapotranspiration (PET) calculated with the Penman-Monteith methodology exceeds rainfall from October through May. In particular, the year 2019 was relatively dry. The mean monthly minimum and maximum air temperatures range between 5–12 °C and 22–28 °C, respectively, without much variation over the study period.

3.2. *Performance of legumes and teff grown as main season crops (Expts I–IV)*

3.2.1. *Biomass productivity*

The grand mean of dry biomass produced across treatments was 4930 kg ha^{-1} in 2018 and 2530 kg ha^{-1} in 2019, indicating that growth conditions were better in 2018 than in 2019. Across treatments and seasons, the mean dry biomass production amounted to 3843.3 kg ha^{-1} for vetch, 1615.8 kg ha^{-1} for clover, and 5724.5 kg ha^{-1} for teff (Table 3). The highest dry biomass was recorded with teff, followed by vetch, whereas clover performed relatively poorly in all experiments. Over years and land preparation methods, camber beds gave (4546.3 kg ha^{-1}) than on BBF (2909.2 kg ha^{-1}). In both years, camber beds produced 38.3 and 23.5% more dry biomass than BBF. The dry biomass of crops was significantly ($P < 0.05$) influenced by crop type in all the four experiments. Phosphorus application also significantly ($P < 0.05$) affected the biomass production of crops in 2018 on both land preparation methods, whereas in 2019, P application did not affect the biomass production of crops.

The interaction effects of crop type by P application were inconsistent among the crops tested. Considering the individual experiments, 2018 gave a higher biomass yield than 2019 (Figure 2). Over the years, the mean dry biomass produced by vetch−P on BBF and camber bed was 2220 and 3860 kg ha^{-1}, respectively, indicating a significant response to P application. The mean dry biomass produced by clover−P was 990 and 1780 kg ha^{-1} on the BBF and camber bed, while Clover+P produced 1130 and 2570 kg ha^{-1} on the BBF and camber bed over years, respectively. Over seasons, teff−P gave 3930 and 6550 kg ha^{-1} on BBF and camber beds, respectively, while the dry biomass produced by teff with P was 5120 and 7030 kg ha^{-1} on the BBF and camber bed, respectively. The overall mean harvest index of teff was 0.42 (ranging from 0.39 to 0.45; data not shown). A comparison of the four experiments across years and land preparation methods showed that year 2018 was better for crop growth and camber bed created suitable environment for better crop performance. Camber bed of 2018 increased the dry biomass of crops by 41.5% compared to the BBF of the same year. In 2019, camber beds gave a 24.1% higher return than BBF of the same year.

Table 3. ANOVA results for crop dry biomass over years and land preparation methods.

Treatment	BBF 2018 (ExpI)	Camber bed 2018 (Exp II)	BBF 2019 (Exp III)	Camber bed 2019 (Exp IV)
***Crop type**				
Teff (T)	5376a	8620a	3674a	5228a
Vetch (V)	4087b	6410b	2202b	2674b
Clover (C)	1445c	3613c	672c	733c
P level				
−P	2808b	5505.8b	1951b	2621a
+P	4464a	6923.3a	2415a	3135a
Interactions (crop type * P level)				
T+P	6522a	9320a	3720a	5276a
T−P	4230bc	7920ab	3628a	5180a
V+P	5230ab	7172bc	2945ab	3270b
V–P	2945cd	5647cd	1489ab	2078bc
C+P	1640de	4277de	610b	860c
C–P	1250e	2950e	734b	606c

*T-teff; V-vetch; C-clover; +P and –P denotes crops with and without P application; For each treatment factor, mean values with the same letter in the same column are significantly different at $P < 0.05$.

Among land preparation methods, in both seasons camber bed gave a higher dry biomass yield than BBF. Considering the crops tested in terms of biomass, higher dry biomass was recorded for teff, followed by vetch and then clover (Figure 3). On average, P application increased ($P < 0.000$) the dry biomass of crops by 37% on BBF 2018 (Exp I), by 20% on camber bed 2018 (Exp II), by 19% on BBF 2019 (Exp III), and by 16% on camber bed of 2019 (Exp IV) over non-P applied treatments. Dry biomass was affected by crop type ($P < 0.05$) in all four experiments.

3.3. *Land preparation methods and seasonal effect*

A combined analysis of variance for dry biomass across years (BBF 2018 and 2019 and camber bed 2018 and 2019) revealed that year and crop type had a significant ($P < 0.000$) impact on the dry biomass. Phosphorus application was weakly correlated to dry biomass production, and the interaction effects were not statistically significant (Table 4).

Land preparation methods influenced the dry biomass of crops. A combined analysis of variance for land preparation methods indicated that land preparation, crop type, and P application significantly influenced dry biomass in 2018, but their interaction effects were not statistically significant. In 2019, the only significant effects on the dry biomass were from the crop type (Table 5).

3.4. *Nitrogen concentration and N accumulation*

The N concentration in the dry biomass of crops varied among the crop species tested. On average, the N concentration in vetch was 3.13%, in clover 2.4%, and in teff 0.76% (data not shown). The N concentration

Table 2. The physical and chemical characteristics of the experimental field.

Depth (cm)	pH (1:1 (H_2O))	N (%)	Organic carbon (%)	P Bray (mg kg^{-1})	Na^+	K^+	Ca^{2+}	Mg^{2+}	*Initial soil mineral N (kg $^{-1}$)				Clay (%)
					cm mol kg ha^{-1}								
0–20	5.3	0.09	1.29	9.2	0.32	1.58	35.3	14.2	14.1	10.9	6.3	9.7	64
20–40	5.8	0.07	0.97	7.1	0.35	1.58	35.3	12.8	7.4	6.9	9.2	11.4	61
40–60	6.5	0.07	0.66	14.8	0.59	1.69	45.3	15.9	* the first two column for BBF and the second two for camber bed				74

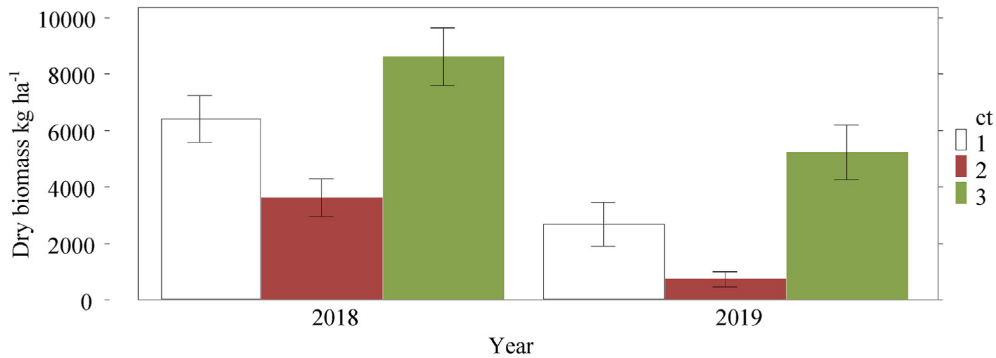

Figure 2. Error bar showing dry biomass production of crops over years on camber bed land preparation methods, Error bar showing at 95% C.I. ct-crop type, 1-vetch, 2-clover, 3-teff.

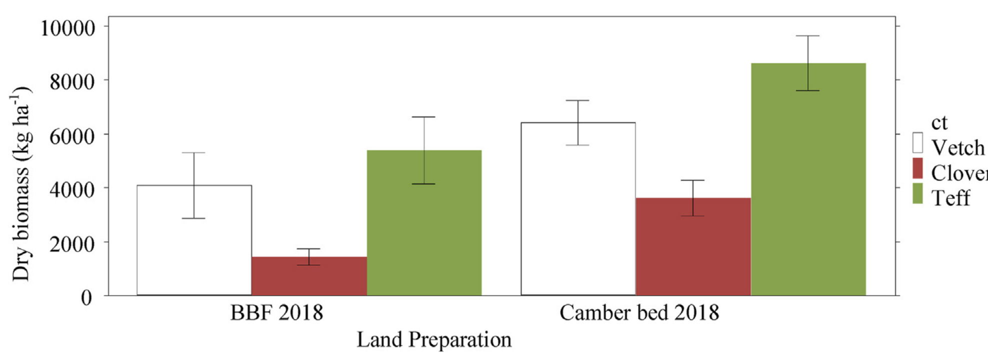

Figure 3. Error bar showing dry biomass production of BBF and camber bed in 2018. Error bar showing at 95% C.I. ct-crop type, 1-vetch, 2-clover, 3-teff.

Table 4. Analysis of variance for dry biomass over years.

Source	DF	BBF 2018 and 2019		Camber bed 2018 and 2019	
		F	P	F	P
year	1	10.59	0.0028	76.54	0.000
ct	2	14.23	0.000	34.11	0.000
pl	1	6.56	0.0157	5.51	0.0257
year*ct	2	0.43	0.6527	0.1	0.904
year*pl	1	2.61	0.117	1.26	0.2708
year*ct*pl	4	0.92	0.4661	0.18	0.9464
Error	30			30	
Total	41			41	
Grand mean	3183.3			4714.7	
CV	42.3			28.29	

ct-crop type, pl-phosphorus level.

Table 5. Analysis of Variance for dry biomass over land preparation methods.

Source	BBF and camber bed 2018			BBF and cambeer bed 2019		
	DF	F	P	DF	F	P
LP	1	34.17	0.0000	1	1.51	0.2303
ct	2	20.19	0.0000	2	39.39	0.0000
pl	1	12.86	0.001	1	2.02	0.1684
LP*ct	2	0.48	0.6232	2	2.69	0.0882
LP*pl	1	0.15	0.6995	1	0.03	0.8749
LP*ct*pl	4	0.49	0.7436	4	0.9	0.4808
Error	36			24		
Total	47			35		
Grand Mean	5219.9			2678.1		
CV	29.57			35.73		

in the dry biomass was significant among crops and, to a lesser extent, between crops. Phosphorus application did not affect the N concentration of crops in three out of four experiments across years and land preparation methods, except in BBF 2018 (Exp 1). The interaction effect of P application and crop type on N concentration showed significant differences among crops in 2018 compared to 2019 (Table 6). Over years and land preparation methods, N accumulation was higher for vetch than clover, and teff showed almost similar N accumulation but lacked statistical significance. Phosphorus application significantly ($P < 0.05$) influenced the N accumulation in three of the four experiments. The interaction effects were more significant between crops than among crops. In general, the N concentration and N accumulation varied greatly among the crops tested, seasons, P application, and land preparation methods. On average, the N concentration of crops ranged from 2.8 to 0.9%, the highest for vetch, followed by clover and teff. The N concentration recorded on camber bed land preparation methods over the years was 2.4% for vetch, 2.3% for clover, and 0.8% for teff. The year had a significant ($P < 0.05$) influence on the N concentration over years. Phosphorus application didn't show a significant difference over the years. A significant interaction effect for the independent variables was shown under BBF land preparation methods, but over years, camber bed land preparation methods showed no interaction effect except for year*crop type (Tables 3 and 5). N accumulation was significantly affected by the crop type. Vetch recorded the highest N yield over years under the same land preparation methods. P application and year has a significant effect on N yield. The interaction effects were also significant (Tables 3 and 5).

Table 6. ANOVA results for N concentration and N accumulation over years and land preparation methods.

Treatments	BBF 2018 (Exp I)		Camber bed 2018 (Exp II)		BBF 2019 (Exp III)		camber bed 2019 (Exp IV)	
	N Yield (kg ha^{-1})	N con. (%)	N Yield (kg ha^{-1})	N con. (%)	N Yield (kg ha^{-1})	N con. (%)	N Yield (kg ha^{-1})	N con. (%)
Crop type (ct)								
Teff (T)	23.0b	0.8c	31.6c	0.8c	14.8b	0.8b	20.7b	0.8b
Vetch (V)	127.6a	3.1a	163.6a	2.6a	53.7a	2.5a	58.8a	2.1a
Clover (C)	32.2b	2.2b	82.9a	2.3b	15.2b	2.3a	16.8b	2.3a
P level								
−P	43.9b	1.9b	79.4b	1.9a	23.9a	1.9a	26.1b	1.7a
+P	78.0a	2.1a	106.9a	1.9a	31.9a	1.8a	38.1a	1.8a
Interactions (crop type *P level)								
T+P	28.4c	0.9e	34.0e	0.7c	14.6b	0.8b	21.2bc	0.8b
T−P	17.6c	0.8e	29.2e	0.7c	15.0bc	0.8b	20.2bc	0.8b
V+P	168.3a	3.2a	185.9a	2.6a	67.1a	2.3a	72.4a	2.2a
V–P	87.1b	2.9b	141.9b	2.5ab	40.1b	2.6a	45.2b	2.1a
C+P	37.4c	2.3c	98.6c	2.3b	13.8c	2.2a	20.6bc	2.4a
C–P	27.0c	2.1d	67.2d	2.20b	16.5bc	2.3a	13.0c	2.1a

*T-teff; V-vetch; C-clover; +P and –P denotes crops with and without P application; For each treatment factor, mean values with the same letter in the same column are significantly different at $P < 0.05$.

3.5. Land preparation methods and seasonal effects on crop productivity

A combined analysis of variance was conducted for dry biomass, N concentration, and N accumulation of experiments conducted in 2018 and 2019 (Table 7). The analysis indicates that the dry biomass of crops was highly influenced by crop type, P application, and land preparation methods. Phosphorus application significantly ($P < 0.000$) affected the dry biomass in 2018, but in 2019 P application didn't show any significant difference. Land preparation methods significantly ($P < 0.000$) increased the dry biomass of crops in 2018, but the effect of land preparation methods in 2019 showed a slight difference. In 2018, the N concentration in the dry biomass of crops was largely affected by crop type, P application, and land preparation methods; in 2019, there was no statistically significant difference found in P application or land preparation methods, except for crop type, which showed a slight difference among crop types. The interaction effect of P application and crop type on N concentration showed significant differences among crops in 2018 compared to 2019 (Table 6). Over years and land preparation methods, N accumulation was higher for vetch than clover, and teff showed almost similar N accumulation but lacked statistical significance. Phosphorus application significantly ($P < 0.05$) influenced the N accumulation in three of the four experiments. The interaction effects were more significant between crops than among crops.

Table 7. Analysis of variance for dry biomass, N concentration, and N yield over the land preparation methods.

Treatment	BBF and camber bed 2018 (Exp I and II)			BBF and Camber bed 2019 (Exp III and IV)		
	Dry biomass (kg ha^{-1})	N concentration (%)	N accumulation (kg ha^{-1})	Dry biomass (kg ha^{-1})	N concentration (%)	N accumulation (kg ha^{-1})
Crop type						
vetch	5249.1 b	2.8 a	145.8 a	2438.4 b	2.3 a	56.3 a
clover	2529.6 c	2.3 b	57.6 b	703.6 c	2.3 a	16.0 b
teff	6998.3 a	0.8 c	27.3 c	4451.3 a	0.8 b	17.8 b
P value	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**
P rate						
−P	4157.8 b	1.9 b	61.7 b	2286.1 a	1.8 a	25.5 b
+P	5694.6 a	2.0 a	92.1 a	2775.3 a	1.8 a	35.0 a
P value	**0.000**	**0.004**	**0.000**	**0.065**	**0.991**	**0.005**
Land preparation						
BBF	3636.4 b	2.1 a	60.9 b	2183.4 b	1.9 a	27.9 a
Camber bed	6215.2 a	1.9 b	92.8 a	2878.5 a	1.8 a	32.2 a
P value	**0.000**	**0.000**	**0.000**	**0.011**	**0.405**	**0.193**
Interaction						
ct*pl	2.820	0.064	0.000	0.094	0.514	0.000
ct*LP	0.093	0.000	0.001	0.064	0.371	0.193
LP*pl	0.575	0.039	0.375	0.923	0.167	0.005
ct*LP*pl	0.156	0.644	0.022	0.884	0.787	0.003
Error	36	36	36	24	24	24
Grand Mean (kg ha^{-1})	4925.4	1.9	76.8	**2531.7**	1.8	30.1
CV (%)	14.8	4.8	18.4	30.2	15.6	31.8

*+P and −P denotes phosphorus applied and non-phosphorus applied treatments, mean values with the same letter in the same column are significantly different at $P < 0.05$, lp-land preparation, ct-crop type, pl-phosphorus level.

A combined analysis of variance conducted for dry biomass and N accumulation of the experiments conducted on the same land preparation methods across years (Table 8) showed that the effect of year, crop type, and P application significantly ($P < 0.000$) influenced the dry biomass of crops. N yield was highly affected by P application and year. The effect of year and P application was more pronounced on the N accumulation in 2018, but N concentration was not affected by the P application in 2019.

3.6. Initial and residual soil mineral N

For determination of the N balance, soil mineral N assessment was performed before and after planting and harvesting the test crops. At the start of the experiments, the total initial soil mineral N at 0–40 cm was 21.4, 17.8, 15.5, and 21.1 kg ha^{-1} on BBF 2018 (Exp 1), camber bed 2018 (Exp II), BBF 2019 (Exp III), and camber bed 2019 (Exp IV), respectively. Soil mineral N detected after the harvest of legumes and teff ranged from 7 to 46, 53 to 82, 9 to 45, and 7–23 kg N ha^{-1} in Expts I, II, III, and IV, respectively. Excluding fallow plots, the man soil mineral N on BBF in 2018 was higher than on the camber bed of the same year. Soil mineral N detected after harvest of legumes was higher compared to soil mineral N monitored after harvest of teff plots. The mean soil mineral N increment after vetch and clover harvest was different from that of the initial soil mineral N following teff harvest, and ranged between 3.5 to 50 and 0.6–26 kg N ha^{-1}, respectively, over years and land preparation methods (data not shown). The ratio of $NO3^{-}$–N to $NH4^{+}$–N in the 0–40 cm soil layer for both land preparation methods and over years was between 1 and 0.4, indicating a slight predominance of ammonium-N over nitrate-N. When compared to teff, a non-leguminous planted plot, the mineral N content of the soil is often higher in soils where legumes are planted.

3.7. The nitrogen balance

The mean N balance varied widely ranging from 53.7 to 163.9 kg ha^{-1} for vetch, 15.2–82.9 kg ha^{-1} for clover and 14.8–31.6 kg ha^{-1} for teff over years and land preparation methods. The N balance of clover and teff were lower than vetch in all the experiments. Over years and land preparation methods, the N balance of Vetch+P ranged from 72.5 to 168.3 kg ha^{-1}, while vetch-P ranged from 40.1 to 141.9 kg ha^{-1}. In Expts I, III, and IV, the N balance of clover with and without P treatments showed negative values, except in Expt. II (67.2 versus 98.6 kg ha^{-1}). The N balance of teff−P ranged from 15.0 to 29.2 kg ha^{-1}, while teff+P ranged from 14.6 to 34.0 kg ha^{-1} across years and land preparation methods. In clover and teff, the effects of P on the N balance correspond with the effects of P on biomass accumulation. The N balance of all crops was higher in 2018 and on camber beds compared to 2019 and on BBF. The N balance of crops was higher under P applied treatment. The N balance calculated was positive for all crops, but the values differed between species, land preparation methods, P treatments, and years (Table 9).

3.8. N balance and estimation of nitrogen fixation

The estimation of N fixation by the N balance method using teff+P as a reference crop ranged from 13 to 95 and 61–127 kg ha^{-1} for vetch-P and Vetch+P over seasons and land reparation methods, respectively. In three out of four cases, no net contribution to fixation was calculated for clover (Expts I, III, and IV), while estimated N fixation amounted to 10 and 50 kg ha^{-1} for clover–P and Clover+P in Expt II, respectively. Across seasons and land preparation methods, the estimated N fixation of vetch-P ranged from 44 to 132 kg ha^{-1} and 78–165 kg ha^{-1} for Vetch+P. Comparable clover figures were 14.6 kg ha^{-1} for clover−P and 14.9 kg ha^{-1} for Clover+P.

The calculated or estimated atmospheric N fixation of vetch varied with year, land preparation methods, and P nutrition in this study. To explain the variation in the estimated N fixation of clover, a graph was plotted as a function of the N content of teff and as a function of the biomass of teff at its maturity (Figure). The three plots show a strong association between clover N fixation and teff performance, as measured by N content or biomass. The associations between N fixation in vetch and teff performance differed for the two levels of P supply, indicating that vetch had a stronger positive response to extra P than teff. Apart from the different levels of P supply, the teff data are from plots with essentially identical input. The association between teff performance and N fixation can be essential to assessing the N fixation that may be expected from clover when no direct data are available (Figures 4 and 5).

3.9. Estimation of N_2 fixation and N balance

The N balance of after crops were positive, with significant differences between species, P application, and land preparation methods across years. The mean N balance varied widely, ranging from 74 to 156, 9 to 83, and 19–70 kg ha^{-1} for vetch, clover, and teff over years and land preparation methods, respectively. The N balance of clover and teff was lower than vetch. These values can be influenced by soil nitrate, crop growth, dry matter yield, and the N harvest index. The N balance of vetch was highest for P-applied treatments than non-P applied. This experiment could not find any clear trend for the increase in the N balance of clover and teff with P application or the difference in N balance between these two crops. However, approximately a 50 % increase in N balance was

Table 8. Analysis of variances for dry biomass, N concentration, and N yield over years on the same land preparation methods.

Source	BBF 2018 and 2019 (Exp I and Exp III)						Camber bed 2018 and 2019 (Exp II and Exp IV)					
	Dry biomass (kg ha^{-1})			N accumulation (kg ha^{-1})			Dry biomass (kg ha^{-1})			N accumulation (kg ha^{-1})		
	DF	F	P	DF	F	P	DF	F	P	DF	F	P
Year	1	35.1	0.000	1	61.6	0.000	1	238.2	0.000	1	289.8	0.000
ct	2	67.5	0.000	2	120.9	0.000	2	161.0	0.000	2	203.3	0.000
pl	1	18.7	0.000	1	24.9	0.000	1	20.0	0.000	1	29.5	0.000
year*ct	2	2.0	0.157	2	24.0	0.000	2	1.3	0.282	2	58.8	0.000
year*pl	1	5.9	0.021	1	9.6	0.004	1	4.4	0.045	1	4.3	0.046
ct*pl	2	4.2	0.025	2	15.4	0.000	2	0.8	0.447	2	7.0	0.003
year*ct*pl	2	1.1	0.346	2	2.8	0.078	2	0.5	0.636	2	0.7	0.516
Error	30			30			30			30		
Total	41			41			41			41		
Grand mean (kg ha^{-1})	2910				44.431		4547				62.489	
CV (%)	27				30.4		15.25				18.29	

y-year; ct-crop type; pl-phosphorus level; CV-coefficient of variation; N conc.-nitrogen concentration.

Table 9. Calculations of amount of N fixed (kg ha^{-1}) by legumes over the reference crop teff using the total N difference method.

Crop type	Experiment I (BBF 00)		Experiment II (camber bed 00)		Experiment III (BBF 01)		Experiment IV (camber bed 01)	
	N balance	N fixed	N balance	N fixed	N balance	N fixed	N balance	N fixed
Vetch−P	87.1	58.7	141.9	107.9	40.1	25.5	45.2	24.0
Vetch+P	168.3	139.9	185.9	151.9	67.1	52.5	72.4	51.2
Clover−P	27.0	−1.4	67.2	33.2	16.5	1.9	13.0	−8.2
Clover+P	37.4	9.0	98.6	64.6	13.8	−0.8	20.6	−0.6
Teff−P	17.6		29.2		15.0		20.2	
Teff+P	28.4		34.0		14.6		21.2	

Given that the crops were grown on the same type of soil, with the same amount of fertilizer supplied, and under the same management conditions, the variation in N accumulation could be attributable to a differential in N uptake between N2 fixing and non-fixing crops. Therefore, the difference in N accumulation could be due to the differential in N uptake between N2 fixing and non-fixing crops, as shown in Eq. (2). Variations in meteorological conditions, crop type, soil conditions, and management approaches can all contribute to uncertainty. The calculated N fixation will be obtained from the N balance of crops minus Teff+P, which is a reference to a crop without nutrient limitations in this case.

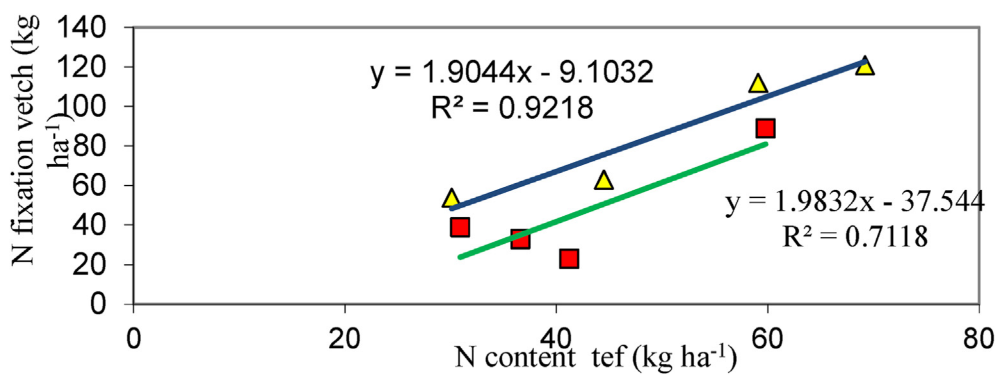

Figure 4. The relationship between total N in dry biomass of teff and N fixation of vetch calculated using N balance method.

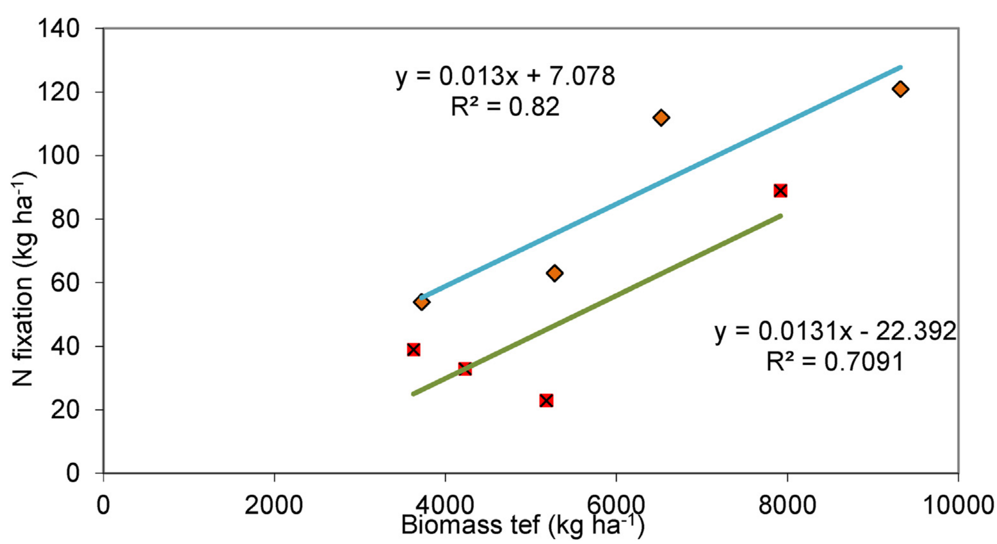

Figure 5. The relationship between dry biomass of teff and N fixation of vetch using N balance method.

recorded for clover over teff in 2018 on camber beds. Using teff+P as a control, the estimation of N fixation revealed positive values for vetch but positive and negative values for clover (Figure 4). Thus, maintenance of soil fertility can be achieved only if legumes grow in low-nitrate soils and yields are sufficiently high to provide a reasonable potential for N fixation.

We observed that the calculated (or estimated) atmospheric nitrogen fixation varied depending on the year, land preparation method, and P nutrition. In an attempt to explain this variation, the estimated fixation of clover was plotted as a function of the N content of teff and as a function of the biomass of teff at its maturity. The plots show a strong association between clover N fixation and teff performance, as measured by its N content or biomass. The associations between N fixation in vetch and performance in teff differed for the two levels of P supply, consistent with a positive response to extra P in vetch than in teff.

Teff data are from plots with essentially similar inputs, aside from different levels of P supply. The variation in teff performance, reflects the variation in growth conditions. Vetch N-fixation appears to be similarly affected by growth conditions as teff performance (Figure 5). The association between teff performance and N fixation can be used to assess the N fixation that may be expected from clover when no direct data are available, while data on teff performance are at hand.

3.10. Legume N fixed calculated using the N difference method

The N fixation estimated by the N-difference method showed a wide variation between legume type, P application, land preparation, and across years (Table 9). On BBF and camber beds in 2018, Vetch+P fixed 139.9 and 151.9 kg ha^{-1} N, respectively. Vetch-P fixed 58.7 and 107.9 kg ha^{-1} on BBF and camber beds in 2018, respectively. Regardless of P application, clover N fixation was lower and showed inconsistencies across years and land preparation methods. The calculated N balance considering the inputs and outputs in the system indicated that vetch crops with and without P applied showed a high N gain in the system, particularly in 2018 (Appendix A) with a positive N balance under all experiments. Based on the calculation of N balance and gain clover showed positive values in camber bed of 2018. Clover showed positive and negative N balances.

When calculating the N balance, the following inputs and outputs are required. Some of these parameters are biological N fixation, atmospheric N depositions, and Nitrogen losses due to volatilization, denitrification, leaching, surface runoff, soil erosion, and gaseous emissions. However, collecting these parameters is difficult due to several limitations. Therefore, we anticipate that the data at hand may provide some initial insight into variables that may be assessed and controlled using mineral nitrogen from fertilizer and residues. For N management, the N balance calculation helps to determine the N depletion from the soil under similar soil and climatic conditions, a genotypic difference of the crops under test.

4. Discussion

4.1. Drainage improvement and soil fertility for reference

Improving the drainage system on vertisols is one of the prerequisites for sustainable crop production. These soils are prone to waterlogging during the long rainy season, sticky when wet, and hard when dry, restricting the traditional farm implements' use for plowing. In this study, two drainage systems were tested by planting legumes during the crop growing season for their contribution to increasing dry biomass production and N accumulation in two legume species. Growing crops during the crop growing season may reduce the impact of rain on the land, as the traditional farming system leaves the farmland due to fear of waterlogging. In particular, camber beds showed better drained excess water and a substantially increased biomass production and N accumulation of legumes. Crop production on vertisols is dependent particularly on the efficiency of the drainage system to remove the excess water from the farmland (Manik et al., 2019; Erkossa et al., 2005; Hess et al., 2020). The camber beds produced drier biomass than the BBF (Tables 3 and 5). Camber beds have higher raised and deeper drainage furrows and can effectively drain excess water from farmland. In years of above-average rainfall, BBF beds settle down, and the silt is deposited in the BBF furrows, prohibiting the safe disposal of the extra water from the farmland. The performance and ground cover of the vetch was better than the clover, whereas the clover showed poor germination and vegetative growth. A study conducted on Australian soils also showed that the poor performance of clover on heavy clay soils was a problem (Striker and Colmer, 2017a,b; Striker and Colmer, 2017b; Roughley and Date, 1986). This study confirmed the importance of drainage on vertisols for sustained crop production (Elias et al., 2022; Tekalign et al., 1993).

Waterlogging is a problem on the vertisols of the highlands of Ethiopia in years of high rainfall, which affects crop growth and hinders nutrient availability (Striker and Colmer, 2017a). Farmers in the Ethiopian highlands typically avoid planting crops during the crop-growing season and instead rely on residual moisture to grow crops. An improved drainage system allows for planting crops on time, creates vegetative cover for the farmland, and reduces soil erosion. Planting legumes under an improved drainage system may improve soil fertility in this low-input agriculture and allow farmers to practice double cropping with reduced inorganic fertilizers. However, the crops that take the place of the crop growing season need to improve the soil's fertility and take up fewer nutrients from the soil. Legumes can be the best alternative for this farming system because they fix nitrogen and ameliorate the soil for the subsequent crop. A yearly variation in weather conditions and the land preparation methods significantly influenced the biomass production and N accumulation of these legumes during the two growing seasons. In particular, 2019 had less rainfall and reduced the biomass produced by legumes. Improving the drainage system on vertisols creates better soil-moisture relationships for plant growth and increases crop productivity (Arduini et al., 2019). In 2019, the biomass of crops on both land preparation methods was reduced by at least 40%. In particular, rainfall in 2018 was excessive, and the improved drainage system increased dry biomass production and N accumulation. In years of below-average annual rainfall, crops may suffer from dry spells, and improving the drainage system may further deplete the soil moisture. Therefore, agro-climatic data analysis is essential for this farming system (Regassa and Elias, 2022, accepted and under publication), Optimal moisture availability is required for vertisol farming because excess or shortage is a crop production constraint for plant growth, nutrient availability, and the development of rain-fed agricultural planning.

4.2. Phosphorus nutrition and biomass productivity

Vertisols are typically nitrogen- and phosphorus-deficient (Elias, 2019; Mamo et al., 2002; Tekalign et al., 1993). As result, improving soil drainage and applying the necessary nutrients are critical for successful crop production. In low-input agriculture, such as in Ethiopia, incorporating legumes into the farming system may reduce chemical fertilizer input while increasing crop production. For soil fertility improvement, legumes play an essential role in the farming systems of resource-poor farmers. On the other hand, improving drainage increases nutrient efficiency and availability (Tripolskaja and Asakaviciute, 2019). However, growing legumes during the long rainy season can reduce biomass productivity and nutrient uptake (Arduini et al., 2019).

The performance and growth of legumes and teff were good because the environmental conditions, particularly rainfall distribution, were conducive in 2018. However, the opposite trend was observed in weather conditions in 2019. Both land preparation methods resulted in lower dry biomass and N accumulation. In particular, lower values of dry biomass and N accumulation were recorded for clover, explaining the poor nitrogen fixation capacity and low N fertilizer use efficiency manifested in the lower dry biomass production and N concentration. Legumes' nitrogen fixation is usually restricted because nodule formation is retarded without P nutrition (Faucon et al., 2015; Castagno et al., 2014). There is a lot of evidence in the literature that nutritional restrictions can affect a legume's ability to develop and fix N (Stagnari et al., 2017; Journal and Agriculture, 2001). A nutritional imbalance also influences the creation of less dry biomass. In general, to maintain the high dry biomass of legumes, P application becomes very important for legume production (Moir et al., 2016).

4.2.1. Concentration and N accumulation

A positive relationship was found between biomass production, N concentration, and N accumulation. Past studies indicate that the N concentration and N accumulation are closely related to crop dry biomass production (Grüner et al., 2021; Emmanuel et al., 2018; Anglade et al., 2015). However, the reference crop teff produced a higher dry biomass yield, but the N concentration was typically less than 1%. The study is in agreement with the previous studies conducted regarding the relationship between dry biomass and N concentration (Manoj et al., 2021;

Adams et al., 2018; Anglade et al., 2015). The uptake of teff is solely dependent on soil mineral N as it is a non-N-fixing cereal crop with a high C/N ratio (Santi et al., 2013), whereas legumes use both N from the atmosphere and inorganic N from the soil (Pampana et al., 2018). Over years and different land preparation methods, the dry biomass of the tested crops showed wide variations. The variation is mainly associated with climatic conditions, land preparation methods, and P applications. The effects of year, land preparation methods, P rate, and crop type and their interactions with crop type by P application had a substantial impact on nitrogen concentration in dry biomass (Tables 4 and 5). The highest biomass was produced by vetch, which also had a high (3.1%) N content. The teff crop had the lowest N concentration (0.76%). Phosphorus application significantly increased the N content of the dry biomass of the crops studied ($P < 0.001$). In general, in the dry biomass of crops, nitrogen concentration and N accumulation increased as the rate of P increased. It implies that the soil is deficient in P nutrition and that a response is expected (Faucon et al., 2015; Mamo et al., 2002).

4.3. The N balance and estimated N fixation

The estimated values for each parameter for the N input and output computations are shown in Table 9. Positive and negative N balances were detected, with significant differences between crop types, P application, land preparation methods, and over years. Climatic factors, soil management practices, and soil mineral N in the soil determine the N balance in a system (Tripolskaja and Asakaviciute, 2019; Sainju, 2017; Sainju et al., 2017). Soil nitrate, crop characteristics, dry matter yield, and the N harvest index can also influence the N balance. The total N difference for this cropping system indicated that Vetch+P showed higher values in 2018 under both land preparation methods than in 2019.

The N fixation was higher on the camber bed across the years. The estimation of fixed N was closely correlated to the amount of the total biomass, which concurs with the findings of Sanginga (1996). The low amount of N fixed in clover was related to limited biomass production due to the early establishment problem and poor vegetative growth. Climate conditions, soil type, soil moisture, and the amount of total soil N directly or indirectly affect crop uptake and N balance in crops. In this experiment, the P application significantly influenced N balance, while clover was less affected by the P application. The variation in estimated N fixation across seasons and land preparation methods was related to the suitability of each season for crop production because N fixation was strongly associated with the accumulation of dry matter and nitrogen in teff. For example, Figure 4 shows the association between N fixation in vetch and biomass production in teff; the data points for +P and –P treatments fall on separate lines.

Taking into account uncertainties due to pool substitution between 14N and 15N and the uneven distribution of 15N in the soil profile, it can be assumed that results obtained with the total N difference method are more reliable than those obtained with the 15N isotope dilution method. The total N difference method is believed to be a cheap and simple alternative to the other methods. The calculation of the amount of N fixed by legumes using the total N difference method. The N fixation estimated by the N-difference method showed a wide variation between legume type, P application, and year. Planting legumes in the system may ameliorate the soil and reduce the use of inorganic fertilizer for smallholder farmers of low socioeconomic status (Kebede, 2021; Sánchez-Navarro et al., 2019).

5. Conclusion

In the central highlands of Ethiopia, where vertisols are the dominant soil types, soil fertility maintenance and drainage improvement are prerequisites. Among the land preparation methods tested, camber beds had an advantage over BBF in all measured crop parameters. Clover performed poorly in all experiments, whereas vetch has consistently performed well over time and with various land preparation methods. However, the dry biomass of teff was higher than that of both legumes, but the N concentration and N content were significantly lower. Teff tolerates and performs well in water-logged conditions. Our study showed that teff on drained soil also showed excellent performance and higher biomass production, which needs further investigation. Phosphorus application boosted the dry biomass, N accumulation, and N concentration of the crops studied considerably. Crop N concentration and accumulation are related to crop species and dry biomass yield. However, this was not true for non-nitrogen-fixing teff crops, which produced higher dry biomass than vetch and clover on both land preparations but had lower N concentration and N accumulation. Short-duration crop cultivars are necessary for maintaining soil fertility and implementing double cropping on vertisols. Improving the drainage system on vertisols and sustainable agricultural practices are crucial to boost crop productivity. Nitrogen accumulated in the dry biomass of vetch was very high compared to clover. The potential of vetch N accumulation in the dry biomass can fulfill the N requirement of subsequent crops if incorporated into the soil. This may drastically reduce the use of chemical fertilizers for smallholder farmers.

Declarations

Author contribution statement

Hailu Regassa Bedane, MSc: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Eyasu Elias Elias, PhD (Prof.): Contributed reagents, materials, analysis tools or data.

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Data availability statement

Data included in article/supplementary material/referenced in article.

Declaration of interests statement

The authors declare no competing interests.

Additional information

No additional information is available for this paper.

Appendix A. The calculated N gain from legume cropping systems

	Exp I (BBF 2018)					Exp II (Camber bed 2018)				
Crop type	DM (t ha^{-1})	% N content	N Fertilizer Yield (kg ha^{-1})	(Uptake + harvest N min)-(Initial N min-fertilizer N)	Total N difference method (gain)	DM (t ha^{-1})	% N content	N Fertilizer Yield (kg ha^{-1})	(uptake + harvest N min)-(Initial N min-fertilizer N)	Total N difference method (gain)
Vetch−P	2.95	3.1	87.1	77.2	28.2	5.65	2.51	141.9	136	119
Vetch+P	5.23	3.2	168.3	157.1	130.8	7.17	2.59	186.0	169	144
Clover−P	1.25	2.2	27	20	−29	2.95	2.28	67.20	60	43
Clover+P	1.64	2.3	37.4	20	−6.3	4.28	2.3	98.60	98	73
Teff−P	2.48	0.9	17.6	49		4.62	0.8	29.20	17	
Teff+P	3.81	0.9	28.4	26.3		5.44	0.8	34.01	25	
S.E	300.8	0.03	7.8	8.5		265.7	0.06	6.3	5.7	
Crop type*P	0.001	0.001	0.001	0.001		0.001	0.001	0.001	0.001	
	Exp III (BBF 2019)					Exp IV (Camber bed 2019)				
Crop type	DM (t ha^{-1})	% N content	N Fertilizer Yield (kg ha^{-1})	(Uptake + harvest N min)-(Initial N min-fertilizer N)	Total N difference method (gain)	DM (t ha^{-1})	% N content	N Fertilizer Yield (kg ha^{-1})	(Uptake + harvest N min)-(Initial N min-fertilizer N)	Total N difference method (gain)
Vetch+P	1.49	2.64	40.1	66	62	2.09	2.17	45.3	75	2
Vetch+P	2.92	2.30	67.2	81	61	3.27	2.22	72.5	126	65
Clover−P	0.73	2.26	16.6	9	5	0.62	2.16	13.1	53	−20
Clover+P	0.61	2.25	13.8	11	−9	0.86	2.45	20.7	54	−7
Teff−P	2.12	0.80	15.0	4		3.02	0.80	20.2	73	
Teff+P	2.17	0.8	14.6	20		3.08	0.9	21.2	61	
S.E	320.1	0.11	5.8	8.2		251.6	0.2	5.6	5.2	
Crop type *P	0.01	0.001	0.001	0.001		0.001	0.001	0.001	0.001	

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