



## Research article

## Effects of preceding crops and nitrogen fertilizer on the productivity and quality of malting barley in tropical environment

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## ABSTRACT

The growing demand for malt has generated interest for improving productivity through sustainable means such as cropping sequences with malting barley along with optimum nitrogen (N) fertilization. Cropping sequence has many benefits for optimum yield and quality, but knowledge of rotational effects of preceding crops on malting barley is still limited. Thus, this study was conducted to determine the effects of legume and non-legume preceding crops, and N fertilization on productivity and quality of malting barley grown the following year in two locations in the southeastern highland of Ethiopia. The experiment was split plot design with six preceding crops (fababean, Ethiopian mustard, potato, linseed, wheat and malting barley) as main plots and four levels of N (0, 18, 36 and 54 kg N ha<sup>-1</sup>) for the succeeding crop as split plot treatments with 3 replications. Malting barley grown after fababean, Ethiopian mustard and potato exhibited 13–16, 14–34 and 14%, respectively grain yield increments compared to growing malting barley after malting barley. Similarly, application of 36–54 kg N ha<sup>-1</sup> gave 4–29 and 3–19% grain yield increments compared to the control (no N) and previous recommendation (18 kg N ha<sup>-1</sup>), respectively with no detrimental effect on kernel protein concentrations. Seeding malting barley at a rate of 54 kg N ha<sup>-1</sup> gave 250–915% increase in economic benefit. Use of break crops other than barley and increasing the rate of N application from 18 to 54 kg ha<sup>-1</sup> have been recommended to boost malting barley yield without surpassing the acceptable range of kernel protein concentrations, reduce costs of production, increase profitability and improve soil fertility to enhance long-term sustainability of the cropping system.

## 1. Introduction

Barley (*Hordeum vulgare* L.) is a cool-season crop with a wide range of adaptation. It grows well at an altitude of about 3,000 m above sea level (m a.s.l.) or above. It is one of the few crops that grows at this altitude, and provides food, homemade drinks, animal feed, cash and other necessities to many millions of people (Berhanu et al., 2005; Mulatu and Lakew, 2011). It grows best on well-drained soils, and grows better on alkaline soils than any other small grain crops (Berhanu et al., 2005; Verma, 2018). Non-malting food barley is commonly cultivated in stressed areas like steep slopes, degraded soils, and in areas with occasional drought and frost, where other cereals fail to grow. In contrast, malting barley requires a favorable environment to produce a plump and mealy grain (Berhanu et al., 2005).

Barley is one of the major food and industrial crops used as a raw material for global malting and brewing industries including in Ethiopia. It is one of the most important cereal crops in the Ethiopian highlands,

ranking fifth after teff (*Eragrostis tef*), maize (*Zea mays*), sorghum (*Sorghum bicolor*) and wheat (*Triticum aestivum*), and covers an area of 0.95 million ha (CSA, 2020). In Ethiopia, there is significant opportunity for the production of malting barley and can be one of the major sources of income for smallholder farmers due to the booming demand for malt following the expansion of breweries (Mohammed and Legesse, 2003). However, there exists a paradox whereby there are plenty of opportunities, but a scarcity of malt barley due to very low production of this crop in Ethiopia. In 2015, for example, domestic malt barley production met only 35% of the demands of malting and brewing industries (ICARDA, 2016).

The mean national barley grain yield, 2.5 t ha<sup>-1</sup> (CSA, 2020), is quite low compared to the world average (2.95 t ha<sup>-1</sup>), and the top producing countries in the world (e.g., Germany, 5.9 t ha<sup>-1</sup>) (FAOSTAT, 2018). However, the yield potential of some of the recently released improved malting barley varieties can be more than 6 t ha<sup>-1</sup> (ICARDA, 2016). Malting barley production in the Ethiopian highlands is constrained by collective effects of physical and biotic factors including mono-cropping,

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soil fertility depletion, soil acidity, weed infestation, disease incidences, drought, drainage limitations for regions with Vertisol, and use of very low external inputs (Mulatu and Lakew, 2011; Agegnehu et al., 2014). The practice of mono-cropping, in which cereals occupied 82% of the total cropped land (CSA, 2020) in the peasant farming systems, is likely the main reason for the current low productivity of malting barley. In this region, bread wheat, teff and barley are the most common cereals under production. Growing of more barley every year without involving break crops such as food legumes in the farming system appears to be unsustainable, because yields of cereals usually decline under monoculture (Asefa et al., 2000; Agegnehu et al., 2014). The grain yields obtained from the continuous malting barley were lower than those achieved when preceded by a non-barley crop even with the highest fertilizer rate (Agegnehu et al., 2014).

Deficiency of important nutrients especially nitrogen (N) and phosphorous (P) are the other most important factors limiting malting barley production in the southeastern highlands of Ethiopia (ATA, 2016). Conversely, the use of external inputs to maintain soil fertility and increase malting barley yield is very low. For example, out of the 0.95 million ha area covered by barley in 2017, only 0.63 million ha of this area (66.5%) was fertilized indicating how fertilizer use on both food and malting barley was very low (CSA, 2017). The optimum supply of N is very crucial due to its influence on yield, kernel protein content and malting quality (Spaner et al., 2001). A sub-optimal supply of N results in low grain yield and protein content of malting barley, which creates low enzymatic activity and hence creates reduced quality of malt and beer (Vanova et al., 2006). The low N also produced low yield and low kernel properties such as lower seed size and plumpness, which translate into lower amounts of carbohydrate and eventually less malt extract and lower alcohol (beer) yields per unit of raw material (MAGB, 2018). In contrast, excessive rates of N reduce test weight, decrease kernel plumpness and increase the kernel protein concentrations to unacceptable levels (O'Donovan et al., 2011). Increased kernel protein concentration, in turn, causes insufficient water absorption during malting and lower carbohydrate content which results in uneven kernel modification and lower malt extracts which can negatively affect the brewing process (Schelling et al., 2003; Petterson, 2006; O'Donovan et al., 2011; Edney et al., 2012). With increased kernel protein content, the entire malting process takes longer time; the extended steeping period may create ideal conditions for the growth of fungi, which result in a danger of mold development in the absence of air on top of the increase in costs for malting (Vanova et al., 2006; BMBRI, 2014). Moreover, excessive N fertilization can increase the potential for N leaching in soils by increasing soil N mineralization and residual N accumulation (Sainju et al., 2009).

To feed the ever-increasing population of the region, and sustainably supply adequate raw materials of sufficient quality for the booming demand of Ethiopian brewing industries will require boosting malting barley yields beyond the current level. There is a wide yield gap between the national average of the country (2.5 t ha<sup>-1</sup>; CSA, 2020) versus other top barley producing countries, for instance, Germany (5.9 t ha<sup>-1</sup>; FAOSTAT, 2018). This indicated that there is great potential to increase Ethiopian malt barley production through improved agronomic practices. To achieve a balance between optimum yield and kernel protein concentrations of malting barley, a better understanding of the roles of crop rotation and application of optimum level of N are needed (McKenzie et al., 2005).

Information on the benefits of diverse cropping sequences and N fertilizer management to increase wheat yields and quality compared to traditional systems is available (Amanuel et al., 2000; Asefa et al., 2000). However, relatively little is known and limited recommendations exist about their effects on malting barley productivity and quality in Ethiopia in general and the southeastern highlands of Ethiopia in particular. Therefore, the aim of this study was to investigate the effects of legume and non-legume preceding crops and N fertilizer rates on the productivity and quality of malting barley in the southeastern Ethiopian highlands.

## 2. Materials and methods

### 2.1. Description of the study sites

This study was conducted on three farmers' fields in the Kofele and three farmers' fields in the Chole districts from 2011 to 2013 cropping seasons in the southeastern Ethiopian highlands. Kofele and Chole are potential districts for both food and malting barley production. The Kofele and Chole districts are categorized as warm temperate per humid and warm temperate humid, respectively (MoA, 2000); the former is wettest than the later. The dominant soil type of both the Kofele and Chole districts is pellic Vertisol (IUSS Working Group WRB, 2014). The study sites in the Kofele district were located between 7°05'00.2" and 7°13'31.2" N latitude and 38°47'06.8" to 38°56'70.6" E longitude. Experimental sites in the Chole district were located between 8°07'01.5" to 8°12'14.6" N latitude and 39°53'58.4" to 39°55'22.8" E longitude. The sites in the Kofele and Chole districts are at 2682–2811 and 2721–2967 m a.s.l., respectively.

There were no established weather stations in the study sites in both locations. For that reason, the public domain software program and database called *New LocClim: Local Climate Estimator* developed by FAO (FAO, 2005) was used to characterize the long-term weather conditions of both locations. Employing the geographic coordinates and elevations of the target areas as inputs, the programme enables to extract and display weather data from the FAOCLIM (FAO, 2001) database. Thus, by interpolating from the nearby weather stations, the programme generates weather data for the target areas. Accordingly, both the Chole and Kofele districts have an extended rainy season, which starts in March and continues to October. The highest rainfall concentrations are in June, July and August. The annual average rainfall of Chole and Kofele districts were 1014 and 1170 mm, respectively. The mean minimum and maximum annual temperatures of the Chole district were 6.32 °C and 26.67 °C, respectively. The corresponding values for the Kofele district were 8.51 °C and 19.63 °C, respectively.

For the purpose of site characterization, representative soil samples from each site were collected at a depth of 0–20 cm before sowing. The collected soil samples were combined into one composite per site, dried, sieved to pass through a 2-mm mesh, and analyzed at the soil and plant nutrition laboratory of the Kulumsa Agricultural Research Center (KARC). The methods employed for the analysis of total nitrogen (N) content was Kjeldahl (Bremner and Mulvaney, 1982); for organic carbon (OC) it was the Walkley and Black Method (Walkley, 1947); for available phosphorous (P) it was the Mehlich III (Mehlich, 1984); and for soil pH it was based on determining pH in a 1:1.25 solution of soil and water (McKeague, 1978). Soil chemical analyses results showed that the pH, available P, total OC and total N for Kofele were 5.43, 13.33 mg kg<sup>-1</sup>, 4.18 % and 0.33 g 100<sup>-1</sup>, respectively. While the pH, available P and total N for Chole were 5.0, 26.4 mg kg<sup>-1</sup> and 0.28 g 100<sup>-1</sup>, respectively.

### 2.2. Experimental set-up and procedures

The experiments in both locations were a 3-year rotation and performed in fixed plots at each of the six sites (three at each location). It was designed in split plot with preceding crops as main plot and four levels of N (0, 18, 36 and 54 kg N ha<sup>-1</sup>) for the succeeding crop as sub plot treatments with 3 replications. The first cropping season (2011) was dedicated to preparation for the establishment of the target precursor crops at each location whereas the second and third cropping seasons (2012 and 2013) were the test years for investigating the response of malting barley to the applied N fertilizer under different residues left by the preceding crops. In the first year, the preceding crops for the respective districts were sown at their appropriate dates in randomized complete block design with 3 replications. Fababeen (*Vicia faba* L. cv. Degaga), Ethiopian mustard (*Brassica carinata*, cv. Yellow Dodola), potato (*Solanum tuberosum* L., cv. Gudeneva), linseed (*Linum usitatissimum* L., cv. Chilalo), bread wheat (*Triticum aestivum* L., cv. Digelu) and malting

barley (*Hordeum vulgare L.*, cv. Holker) were the preceding crops in the Kofele sites while these preceding crops were also used in the Chole sites, except for potato. During the same year, malting barley was also sown as a control treatment. Based on their respective recommended fertilizer rates, 18–20, 27–30, 105–40, 23–10, 73–30 and 18–20 kg N–P ha<sup>-1</sup> from urea and di-ammonium phosphate were applied for fababean, Ethiopian mustard, potato, linseed, bread wheat and malting barley, respectively. In addition, all relevant agronomic practices were undertaken as per the local recommendations for each crop. All the crop residue, fallen leaves and branches were deliberately left on the respective experimental fields after harvesting of each preceding crops. During land preparation for the second year trial, they were carefully incorporated in to the soil using an ox-drawn implement, locally called *maresha*, without mixing the main plots.

Following the first year's preceding crops, the experiment continued for two more consecutive years with malting barley as a target crop, and different N treatments. The experiment was arranged in such condition to enable evaluation of the response of malting barley to the applied N for two consecutive cropping seasons under different levels of residues left by the preceding crops. Thus, the experiment was carried out for a total 3 years at each site and location in fixed plots. In the second and third years, each of the main plots was divided in to 4 sub plots with an equal size of 15 m<sup>2</sup> (3 m by 5 m). The spacing between plots and blocks were 0.5 m and 1 m, respectively. Each plot was sown with malting barley (cv Holker) at 4 levels of N (0, 18, 36 and 54 kg N ha<sup>-1</sup>). The recommended rate of P (20 kg P ha<sup>-1</sup>) for malting barley was uniformly applied to all plots at sowing. Half of the recommended rate of each level of N was applied at sowing and the remaining half at the tillering stage. The sources of N and P fertilizers used during the second and third years were urea and triple super phosphate, respectively.

During the early and later stages of the malting barley crop development, incidences of shoot fly and leaf diseases (scald and net blotch), respectively were observed at each site and location during the second and third years of the experimental period. The insecticide Fenithrothion (Ethiothrothion 50% EC) was sprayed against shoot fly to suppress the infestation and avoid economical yield reduction. Fungicide, namely Propiconazole (Tilt®25% EC) was also applied for management of net blotch and scald to limit the detrimental effects of leaf disease development. It has been reported that stubble-borne leaf diseases such as scald and net blotch are greatly impacted by crop rotation. A well designed leaf diseases survey among preceding crops was not carried to evaluate the positive contribution of cropping sequences against leaf diseases. That was the limitation of the study; however, the interference of these diseases was mitigated by the application of fungicides for all treatments during the second and third years of the experiments.

### 2.3. Data collection

The measured (computed) variables for yield, yield attributes and quality of malting barley were number of tiller plant<sup>-1</sup>, spike m<sup>-2</sup>, plant height, grain and above-ground total biomass yields, harvest index, kernel weight and grain protein content. For grain and aboveground biomass yields measurements, the entire crop was harvested from a net plot area of 6 m<sup>2</sup> (2 m by 3 m). The whole harvest from each plot was subjected to drying and weighing for the determination of aboveground total biomass yields. The air-dried samples were threshed manually, cleaned and weighed for grain yield determination. The moisture contents of the grain samples were measured using a moisture tester device and adjusted to a standard value of 12.5%. The weighed samples of the aboveground biomasses and grains from each plot were converted to kg ha<sup>-1</sup> for statistical analyses. Grain samples were collected from each plot and their respective kernel and hectoliter weights were determined using seed counter and hectoliter weighing devices, respectively in the crop physiology laboratory of KARC. Kernel N concentrations were determined using the Kjeldhal method in the plant nutrition laboratory of KARC.

Plant population and the number of spikes were counted from 10 0.5 m long sampling locations in each sub plot, and were converted to m<sup>-2</sup> for the purpose of statistical analysis. The number of tillers per each plant was counted from 10 plant samples from each plot. Plant heights from the ground surface to tip of the plant excluding awns were measured at physiological maturity based on 10 plant samples per plot.

### 2.4. Economic analysis

The CIMMYT (1988) procedure for the partial budget analysis was employed to evaluate the economic optimum rate of nitrogen (N) fertilizer for malting barley production. The variable cost (VC) and gross field benefits (GB) were calculated based on the average values over locations and at the farm gate market prices during the 2020 cropping season. Since there was no interaction effect between preceding crops and N rates, the partial budget analysis was conducted for the N source of fertilizer (Urea) only. Hence, the VC estimated for N rates is the price of urea fertilizer, whereas the GB were calculated based on the current market prices of grains and straws of malting barley. Prior to calculation, the grain and straw yields of malting barley were adjusted downwards by 10% to reflect the actual production conditions of the farmers. The treatments were listed according to their increasing sequences of VC. The marginal rate of return (MRR) was calculated for the whole treatments of N rates. The minimum acceptable rate of return considered to declare economical profitability in this study was greater than or equal to 100%. Sensitivity analysis was also carried out based on the hypothesis of maintaining the costs of inputs that do not vary constant, but increasing all VC by 10% per annum for 3 consecutive years with the base year taken as 2020, which makes a total of 30%.

### 2.5. Data analysis

All yield, yield components and quality data were subjected to analysis of variance using PROC MIXED of SAS statistical package version 9.0 (SAS Inc., Cary, NC) following the procedure set by Littell et al. (2006). The test of homogeneity of variance was performed, and the statistics and distributions of the residual plots were found normal. Thus, results were pooled across sites and years within districts. Cropping sequence and N rate were regarded as fixed effects. Location by year combinations and replicates within environments, and the environment interaction with the applied treatments (fixed effects) were considered as random effects. Year and location effects and their interactions with fixed effects are suggested to be considered as random since the ultimate goal of most agronomic studies is to infer future performance at many untested locations (Yang, 2010). The LSMEANS option of PROC MIXED was employed to obtain least-square means when treatments and their interactions were significant (Littell et al., 2006). For the cropping sequence treatment, means were compared using least significant difference (LSD) test. When treatment effects were significant, mean separation was performed using the PDMIX800 macro of Saxton (1998). Single degree of freedom orthogonal contrasts were carried out to test for the linear, quadratic and cubic responses of malting barley to the 4 equally spaced rates of the applied nitrogen fertilizer. The same tool was employed to fit regression equations that best described the relationship between the dependent variables and N fertilizer rate based on the nature of the responses.

## 3. Results and discussion

The statistical tests and residual plots as obtained through the homogeneity of variances were found normal. The effects of preceding crops and N fertilizer were reasonably consistent among the 3 environments over 3 years at Kofele, and 3 environments over 3 years at Chole (data not shown). Thus, results were combined across sites and seasons within the district. However, location (district) was not pooled together for the fact that the precursor crops tested during the first year were not

similar. Analysis of variance over years and locations indicated that cropping sequence and nitrogen (N) fertilization significantly influenced the productivity and quality of malting barley (Tables 1 and 2). However, there were no significant interaction effects between preceding crops and N fertilizer for the variables measured or computed except for the kernel weight and protein content in Kofele, and plant height in Chole (Tables 1 and 2). Hence, the main effects of preceding crops and N fertilizer have been presented below.

### 3.1. Effect of preceding crops on productivity and quality of malting barley

Results indicated that preceding crops significantly influenced the grain and biomass yields, yield components and protein concentrations of malting barley in the Kofele and Chole experimental sites (Tables 1 and 2). Analysis of variance showed that malting barley grown after non-malting barley crops gave very highly significant ( $p < 0.001$ ) grain and biomass yield increments than when malting barley was the preceding crop in these experimental sites (Tables 1 and 2).

The highest grain yields of malting barley averaged over sites in the Kofele district occurred when malting barley was preceded by any of the non-host crops, while differences between non-host preceding crops were not significant (Table 3). The lowest grain yields of malting barley occurred for the continuous barley treatment. Seeding malting barley after potato gave statistically superior biomass yield ( $9723 \text{ kg ha}^{-1}$ ) versus all other preceding crops averaged over sites in the Kofele district (Table 3). Biomass yields following fababean ( $8702 \text{ kg ha}^{-1}$ ), Ethiopian mustard ( $8543 \text{ kg ha}^{-1}$ ), wheat ( $8374 \text{ kg ha}^{-1}$ ) and linseed ( $8202 \text{ kg ha}^{-1}$ ) were also statistically higher than seeding malting barley following the same crop (Table 3). Biomass yield increments were 30.3, 16.6, 14.5, 12.2 and 9.9% for potato, fababean, Ethiopian mustard, wheat and linseed, respectively as precrop versus malting barley had the precrop. The lowest biomass yield ( $7464 \text{ kg ha}^{-1}$ ) averaged over sites in the Kofele district was recorded from seeding malting barley succeeding malting barley. Differences between Ethiopian mustard, fababean, linseed and wheat were not significantly different (Table 3).

Unlike the average over sites in the Kofele district, the highest grain ( $3478 \text{ kg ha}^{-1}$ ) and biomass ( $8193 \text{ kg ha}^{-1}$ ) yields of malting barley averaged over sites in the Chole district were obtained from growing malting barley following Ethiopian mustard, which was statistically superior over all other preceding crops including fababean (Table 4). Seeding malting barley succeeding Ethiopian mustard even outperformed the grain and biomass yields of malting barley after fababean by 18.9 and 11.8%, respectively. Next to Ethiopian mustard, fababean, linseed and wheat gave statistically similar but superior grain and biomass yields of malting barley compared to continuous malting barley (Table 4). Averaged across sites in Chole district, there were 34.2, 12.9, 10.9 and 9.9% rises in malting barley grain yield, and 25.3, 12.0, 10.9 and 7.9% increases in malting barley biomass yield following Ethiopian mustard, fababean, linseed and wheat, respectively compared to when malting barley was the preceding crop. However, increases amongst fababean, linseed and wheat were not significantly different. Similar to the averages over sites in the Kofele district, the lowest grain ( $2591 \text{ kg ha}^{-1}$ ) and biomass ( $6542 \text{ kg ha}^{-1}$ ) yields of malting barley averaged over

sites in the Chole district were harvested from seeding malting barley after malting barley (Table 4).

Generally, the superior productivity of malting barley following fababean, Ethiopian mustard, potato, linseed and wheat compared to when malting barley was the preceding crop indicated the vital advantage of crop rotation. These legume and non-legume preceding crops provided positive yield benefits to the subsequent malting barley. This result was in agreement with the previous studies including Asefa et al. (1997), Turkington et al. (2012), Upendra et al. (2013), Agegnehu et al. (2014) and O'Donovan et al. (2014).

The benefits provided by these preceding crops to the subsequent crop were likely not only related to the N contributions from the legumes. The impact of non-barley crops may have been related to the lower penetrometer resistance, which was characteristic to deep tap roots on soil structure from crops like Ethiopian mustard (Amanuel et al., 2000). Lower penetrometer resistance indicates reduction in soil compaction and bulk density; thereby enhances infiltration of rainfall and increases moisture retention as opposed to runoff in compacted soils. Other factors may have been related to weed control (Asefa et al., 2000), reduction of take-all (*Gaeumannomyces graminis*) and eyespot (*Pseudocercospora herpotrichoides*) diseases (Tezera et al., 1995; Schreiner et al., 2010).

Suppression of the prevalence of diseases, pests or weeds that may not be fully controlled with the sole application of pesticides is among the major benefits of crop rotation. In this regard, short rotations of two to three crops are usually employed (Walters et al., 2012). Cropping sequence has most impact on soil borne diseases such as take-all, eyespot and other diseases, which could significantly impact the global production of barley (Hornby, 1998). In mono-cropping, these soil-borne diseases such as take-all and eyespot are usually present in the crop residues from previous barley crop, spread to the second or subsequent barley crop through trashes from previous crop and result in worse yield reduction (Oxley and Burnett, 2010). In continuous cropping, soil-borne diseases are usually more common in a second, third or fourth consecutive barley crop as the fungus builds up in the soil. Generally, the mechanism of disease control is through reduction in the inoculum of soil-borne pathogenic microbes by growing a non-host crop, which leads the pathogen in the soil to die or its population is significantly reduced to a level that will result in negligible crop damage (Walters et al., 2012). Crop rotation; however, usually less influenced foliar diseases including mildew and rusts (Oxley and Burnett, 2010). Despite the mild influence, breaking the continuous cropping sequence could be useful in reducing inoculum of foliar pathogens which can be spread from crop residues, for example *Rhynchosporium commune* (Oxley and Burnett, 2010).

The N residue left after the harvest of fababean (Díaz-Ambrona and Mínguez, 2001; Neugschwandtner et al., 2015), and the improved soil structure due to the foliage and root systems of potato and Ethiopian mustard could have attributed to the increased yield of the subsequent malting barley (Agegnehu et al., 2014). Agegnehu et al. (2014) also reported the beneficial effects of non-barley preceding crops to the yield of malting barley. In this regard, Ethiopian mustard was superior even over fababean for the average of the Chole district sites. This result was in agreement with Asefa et al. (1997), who reported that the yield of barley after fababean was 9% lower than barley after Ethiopian

**Table 1.** P values from the analysis of variance for the effects of preceding crop and N fertilizer rate on yield and yield components of malting barley in Kofele. Environments (year and location), replications within environments and their interactions with fixed effects were considered as random effects.

Effects	Spike $\text{m}^{-2}$ [No]	Plant height [cm]	Harvest index [%]	Grain yield [ $\text{kg ha}^{-1}$ ]	Biomass yield [ $\text{kg ha}^{-1}$ ]	Seed weight [mg]	Grain protein [%]
Preceding crop [PC]	<0.0001	0.0029	0.1296	<0.0001	<0.0001	<0.0001	<0.0001
Nitrogen rate [N]	0.0078	0.0319	0.1625	0.0079	0.0651	0.0002	0.0104
N <sub>linear</sub>	0.1219	0.0116	0.9884	0.0063	0.0696	0.0102	0.1511
N <sub>quadratic</sub>	0.8152	0.5450	0.3905	0.6802	0.8444	0.5139	0.6694
N <sub>cubic</sub>	0.6668	0.5997	0.4765	0.9253	0.7162	0.6263	0.8653
PC*N	0.0302	0.1196	0.3151	0.8305	0.1931	<0.0001	<0.0001

**Table 2.** P values from the analysis of variance for the effects of preceding crop and N fertilizer rate on yield and yield components of malting barley in Chole. Environments (year and location), replications within environments and their interactions with fixed effects were considered as random effects.

Effects	Tiller plant <sup>-1</sup> [No]	Plant height [cm]	Harvest index [%]	Grain yield [kg ha <sup>-1</sup> ]	Biomass yield [kg ha <sup>-1</sup> ]	Seed weight [mg]	Grain protein [%]
Preceding crop [PC]	0.0797	0.0002	<0.0001	<0.0001	<0.0001	<0.0001	0.2627
Nitrogen rate [N]	0.0304	<0.0001	0.0002	<0.0001	<0.0001	0.0031	<0.0001
N <sub>linear</sub>	0.0244	<0.0001	0.0071	<0.0001	<0.0001	0.0034	<0.0001
N <sub>quadratic</sub>	0.5075	0.2883	0.4028	0.6096	0.8625	0.8276	0.9326
N <sub>cubic</sub>	0.6252	0.7336	0.9303	0.8310	0.9058	0.5875	0.7329
PC*N	0.6344	<0.0001	0.9209	0.1205	0.3114	0.1215	0.3544

**Table 3.** Means for the main effect of preceding crop on the yield and yield components of malting barley crop in Kofele.

Preceding crop	Spike m <sup>-2</sup> [No]	Plant height [cm]	Harvest index [%]	Grain yield [kg ha <sup>-1</sup> ]	Biomass yield [kg ha <sup>-1</sup> ]	Seed Weight [mg]	Grain protein [%]
Ethiopian mustard	579 <sup>d</sup>	105.51 <sup>b</sup>	43.74	3661 <sup>a</sup>	8543 <sup>b</sup>	49.33 <sup>b</sup>	10.84 <sup>cd</sup>
Fababean	663 <sup>b</sup>	107.9 <sup>a</sup>	43.20	3718 <sup>a</sup>	8702 <sup>b</sup>	50.00 <sup>ab</sup>	12.58 <sup>a</sup>
Potato	719 <sup>a</sup>	97.0 <sup>c</sup>	38.43	3666 <sup>a</sup>	9723 <sup>a</sup>	50.92 <sup>a</sup>	12.53 <sup>a</sup>
Linseed	623 <sup>c</sup>	106.9 <sup>ab</sup>	44.03	3568 <sup>a</sup>	8202 <sup>b</sup>	49.00 <sup>b</sup>	11.10 <sup>bc</sup>
Wheat	611 <sup>cd</sup>	105.9 <sup>ab</sup>	43.30	3575 <sup>a</sup>	8374 <sup>b</sup>	49.33 <sup>b</sup>	11.30 <sup>b</sup>
Malt barley	602 <sup>cd</sup>	104.9 <sup>b</sup>	43.88	3221 <sup>b</sup>	7464 <sup>c</sup>	45.33 <sup>c</sup>	10.65 <sup>d</sup>

Note: (1) means with the same letter are not statistically different, (2) values without letters indicated insignificant responses.

**Table 4.** Means for the main effect of preceding crop on the yield and yield components of malting barley crop in Chole.

Preceding crop	Tiller plant <sup>-1</sup> [No]	Plant height [cm]	Harvest index [%]	Grain yield [kg ha <sup>-1</sup> ]	Biomass yield [kg ha <sup>-1</sup> ]	Seed weight [mg]	Grain protein [%]
Ethiopian Mustard	4.6	93.8 <sup>a</sup>	42.95 <sup>a</sup>	3478 <sup>a</sup>	8193 <sup>a</sup>	51.53 <sup>a</sup>	9.37
Fababean	4.8	89.8 <sup>b</sup>	41.05 <sup>b</sup>	2925 <sup>b</sup>	7325 <sup>b</sup>	49.83 <sup>b</sup>	9.43
Linseed	4.7	91.2 <sup>b</sup>	40.40 <sup>b</sup>	2873 <sup>b</sup>	7254 <sup>b</sup>	50.78 <sup>a</sup>	9.53
Wheat	4.8	90.8 <sup>b</sup>	40.80 <sup>b</sup>	2848 <sup>b</sup>	7058 <sup>b</sup>	49.61 <sup>b</sup>	9.77
Malt barley	4.4	89.7 <sup>b</sup>	40.30 <sup>b</sup>	2591 <sup>c</sup>	6542 <sup>c</sup>	49.39 <sup>b</sup>	9.43

Note: (1) means with the same letter are not statistically different, (2) values without letters indicated insignificant responses.

mustard. O'Donovan et al. (2014) also reported that among the legume crops they tested; field pea, fababean, lentil and canola; fababean was the least to provide yield benefit to the subsequent malting barley. The major reason accounted for the superiority of Ethiopian mustard over fababean for the Chole district sites could be related to the relatively lower yield of fababean and its possible meager residual N benefit during the first year. Here the amount N residue left behind in the soil for subsequent crops is generally related to the yield that the previous legume attained (Przednowek et al., 2004).

The effects of preceding crops on the grain and biomass yields of malting barley were pronounced more in Kofele than Chole (Tables 3 and 4). Averaged over locations, the mean grain yields of malting barley succeeding non-malting barley preceding crops averaged over sites in the Kofele and Chole districts were 3568 and 2943 kg ha<sup>-1</sup>, respectively. Whereas the corresponding overall mean biomass yields of malting barley averaged over sites in the Kofele and Chole districts were 8501 and 7275 kg ha<sup>-1</sup>, respectively. These showed 625 (18%) and 1226 (14%) kg ha<sup>-1</sup> grain and biomass yield advantages for legume versus non-legume pre-crops, respectively the average of the Kofele sites compared to the average of the Chole sites. The preceding crops resulted in 348–498 kg ha<sup>-1</sup> (10.8–15.5%) higher grain yields following non-malting barley crops than following malting barley in Kofele (Table 3); however, the corresponding results for Chole were from 257–887 kg ha<sup>-1</sup> (9.9–34.2%) (Table 4). Similarly, preceding crops brought 738–2258 kg ha<sup>-1</sup> (9.9–30.3%) increases in biomass yields

following non-malting barley crops than following malting barley when averaged over the Kofele sites (Table 3); however, the corresponding increases for the average over the Chole sites were 516–1650 kg ha<sup>-1</sup> (9.9–25.2%) (Table 4). Although the scale of change in yield responses following non-malting barley preceding crops compared to malting barley as a preceding crop was superior for the Chole than Kofele sites, the overall mean grain and biomass yields of malting barley for the Chole sites (2943 and 7275 kg ha<sup>-1</sup>, respectively) were lower than the average values for the Kofele sites (3568 and 8501 kg ha<sup>-1</sup>, respectively) (Tables 3 and 4). The greater yields could partially be attributed to the relatively higher N content (0.33 g 100g<sup>-1</sup>) and pH (5.43) of the soil for the Kofele than Chole sites (0.28 g 100g<sup>-1</sup> and 5.0, respectively) districts. Although the available soil phosphorus in the Chole sites (26.4 mg kg<sup>-1</sup> soil) was significantly higher than the Kofele sites (13.3 mg kg<sup>-1</sup> soil), it might not be fully available for the crop owing to the relatively lower soil pH.

Growing malting barley following non-malting barley preceding crops generally resulted in significantly higher ( $p < 0.001$ ) kernel weight in Kofele and Chole (Tables 1 and 2). The highest kernel weights averaged over sites in the Kofele district were recorded following potato (51 mg) and fababean (50 mg) (Table 3). Whereas the uppermost kernel weights averaged over sites in the Chole district were from growing malting barley preceded with Ethiopian mustard (52 mg) and linseed (51 mg) (Table 4). Except for fababean and wheat in Chole, the kernel weights of malting barley were significantly lower in monocultures than

when malting barley preceded by non-malting barley crops (Tables 3 and 4).

The plump kernel results in more starch and gives a higher percent of malt extract, which in turn produces a greater amount of beer from a given weight of malt (BMBRI, 2014). Thus, a plump kernel is required for malting. The highest kernel weights of malting barley were following fababean and potato for the Kofele district sites compared to Ethiopian mustard for the Chole district sites and reflected the trend for grain yields reported previously. Kernel weight increments of 3.7–5.6 mg (8.1–12.3%) and 0.2–2.1 mg (0.4–4.3%) were obtained for the Kofele and Chole districts sites, respectively following preceding crops that were non-hosts compared to the monoculture treatment (Tables 3 and 4). The superior kernel plumpness observed for the Chole district sites (50.4 mg) compared to the Kofele sites (49.7 mg) could account to the relatively higher initial phosphorus content of the soil (26.4 and 13.3 mg kg<sup>-1</sup> for Chole and Kofele sites, respectively) and its consequential contribution to seed formation in the Chole than Kofele sites. Papastylianou (2004) also reported that seeding malting barley after vetch improved the kernel weight of malting barley.

Results further indicated that preceding crops significantly ( $p < 0.001$ ) affected the grain protein concentrations of malting barley for the Kofele sites (Table 1) with no effect in the Chole sites (Table 2). The ranges of malting barley kernel protein concentrations were from 10.7% following malting barley to 12.6% following fababean for the Kofele sites (Table 2). Averaged over the Kofele sites, 1.8–18.1% increases in kernel protein concentrations were obtained when growing malting barley on non-malting barley crop residues. All malting barley seeded after non-malting barley preceding crops, except Ethiopian mustard resulted in higher kernel protein concentrations compared to monocropping of malting barley for the Kofele district sites (Table 3). The overall mean protein concentration of malting barley for the Kofele sites (11.5%) was higher than the Chole sites (9.5%). These trends could be attributed to the relatively higher initial N content of the soil for the Kofele (0.33 g 100g<sup>-1</sup>) than Chole (0.28 g 100g<sup>-1</sup>) sites. The potential reason for higher protein concentrations in malting barley following non-malting barley preceding crops for the sites in both locations may be due to better N availability and higher subsequent N uptake from the soil, and translocation in to the grain. The higher N uptake by malting barley late in the growing season (McKenzie et al., 2005), and the release of N from decomposition of the residues left by the preceding crops late in the season (O'Donovan et al., 2014) likely resulted in the observed increased kernel protein concentrations.

All of the kernel protein concentrations recorded for the sites in the Chole district were within the threshold range for malting barley. However, fababean (12.58%) and potato (12.53%) resulted in somewhat higher values than the upper acceptable level of protein (11.5%) for the Kofele district sites. The malt factories in Ethiopia follow the European Brewery Convention standard, which is within the range of 9.5–11.5% kernel protein concentration (Atherton, 1984). Thus, the higher protein following fababean and potato for the Kofele sites suggests that N fertilizer rates in this district needs to be carefully managed and applied based on soil test results. If N fertilizer rates are managed carefully, it is unlikely that these pre-crop treatments would result in unacceptable protein concentrations for subsequent malting barley crops. Currently, growers who hesitate to practice legume and non-legume-malting barley cropping sequences do so based on the suspicion that these pre-crops can lead to surpassing the threshold limit for acceptable kernel protein contents and rejection for malting grade. Results of the current study should encourage these malt barley growers to utilize legume and non-legume pre-crops without the risk of exceeding acceptable protein thresholds, especially if N fertilizer application is managed appropriately. Other studies also reported that seeding malting barley directly on fababean (O'Donovan et al., 2014) and field pea (Turkington et al., 2012) residues did not consistently result in an increase in kernel protein.

Seeding malting barley following non-malting barley crops significantly ( $p < 0.01$ ) influenced plant height in testing sites of both districts

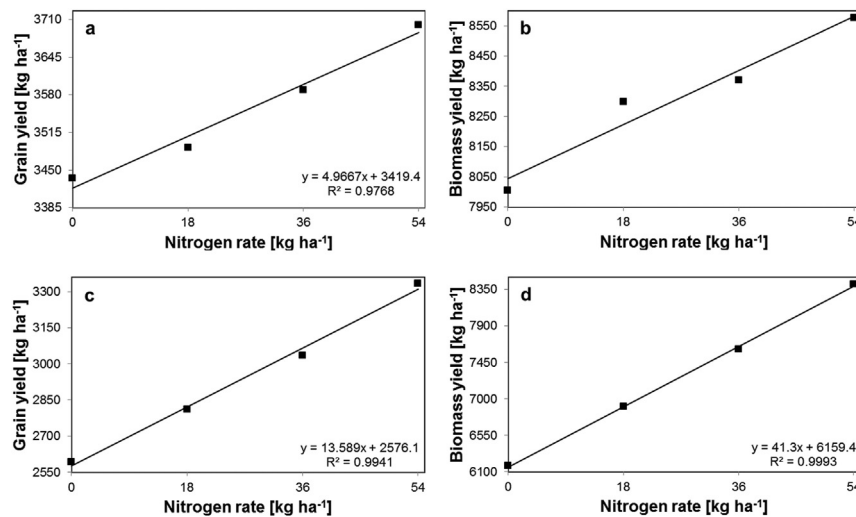
(Tables 1 and 2). The tallest plant in the Kofele (108 cm) and Chole (94 cm) districts were recorded from growing of malting barley following potato and Ethiopian mustard, respectively (Tables 3 and 4). Equivalent plant heights were also observed when malting barley was grown after linseed (107 cm) and wheat (106 cm) in the Kofele district sites (Table 3). The number of spikes per square meter ( $p < 0.01$ ) and harvest index ( $p < 0.0001$ ) of malting barley were also significantly influenced due to cropping sequences in the Kofele and Chole districts, respectively (Tables 1 and 2). The largest number of spikes per m<sup>-2</sup> (719) and highest harvest index (43%) were recorded when malting barley was preceded with potato and Ethiopian mustard, respectively (Tables 3 and 4). Seeding malting barley after the same crop resulted in the lowest harvest index (40%) and plant height (89.7 cm) for the Chole sites, but only compared to Ethiopian mustard; differences compared with the other non-barley pre-crops were not significant (Table 4). Compared to seeding malting barley in monoculture, other preceding non-host crops had no significant influences on the harvest index and number of tillers of malting barley for sites in the Kofele and Chole, respectively (Tables 1 and 2).

### 3.2. Effect of nitrogen fertilizer on productivity and quality of malting barley

The application of N fertilizer markedly influenced the yield, yield components and kernel protein concentrations of malting barley for sites in Kofele and Chole districts (Tables 1 and 2). The relationship between N fertilizer rates and the response variables were linear in nature, while the cubic and quadratic effects were not significant. Grain yields for the Kofele (3701 kg ha<sup>-1</sup>) (Figure 1a) and Chole (3333 kg ha<sup>-1</sup>) (Figure 1c) districts sites increased as the rate of N fertilizer increased from 0 to 54 kg N ha<sup>-1</sup>. Applications of 54 and 36 kg N ha<sup>-1</sup> gave grain yield increments of 265 kg (8%) and 152 kg (4%), respectively compared to the control (no N), and 212 kg (6%) and 99 kg (3%), respectively compared to the previous recommendation (18 kg N ha<sup>-1</sup>) in Kofele (Figure 1a). In contrast to the control and previous recommendation, application of 54 kg N ha<sup>-1</sup> in Chole gave grain yield augmentations of 741 kg (29%) and 521 kg (19%), respectively (Figure 1c). The corresponding yield advantages when malting barley was sown using 36 kg N ha<sup>-1</sup> were 443 kg (17%) and 223 kg (8%), respectively (Figure 1c). The lowest grain yield in Kofele (3436 kg ha<sup>-1</sup>) and Chole (2592 kg ha<sup>-1</sup>) were recorded from the plots not treated with N fertilizer (Figure 1a and c).

N fertilization had a highly significant ( $p < 0.001$ ) effect on the biomass yield of malting barley for the Chole sites (Table 2). The N fertilization brought a linear response with the highest biomass yield recorded from the application of 54 kg N ha<sup>-1</sup> (8413 kg ha<sup>-1</sup>) followed by 36 kg N ha<sup>-1</sup> (7612 kg ha<sup>-1</sup>) and 18 kg N ha<sup>-1</sup> (6901 kg ha<sup>-1</sup>) (Figure 1d). Compared to the control (no N), applications of 54, 36 and 18 kg N ha<sup>-1</sup> gave biomass yield advantages of 2241 kg (36%), 1440 kg (23%) and 729 kg (12%), respectively. In contrast to the previous recommendation (18 kg N ha<sup>-1</sup>), 1512 kg (22%) and 710 kg (10%) biomass yield advantages were obtained owing to applications of 54 and 36 kg N ha<sup>-1</sup>, respectively (Figure 1d). Significant differences among the 4 treatments were not observed in Kofele though biomass yield tended to increase with increasing N fertilization rates (Figure 1b). Applications of 54, 36 and 18 kg N ha<sup>-1</sup> resulted in biomass increases of 572 (7%), 365 (5%) and 293 (4%), respectively relative to the treatment with no N (Figure 1b).

Generally, the response of malting barley to N fertilization and the lack of a significant interaction between pre-crop and N rate showed that grain and biomass yields increased with increased rates of N for sites in both districts irrespective of preceding crops. Accordingly, the agronomic optimum rate of N for enhanced malting barley productivity was 54 kg N ha<sup>-1</sup> for the Kofele and Chole districts sites regardless of preceding crops. Similar results of increased malting barley grain yield with increased N fertilization rates were also reported by several researchers including Halvorson and Reule (2007a,b), O'Donovan et al. (2011), Upendra et al.



**Figure 1.** Grain and above ground total biomass yields of malting barley grown under four rates of N fertilizer (0, 18, 36 and 54 kg ha<sup>-1</sup>) in Kofele (a and b) and Chole (c and d) districts in the southeastern highlands of Ethiopia.

(2013), Agegehu et al. (2014), O'Donovan et al. (2014) and Kassie and Tesfaye (2019). Similarly, increased malting barley biomass yields with increased N fertilization rates were also reported based on several global studies including Halvorson and Reule (2007a,b) and Abeledo et al. (2008). Manitoba Agriculture, Food and Rural Development (2014) and O'Donovan et al. (2014) also reported higher yield potentials owing to application of N fertilizer after legume preceding crops.

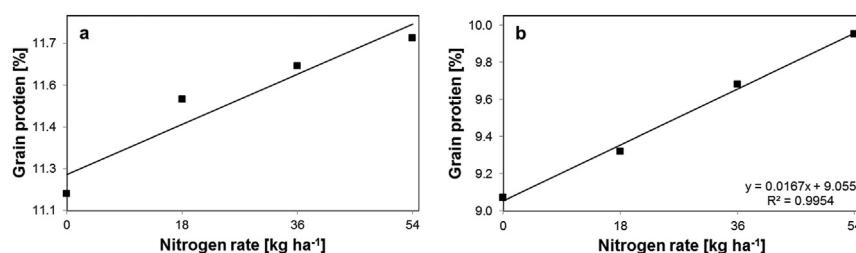
Similar to the preceding crops, the effects of N fertilizer on the grain and biomass yields of malting barley were pronounced more for the Kofele than Chole sites (Figure 1). The overall mean grain and biomass yields of malting barley due to application of N fertilizer for the Kofele (3553 and 8314 kg ha<sup>-1</sup>, respectively) sites were higher than the Chole (2943 and 7275 kg ha<sup>-1</sup>, respectively) sites. Averaged over all levels and sites, N fertilization gave grain and biomass yield advantages of 610 and 1039 kg ha<sup>-1</sup>, respectively for the Kofele compared to Chole sites (Figure 1). However, larger changes in the responses of malting barley to applied N fertilizer were observed for the Chole than Kofele sites (Figure 1). Higher incremental responses to N fertilization and lower yields for the Chole compared to Kofele district sites could partially be attributed to the relatively lower initial N content (0.28 g 100g<sup>-1</sup>) and soil pH (5.0) for the Chole sites than the relatively higher initial N (0.33 g 100g<sup>-1</sup>) and soil pH (5.43) for the Kofele sites.

Results also demonstrated that N fertilization significantly influenced the kernel protein concentrations of malting barley for the Kofele ( $p < 0.05$ ) and Chole ( $p < 0.0001$ ) districts sites (Tables 1 and 2). The general tendency exhibited steady increases in the kernel protein concentrations of malting barley with the corresponding increase in N fertilizer rates for Kofele (Table 1) and Chole districts sites (Table 2). The orthogonal contrasts also showed that the grain protein responses of malting barley to N fertilization for the Chole sites were linear (Figure 2b). Although there was a similar trend, the linear, quadratic

and cubic effects were not significant for the Kofele sites (Table 1). Compared to the control, N fertilization brought 2.8–9.7% increases in kernel protein contents for the Chole sites (Figure 2b). The ranges of mean kernel protein contents for the N treated plots were from 11.5–11.7% and 9.3–10.0% for the Kofele and Chole sites, respectively (Figure 2a and b). The kernel protein concentrations for sites in Chole district were within the acceptable range (9.1–10%). However, there was marginally higher than the upper threshold (11.5%) levels for sites in the Kofele district (Figure 2a) although the linear contrast for N rate was not significant. Generally, the mean value of kernel protein concentrations for the Kofele sites (11.5%) was higher than the Chole sites (9.5%).

Increased N supply induced enhanced N uptake by crops and thus increased kernel protein concentration (Olsen et al., 1976; Tsai et al., 1992; Oikeh et al., 1998). When the uptake and assimilation of N to protein in the seeds comparably exceeds the rise in seed yield, kernel protein concentrations increase (O'Donovan et al., 2014). It also happens when crop accesses N at their latest development stage (O'Donovan et al., 2014). Changes in kernel protein contents among N treatments were not significant in the Kofele sites with the Chole sites perhaps reflecting differences in yields and soil fertility statuses between the two locations. The lower the soil fertility, the greater was the effects of crop rotation and N fertilizer applications. Increased malting barley kernel protein concentrations with increased N fertilization rates have been documented by several studies including Halvorson and Reule (2007a,b), O'Donovan et al. (2011); O'Donovan et al. (2014); Agegehu et al. (2014) and Kassie and Tesfaye (2019).

N fertilization significantly affected the kernel weight of malting barley in Kofele ( $p < 0.001$ ) and Chole ( $p < 0.01$ ) districts sites as indicated by significant linear responses to increasing N rates whereby kernel weight increased with increasing rates of N (Tables 1 and 2, and



**Figure 2.** Grain protein concentrations of malting barley grown under four rates of N fertilizer (0, 18, 36 and 54 kg ha<sup>-1</sup>) in Kofele (a) and Chole (b) districts in the southeastern highlands of Ethiopia.

Figure 3). The biggest kernels were recorded from the highest rate of N ( $54 \text{ kg N ha}^{-1}$ ) in Kofele ( $49.83 \text{ mg}$ ) (Figure 3a) and Chole ( $50.93 \text{ mg}$ ) (Figure 3b). Generally, N fertilization improved the seed weight of malting barley within ranges of 1–4 and 7–9% in Kofele and Chole districts, respectively compared to the unfertilized treatment (Figure 3). Increased malting barley kernel weight with increased N fertilizer rates was also reported in previous studies (e.g., McKenzie et al., 2005; O'Donovan et al., 2011; Upendra et al., 2013 and Kassie and Tesfaye, 2019). Similar to the effect of cropping sequence, the mean kernel weight of malting barley for the Chole ( $50.23 \text{ mg}$ ) sites (Figure 3b) was somewhat higher than the Kofele ( $48.99 \text{ mg}$ ) sites (Figure 3a), which could be attributed to the relatively higher initial phosphorous concentrations in the soil for the Chole ( $26.4 \text{ mg kg}^{-1}$ ) sites compared to Kofele ( $13.33 \text{ mg kg}^{-1}$ ) sites, and to its consequent positive impact on seed formation. This is because phosphorus is a vital component of ATP, which is formed during photosynthesis. Photosynthesis has phosphorus in its structure, and involves in the processes from seedling growth through to seed formation and maturity (Malhotra et al., 2018). Increase in kernel weight with increase in NP application was reported in previous studies including Saneoka and Koba (2003) and Hussain et al. (2006). Owing to its role in good root growth (Malhotra et al., 2018), phosphorus directly affects the kernel weight (Hussain et al., 2006).

The influence of N fertilization on the plant height of malting barley was also significant both for the Kofele (Table 1) and Chole (Table 2) sites. Similar to other measured variables, orthogonal contrasts showed that the plant height of malting barley responded linearly whereby increased levels of N fertilizer resulted in increased plant heights indicating the role of nitrogen in enhancing vegetative growth (Figure 4). The tallest plants for the Kofele (Figure 4a) and Chole (Figure 4b) sites were recorded for the application of  $54 \text{ kg N ha}^{-1}$  (107 and 88 cm, respectively). Generally, 1–3 and 2–9% increases in plant heights at Kofele (Figure 4a) and Chole (Figure 4b) districts were recorded due to N fertilization relative to the unfertilized treatment.

This study generally showed that the number of tillers  $\text{plant}^{-1}$  increased with increased rates of N fertilizer application for the Chole sites (Figure 5a). N fertilization increased the tillering capacities of malting barley for the sites in the Chole district sites (Figure 5a) with no effect in the Kofele district sites (data not shown). Compared to unfertilized plots with 4 tillers per plant, fertilized plots (5 tillers per plant) resulted in increased number of tillers (Figure 5a). The promoted plant tillers in Chole district attributed to the enhanced N availability due to increased rates of N. The application N fertilizer promotes tillers development as it increases the cytokinin content within tiller nodes of the culm and further boosts the growth of the tiller primordium (Sakakibara et al., 2006). Thus, tiller formation depends largely on the N absorbed and the carbohydrates produced at the growth stage when the tiller primordium grows or upon the nutrients stored in the culm (Tanaka and Garcia, 1965). N deficiency results in fewer numbers of tillers, which consequently produce a smaller population of spikes  $\text{m}^{-2}$  (Prystupa et al., 2003; Mitchell et al., 2012). Conversely, surplus of surviving tillers due to excessive N can lead to a larger population resulting in higher competition for limited resources (Wang et al., 2009). Adequate supply of N rate, therefore, optimizes productive tiller density and enhances grain yield.

Results further revealed that the spike density of malting barley was significantly influenced by N fertilization for the Kofele sites (Table 1 and Figure 5b) with no response for the Chole sites (data not shown). The maximum number of plants  $\text{m}^{-2}$  (399) was obtained from the application of  $54 \text{ kg N ha}^{-1}$  whereas the least number of mature plants  $\text{m}^{-2}$  (329) was obtained from application of no N (Figure 5b). Compared to the unfertilized treatment, application of 18, 36 and  $54 \text{ kg N ha}^{-1}$  produced 23 (7%), 64 (19%) and 70 (21%) more spikes, respectively indicating the contribution N for enhanced plant growth. The current result was consistent with the reported findings of O'Donovan et al. (2011). Results also showed that N fertilization had no significant influence on the harvest index of malting barley for the Kofele sites (Table 1).

Generally, the orthogonal contrast among the 4 rates of N fertilization showed linear responses for majority of the measured or computed variables. A linear response from the lowest to the highest quantitative treatment levels may imply that the chosen range of treatments was inadequate to define the maximum yield, whereby they would start to see leveling off in response as would be indicated by significant quadratic effects. These results suggest that the agronomic optimum rate of N fertilizer was not attained in this study. Increasing the rate of N beyond  $54 \text{ kg N ha}^{-1}$  could likely surpass the upper threshold of the grain protein concentration (11.5%) in malting barley for malting purpose. However, and the objective of this study was met, the responses at higher N levels than the currently tested ones could found to be conducive to prompting productivity by maintaining protein levels within acceptable levels for malting barley, while this barley could also be used for other food and feed uses.

### 3.3. Economic analysis

Seeding malting barley at any rate of N regardless of preceding crop was found to be economically profitable for the sites in the Kofele and Chole districts since they gave acceptable rates of return above 100% (Tables 5 and 6). Increasing N fertilizer rate from 0 to  $54 \text{ kg N ha}^{-1}$  for the Kofele district, increased the net benefit obtained correspondingly from US\$1,883 to  $1,975 \text{ ha}^{-1}$  (Table 5). The increase in net benefits for the corresponding N rates for the sites in the Chole district were from US\$1,429 to  $1,817 \text{ ha}^{-1}$  (Table 6). The highest MRR of US\$2.5 and US\$9.15 for every US\$1.0 investment were attained from the application of  $54 \text{ kg N ha}^{-1}$  for the sites in the Kofele and Chole districts, respectively (Tables 5 and 6). Despite the relatively lower yield for the sites in the Chole compared to Kofele sites, the MRR for every level of N was superior for the Chole sites. This can be ascribed to the higher magnitude of responses of malting barley for the applied N, and the enhanced responses with increasing rate of N for the Chole sites.

Currently, study result showed that seeding malting barley at higher rates of N ( $54 \text{ kg N ha}^{-1}$ ) could enable farmers to earn the corresponding higher yields (Tables 1 and 2, and Figure 1a and c) and economic returns (Tables 5 and 6) per unit of their investment compared to the previous recommendation ( $18 \text{ kg N ha}^{-1}$ ). This economic benefit due to the application of N fertilizer is on top of soil quality improvements, which we did not analyze, quantify and include their equivalent economic values in this study. Generally, the economic profitability agrees well

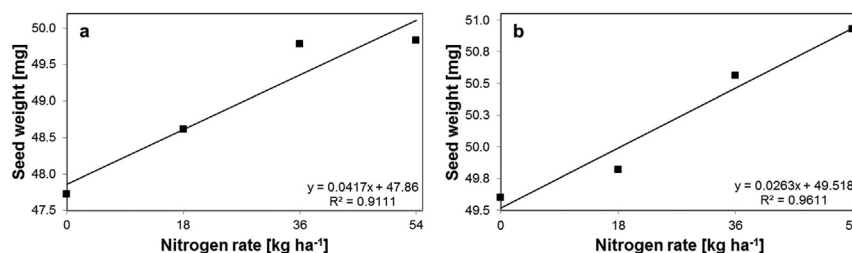


Figure 3. Seed weight of malting barley grown under four rates of N fertilizer (0, 18, 36 and  $54 \text{ kg ha}^{-1}$ ) in Kofele (a) and Chole (b) districts in the southeastern highlands of Ethiopia.



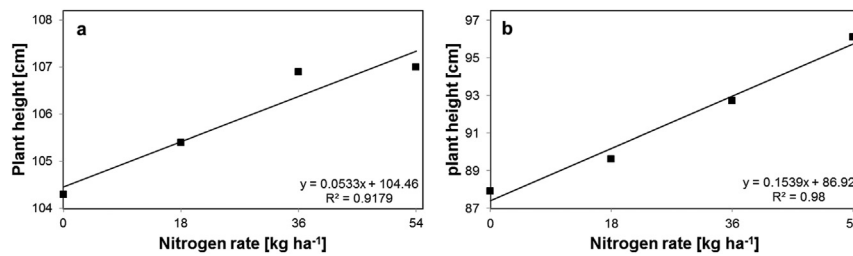


Figure 4. Plant height of malting barley grown under four rates of N fertilizer (0, 18, 36 and 54 kg ha<sup>-1</sup>) in Kofele (a) and Chole (b) districts in the southeastern highlands of Ethiopia.

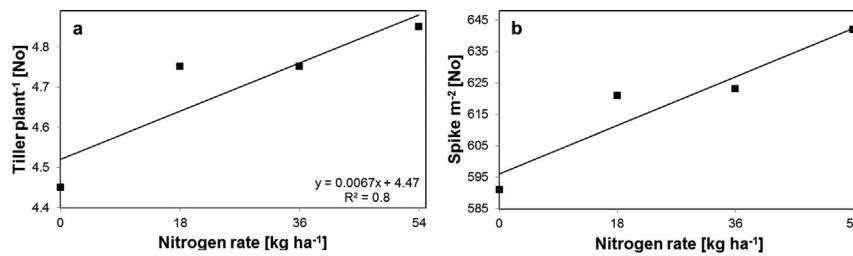


Figure 5. Numbers of tillers (a) and spikes (b) of malting barley grown under four rates of N fertilizer (0, 18, 36 and 54 kg ha<sup>-1</sup>) for the Chole and Kofele districts, respectively in the southeastern highlands of Ethiopia.

Table 5. Economic analysis for effect of nitrogen fertilizer levels on yield and grain quality of malting barley in Kofele in the southeastern highlands of Ethiopia.

Treatments for N rate [kg ha <sup>-1</sup> ]	Adjusted grain yield [kg ha <sup>-1</sup> ]	Adjusted straw yield [kg ha <sup>-1</sup> ]	Gross field benefits [US\$ ha <sup>-1</sup> ]	Total cost that vary [US\$ ha <sup>-1</sup> ]	Net benefit [US\$ ha <sup>-1</sup> ]	Marginal rate of return
0	3,092.13	4,113.09	1,883.04	0.00	1,883.04	
18	3,140.10	4,329.18	1,922.75	16.73	1,906.02	1.37
36	3,228.75	4,304.97	1,966.94	33.46	1,933.47	1.64
54	3,330.63	4,389.66	2,025.47	50.19	1,975.28	2.50

Table 6. Economic analysis for effect of nitrogen fertilizer levels on yield and grain quality of malting barley in Chole in the southeastern highlands of Ethiopia.

Treatments for N rate [kg ha <sup>-1</sup> ]	Adjusted grain yield [kg ha <sup>-1</sup> ]	Adjusted straw yield [kg ha <sup>-1</sup> ]	Gross field benefits [US\$ ha <sup>-1</sup> ]	Total cost that vary [US\$ ha <sup>-1</sup> ]	Net benefit [US\$ ha <sup>-1</sup> ]	Marginal rate of return
0	2,332.49	3,222.23	1,428.68	0.00	1,428.68	
18	2,530.93	3,680.15	1,562.90	16.73	1,546.17	7.02
36	2,731.64	4,118.71	1,696.97	33.46	1,663.50	7.01
54	2,999.55	4,572.42	1,866.83	50.19	1,816.63	9.15

with the agronomic results. Kassie and Tesfaye (2019) also reported a higher MRR of US\$9.76 for every US\$1.0 investment for the application of 48 kg N ha<sup>-1</sup> for malting barley (cv *Holker*) production in Lemu-Bilbilo district in the southeastern highland of Ethiopia.

A sensitivity analysis was also conducted with the assumption of the likely rise in price of input costs that can vary over time. Results revealed that the MRR values were still in excess of 100% entailing the same recommendation of 54 kg N ha<sup>-1</sup> may still hold true in the future should N fertilizer price increase. If the market price of the variable cost increase by 30% within the coming 3 years, farmers who make the decision to seed malting barley with an N rate of 54 kg N ha<sup>-1</sup> potentially could earn an additional US\$1.69 and US\$6.81 based on sites for the Kofele and Chole districts, respectively for every US\$1.0 investment.

#### 4. Conclusion

The present study demonstrated that malting barley sown preceding legume and non-legume versus barley on barley, particularly fababean,

Ethiopian mustard and potato, and increased rate of nitrogen fertilizer irrespective of preceding crops, improved malting barley yield without exceeding the acceptable malting barley range for kernel protein concentrations. As a result of higher yields, optimum kernel protein concentrations, plump kernel proportions and increased economic benefits, cropping sequences of fababean-malting barley, Ethiopian mustard-malting barley and potato-malting barley along with fertilizer rates of 54 kg N ha<sup>-1</sup> regardless of preceding crops can be used as alternate management options to sustain yield and quality for malting purpose for the trial sites located in the Kofele and Chole districts of the southeastern highlands of Ethiopia. This recommendation can be extended to other regions of similar agro-ecologies in the country and other parts of the world. The preceding crops and N fertilizer rates have the potential to increase grain production with acceptable protein concentrations, while promoting enhanced economic returns for smallholder farmers and sustain the supply of raw material for malting factories.

Although the rate of increase in kernel protein content was slower and did not exceed the acceptable level, this study confirmed that the kernel

protein concentrations of malting barley increased with non-barley preceding crops and increased rates of nitrogen applications. Hence, application of nitrogen fertilizer needs to be based on soil test results, particularly following fababean and potato, and in areas where the soil fertility is modest in order not to exceed the threshold level desired by malters. In the current study, the cut-off point for the maximum nitrogen fertilizer rates was not reached, while the response to nitrogen fertilizer after fababean was linear in this study. Therefore, further investigation is recommended to determine the response curve for nitrogen fertilizer after each preceding crop over long periods at representative locations across the major malting barley producing areas in Ethiopia.

## Declarations

### Author contribution statement

Kassu Tadesse: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Wrote the paper.

Dawit Habte: Conceived and designed the experiments; Performed the experiments; Wrote the paper.

Wubengeda Admasu; Almaz Admasu; Birhan Abdulkadir: Conceived and designed the experiments; Performed the experiments.

Amare Tadesse; Asrat Mekonnen; Anbessie Debebe: Performed the experiments.

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### Data availability statement

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

### Declaration of interests statement

The authors declare no conflict of interest.

### Additional information

No additional information is available for this paper.

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