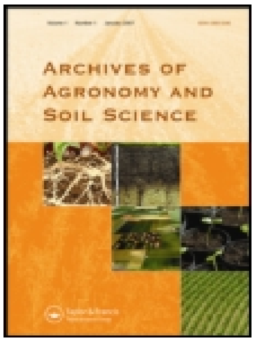

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Cropping sequence and nitrogen fertilizer effects on the productivity and quality of malting barley and soil fertility in the Ethiopian highlands

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The productivity and quality of malting barley were evaluated using factorial combinations of four preceding crops (faba bean, field pea, rapeseed, and barley) as main plots and four nitrogen fertilizer rates (0, 18, 36, and 54 kg N ha^{-1}) as sub-plots with three replications at two sites on Nitisols of the Ethiopian highlands in 2010 and 2011 cropping seasons. Preceding crops other than barley and N fertilizer significantly improved yield and quality of malting barley. The highest grain yield, kernel plumpness, protein content, and sieve test were obtained for malting barley grown after faba bean, followed by rapeseed and field pea. Nitrogen fertilizer significantly increased yield, protein content, and sieve test of malting barley. All protein contents were within the acceptable range for malting quality. Inclusion of legumes in the rotation also improved soil fertility through increases in soil carbon and nitrogen content. We conclude that to maximize yield and quality of malting barley, it is critical to consider the preceding crop and soil nitrogen status. Use of appropriate break crops may substitute or reduce the amount of mineral N fertilizer required for the production of malting barley at least for one season without affecting its quality.

Keywords: cropping sequence; malting barley; malt quality; nitrogen; productivity

Introduction

Barley (*Hordeum vulgare* L.) is one of the most important cereal crops in the world, ranking fourth after wheat, maize, and rice in terms of production (Lapitan et al. 2009). It is an important food grain and malting crop in the Ethiopian highlands, with malting barley a major source of income for smallholder farmers (Yirga et al. 1998). Barley is predominantly grown from 2000 to 3500 m above sea level in Ethiopia (Lakew et al. 1996) and is nationally the fifth most important crop after teff (*Eragrostis tef*), maize, sorghum, and wheat. It covers an area of about 1.13 million ha, but its national average yield is low at 1.5 t ha^{-1} (CSA 2010). In recent years, the demand for malting barley has increased significantly because of the increase in demand from breweries (Mohammed & Legesse 2003). According to Asella Malt Factory (AMF), the limit for protein content in malting barley for brewing industries in Ethiopia is 9.0% to 11.5%.

In the highlands of Ethiopia where farmers practice barley-based farming systems, they have very few alternative crops. One source of income could be growing malting barley, which has dependable local buyers in the country (Mulatu & Lakew 2011).

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Although there is a considerable potential for increased production of high quality malting barley, the production of malting barley in Ethiopia has not expanded enough to benefit most barley growers. The factors constraining the productivity of barley in the different barley production systems have been identified and documented (Yirga et al. 1998; Mulatu & Lakew 2011). The most important abiotic stresses include low soil fertility, low soil pH, poor soil drainage, drought, and poor agronomic practices. Fertilizer use on food and malting barley is the lowest among all cereals, that is, only 48.3% of the total area of land covered by barley compared to teff, wheat, and maize receiving fertilizer on 59.7%, 69.1%, and 56.3% of their total land area, respectively (CSA 2010). Cropping system practices are the major factor directly affecting the productivity and quality of malting barley (Turkington et al. 2012). For example, where barley–cereal, barley–legume, barley–oil crop, and barley–potato rotations are practiced, the same amount of N fertilizer is applied regardless of the preceding crop (Agegnehu et al. 2011). Such rotations are relatively uncommon; the predominant cropping system is continuous barley, which is not ideal. Continuous cultivation of the same crop in the same field, over time, results in nutrient deficiencies in the plants unless soil fertility is maintained in other ways.

One important factor influencing malting barley production is the supply of N because of its effects on yield, on the one hand, and grain protein content and malting quality, on the other (Spaner et al. 2001). Excess soil N may raise the protein content of the kernel, which is undesirable for malting. Barley grains with high protein content are more difficult to malt, yield low amounts of extracts and can cause difficulties in brewing (Mather et al. 1997; Schelling et al. 2003). In Ethiopia, where pH, organic carbon, and N content of most soils are low, nitrogen fertilizer rates applied for malting barley production vary between 18 and 41 kg N ha^{-1}. The N rate above 41 kg ha^{-1} has been considered to produce higher grain N content. Soil pH and organic carbon content are among the yield limiting factors for crop production (Fageria & Baligar 2008; Marschner 2011). Plants grown on acidic soils may be limited by deficiencies of N, P, K, Ca, Mg, or Mo; toxicity of Al or Mn; reduced organic matter breakdown and nutrient cycling; and reduced uptake of nutrients by plant roots and inhibition of root growth (Marschner 2011). Soil acidity adversely affects morphological, physiological, and biochemical processes in plants and thus N uptake and use efficiency (Fageria & Baligar 2005; Marschner 2011). Negative effects of high N fertilizer rates on malting barley kernel characteristics and malt quality have been reported by several researchers (Bertholdsson 1999; Petterson 2006; O'Donovan et al. 2011; Edney et al. 2012). The frequency of rejection of malting barley owing to high grain N content by malt factories in Ethiopia is low compared to other quality parameters, such as kernel size, moisture content, and so on, as the N rate applied by producers is low. However, many producers are reluctant to apply N fertilizer to malting barley (Mohammed & Legesse 2003).

To maximize yield and quality of malting barley, it has been shown that N management practices should be adjusted according to anticipated availability of water and N in the soil (McKenzie et al. 2005) and the needs of particular cultivars (Bertholdsson 1999; Petterson 2006; Edney et al. 2012). Diversification of crops in cropping systems improves production efficiencies and resilience of agricultural systems. Studies have indicated that fertilizer use and inclusion of food and pasture legumes in rotation systems resulted in a significant barley (Jones & Singh 1995; Ryan et al. 2008) and wheat (Tanaka et al. 2010) yield advantages even under the driest conditions as a result of improved soil water use efficiency. However, continuous cropping was highly exploitive of soil nutrients, particularly nitrogen. Váňová et al. (2006) also reported that grain yield and protein content of malting barley obtained after maize and sugar beet were lower compared to that obtained after winter wheat and rapeseed. Thus, management of N is a critical issue for yield and quality of malting barley. Although it is expected that N fertilizer rates and the nature of the preceding crop are important, little is known about their effects and interactions in the Ethiopian context. Therefore, the objective of this study was to determine the effects of cropping sequence and N fertilizer rates on the yield and quality of malting barley under rain-fed conditions in the Ethiopian highlands.

Materials and methods

Characteristics of experimental sites

The experiment was conducted for 2 years (2010 and 2011 main cropping seasons) at Holetta and Jeldu in the central highlands of Ethiopia. Both food and malting barley are widely grown in these areas. The environment is seasonally humid and the soil type was Eutric Nitisol at Holetta and Humic Nitisol at Jeldu (FAO Soil Classification). Holetta is located between 09° 03′ N latitude and 38° 30′ E longitude, 30 km west of Addis Ababa, at an altitude of about 2400 m above sea level. While Jeldu is located between 09° 16′ N and 38° 05′ E, about 115 km west of Addis Ababa, at 2800 m above sea level. At Holetta, the long-term average annual rainfall is 1100 mm, about 85% of which is received from June to September with the remainder from January to May. The average minimum and maximum air temperatures at Holetta are 6.2°C and 22.1°C respectively. At Jeldu, the average annual rainfall is about 1200 mm, and the average minimum and maximum air temperatures are 2.1°C and 16.9°C, respectively.

Soil samples (0–20 cm depth) were taken from the experimental sites before planting. A total of 25 samples were taken and combined into one composite per site for analysis. Soil samples were analyzed for pH using a ratio of 2.5 ml water to 1 g soil (Peech 1965); for available P using Bray-II method (Bray & Kurz 1945); for organic C content using Walkley and Black (1954) method; for total N content using Kjeldahl method (Bremner & Mulvaney 1982); for exchangeable cations and cation exchange capacity (CEC) using ammonium acetate method (Chapman 1965) at the soil and plant analysis laboratory of Holetta Agricultural Research Center. Not all soil samples were analyzed for all parameters. Pre-planting values for pH, total C, total N, available P, and CEC were 4.98, 1.07%, 0.11%, 8.02 mg kg^{-1}, and 21.26 cmol$_c$ kg^{-1}, respectively, at Holetta, and 5.56, 2.78%, 0.23%, 18.12 mg kg^{-1}, and 26.58 cmol$_c$ kg^{-1}, respectively, at Jeldu.

Experimental set-up and procedure

The experiment was a factorial split-plot design with four preceding crops as main plots and four N fertilizer levels as sub-plots (2.5 m × 4 m each) and three replications for each treatment. The spacing between plots and blocks were 0.5 m and 1 m, respectively. The preceding crops were appropriate culitvars of faba bean (*Vicia faba* L.), field pea (*Pisum sativum* L.), rapeseed (*Brassica napus* L.), and barley (*H. vulgare* L.). Faba bean and field pea received 18/20 kg N/P ha^{-1}, rapeseed 46/30 kg N/P ha^{-1}, and barley 41/20 kg N/P ha^{-1} in the form of urea and di-ammonium phosphate (DAP). The total aboveground biomass of the preceding crops were 4582, 3975, 14,232, and 5421 kg ha^{-1} for faba bean, field pea, rapeseed, and barley, respectively, at Holetta, and 5285, 4863, 15,497, and 6178 kg ha^{-1} for the same crops, respectively, at Jeldu. After harvesting the preceding crops, the fallen leaves and stubble left in the field were incorporated into the soil during land preparation using ox-drawn implement without affecting the experimental design. In the second year of the experiment, all the experimental plots at both locations were planted with two-row malting barley (variety *Miscal)*. Sowing took place at the onset of rainfall in each location, this being the third week of June at Holetta and last week of June at Jeldu. The levels of N fertilizer (0, 18, 36, and 54 kg N ha^{-1}) were applied as urea. The industry standard application rate for malting barley production is 36 kg N ha^{-1}. The recommended phosphorus fertilizer amount (20 kg P ha^{-1}) was uniformly applied as triple supper phosphate (TSP) to all plots at planting. Nitrogen fertilizer was applied evenly to the surface in two doses: half at planting and half at tillering stage after weeding and during the presence of light rainfall to avoid the potential loss of N into the atmosphere. Other agronomic practices were applied based on local research recommendations. Despite some incidence of shoot fly at the initial growth stage of malting barley at Holetta, insecticides were not applied.

Data collection and analysis

Plant parameters collected were grain yield, above-ground total biomass, harvest index, thousand kernel weight, spike length, and plant height (average of ten plants). Mature plant height was measured from the ground level to the tip of the spike excluding the awns at physiological maturity. Spike length (SL in cm) was measured from the base to the top of the spike excluding awns. Thousand kernel weight (TKW in g) was measured on a sample of 250 seeds. To measure total biomass and grain yields, the entire plot was harvested at maturity in November at Holetta and December at Jeldu. After threshing, the seeds were cleaned and weighed, and the moisture content was measured. Total biomass (dry matter basis) and grain yields (adjusted to a moisture content of 12.5%) recorded on plot basis were converted to kg ha^{-1} for statistical analysis. Protein content, the major quality parameter of malting barley, was determined using a near infrared reflectance spectrometer (Foss NIRS-500, Foss GmbH, Rellingen, Germany). Grains were size graded using slotted sieves (2.8 mm and 2.5 mm apertures) following the standard procedure of the Holetta Research Centre Micro-malt Laboratory. Heavy grade barley is the material retained on a 2.8-mm sieve, while intermediate grade is the material that passes through the 2.8-mm sieve but is retained on a 2.5-mm sieve (O'Rourke 2002). For the post-harvest soil samplings, five samples were taken from each plot and combined into one composite sample per plot for analysis. Soil samples were analyzed as described above.

The data were subjected to analysis of variance using the general linear model procedure (PROC GLM) of SAS statistical package version 9.0 (SAS Institute, Cary, NC, USA). The total variability for each trait was quantified using the following model:

$$T_{ijk} = \mu + R_i + P_j + R(P)_{ij} + N_k + PN_{(jk)} + e_{ijk}$$

where T_{ijk} is the total observation, μ is the grand mean, R_i is the effect of the ith replication, P_j is the effect of the jth preceding crop, N_k is the effect of the kth nitrogen level, PN is the interaction, and $R(P)_{ij}$ and e_{ijk} are the variations due to random error for main and sub-plots, respectively. Significance of the P effect was tested against the $R(P)_{ij}$ mean square as an error term. All other effects were tested against the residual. Means for the main effects of preceding crops (n = 4) were compared using the MEANS statement with the least significant difference (LSD) test at the 5% level of probability. Single degree of freedom orthogonal contrasts were performed to determine the nature of the crop response to the rates of applied N fertilizer. Means for the interactions were compared using the PDIFF STDERR option in the LSMEANS statement of the GLM procedure, in particular specifying the $R(P)$ as an appropriate error term for separating LSMEANS for the interaction of preceding crop and N fertilizer rate.

Results

Weather

In spite of higher total rainfall at Jeldu, the precipitation pattern was similar for both locations in 2010 and 2011 (Figure 1). The rainfall for June was lesser in 2010 than in 2011, but it was higher for September in 2010 than in 2011 at Holetta and Jeldu (Figure 1). At Holetta, there was no precipitation in October in both years. When compared with the long-term average, rainfall in September was higher by 63 mm in 2010 and 39 mm in 2011 for Holetta, implying average moisture condition in both growing seasons. At Jeldu, the rainy season was extended until October in both the years, which was favorable for barley production as crop growing period and was relatively longer than at Holetta.

Yield and yield components of malting barley

Grain yield, total above-ground biomass, and spike length of malting barley all responded significantly ($p \leq 0.05$ and $p \leq 0.01$) to preceding crop and N fertilizer rate at both Holetta and Jeldu (Table 1). Plant height was significantly ($p \leq 0.01$) affected by N fertilizer at both locations, but not by preceding crops. Harvest index significantly ($p \leq 0.01$ and $p \leq 0.05$) responded to preceding crop at Holetta and Jeldu, but to N fertilizer only at

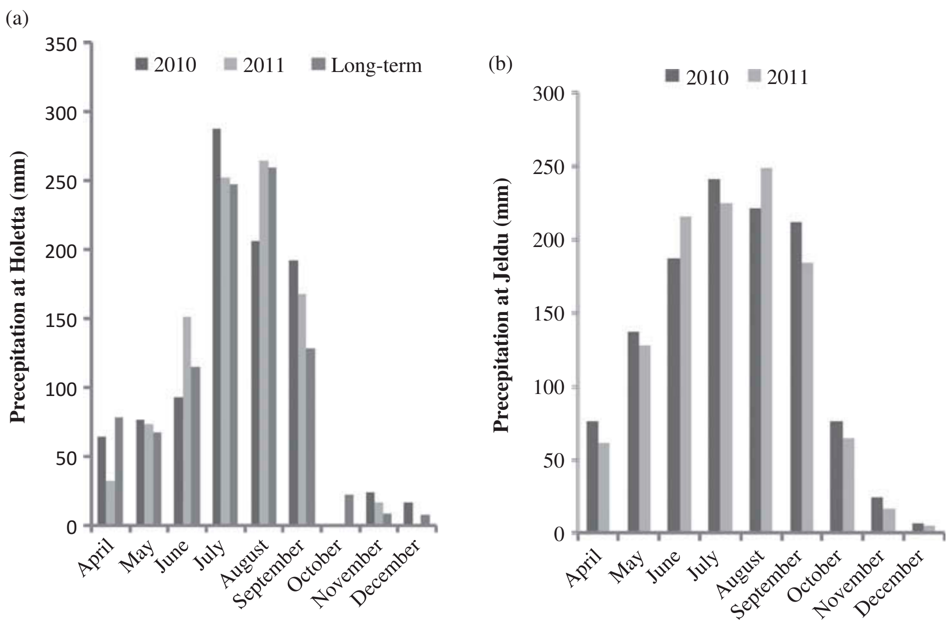

Figure 1. Monthly total rainfall for 2010–2011 crop growing seasons including the 30-year average at Holetta (a) and Jeldu (b).

Table 1. Significance of the effects of preceding crop (PC), N fertilizer rate (N) and their interaction on plant and soil parameters at the two sites, and coefficient of variation (CV) for the parameters.

	Holetta				Jeldu			
Parameter	PC	N	PC × N	CV (%)	PC	N	PC × N	CV (%)
Grain yield	*	***	ns	17.2	**	***	ns	13.2
Biomass yield	*	***	ns	13.3	*	***	ns	13.3
Harvest index	**	ns	ns	16.3	*	*	ns	11.5
Plant height	Ns	**	ns	4.6	ns	**	ns	4.3
Spike length	*	*	ns	8.1	*	*	ns	7.1
Kernel weight	Ns	ns	ns	4.8	**	ns	ns	4.1
Protein content	**	**	ns	4.3	*	**	ns	6.4
Sieve test 2.8 mm	***	***	*	14.5	*	**	*	4.6
Sieve test 2.5 mm	**	**	*	9.8	**	**	*	13.2
2.5 mm + 2.8 mm	**	*	ns	6.0	ns	ns	ns	3.5
Soil C	***	**	**	2.7	**	*	*	3.5
Soil N	***	**	*	10.3	***	*	ns	8.3
Soil P	**	ns	*	5.3	**	*	*	5.6
Soil K	***	**	**	3.4	*	*	*	6.4
Soil Na	**	**	**	10.1	**	**	**	6.2
CEC	***	**	**	3.1	***	*	**	2.5

Note: Significant at *$p \leq 0.05$, **$p \leq 0.01$, ***$p \leq 0.001$; ns, not significant.

Jeldu. Thousand kernel weight of malting barley was significantly ($p \leq 0.01$) affected by preceding crop only at Jeldu and not by N fertilizer application at either location. There was no significant interaction ($p \leq 0.05$) between preceding crop and N fertilizer rate for any of the measured plant parameters.

Yields of malting barley were greater with all rotations than with continuous barley at both locations. Malting barley following faba bean had always numerically the highest yield, but it was not statistically different when compared with malting barley after rapeseed (Tables 2 and 3). The second most effective preceding crop was rapeseed, but the differences in grain yield were not significantly different amongst the three non-barley preceding crops at Holetta ($p \leq 0.05$). However, at Jeldu, there were significant differences between barley yields following all the non-barley preceding crops. The effects of preceding crop were greater at Holetta than at Jeldu, being 67–93% higher following non-barley crops than following barley at Holetta and 26–47% higher at Jeldu (Tables 2 and 3). Mean grain yield advantages of malting barley over the two locations after faba bean, field pea, and rapeseed were also greater by 67%, 43%, and 53%, respectively, than malting barley after barley (data not shown), indicating that the lack of crop rotation has already been manifested in the continuous barley plots. Overall, mean grain yields of malting barley were lower at Holetta (2737 kg ha^{-1}) than at Jeldu (3012 kg ha^{-1}). The effect of preceding crop (barley versus faba bean) on grain yield was similar in magnitude to that of N fertilizer rate (0 versus 54 kg ha^{-1}) (Tables 2 and 3).

Grain yield and total biomass, protein content, spike length, and plant height of malting barley have been significantly and consistently increased as N fertilizer rate increased. Although differences in yields between the highest two N rates were not statistically significant ($p \leq 0.05$), the maximum grain yields of malting barley were recorded from the highest N rate at both locations. The application of N fertilizer at the

Table 2. Means for main effects of preceding crop and N fertilizer rate on malting barley crop parameters at Holetta, 2010–2011.

Treatments	Grain yield (kg ha^{-1})	Biomass yield (kg ha^{-1})	Harvest index (%)	Thousand kernel weight (g)	Plant height (cm)	Spike length (cm)	Protein content (%)
Preceding crop							
Faba bean	3321	6842	48.5	48.6	87.8	6.9	11.3
Field pea	2859	6235	45.8	48.9	85.4	6.8	11.0
Rape seed	3051	6279	48.6	50.1	87.7	6.7	11.3
Barley	1718	5021	34.2	49.0	85.0	6.3	10.5
LSD	472	746	5.9	ns	ns	0.4	0.54
Nitrogen (kg ha^{-1})							
0	2122	5031	42.2	48.7	81.1	6.4	10.4
18	2680	6086	44.1	49.8	87.5	6.8	11.0
36	3013	6569	45.9	48.8	88.3	6.9	11.1
54	3123	7175	43.5	49.3	89.2	6.9	11.5
Control vs. N fertilizer	***	***	ns	ns	***	*	**
N_{linear}	***	***	ns	ns	**	*	**
$N_{quadratic}$	***	***	ns	ns	**	ns	*
PC × N	ns	ns	ns	ns	ns	ns	ns

Note: Significant at *$p \le 0.05$, **$p \le 0.01$, ***$p \le 0.001$; ns, not significant; LSD, least significant difference; PC, preceding crop; N, nitrogen.

Table 3. Means for main effects of preceding crop and N fertilizer rate on malting barley crop parameters at Jeldu, 2010–2011.

Treatments	Grain yield (kg ha^{-1})	Biomass yield (kg ha^{-1})	Harvest index (%)	Thousand kernel weight (g)	Plant height (cm)	Spike length (cm)	Protein content (%)
Preceding crop							
Faba bean	3502	7348	47.7	51.8	90.6	7.2	12.0
Field pea	2991	6545	45.7	48.9	89.8	7.0	11.7
Rape seed	3186	6903	46.2	49.3	89.2	7.1	11.6
Barley	2374	5713	41.6	51.0	86.3	6.7	10.8
LSD	375	904	4.8	2.5	ns	0.4	0.4
Nitrogen (kg ha^{-1})							
0	2390	5353	44.7	50.4	80.6	6.6	11.0
18	2802	6042	46.4	49.8	90.0	7.0	11.5
36	3274	7078	46.3	51.4	90.2	7.1	11.7
54	3584	7343	48.8	49.4	96.2	7.1	11.9
Control vs. N fertilizer	***	***	ns	ns	***	*	***
N_{linear}	***	***	ns	ns	**	ns	**
$N_{quadratic}$	***	***	ns	ns	**	ns	*
PC × N	ns	ns	ns	ns	ns	ns	ns

Note: Significant at *$p \le 0.05$, **$p \le 0.01$, ***$p \le 0.001$; ns, not significant; LSD, least significant difference; PC, preceding crop; N, nitrogen.

rates of 18, 36, and 54 kg N ha^{-1} resulted in linear and quadratic responses with mean grain yield advantages of 26%, 42%, and 47%, respectively, at Holetta compared to the control (no fertilizer), and the same rates resulted in linear and quadratic responses with yield increases of 17%, 37%, and 50%, respectively, over the control at Jeldu (Tables 2 and 3). Similarly, yield increments of 22%, 39%, and 49% were recorded for similar N rates across locations (data not shown). The tallest plant height and largest spike length of malting barley were recorded from the highest N level. Differences in harvest index were observed among N fertilizer levels, but they were not statistically significant.

Protein content and sieve test analysis

Preceding crop and N fertilizer application significantly influenced grain protein content of malting barley (Table 1). At Holetta, malting barley grain protein content ranged from 10.5% following barley to 11.3% following faba bean and from 10.78% to 11.98% at Jeldu for the same cropping sequences (Tables 2 and 3), all of which are within the acceptable range. Protein contents were significantly higher following all non-barley crops (with no significant difference between them) than following barley ($p \leq 0.05$). Nitrogen fertilizer rates resulted in linear and quadratic responses with mean protein contents of 11–11.5% at Holetta and 11–11.9% at Jeldu (Tables 2 and 3). Preceding crops and application of N fertilizer increased grain yield more than they did grain protein content. The moisture contents of malting barley grain were 9.3% at Holetta and 9.5% at Jeldu (data not shown); a moisture content of over 13.5% is unacceptable for malting purpose.

High kernel plumpness and uniformity are desirable quality characteristics since potential malt extract is directly associated with barley kernel size. Sieve test analysis results using 2.8 mm and 2.5 mm sieve size responded significantly ($p \leq 0.01$ and $p \leq 0.001$) to preceding crop and N fertilizer rate. The orthogonal contrast showed that preceding crop by N fertilizer interaction significantly ($p \leq 0.05$) affected sieve test only at Holetta but not at Jeldu (Table 4). The standard requirement for official AMF grade is specified at 90% or more of seeds retained over 2.8 and 2.5 mm slotted screen for two-rowed malting barley varieties. Higher sieve test percentages were recorded from malting barley harvested after faba bean, field pea, and rapeseed (similar between them) than after barley and to which N fertilizer had been applied (Table 4). Mean grain grading percentages of malting barley for preceding crop were 76.8–90.5% at Holetta and 93.8–95.9% at Jeldu. Nitrogen fertilizer rates resulted in linear and quadratic responses with mean sieve test percentages of 82.7–88.5% at Holetta and 92.7–95.9% at Jeldu (Table 4). Sieve test percentages were generally greater at Jeldu than at Holetta. The interaction of preceding crop and N fertilizer rate revealed that grading percentages for 2.8 mm sieve size increased as the N rate increased, but decreased for 2.5 mm sieve size at Holetta (Figure 2).

Soil analysis results

Soil nutrient status after harvesting differed substantially between experimental treatments. Total soil organic C and N, available P, exchangeable K and Na contents, and CEC of the experimental soils were significantly ($p \leq 0.05$ and $p \leq 0.01$) affected by preceding crop at Holetta and Jeldu (Table 1). Soil C, N, exchangeable Na, and CEC showed significant linear and quadratic responses to N fertilizer rate at both locations, but available P did not show significance response to N rate (Tables 5 and 6). There was a significant interaction between preceding crop and N fertilizer rate ($p \leq 0.05$ and

Table 4. Sieve test of malting barley as affected by preceding crop and nitrogen fertilizer at Holetta and Jeldu, 2010–2011.

	Holetta			Jeldu		
Treatments	>2.8 mm	>2.5 mm	2.8 + 2.5 mm	>2.8 mm	>2.5 mm	2.8 + 2.5 mm
Preceding crop						
Faba bean	55.3	35.2	90.5	71.2	24.4	95.6
Field pea	52.6	37.7	90.3	74.6	20.1	94.7
Rape seed	50.1	40.5	89.6	72.1	23.8	95.9
Barley	28.6	48.2	76.8	62.0	31.8	93.8
LSD	5.3	3.8	4.5	3.8	3.4	ns
Nitrogen (kg ha^{-1})						
0	37.8	44.9	82.7	65.5	27.2	92.7
18	47.8	39.7	87.5	74.5	21.4	95.9
36	49.5	38.3	87.8	71.9	24.0	95.9
54	50.6	37.9	88.5	67.9	27.5	95.4
Control vs. N fertilizer	***	***	**	***	*	ns
N_{linear}	***	**	*	***	**	ns
$N_{quadratic}$	**	**	ns	***	**	ns
PC × N	*	*	ns	ns	ns	ns

Note: Significant at *$p \leq 0.05$, **$p \leq 0.01$, ***$p \leq 0.001$; ns, not significant; LSD, least significant difference; PC, preceding crop; N, nitrogen.

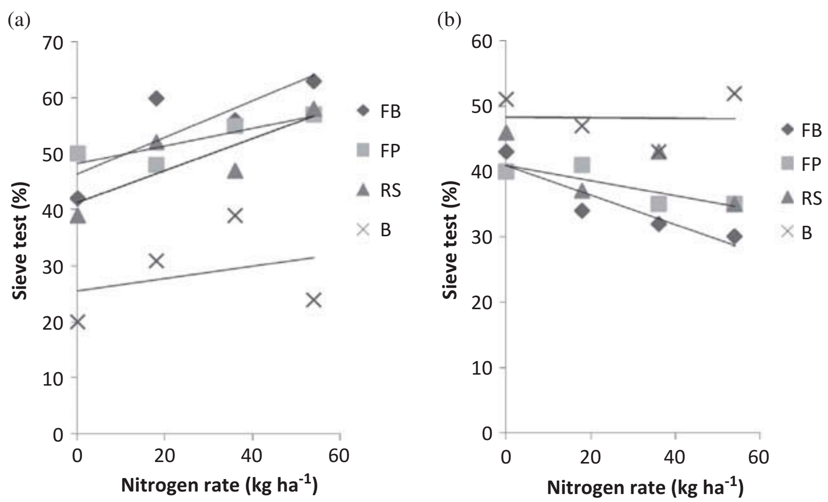

Figure 2. Sieve test of malting barley as affected by the interaction of preceding crop and nitrogen fertilizer: (a) 2.8 mm size sieve test and (b) 2.5 mm size sieve test at Holetta.
Note: Standard errors ($p < 0.05$) for 2.8 and 2. 5 mm sieve size are 3.5 and 2.3, respectively; FB, faba bean; FP, field pea; RS, rapeseed; B, barley.

$p \leq 0.01$) for soil C, available P, and exchangeable Na at both sites and for exchangeable K and CEC only at Holetta (Tables 5 and 6). Soil C, N, and available P contents and CEC were higher at Jeldu than at Holetta, in keeping with the differences in pre-trial soil analysis results as well as yield and protein content of malting barley between sites. Higher concentrations of these nutrients were recorded in plots having non-barley

Table 5. Effects of preceding crop and N fertilizer rate on soil nutrient contents (soil depth 0–20 cm) after harvesting malting barley at Holetta, 2011.

Treatments	Organic C (%)	Total N (%)	Available P (mg kg^{-1})	Exch. K (cmol$_c$ kg^{-1})	Exch. Na (cmol$_c$ kg^{-1})	CEC (cmol$_c$ kg^{-1})
Preceding crop						
Faba bean	1.24	0.21	10.5	1.59	0.14	24.5
Field pea	1.15	0.20	9.6	1.22	0.12	22.0
Rape seed	1.22	0.20	9.8	1.20	0.10	23.6
Barley	1.05	0.14	8.3	1.17	0.08	20.9
LSD	0.03	0.02	0.41	0.04	0.01	0.62
Nitrogen (kg ha^{-1})						
0	1.08	0.14	9.3	1.30	0.08	19.6
18	1.14	0.21	9.5	1.21	0.10	23.1
36	1.22	0.21	9.7	1.30	0.14	24.5
54	1.21	0.20	9.7	1.36	0.13	23.9
Control vs. N fertilizer	**	**	ns	ns	**	***
N_{linear}	***	**	ns	**	**	**
$N_{quadratic}$	**	**	ns	**	**	**
PC × N	*	ns	**	*	*	**

Note: Significant at *$p \leq 0.05$, **$p \leq 0.01$, ***$p \leq 0.001$; ns, not significant; LSD, least significant difference; PC, preceding crop; N, nitrogen.

Table 6. Effects of preceding crop and N fertilizer rate on soil nutrient contents (soil depth 0–20 cm) after harvesting malting barley at Jeldu, 2011.

Treatments	Organic C (%)	Total N (%)	Available P (mg kg^{-1})	Exch. K (cmol$_c$ kg^{-1})	Exch. Na (cmol$_c$ kg^{-1})	CEC (cmol$_c$ kg^{-1})
Preceding crop						
Faba bean	3.18	0.31	24.8	0.41	0.09	30.3
Field pea	3.13	0.28	24.7	0.40	0.08	30.1
Rape seed	3.10	0.29	22.3	0.39	0.09	29.2
Barley	2.90	0.25	20.5	0.36	0.04	24.6
LSD	0.09	0.02	1.07	0.02	0.004	0.62
Nitrogen (kg ha^{-1})						
0	2.99	0.26	22.1	0.37	0.06	27.9
18	3.06	0.29	23.4	0.40	0.06	28.7
36	3.09	0.30	22.2	0.39	0.06	28.9
54	3.12	0.29	23.7	0.40	0.08	29.0
Control vs. N fertilizer	*	**	*	*	**	*
N_{linear}	*	**	ns	ns	**	*
$N_{quadratic}$	*	*	ns	ns	**	*
PC × N	*	ns	**	ns	*	ns

Note: Significant at *$p \leq 0.05$, **$p \leq 0.01$, ***$p \leq 0.001$; ns, not significant; LSD, least significant difference; PC, preceding crop; N, nitrogen.

preceding crops than in those with continuous barley. For instance, the maximum soil C content recorded at Holetta (1.24%) and Jeldu (3.18%) were from plots that had had faba bean (Tables 5 and 6). The soil organic C content at a depth of 20 cm following faba bean, field pea, rapeseed, and barley were about 24.8, 23.0, 24.4, and 21.0 t ha^{-1}, respectively, at Holetta, and 63.6, 62.6, 62.0, and 58.0 t ha^{-1}, respectively, at Jeldu. The values for N and P content after faba bean, field pea, rapeseed, and barley precursors were 0.14–0.21% and 8.3–10.5 mg kg^{-1}, respectively, at Holetta, and 0.25–0.31% and 20.5–24.8 mg kg^{-1}, respectively, at Jeldu (Tables 5 and 6).

Discussion

Our results showed clear effects of cropping sequence and N fertilizer on yield and quality of malting barley in the Ethiopian highlands. In this environment, where demographic and economic pressures are intense, monocropping is a common practice, soil fertility depletion is severe, and use of external inputs is very low. The farmers' main response to such pressures has been to grow more barley every year without involving break crops such as highland food legumes in the farming system. This strategy appears to be unsustainable, because yields of cereals usually decline under monoculture (Tanner et al. 1999; Taa et al. 2004). According to the results of this study, even with the highest fertilizer rate, the grain yields of malting barley were not as high as those achieved following a non-barley crop.

Economic benefits could be expected from using the crop rotations studied rather than continuous barley because of improved yields of malting barley. Moreover, all the non-barley preceding crops included in this study are cash crops produced for local industries and export purposes, meaning that involving them in the rotation system ensures yield and economic sustainability in the long-term. Other studies have also shown that wheat and barley yields tend to be higher with rotation than continuous cropping (Arshada et al. 1999; Taa et al. 2004; Sainju et al. 2009; Tanaka et al. 2010; Agegnehu et al. 2011) and barley-fallow rotation (Jones & Singh 1995). Grain yield, kernel weight, test weight, and kernel plumpness were lower for barley grown on barley residue compared with canola and field pea residues (Turkington et al. 2012). Other researchers also reported that wheat after canola yielded an average increase of 22% (Moghaddam et al. 2011) and protein content increased by 1.3% (Kirkegaard et al. 1994) compared to wheat after wheat. Substantial break-crop yield increments from lupins (0.4 t ha^{-1}) were persistent to a third wheat crop, but effects were inconsistent beyond that point (Seymour et al. 2012).

In this study, barley yield improvements following non-barley crops rather than continuous barley were more pronounced at Holetta than at Jeldu, which may be due to lower soil fertility at Holetta. The main benefits of crop rotations compared with monocropping is that they have the ability to effect changes in soil fertility, organic matter content, biology, and water status (Lupwayi et al. 1998; Taa et al. 2004; Johnston et al. 2005; Moghaddam et al. 2011), provide succeeding crops with N, and reduce disease incidence and weed populations (Diaz-Ambrona & Minguez 2001; Harker et al. 2009; Turkington et al. 2012). Overall, higher yields after faba bean and field pea versus barley were most likely the result of additional N release from the residues of these crops. The atmospheric N_2 fixed by legumes in the rotation not removed in harvested products can increase soil N content and become available to succeeding crops as the residues decompose (Diaz-Ambrona & Minguez 2001). The difference in yield of malting barley following faba bean and field pea might be due to differences in growth between the two crops. Visual observations indicated that the faba bean crop was more vigorous than the field pea, which might have led to differences in nodulation and atmospheric N_2 fixation, plant biomass production, and N contribution to the subsequent crop. Moreover, legumes species differ in their ability to fix N_2. Studies have shown that the N_2 fixing capacity of faba bean is higher than that of field pea (Schulz et al. 1999; Unkovich & Pate 2000). On the other hand, the yield increase in malting barley after rapeseed could be attributed to effects of its high biomass production on soil fertility, weed suppression through its shading effect and perhaps bio-fumigation effect on soil-borne diseases. It might be also due to its positive effects on soil physical properties, as brassicas tend to have a strong tap root system that can penetrate hard layers and improve the ability of the subsequent crop to access water deep in the profile.

Nitrogen fertilizer application at optimum level is required to grow an ideal quality malting barley; not so much as to increase the grain protein content to an undesirably high level. In this study, use of break crops other than barley and application of N fertilizer up to 54 kg ha^{-1}, higher than the existing practice, did not result in greater protein content exceeding the acceptable level. However, if producers apply N fertilizer rates greater than the highest rate used in this study, the likelihood of surpassing the desired level of protein is great, particularly in areas where the soil fertility is modest. Studies have shown that N fertilizer rate can be a major factor affecting yield, kernel plumpness, and grain N content of malting barley (Baethgen et al. 1995; McKenzie et al. 2005; O'Donovan et al. 2011). High rates could result in increased plant height and lodging, reduced test weight, decreased kernel plumpness, and increased grain protein content (Petrie et al. 2002). In a rotation system, N fertilizer strategies for malting barley production should ensure adequate amounts of available N for crop establishment and tiller development, and the amount required should be based on the cropping system and soil fertility management practices.

The increase in grain protein content with N fertilizer addition was similar to that caused by the non-barley preceding crops, suggesting that both treatments improve N supply. However, crop rotation sequences did not increase grain protein content beyond the acceptable level, which is 9–12% for malting barley (Bertholdsson 1999; Fox 2008). At the site with higher yield, carbon, and N in the soil, the malting barley fertilized with 54 kg N ha^{-1} had a mean protein content of 11.9%, which means that in similar fields of malting barley, producers will exceed 12% protein content with this N rate with time. Although both protein content and yield increased with non-barley preceding crops and increased rates of N application, protein content increased at a slower rate. The difference in grain protein content among treatments (N supply levels) was more apparent at Holetta than at Jeldu, reflecting differences in yield and soil fertility between the sites, so the lower the site fertility, the greater the effects of crop rotation and fertilizer that might be expected. The trend in grading percentage increases in relation to preceding crops, and N levels were similar to the increments in yields and protein percentages.

Soil fertility was sub-optimal for the production of malting barley, particularly at Holetta. This had a direct relationship with the crop growth and yields, which were higher at Jeldu than at Holetta. In most cases, soils with pH less than 5.5 are deficient in available P and exchangeable cations (Agegnehu & Sommer 2000; Marschner 2011). In such soils, P becomes unavailable to a crop and the P fertilizer rate inadequate (Marschner 2011), unless liming materials are applied. Higher variability in grain yield of malting barley at Holetta than at Jeldu may have been related to greater variability in the less fertile environment. Experimental plots treated with preceding crops other than barley exhibited improvement in some soil chemical properties.

Conclusion

An important finding in this study was that yield and quality of malting barley were significantly improved when barley was grown after legume and non-legume crops other than barley with no detrimental effect on grain protein content. Any of the cropping sequence options identified in this study can be recommended to minimize risk of poor yield or quality in malting barley, that is, faba bean, field pea, and rapeseed were all good break crops. The more N fertilizer was added, the better (up to 54 kg ha^{-1} N) were the yield and quality of malting barley irrespective of preceding crop. However, the interaction between rotation and fertilizer management should be tested over longer periods involving representative locations across major malting barley producing areas of the country. Overall, the use of appropriate crops in a rotation system may maintain satisfactory crop yield and quality, reduce the costs of production, and therefore increase profitability and improve soil fertility to enhance long-term sustainability of the cropping system.

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