SOIL & CROP SCIENCES | RESEARCH ARTICLE

Plant density of lupine (Lupinus albus L.) intercropping with tef [Eragrostis tef (zucc.) trotter] in additive design in the highlands of Northwest Ethiopia

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Abstract: Intercropping of cereals and legumes is common in Ethiopia. However, intercropping of lupine with tef is a new practice in Northwestern Ethiopia's tef-based cropping system. In the 2016 and 2017 main cropping seasons, a field experiment was conducted in Gozamin District, East Gojjam Zone, to assess the effect of plant density of lupine intercropping with tef on the productivity of tef fields. The two experimental factors were two inter-row spacings (20 and 40 cm) and three intra-row spacings (10, 15, and 20 cm) of lupine intercropped with tef, and their factorial combination was studied using a randomized complete block design (RCBD) with three replications. The highest tef grain yield (1.80 t ha⁻¹) was recorded from 40 and 20 cm inter- and intra-row spacing of lupine intercropped with tef, respectively. The highest lupine yield (2.74 t ha⁻¹) was recorded from sole cropping. A total of 40 and 15 cm inter- and intra-row spacing of lupine intercropped with tef improved tef equivalent yield (2.32 t ha⁻¹), area time equivalent ratio (1.09), actual yield loss (0.87), monetary advantage index (396.2 USD), net benefit (2479.5 USD ha⁻¹), and marginal rate of return (MRR) (682%). Among all planting densities, 40 and 15 cm inter- and intra-row spacing of lupine were the most profitable and had the highest yield advantage based on equivalent yield and other economic benefits. To maximize the productivity of tef fields, 40 cm of inter- and 15 cm of intra-row spacing of lupine intercropping with tef was recommended.

Subjects: Soil Conservation Technology; Agronomy; Zoology

Keywords: Intercropping; lupine; spacing; tef; yield

1. Introduction
The global human population is expected to reach 9.8 billion people in 2050 (United Nations (UN), 2017). Ethiopia's highlands are Africa's most densely populated regions, with low crop productivity due to limited land size (Derek et al., 2014). To feed this rapidly growing population, agriculture must rely on scientific methods and inputs (Dietrich et al., 2014). Crop productivity should be enhanced further without deteriorating soil fertility, the environment, or food quality (Bedoussac et al., 2015; Lal et al., 2003). Intercropping is an alternate technique for increasing agricultural output by maximizing the use of available land (Lithourgidis et al., 2011). Intercropping is essential, particularly in areas with limited land resources (Tsubo et al., 2005).
Intercropping has a number of advantages, including greater land use efficiency, resource efficiency, weed, pest, and disease control, and lengthening production cycles (Jjuyah, 2012). Farmers use intercropping of different legumes with other crops as one of their strategies to address the scarcity of arable land, and they attribute several crops to crop diversification, high productivity per unit area, and soil fertility maintenance and improvement (Seran & Brinthan, 2010). According to Chu et al. (2004), intercropping improves crop production stability and profitability. Intercropping cereals with legumes increases soil fertility through nitrogen fixation (Adu-Gyamfi et al., 2007).

Tef is a major staple crop in Ethiopia. Ethiopia is the largest tef producing country in the world and the only country to have adopted tef as a staple crop. The country produces more than 90% of the tef in the world (Anadolu, 2017). Tef is mostly used to prepare “injera” (Tamirat & Tilahun, 2020), which is consumed by about 70% of the Ethiopian people (Tamirat & Tilahun, 2020). More than 6.5 million smallholder farmers grow tef, and it is indispensable to the livelihoods of many Ethiopians (FAO, 2018). Tef fills in as a staple food for more than 50 million people in the Horn of Africa (Tadele & Assefa, 2012).

Moreover, tef is the most important crop in terms of production and cultivation area, with excellent storage properties, high-quality food, and the unique ability to thrive in extreme environmental conditions (Minten et al., 2013). Tef is a major cereal crop and is extensively cultivated in most of the agro-ecological zones of Ethiopia (Miretu & Abebaw, 2020). In Ethiopia, a total of 3 million hectares of land was covered in Tef (CSA (Central Statistics Agency), 2017). From this, 5.5 million tons of yield were produced. At the country level, tef contributes 24.32% of the total cultivated cereal crops and 17.22% of the total production (CSA (Central Statistics Agency), 2017). Tef contributes 25.4% of total area coverage and 32% of total production in the Amhara region (CSA (Central Statistics Agency), 2017). Tef is more readily eaten by urban households (61 kg/person/year) than by rural households (20 kg/person/year; FAO, 2018). Fikadu et al. (2019) reported that tef has a significant role in Ethiopian agriculture, food, and trade sectors. Therefore, Ethiopia has a great chance to assure food security by increasing tef production.

Tef was the first cash crop in the study area, but its productivity (1.6 t ha\(^{-1}\)) is low (East Gojjam zone agriculture office, 2017), especially when compared to the national average tef yield (1.80 t ha\(^{-1}\); CSA (Central Statistics Agency), 2017) and the highest yields of 3.08 t ha\(^{-1}\) and 2.70 t ha\(^{-1}\) reported by Asaye et al. (2020) and Tamirat and Tilahun (2020). Low soil fertility and acidity (Negassa et al., 2017) and severe organic matter loss (International Food and Policy Research Institute (IRPRI), 2010) are the main causes of low crop yield. These problems are real challenges in the study area.

Lupine has traditionally been grown as an intercrop with cereals and oil crops by low-input farmers; it is only restricted to low-income people during droughts (Jansen, 2006). Lupine is one of Ethiopia’s most important highland food legumes (Yayeh et al., 2014). Low-input farmers have traditionally grown lupine as an intercrop with cereals (Jansen, 2006). They grow it as part of a traditional additive intercropping system, with lupine as a minor crop and cereals as the main crop (Yayeh et al., 2014). Farmers in East Gojjam are seriously affected by small farm sizes due to the rising human population (East Gojjam zone agriculture office, 2017).

Intercropping lupine with tef was chosen first among other legumes for the study area because of its adaptability, stability, and practicality of production under poor soil fertility and biotic environments. Furthermore, unlike cereals, lupine’s tapered root structure allows it to reach deeper soil layers for water and nutrients (Jansen, 2006). Thus, growing lupine as an intercrop in tef fields without affecting tef productivity would be a huge benefit to tef farmers in particular and the country as a whole, as it would increase tef field productivity per unit area while also providing a great opportunity to expand and increase lupine production. Farmers in Ethiopia have been intercropping lupine with finger millet in poor soil (Lekawunt et al., 2012).
Furthermore, tef intercropping with faba bean has been done in the central Ethiopian highlands, and tef intercropping with faba bean is economically and environmentally beneficial in the Ethiopian highlands, which are characterized by high population density and small farm sizes (Getachew et al., 2006). However, in the study area, tef lupine intercropping and its effect on tef field productivity have yet to be explored. Rather, many studies in Ethiopia are primarily focused on intercropping of major cereal crops with beans (Vidigal et al., 2019). As a result, before proposing and popularizing tef-lupine intercropping, it is important to determine the appropriate lupine plant density in tef fields.

As the study area’s population grows, the current production system cannot meet consumer demand because farmers use traditional and sole cropping systems that are not supported by different cropping systems due to a lack of understanding of the effectiveness of intercropping
systems. Therefore, tef lupine intercropping is an ideal research agenda. The proposed study aimed to determine the effect of plant density of lupine intercropping with tef on tef fields productivity.

2. Materials and methods

2.1. Description of the study area

A study was conducted in the 2017/18 main cropping season at Enerata, Gozamin district, East Gojjam Zone, north-west Ethiopia highlands to assess the effect of plant density and intercropping with lupine in tef fields. The experimental site is located at an elevation of 2,481 meters above sea level, latitude 10°23′N and longitude 37°44′E. The study year map is presented in Figure 1. The weather data source was Debre Markos Meteorological Station, and based on 15 years of (2003–2017) meteorological data, the average annual rainfall of the study area was 1,335 mm (Figure 2). The mean minimum and maximum temperatures were 10.7 and 23.2°C, respectively (Figure 2). The rainfall distribution in the study years is unimodal, with the main rainfall extending from mid-June to October and a peak in mid-July to end-August (Figure 2).

Soil samples were taken at five places diagonally at 0–20 cm soil depth and composited to identify the general soil characteristics of the study site before the start of the experiment. The composite soil samples were submitted to Debre Markos soil laboratory. The soil samples were air-dried, crushed, and sieved using a 2 mm sieve to determine soil texture, total nitrogen, pH, available phosphorus, organic carbon, and cation exchange capacity. The pH of the soil was determined using a pH meter in a 1:2.5 soil–H₂O ratio (Hazelton & Murphy, 2007). The soil texture was determined using the Bouyoucos hydrometer method (Bouyoucos, 1951). To extract soil organic carbon (OC), the Walkley–Black wet digestion method was used (Walkley & Black, 1934). The Kjeldahl’s digestion method was used to calculate total N (Havlin et al., 1999). To extract accessible soil P, the Olsen NaHCO₃ extraction method was used (Tadese et al., 1991). The cation exchange capacity (CEC) was determined using the 1 N ammonium acetate extraction method described by Black (Landon, 1991).

The results of the soil laboratory analysis are presented in Table 1. The experimental soil was classified as a nitosol, the textural class was clay, and it had a pH of 5.1, making it strongly acidic (Hazelton & Murphy, 2007). Havlin et al. (1999) considered low N content to be 0.09%. According to Walkley and Black (1934), the OC concentration in the soil was 1.27 percent, which is low. The available P level of the experimental soil was 6.85 ppm, which is quite low (Landon, 1991).

| Soil property          | Soil analysis | Rating reference(s)          |
|------------------------|---------------|------------------------------|
| Particle distribution   |               |                              |
| Sand (%)               | 32            |                              |
| Silt (%)               | 25            |                              |
| Clay (%)               | 43            |                              |
| Soil texture class     | Clay          |                              |
| pH (H₂O)               | 5.1           | Strong acidic                |
| Total N (%)            | 0.09          | Low                          |
| Organic C (%)          | 1.27          | Low                          |
| Avail. P (ppm)         | 6.85          | Very low                     |
| CEC                    | 20.20         | Moderate                     |
2.2. Experimental treatments, design, and procedures

The two experiment factors were two inter-row spacing (20 and 40 cm) and three intra-row spacing (10, 15, and 20 cm) of lupine, and their factorial combination was studied using randomized complete block design (RCBD) with three replications. Seeds of tef were drilled in rows at its recommended, inter-row spacing of 20 cm, while seeds of lupine were planted in rows between every after one (1:1 row ratio), two (2:1 row ratio) rows of tef, 100% of the recommended seed rate of the main tef crop, (additive design). Tef and lupine were sown in sole crop. The experimental field was ploughed four times using an oxen-powered local plowing facility before being manually separated into blocks (replications) and plots based on the treatments and design. With a gross plot size of 4 m × 3 m (12 m²), the net plot area was 2.4 m × 2 m (4.8 m²). A 1.0 m and 0.5 m walkway separated adjacent plots and blocks, respectively. In early July, tef seeds were drilled in rows 20 cm apart at the recommended rate of 10 kg ha⁻¹ in both cropping seasons. In the sole cropping system, lupine was planted at a 40 cm inter-row spacing and 10 cm intra-row spacing. Lupine in intercropping was planted on the same day as the test sowing.

Both tef cropping systems received 100 kg/ha N and 50 kg/ha P, but the lupine cropping system received only 60 kg/ha N and 26 kg/ha P (East Gojjam zone agriculture office, 2017). All additional agronomic management measures were applied equally to all experimental plots in accordance with the research area’s tef recommendations.

2.3. Crop data collection

Using their standard methods and procedures, data for sole and intercropped tef growth and yield-related parameters were collected on time as follows:

2.3.1. Tef growth parameters and yield components

Panicle length was measured as the length of the panicle in a centimeter of the main shoot from the node where the first panicle branch starts to the tip of the panicle by randomly selecting 10 plants at physiological maturity.

The number of effective tillers was counted from an area of 10 randomly chosen tef plants from each net plot.

Thousand seed weight was determined by taking 1,000 seeds from each net plot using a sensitive balance.

Above-ground biomass was determined by taking the total weight of the harvest, including the grains from each net plot area. After harvesting and appropriate drying with sunlight, the biomass yield in each net plot area was weighed using a sensitive electrical balance.

Grain yield was calculated as the weight of the air-dried tef seeds harvested from the net plot area of each plot. For analysis, one gram per plot was converted to a kilogram per hectare. The moisture percentage of the grain yield and thousand grain weight were adjusted to 12.5%.

Straw yield was measured by subtracting the grain yield of tef from the above-ground dry biomass yield of the crop.

2.3.2. Growth parameters and yield components of lupine

Number of branches per plant was determined from ten randomly selected plants from the net plot area.

Number of pods per plant was determined from ten randomly sampled plants from the net plot.

Grain yield was calculated by threshing the dried plants from the net plot area, and adjusting to a moisture content of 10% seed.
2.4. Statistical data analysis

All crop data was submitted for analysis of variance (ANOVA) using SAS software version 9.4’s General Linear Procedure (SAS (Statistical Analysis System) Institute, 2014). Since the homogeneity test of the two years for all parameters was not significant, the combined analysis of variance was also done for each parameter over the two years. The mean separation (mean differences comparison) was undertaken by the Least Significant Differences at a 5% level of probability.

2.5. Analysis of indices for intercrop efficiency

3. Aggressivity

Aggressivity (A) indicates the relative yield increase in crop “a” compared to crop “b” in an intercropping situation (McGilchrist, 1964). The aggressivity (A) of the tef + lupine intercropping system can be derived from the following formula:

\[
AT = \left( \frac{YTL}{YT \times ZTL} \right) - \left( \frac{YLT}{YL \times ZLT} \right) \\
AL = \left( \frac{YLT}{YL \times ZLT} \right) - \left( \frac{YTL}{YT \times ZTL} \right)
\]  
(1)

YTL and YLT represent grain yields of tef and lupine in intercropping, respectively, where as ZTL refers to the planted share of tef in intercropping and ZLT means the sown share of lupine in intercropping, YTL and YLT denote grain yields of tef and lupine in intercropping, and YT and YL denote grain yields of tef and lupine in sole cropping.

4. Competitive ratio

In an intercropping system, the competitive ratio (CR) evaluates the competitiveness of both crops (Willey, 1980). The competitive ratio shows the proportion of both crops planted in intercropping as well as the ratio of individual LER for both crops

\[
CRT = \left( \frac{LER_{T}}{LER_{L}} \right) X \left( \frac{ZTL}{ZLT} \right) \\
CRL = \left( \frac{LER_{L}}{LER_{T}} \right) X \left( \frac{ZLT}{ZTL} \right)
\]  
(2)

Where LERT and LERL shows the tef and lupine land equivalent ratios, respectively.

5. Actual yield loss

Actual yield loss (AYL) is the proportionate yield loss or gain of component crops in an intercropping system in comparison to the respective pure stand. This index is based on the actual sown proportion of the component crops with which it is solely planted. It is calculated by the following formula (Banik et al., 2006):

\[
AYL = AYLT + AYLL \\
AYLT = \left\{ \frac{(YT \times ZTL)}{(ZTL)} \right\} - \left\{ \frac{(YT)}{(ZTL)} \right\} \\
AYLL = \left\{ \frac{(YT)}{(ZTL)} \right\} - \left\{ \frac{(YL)}{(ZLT)} \right\}
\]  
(3)

Where AYLT stands for tef partial actual yield loss, AYLL stands for lupine partial actual yield loss, ZTT stands for tef sole cropping sown proportion, and ZLL stands for lupine sole cropping sown proportion.

6. Monetary advantage index

As a result, none of the preceding competition indices provided any data on the financial advantage of the intercropping system, and the monetary advantage index (MAI) became advanced (Aasim et al., 2008).

\[
MAI = \left( \frac{LER - 1}{LER} \right) X (\text{Value of combined intercrops})
\]  
(5)
7. Land Equivalent Ratio
The Land Equivalent Ratio is the amount of land required to provide the same yield as an intercropping system when mono cropping is utilized (Willey, 1980).

\[ LER = \frac{Y_{TL}}{Y_{TT}} + \frac{Y_{TL}}{Y_{TT}} \]

8. Area time equivalent ratio
Since the grain yield advantage of intercropping over sole cropping was found, the area time equivalent ratio (ATER) is the practical comparison index. It takes into consideration the time spent by both crops in intercropping systems. ATER was calculated as follows (Hauggaard-Nielsen et al., 2001):

\[ ATER = \frac{PLERTXTL + PLERLXTL}{T} \]

Where PLERT and PLERL are partial land equivalent ratios for tef and lupine, respectively, TT is the tef growth period in days; TL is the lupine growth period in days; and T is the total duration of the intercropping system.

9. Tef equivalent yield
It is the conversion of crop yields into one form that allows us to compare the crops grown under mixed cropping, intercropping, or sequential cropping (De Wit, 1960).

The total of intercrop tef yield and converted lupine yield was used to compute tef equivalent yield (TEY), which was then compared to the sole crop tef yield. The conversion is done in the form of a tef equivalent yield by considering the lupine yield and market price of tef and lupine (Singh et al., 2009).

\[ TEY = Y_T + L \left( \frac{P_L}{P_T} \right) \]

Where PT is price of tef t/ha and PL is price of lupine t/ha.

9.1. Partial budget analysis
In order to decide which treatment to recommend for the study area, it is necessary to know the treatments with the highest net benefit and an acceptable level of marginal rate of return. A partial budget analysis will be performed following the CIMMYT partial budget methodology (CIMMYT (International Maize and Wheat improvement center), 1988). It examines the gross benefit (GB), the total variable cost (TVC), the net benefit (NB), and the marginal rate of return (MRR). The value of grain and straw yields will be adjusted by 10% in order to narrow the yield gap between experimental plots and farmers' fields. The prices (USD/kg) of tef grain yield, lupine grain yield, and tef straw yield were 0.95, 0.55, and 0.15, respectively. The cost of labor varies across each treatment and will be considered a variable cost when considering other costs as constant for each treatment. The labor cost per man day was 3.30 USD.

10. Results and discussion
10.1. Growth and grain yield of tef
Cropping systems had a significant (P < 0.05) effect on panicle length, effective tiller per lupine plant, straw yield, and grain yield of tef in both years and combined over years (Tables 2 and 3). The longest panicle length of tef (51 cm) was obtained from 40 and 20 cm inter-and intra-row spacing of lupine intercropped with tef, respectively, while the shortest (24.8 cm) panicle length of tef was obtained from 20 to 10 cm inter-and intra-row spacing of lupine intercropped with tef (Table 2). The longest panicle length of tef in 40 and 20 cm of inter- and intra-row spacing of lupine might be an absence of interspecific competition for above and below ground resources. The results of this experiment are in agreement with those of Khan et al. (2005), who reported that wheat intercropping with legumes had an effect on wheat spike length. Yayeh et al. (2019) also showed the
Table 2. Effect of plant density of white lupine intercropping with tef on growth and yield of tef in 2016 and 2017 main cropping season in northwest Ethiopian highlands

| Two way interaction | No. of effective tillers of tef | Panicle length of tef (cm) | Grain yield of tef (t/ha) | Straw yield of tef (t/ha) |
|---------------------|---------------------------------|---------------------------|--------------------------|--------------------------|
|                     | T 1 IR1 (cm) IR2 (cm) | 2016 | 2017 | COY | 2016 | 2017 | COY | 2016 | 2017 | COY | 2016 | 2017 | COY |
| T 1                 | 20 10                          | 2.2 | 2.3 | 2.2 | 25.5 | 24.0 | 24.8 | 0.64 | 0.63 | 0.64 | 2.33 | 2.57 | 2.42 |
| T 2                 | 15                             | 3.6 | 3.4 | 3.5 | 40.3 | 41.6 | 40.8 | 0.97 | 0.92 | 0.94 | 2.75 | 2.91 | 2.80 |
| T 3                 | 20                             | 4.0 | 4.2 | 4.1 | 42.3 | 43.3 | 42.8 | 1.01 | 1.00 | 1.01 | 3.33 | 3.20 | 3.26 |
| T 4                 | 40 10                          | 3.3 | 2.6 | 2.9 | 44.0 | 43.6 | 43.8 | 1.08 | 1.11 | 1.10 | 3.54 | 3.73 | 3.63 |
| T 5                 | 15                             | 5.5 | 5.0 | 5.3 | 47.5 | 43.3 | 45.4 | 1.73 | 1.69 | 1.71 | 4.42 | 4.48 | 4.38 |
| T 6                 | 20                             | 7.5 | 6.9 | 7.2 | 50.8 | 53.2 | 52.0 | 1.78 | 1.81 | 1.80 | 4.90 | 5.06 | 4.98 |
| Sole                |                                | 7.3 | 6.7 | 7.0 | 50.0 | 50.4 | 50.2 | 1.77 | 1.73 | 1.75 | 4.77 | 4.83 | 4.80 |
| P-value             |                                | *   | *   | *   | *    | *    | *    | *    | *    | *    | *    | *    | *    |
| SE±                 |                                | 0.61 | 0.50 | 0.06 | 2.6 | 4.7 | 3.1 | 0.06 | 0.07 | 0.05 | 0.22 | 0.30 | 0.23 |
| CV%                 |                                | 12.3 | 17.2 | 6.8 | 7.6 | 13.2 | 8.1 | 6.8 | 7.7 | 5.8 | 7.5 | 10.1 | 7.8 |

Means within a column followed by the same letter(s) are not significantly different: * = significant at P < 0.05; T = Treatment; TND = total niche differentiation; IR1 = inter-row spacing of lupine; IR2 = intra-row spacing of lupine; SE ± = standard error; CV = coefficient of variation; COY = combined over years.

Panicle length of finger millet was significantly affected by finger millet lupine intercropping. The longest panicle was recorded in finger millet haricot bean row intercropping at a 100:50 planting ratio, while the lowest finger length was recorded at a planting ratio of 100.75, which is in line with our study.

The highest effective tef tillers per plant (7.2) were obtained from 40 and 20 cm inter-and intra-row spacing of lupine intercropped with tef (statistically similar to 7.0 effective tef tillers per plant obtained from the sole tef crop), while the lowest effective tef tillers per plant (2.2) were obtained from 20 to 10 cm inter-and intra-row spacing of lupine (Table 2). In tef fields, wider-spaced lupine plants were less competitive with tef and increased tef growth, resulting in more tef-effective tillers per plant. Narrow spacing, on the other hand, would strongly compete with tef, preventing

Table 3. Effect of plant density of white lupine intercropping with tef on growth and yield of lupine in 2016 and 2017 main cropping season in northwest Ethiopian highlands

| Two way interaction | No. of branches per lupine | No. of pods per lupine plant | Grain yield of lupine (t/ha) |
|---------------------|---------------------------|----------------------------|---------------------------|
|                     | T 1 IR1 (cm) IR2 (cm) | 2016 | 2017 | COY | 2016 | 2017 | COY | 2016 | 2017 | COY |
| T 1                 | 20 10                          | 2.6 | 1.4 | 2.0 | 31.3 | 30.6 | 31.0 | 1.37 | 1.42 | 1.40 |
| T 2                 | 15                             | 4.6 | 4.0 | 4.3 | 32.0 | 34.0 | 33.0 | 1.50 | 1.55 | 1.53 |
| T 3                 | 20                             | 4.6 | 4.3 | 4.5 | 32.8 | 33.8 | 33.3 | 1.40 | 1.50 | 1.45 |
| T 4                 | 40 10                          | 4.7 | 5.0 | 4.8 | 33.0 | 32.6 | 32.8 | 1.60 | 1.66 | 1.63 |
| T 5                 | 15                             | 5.0 | 5.3 | 5.2 | 40.7 | 42.3 | 41.5 | 1.43 | 1.37 | 1.40 |
| T 6                 | 20                             | 7.5 | 7.3 | 7.4 | 45.6 | 47.0 | 46.3 | 1.11 | 1.01 | 1.06 |
| Sole                |                                | 7.6 | 7.8 | 7.7 | 46.3 | 47.7 | 47.0 | 2.78 | 2.68 | 2.74 |
| P-value             |                                | *   | *   | *   | *    | *    | *    | *    | *    | *    |
| SE±                 |                                | 0.30 | 0.32 | 0.26 | 0.43 | 2.3 | 2.1 | 1.3 | 0.08 | 0.07 |
| CV%                 |                                | 8.3 | 7.8 | 4.8 | 11.7 | 13.3 | 10.6 | 9.5 | 6.8 | 6.5 |

Means within a column followed by the same letter(s) are not significantly different: * = significant at P < 0.05; T = Treatment; IR1 = inter-row spacing of lupine; IR2 = intra-row spacing of lupine; COY = combined over years; SE ± = standard error; CV = coefficient of variation.
tef growth from bearing successful tillers per plant. In accordance with the current analysis, Girma et al. (2019) found that the highest tiller amount of barley (7.67) was found in a 2:1 barley to faba bean intercropping row ratio. In agreement with this result, Yayeh et al. (2014) showed that in a cereal-lupine additive design intercropping experiment, finger millet effective tiller per plant decreased with increasing lupine seed proportion. Furthermore, intercropping encourages legume and cereal plants to use root-induced processes to acquire phosphate and nitrogen. Legumes may provide the potential to sustain enhanced plant numbers and higher tiller numbers for intercropped species due to their adaptability to different cropping patterns and ability to fix nitrogen (Latati et al., 2016).

The highest over-years mean tef grain yield (1.80 t/ha) was obtained from 40 and 20 cm inter- and intra-row spacing of lupine intercropped with tef, respectively, but was statistically similar to the tef grain yield (1.71 t/ha and 1.75 t/ha from 40 to 15 cm inter- and intra-row spacing of lupine and sole tef, respectively; Table 2). The reason for the increase in growth and yield parameters was mainly due to the efficient use of available resources as well as the lupine’s minimal shading effect, which improved photosynthesis efficiency. According to this study, the grain yield of tef increased as the seeding ratio of lupine in the intercrop decreased and vice versa. Similarly, Getachew et al. (2008) and Yayeh et al. (2020) found that as the faba bean and lupine seeding rate in the intercrop decreased, wheat and finger millet yields increased. Similarly, Megawer et al. (2010) showed that the barley lupine of 2:1 row ratio intercropping produced the maximum grain yield of barley, while the barley lupine of 1:1 row ratio produced the lowest yield. Intercropping resulted in increases in crop productivity due to the complementary use of growth resources (Zhang & Li, 2003).

On the other hand, tef equivalent yield (TEY) is the best tool for determining an intercropping system’s overall productivity capacity. Our research found that the highest TEY (2.32 t/ha) was obtained from 40 and 15 cm inter- and intra-row lupine spacing, respectively, which had a 33% yield advantage over the sole TEF (Table 6). Recent studies have shown that, in line with current studies, the equivalent yield of cereals in intercropping crops was significantly higher than that in sole crops (Latati et al., 2016). This may be because intercropping enhances the ability of legumes and grains to promote phosphorus and nitrogen uptake through root-induced processes. In addition, legumes have the ability to adapt to different cropping patterns and fix nitrogen, which may provide an opportunity to maintain an increase in plant biomass for intercropped crops (Latati et al., 2016). In line with this study, Jabbar et al. (2009) found that intercropping produces a higher grain equivalent yield than sole cropping of cereals. The higher tef equivalent yield from intercropping tef with lupine is due to improved soil fertility, either from biologically fixed nitrogen or root excretion from the associated legume crop (Ghosh, 2004). The maize yield response in maize-legume intercropping can be explained by the transfer of fixed nitrogen from legume to cereal crop (Alemayehu et al., 2016), as well as the improvement of phosphorus uptake as its mobilization is assisted by the rhizosphere via legume root release of organic acids.

Lupine intercropped with tef at 40 and 20 cm inter-and intra-row spacing provided the highest tef straw (4.78 t ha⁻¹) but was statistically similar to treatment 5 and sole tef cropping (Table 2). Getachew et al. (2006) discovered that increasing the proportion of faba bean in the mixture from 12.5 to 62.5 percent decreased tef straw production from 94% to 71%. Increasing the proportion of barley and faba bean in the spatial arrangements reduced the straw yield of barley (Hidoto et al., 2015). This might be attributed to the increasing number of plants per unit area, which aggravated competition for resources, leading to plants with smaller sizes. Similar results were reported by Chen et al. (2004) for intercropping of pea and barley and Hauggaard-Nielsen et al. (2001) for field bean and wheat.

10.2. Growth and yield of lupine
In both years and when combined over years, the intercropping system had a significant (P 0.05) influence on the number of branches, pods, and grain yield of lupine (Table 3). In the combined
years, the sole crop produced the highest number of branches per plant (Table 2). From the intercropping treatment, the highest number of branches (7.4) was recorded in low planting densities (40 and 20 cm inter and intra-row spacing) of lupine intercropped with tef than in other planting densities. The result revealed that as the planting density of lupine increases, the number of branches per plant decreases (Table 3). The reason might be that tef causes nearly complete dominance in the early stages of the minor crop. Similarly, Yayeh et al. (2014) reported that the lowest number of branches per lupine plant was recorded from a high seeding ratio in a lupine barley intercropping system. In agreement with our study, Megawer et al. (2010) discovered that as lupine planting density increases, the number of branches per plant decreases in barley-lupine intercropping.

The highest number of pods per plant (47) was recorded from sole lupine (Table 3). Furthermore, 40 and 20 cm inter-and intra-row spacing of lupine intercropped with tef produced the highest pods per plant (46.3; Table 3) due to the low planting density of lupine compared to the high planting density of lupine. Similar to these results, Tilahun (2002) reported that planting density of faba bean significantly affected the number of pods per plant of faba bean intercropped with maize. The highest pod/plant in sole lupine was recorded due to the absence of inter-specific and intra-specific competition between lupine crops, which favored efficient utilization of growth resources. Oskoii et al. (2015) reported that decreasing the number of faba bean pods per plant in intercropping can contribute to a rise in interspecific competition. Furthermore, increased competition for light and minerals, as well as increased shading in intercropping, leads to a decrease in photosynthesis, more abscission, and fewer pods per plant. This finding is further supported by Ghosh (2004), who reported that the pod yield of groundnut was lower in groundnut-cereal intercropping than in monoculture.

The sole lupine cropping system produced the highest lupine grain yield (2.74 t ha⁻¹), which might be attributable to the optimal population in sole cropping. From the intercropping system, the 40 and 10 cm inter and intra-row spacing of lupine produced the maximum grain production (1.63 t ha⁻¹) while the narrow spacing produced the lowest grain yield (1.06 t ha⁻¹; Table 3). This is probably due to the shading effect of tef, which prevented solar radiation from penetrating into the lupine, reducing photosynthetic rate and dry matter accumulation. Yield reduction could also be due to inter-specific competition for growth resources between the component species, which in turn reduces the number of branches/plants or pods/plant.

This finding is supported by a number of research results which report a decrease in the legume yield component because of cereal-legume intercropping. Egbe (2010) reported that cowpea grain yield was depressed in maize-cowpea intercropping systems. According to Onuh et al. (2011) and the sole mung bean provided the maximum seed production when compared to the intercropped mung bean. Oseni (2006) reported the lowest yield in cowpea intercropped with sorghum and found comparable findings. Berhane (2016) backs up this finding by demonstrating that cowpea plant density has a substantial impact on grain output in intercropped cowpea, with the lowest cowpea plant density resulting in the maximum grain yield. In contrast to this study, Ashenafi (2016) showed that maize intercropped haricot bean (100% seeding ratio) produced the highest haricot bean yield.

10.3. Competition indices

The aggressivity results revealed that lupine was the dominant species, with positive values in treatments 1, 2, 3, and 4, but negative A values in treatments 5 and 6, indicating that tef dominated lupine (Table 4). The lower A values of tef in narrow spacing were due to the shading effect of lupine (Table 4). In barley–faba bean (Strydhorst et al., 2008) and maize–groundnut (Inal et al., 2007) intercropping systems, the aggressive crops are barley and maize, while the suppressed crops are faba bean and groundnut. As the positive aggressivity of one crop in the
Table 4. Competitive ratio and aggressivity of tef and lupine in tef-lupine intercropping system in 2016 and 2017 main cropping season in northwest Ethiopian highlands

| Twoway interaction | 2016  | 2017  | COY  | 2016  | 2017  | COY  |
|-------------------|-------|-------|------|-------|-------|------|
|                   | CRT   | CRL   | CRT  | CRL   | CRT   | CRL  | AT   | AL   | AT   | AL   | AT   | AL   |
| T1                | 20    | 10    | 0.70<sup>bc</sup> | 1.44<sup>b</sup> | 0.72<sup>c</sup> | 1.40<sup>d</sup> | 0.72<sup>c</sup> | 1.41<sup>bc</sup> | −0.14<sup>b</sup> | 0.14<sup>b</sup> | −0.28<sup>c</sup> | 0.28<sup>c</sup> | −0.15<sup>b</sup> | 0.15<sup>b</sup> |
| T2                | 15    | 10    | 0.99<sup>b</sup> | 1.01<sup>cd</sup> | 0.94<sup>b</sup> | 1.06<sup>d</sup> | 0.97<sup>bc</sup> | 1.03<sup>b</sup> | −0.03<sup>bc</sup> | 0.03<sup>bc</sup> | 0.13<sup>b</sup> | −0.13<sup>bc</sup> | −0.01<sup>b</sup> | 0.01<sup>b</sup> |
| T3                | 20    | 10    | 1.08<sup>a</sup> | 0.92<sup>cd</sup> | 1.07<sup>b</sup> | 0.94<sup>c</sup> | 1.08<sup>c</sup> | 0.92<sup>a</sup> | 0.03<sup>bc</sup> | −0.03<sup>bc</sup> | −0.18<sup>c</sup> | +0.18<sup>c</sup> | +0.04<sup>c</sup> | −0.04<sup>bc</sup> |
| T4                | 40    | 10    | 0.49<sup>c</sup> | 1.90<sup>d</sup> | 0.51<sup>d</sup> | 1.94<sup>d</sup> | 0.53<sup>d</sup> | 1.92<sup>d</sup> | −0.87<sup>d</sup> | 0.87<sup>bc</sup> | −0.02<sup>c</sup> | 0.02<sup>b</sup> | −0.85<sup>c</sup> | 0.85<sup>a</sup> |
| T5                | 15    | 10    | 1.03<sup>bc</sup> | 0.98<sup>c</sup> | 1.02<sup>d</sup> | 0.99<sup>c</sup> | 1.02<sup>bc</sup> | 0.98<sup>c</sup> | 0.17<sup>b</sup> | −0.17<sup>c</sup> | 0.15<sup>b</sup> | −0.15<sup>b</sup> | 0.02<sup>b</sup> | −0.02<sup>c</sup> |
| T6                | 20    | 10    | 1.17<sup>a</sup> | 0.86<sup>a</sup> | 1.36<sup>a</sup> | 0.74<sup>d</sup> | 1.28<sup>a</sup> | 0.80<sup>a</sup> | 0.18<sup>a</sup> | −0.18<sup>a</sup> | 0.48<sup>a</sup> | −0.48<sup>a</sup> | 0.30<sup>a</sup> | −0.30<sup>a</sup> |

CR = competitive ratio of tef and lupine in intercropping; A = aggressivity of tef and lupine in intercropping; T = Treatment; IR1 = inter-row spacing of lupine; IR2 = intra-row spacing of lupine; COY = combined over years; SE ± = standard error.

Intercropping system affects the performance of the component crop (Ram & Meena, 2014), it is reflected in the negative aggressivity.

When the main crop was intercropped with 15 and 20 cm intra-row and 40 cm inter-row spacing of lupine, the main crop proved to be more efficient. Treatments with a higher population (Treatments 1, 2, 3, and 4) and tef with a lower lupine population (Treatments 5 and 6) had higher competitive ratios (Table 4). Lupine’s rapid growth, large number of lateral branches per plant, and tallest plant height were observed in higher lupine populations (Treatments 1, 2, 3, and 4), resulting in a higher CR of lupine than tef. Only intercrop competition (inter-specific competition) is measured by the competitive ratio (Trydeman et al., 2014). The results showed that intercropped lupine had higher competitive ratios in all proportions with tef except treatments 5 and 6, indicating that lupine was more competitive (CR > one) than tef (CR one; Table 4). However, in treatments 5 and 6, the values of CR for tef were greater than for lupine, indicating the dominance of tef. This corroborates with Trydeman et al. (2014), who stated that barley was dominant over lupine in intercrops. The CR of tef decreased as inter and intra-row spacing of lupine decreased (Table 4). However, a higher CR value for lupine was recorded at 10 and 40 cm intra and inter-row spacing of lupine (Table 4). This could probably occur through lowering its abundance, for example, through uptake of a growth-limiting nutrient resource (Zhang & Li, 2003) or the creation of shade (Berntsen et al., 2003). This result corroborates that of Hauggaard-Nielsen et al. (2005), who reported that the competitive ratio of barley relative to pea showed that barley was most competitive at recommended plant density.

Based on two years of averaged data, actual yield losses of tef, lupine, and total were negative at 20 cm inter-row spacing at all intra-row spacing of lupine. In contrast, at all intra-row spacing of lupine, actual yield loss of tef, lupine, and total was positive at 40 cm inter-row spacing (Table 5). Actual yield losses of 0.75%, 0.87%, and 0.64% were recorded from treatments 4, 5, and 6 (Table 5), which indicates the yield advantages of 75%, 87%, and 64%, respectively. This is probably due to better use of growth capital and low competition between the tef and lupine crops. When yield is compared per plant, the AYL provides more accurate information on inter- and intraspecific competition and can have either positive or negative values, indicating advantage or disadvantage in intercropping. Actual yield loss with a positive coefficient indicates the advantage of intercropping over sole cropping (Aasim et al., 2008).

Substantial agronomic advantages from intercropping do not always ensure an economic advantage, and there is a need for some economic evaluation and absolute yield comparisons of intercropping systems (Tamado & Eshetu, 2000). The Monetary Advantage Index is an indicator of
Table 5. Actual yield loss of tef and lupine in tef-lupine intercropping system in 2016 and 2017 main cropping season in northwest Ethiopian highlands

| Two way interaction | 2016   | 2017   | COY |
|---------------------|--------|--------|-----|
|                     | T      | IR1 (cm) | IR2 (cm) | AYLt | AYLI | AYLtt | AYLt | AYLI | AYLtt | AYLt | AYLI | AYLtt |
| T₁                  | 20     | 10      | −0.60⁺  | −0.40⁺  | −1.00  | −0.52⁺  | −0.47⁺  | −0.99  | −0.57⁺  | −0.40⁺  | −0.97⁺  |
| T₂                  | 15     | −0.46⁺  | −0.49⁺  | −0.92⁺  | −0.45⁺  | −0.42⁺  | −0.87⁺  | −0.45⁺  | −0.45⁺  | −0.89⁺  |
| T₃                  | 20     | −0.43⁺  | −0.44⁺  | −0.87    | −0.41⁻  | −0.45⁺  | −0.79⁻  | −0.42⁻  | −0.46⁻  | −0.89⁻  |
| T₄                  | 40     | 10      | −0.08⁻  | 0.80⁰   | 0.70⁻   | −0.01⁻  | 0.81⁰   | 0.80⁻   | −0.04⁻  | 0.80⁰   | 0.75⁻   |
| T₅                  | 15     | 0.40⁻   | 0.43⁰   | 0.82⁻   | 0.50⁻   | 0.42⁻   | 0.92⁻   | 0.45⁻   | 0.42⁻   | 0.87⁻   |
| T₆                  | 20     | 0.42⁻   | 0.21⁻   | 0.63⁻   | 0.53⁻   | 0.14⁻   | 0.67⁻   | 0.47⁻   | 0.17⁻   | 0.64⁻   |
| SE ±                | 0.05   | 0.08    | 0.09    | 0.05   | 0.08    | 0.10    | 0.04    | 0.05    | 0.10    |

AYLt = actual yield loss of tef; AYLI = actual yield loss of lupine; AYLtt = actual yield loss of total; T = treatment; IR1 = inter-row spacing of lupine = IR2, intra-row spacing of lupine; COY = combined over years; SE ± = standard error.

the economic feasibility of intercropping systems as compared to sole cropping (Aasim et al., 2008). The greatest MAI (396.2 USD) was from treatment 5, while the lowest MAI (~4713.0) was from treatment 1 (Table 6). Except for treatment 1, all intercropping treatments exhibited positive MAI values, which shows a definite yield advantage compared with the respective sole cropping systems tested in this study due to high competition for above and below-ground resources. The result was in line with Dhima et al. (2006) who reported that vetch barley intercropping in different sowing ratios gave negative MAI as compared to sole cropping.

According to Ashenafi (2016), a useful expression in assessing crop productivity in sole cropping systems is mass yield (mass per unit area). Direct comparison is difficult in intercropping systems, however, because the products are different for the different plant species growing on the same area of land (Beets, 1982). Crop productivity should be measured using a standard unit in this case. The land equivalent ratio is a widely used method (Beets, 1982). The combined over-year results in this study revealed that LER was greater than one in all intercropping treatments except treatment 1 (Table 6). Treatment 5 had the highest LER (1.42%). This indicates that 0.42 more area would be required by a sole cropping system to equal the yield of an intercropping system. The reason the amount of LER is more than one is perhaps because of the fixing and absorbing of nitrogen in intercropping sorghum and mungbean (Koocheki et al., 2009). Banik et al. (2006) showed LER greater than one in the maize-haricot bean intercrop. Inal et al. (2007) and Hauggaard-Nielsen et al. (2001) reported similar results in tef-faba bean and wheat-field bean intercropping. Similarly,

Table 6. Production efficiency of tef-lupine intercropping in 2016 and 2017 main cropping season (combined over years) in northwest Ethiopian highlands

| Two way interaction | IR1 (cm) | IR2 (cm) | Partial LER for tef | Partial LER for lupine | Total LER | TEY (t ha⁻¹) | ATER | MAI |
|---------------------|----------|----------|---------------------|-----------------------|-----------|---------------|------|-----|
| T₁                  | 20       | 10       | 0.36⁺               | 0.51⁺                 | 0.87⁺     | 1.34⁺         | 0.71⁺ | −189.0⁺ |
| T₂                  | 15       | 0.54⁺    | 0.55⁰               | 1.10⁻                 | 1.71⁻     | 0.89⁻         | 118.1⁻ |
| T₃                  | 20       | 0.57⁻    | 0.54⁻               | 1.11⁺                 | 1.74⁻     | 0.88⁻         | 128.8⁻ |
| T₄                  | 40       | 10       | 0.63⁻               | 0.60⁻                 | 1.22⁻     | 1.91⁻         | 1.01⁻ | 240.6⁻ |
| T₅                  | 15       | 0.95⁻    | 0.47⁺               | 1.42⁻                 | 2.32⁻     | 1.09⁻         | 396.2⁻ |
| T₆                  | 20       | 0.97⁻    | 0.38⁻               | 1.35⁻                 | 2.23⁻     | 1.03⁻         | 348.9⁻ |
| SE ±                | 0.04     | 0.03     | 0.05                | 0.04                  | 0.03      | 771            |

LER = land equivalent ratio; TEY = tef equivalent yield; ATER = area time equivalent ratio; MAI = monetary advantage index; T = treatment; IR1 = inter-row spacing of lupine; IR2 = intra-row spacing of lupine; SE ± = standard error.
compared with corresponding sole crops, yield advantages have been recorded in pearl millet-cluster bean (Yadav & Yadav, 2001). On the other hand, total LERs below 1 were found in narrow lupine planting (treatment 1), which gave a disadvantage of these mixtures over pure stands (Table 4). This result was in agreement with Ghosh (2004), who reported that common vetch–barley and common vetch-triticale mixtures

The land equivalent ratio does not take into account the duration of the crops in the field and is based on harvested products rather than the desired yield proportion of the component crops. Moreover, the choice of sole cropped yield for standardizing mixture yield in the estimation of LER is not clear (Willey, 1980). Therefore, area time equivalent ratio (ATER) provides a more realistic comparison of the yield advantage of intercropping over sole cropping in terms of the variation in time taken by the component crops of different intercropping systems (Aasim et al., 2008). The area time equivalent ratio values in treatments 4, 5, and 6 showed a 2–25% yield advantage (Table 6). The ATER results were lower than LER in intercropping treatments (Table 6). This could be due to the fact that intercropping systems can actually provide more efficient total resource exploitation and greater overall production than sole crops, optimum mixture ratios, and staggered planting arrangements, particularly planting dates. Khan and Khaliq (2004) reported similar findings. Similarly, yield gains have been shown in various non-legume–legume intercropping systems, including bean–wheat (Hauggaard-Nielsen et al., 2001), groundnut–cereal fodder (Ghosh, 2004), barley–pea (Chen et al., 2004), and faba bean–barley.

### 10.4. Partial budget analysis

The economic analysis system developed by CIMMYT in 1988 was used. Using the final yield and straw yield of tef as well as the grain yield of lupine data, the gross yields of six treatments were determined. The highest net return (2479.3 USD ha⁻¹) was achieved from 40 and 15 cm inter- and intra-row spacing of lupine intercropped with tef (Table 7). Treatment 5 (lupine intercropped with tef at 40 and 15 cm inter- and intra-row spacing) also had the highest marginal rate of return of 682% (Table 7), indicating that the producer would earn birr 6.82 for every birr invested in tef production.

### 10.5. Summary and conclusions

The increasing human population from time to time and the shortage of arable land lead to the lacking of alternative cropping systems in developing countries. Intercropping helps to diversify production and reduces risk for subsistence farmers. As a result, this experiment was conducted in Gozamin District in the 2017/2018 cropping season on tef/lupine intercropping to evaluate the effect of plant densities of the lupine intercropping with tef to maximize the productivity of the intercropping system. Thus, the interaction effects of inter and intra-row spacing of lupine had a significant effect on the vegetative growth and yield-related parameters of the component crops.

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**Table 7. Economic profitability of tef-lupine intercropping as influenced by plant density of white lupine intercropping with tef in 2016 and 2017 main cropping season (combined over years)**

| Treatment | IR1 (cm) | IR2 (cm) | Adj. tef GY (t/ha) | Adj. tef SY (t/ha) | Adj. lupine GY(t/ha) | GB (USD/ha) | VB (USD/ha) | NB (USD/ha) | MRR (%) |
|-----------|---------|----------|-------------------|-------------------|---------------------|-------------|-------------|-------------|----------|
| **Sole tef** |         |          | 1.58              | 3.12              | 0                   | 2066.7      | 36.1        | 2030.5      |          |
| **T₆** | 20      |          | 1.53              | 4.3               | 0.95                | 2513.7      | 116.5       | 2397.2      | 457      |
| **T₅** | 15      |          | 1.51              | 3.95              | 1.26                | 2607.8      | 128.5       | 2479.3      | 682      |
| **T₄** | 40      | 10       | 0.99              | 3.3               | 1.47                | 2145.8      | 152.6       | 1993.2      | D        |
| **T₃** | 20      |          | 0.91              | 2.93              | 1.31                | 1936.3      | 168.7       | 1767.7      | D        |
| **T₂** | 15      |          | 0.86              | 2.53              | 1.37                | 1865.3      | 200.8       | 1664.5      | D        |
| **T₁** | 20      | 10       | 0.58              | 2.18              | 1.26                | 1500.0      | 273.1       | 1226.9      | D        |

IR1 = Inter-row spacing of lupine; IR2 = Intra-row spacing of lupine; GY = Grain yield, SY = Straw yield price; GB = Gross field benefit; VB = Variable cost; NB = Net benefit; MRR = marginal rate of return; (USD kg⁻¹) of tef grain yield; straw yield and luine grain yield were 0.95, 0.55, and 0.15, respectively. Labour cost man day⁻¹ was 3.30 USD.
The longest panicle length, the maximum number of effective tillers per plant, and the grain yield of tef were obtained from treatment combinations of 40 cm and 20 cm inter- and intra-row spacing of lupine intercropped with tef. The maximum branch per plant, number of pods per plant, and grain yields of lupine crops were obtained from the sole lupine cropping system.

Furthermore, 40 and 15 cm inter and intra-row spacing of lupine intercropped with tef resulted in higher tef equivalent yield (2.32 t ha⁻¹), area time equivalent ratio (1.09), actual yield loss (0.87), monetary advantage index (396.2 USD), net benefit (2479.5 USD ha⁻¹) and MRR (682%).

The 40 and 15 cm inter-and intra-row spacing of lupine was the most profitable and had the highest yield advantage based on tef equivalent yield and other economic benefits. Our findings strongly suggest that tef fields can be profitably intercropped with lupine in an additive design using 40 and 15 cm of inter- and intra-row spacing of lupine. Therefore, 40 and 15 cm of inter- and intra-row spacing of lupine intercropping with tef is recommended for farmers in the study area and similar agro-ecological areas. To confirm the results, further research is needed across seasons and locations.

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