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RESEARCH ARTICLE

Productivity, land–use efficiency and competition in bread wheat–sweet lupine intercropping system under additive series in Northwest Ethiopia

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Abstract

Food production on continuously declining agricultural land to feed the ever-increasing population is a severe issue in Ethiopia. The present study was therefore initiated to evaluate inter and intra-row spacing on yield performance, land-use efficiency and competition in bread wheat-sweet lupine additive series intercropping system. Field experiments were conducted for 2 years in Adet and Debre Tabor experimental sites. The treatments consisted of three inter-rows spacing and 3 intra-rows spacing of sweet lupine. Moreover, the sole crop of wheat and lupine were also included as controls. The experiments were laid out in a factorial randomized complete block design with three replications. The results showed that the combination of 20 cm inter-row spacing with 10 cm intra-row spacing of sweet lupine in bread wheat-sweet lupine intercropping system gave the highest total yield of 4.36 t ha^{-1} and 4.75 t ha^{-1} at Adet and Debre Tabor respectively; the land equivalent ratio of 1.43 and 1.57 at Adet and Debre Tabor respectively. System productivity index of 4.96 and 5.88 at Adet and Debre Tabor respectively. Gross monetary value of 2511.26 and 2752.19 USD ha^{-1} at Adet and Debre Tabor experimental sites respectively. Gross monetary value was generally higher for intercrops than sole cropping systems in both locations; it is linked to intercropping yield and economic benefits compared to sole cropping. Farmers in the study area and areas with similar agroecology are recommended to intercrop sweet lupine with bread wheat at 20 cm inter-row spacing with 10 cm intra-row spacing of sweet lupine.

Keywords

Additive series, intercropping, competition, land equivalent ratio, productivity

Introduction

Ethiopia is the second-most populous country, with a population of more than 100 million, and one of the poorest in Sub-Saharan Africa (1). It is known that around 85% of its residents rely on a subsistence farming system (2). The World Bank Group (3) stated that over 12 million people in rural areas are chronically or occasionally food insecure.

Food production for a growing population is a major developmental problem in developing countries (4). According to FAO (5), around 85% of Ethiopia's smallholder farmers have less than 2 hectares of landholding. Increasing population growth, land resources degradation and depletion of soil fertility, withdrawal of legumes from the cropping system, frequent crop failures due to climate variability (6), and increased occurrence of pests are currently observed in developing countries, which make necessitate the adoption of more efficient and sustainable land-use systems necessary (7). It was proposed that the intensification of agriculture through growing cereals with legumes can improve soil fertility and increase production (4). For example, barley-pea intercropping (8).

Intercropping is a farming technique involving growing multiple crops in the same area for a set of times (9). It is one of the most efficient land use systems in tropical places where farmers have limited access to agricultural inputs (10). Intercropping increases crop productivity (11), boosts the land usage ratio (12), considerable reduction in greenhouse gas emissions (13), allows for a well-balanced diet, reduces labor peaks, reduces crop failure (14), helps to keep soil from eroding, improves yield stability and enhances profits (15) compared to the sole cropping system. It was stated that intercropping is vital for optimal space and physical resource utilization (16). Due to the depletion of Ethiopia's soil fertility (17) and the country's growing population pressure, the conventional cereal-based cropping system is not efficient (18). Instead, intercropping cereals and legumes can help boost production and improve soil fertility (19). As a result, to feed an alarmingly growing population, the wheat output must be intensified with legume intercropping. Lupine has traditionally been produced as an intercrop with cereals and oil crops by Ethiopian farmers with low inputs (20). It is cultivated in a classic additive intercropping system, with lupine as a minor crop and cereal as the main crop (21).

Intercropping's performance is mainly determined by the number of compatible crops and the row proportions. Along with the pure stands of each species, the additive intercropping series grows one major species (wheat) with its full density. In comparison, the other species (sweet lupine) is additionally intercropped with variable densities (keeping one species' density constant while varying the density of the other species) (22). In this series, the goal is to obtain a specified yield for the core species. The other species' yield is also a bonus. Even though lupine is cultivated as an intercrop in additive series with various crops, including wheat, there is no scientific research on the intercrops inter and intra-row spacing. Thus, this research aimed to evaluate inter and intra-row spacing on yield performance, land-use efficiency and competition in a bread wheat-sweet lupine intercropping system under an additive series in Northwest Ethiopia.

Materials and Methods

Descriptions of the study sites

During the rainy seasons of 2019 and 2020, this experiment was conducted in 2 key wheat-producing districts in northwest Ethiopia (Adet and Debre Tabor districts). The experimental site of Adet was located at a latitude and longitude of 11°16'N 37°29'E with an altitude of 2240 meters above the mean sea level (23). The experimental site of Debre Tabor was situated in the latitude and longitude of 11°51'N 38°1'E with an elevation of 2630 m above mean sea level. According to Bahir Dar Meteorology Station (2020), the Adet district received a total rainfall of 1592.1 and 1228.1 mm during the 2019 and 2020 cropping seasons respectively (Fig. 1) while the Debre Tabor district received 1926.1 and 1739 mm for the years 2019 and 2020 respectively (Fig. 2). The minimum and maximum temperatures at Adet were 5.4 and 30.2 °C in the 2019 season respectively and 6.8 and 30.7 °C in the 2020 season. The minimum and highest temperatures at Debre Tabor for the cropping seasons of 2019 and 2020 were 7.5 and 25.3 °C and 6.2 and 25.5 °C respectively.

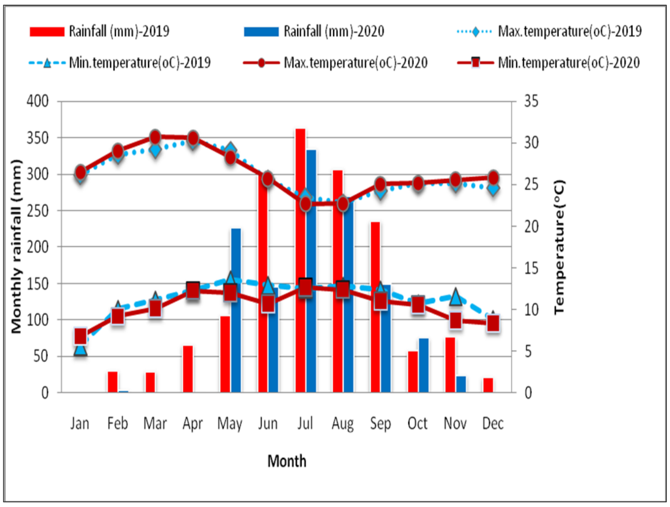

Fig. 1. Average monthly rainfall and temperature dispersion at Adet experimental site during the 2019 and 2020 experimental years (Bahir Dar Meteorology station, 2020).

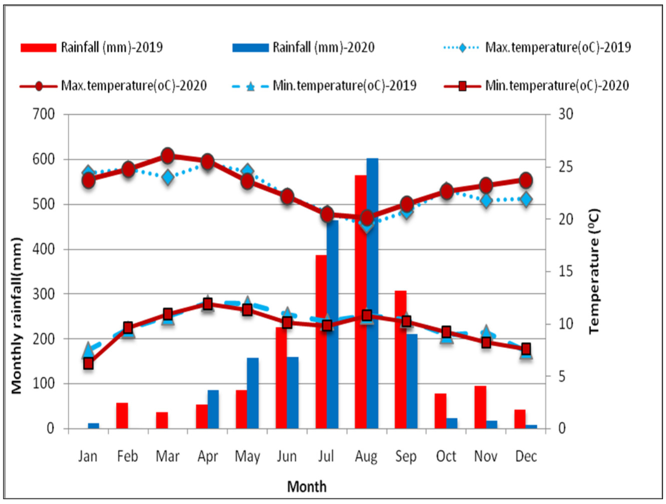

Fig. 2. Average monthly rainfall and temperature dispersion at Debre Tabor during the 2019 and 2020 experimental years (Bahir Dar Meteorology station, 2020).

Soil samples were gathered in the respective year at 5 spots diagonally at 0-20 cm soil depth and composited to characterize the overall soil parameters of both experimental sites before the start of the experiment. The Adet Agricultural Research Center's soil laboratory assessed the composite soil samples. To determine soil texture, total nitrogen, pH, available phosphorous, organic carbon and cation exchange capacity, the soil sample was air-dried, crushed and sieved using a 2 mm sieve. Table 1 shows the findings of the soil analysis as well as the methodologies used.

Table 1. Soil properties of the study sites before the experiment

Soil properties	Adet		Debre Tabor		Method of soil analysis
	value	Rating	value	Rating	
pH (H_2O) 1:2.5	5.08	Moderately acidic[b]	6.24	Slightly acidic[b]	pH meter (H2O 1:2.5)
CEC[cmol(+) kg^{-1}]	38.28	High[c]	42.73	Very high[c]	Ammonium acetate method (24)
OC (%)	1.21	Very low	1.48	Very low[c]	Walkley and Black method (25)
TN (%)	0.17	Low[c]	0.16	Low[c]	Micro-Kjeldahl method (26)
Ava.P (ppm)	3.89	low[c]	21.33	Low[c]	Bray method (27)
Soil texture					hydrometer method (28)
Sand (%)	55	-	56	-	
Silt (%)	11	-	19	-	
Clay (%)	36	-	25	-	
Soil textural class	Sandy clay	Sandy clay[c]	Sandy clay loam	Sandy clay loam[c]	USDA Classification

pH: potential of hydrogen, **CEC**:cation exchange capacity, **OC**: organic carbon, **TN**: total nitrogen, **Ava.P**: available phosphorous, **USDA**: the U.S. Department of Agriculture.

[a]Data were mean of 2 years (2019 and 2020), [b]Panda,(29), [c]*Landon, (30)*

Experimental treatments, design and procedures

Bread wheat was intercropped with sweet lupine at varied inter and intra-row spacing of sweet lupine at Adet and Debre Tabor experimental sites (Table 2). The treatments consisted of 3 inter-row spacing of lupine (20 cm, 40 cm and 60 cm) and three intra-row spacing of lupine (5 cm, 10 cm and 20 cm) with a total of nine treatment combinations in bread wheat-sweet lupine additive series intercropping. Sole cultures of the two crops acted as controls. The experiments were laid out in a 3 × 3 factorial Randomized Complete Block Design (RCBD) with 3 replications plus sole crop of wheat and sweet lupine were also included as controls. The Gross and net plot area of the single experimental plot was 3.6 × 2 m (7.2 m^2) and 3 × 2 m (6 m^2), with 0.5 m and 1 m between adjacent plots and replications respectively.

Table 2. Description of the treatment combinations for the bread wheat and sweet lupine intercropping experiment

Treatments combination		Abbreviations
IERL (cm)	IARL (cm)	
	5	1BW : 1SL + 5 cm
20	10	1BW : 1SL + 10 cm
	20	1BW : 1SL + 20 cm
	5	2BW : 1SL + 5 cm
40	10	2BW : 1SL + 10 cm
	20	2BW : 1SL + 20 cm
	5	3BW : 1SL + 5 cm
60	10	3BW : 1SL + 10 cm
	20	3BW : 1SL+ 20 cm
20	drill	SBW
40	10	SSL

BW: bread wheat; **SL**: sweet lupine; **SBW**: sole bread wheat; **SSL**: sole sweet lupine; **1BW:1SL**: one sweet lupine row was planted between every two rows of wheat; **2BW:1SL:** SL was planted after two rows of bread wheat; **3BW:1SL**: SL was planted after three rows of bread wheat; **IERL**: inter-row spacing of sweet lupine; **IARL**: Intra row spacing of sweet lupine.

The most dominant and adaptable variety of Bread wheat (Taye) and sweet lupine (Sanabor) were used in the present study. Bread wheat was a major crop, while sweet lupine was a minor crop. Sowing of wheat took place on 24 and 25th June 2019 and 2020 respectively. In additive series, one bread wheat (BW): one sweet lupine (SL) row arrangement: wheat was drill planted using the recommended inter-row spacing of 20 cm at the recommended seed rate of 150 kg/ha while the lupine crop was planted between every 2 rows of wheat using at 5 cm, 10 cm and 20 cm intra-row spacing respectively at a seed rate of 90 kg/ha. 2BW: 1SL row arrangement: wheat was drill planted using the recommended inter-row spacing of 20 cm at the recommended seed rate of 150 kg/ha, while the lupine crop was planted after every 2 rows of wheat at 5 cm, 10 cm and 20 cm intra-row spacing respectively at the recommended seed rate of 90 kg/ha. 3BW:1SL row arrangement: wheat was drill planted using the inter-row spacing of 20 cm at the recommended seed rate of 150 kg/ha, while a one-row lupine crop was planted after 3 rows of wheat at 5 cm, 10 cm and 20 cm intra-row spacing at the recommended seed rate of 90 kg/ha. Experimental plots of pure wheat were drill planted (intra-row spacing) using the recommended inter-row spacing of 20 cm and pure lupine were sown at the recommended spacing of 40 cm × 10 cm.

Management of experimental plants

In all cropping systems, wheat grown in Adet was supplied with 74/46 N/P_2O_5 ha^{-1}, while those grown in Debre Tabor was provided with 120/46 N/P_2O_5 ha^{-1} as recommended. The amount of phosphorous in each experimental site was applied at the sowing in the form of Di-ammonium phosphate (DAP). On the other hand, nitrogen in the form of urea was applied in 2 splits where the first one-third were applied at the time of sowing and the remaining two-thirds was applied at tillering stages. Lupine in all cropping systems was supplied with 18/46 N/P_2O_5 in the form of di-ammonium phosphate at the planting time. Weeds were managed uniformly by hand weeding. Weeding and other management activities were carried out following the growth of the crops.

Data collection and analysis

Grain yields of the component crops

Wheat was harvested with a sickle in Adet and Debre Tabor experimental sites on November 14^{th} and 19^{th}, 2019 and 2020 respectively. Sweet lupine was harvested with a sickle in Adet and Debre Tabor respectively on November 20^{th} and 30^{th}, 2019 and 2020. After drying, threshing and cleaning the biomass per plot, the grain yields of the component crops were calculated. Wheat and lupine grain yields were adjusted to 12% and 14% moisture levels respectively. Grain yields recorded on a plot basis were translated to a hectare basis and expressed in tons per hectare. Data analysis for grain yield was conducted using the general linear model (GLM) procedure of SAS version 9.2. Crop characteristics that showed a significant difference ($P<0.05$) were further tested for mean separation.

Yield advantages, Gross monetary value and competitive relationships

Land equivalent ratio (LER)

The total LER is a metric often used to assess the relative benefits of intercropping to sole culture. It denotes the proportion of land area required by the sole crop to provide the yield obtained by intercropping. As shown below, LER is determined as the total yield ratios of each component crop in intercropping systems to its corresponding yield under a sole crop (31).

$$LER = \left(\frac{Yab}{Yaa}\right) + \left(\frac{Yba}{Ybb}\right) \quad \text{.....................(Eqn.1)}$$

Where,

Yaa and Ybb are the yields of the sole crop a and b respectively.

Yab is the intercrop yield of crop a, and Yba is the intercrop yield of crop b; Yaa and Ybb are the yields of the pure crops. Crop a = bread wheat, crop b = sweet lupine; LER of 1.0 suggests that intercropping and solitary cropping have equal benefits. Intercropping has a more significant advantage than solitary cropping if LER is greater than 1.0, whereas values less than 1.0 imply that intercropping has a lesser advantage than sole cropping (31).

Competitive ratio (CR)

According to one report (32), the competitive ratio assesses competition between component crops. The component crops' CR was estimated using the formula below described (32).

$$CRBW = \left(\frac{PLERBW}{PLERSL}\right) X \left(\frac{ZSLBW}{ZBWSL}\right) \quad \text{.......(Eqn.2)}$$

$$CRSL = \left(\frac{PLERSL}{PLERBW}\right) X \left(\frac{ZBWSL}{ZSLBW}\right) \quad \text{........(Eqn.3)}$$

$$PLERBW = \frac{YBWIC}{YBWSC} \quad \text{...............................(Eqn.4)}$$

$$PLERSL = \frac{YSLIC}{YSLSC} \quad \text{..................................(Eqn.5)}$$

Where,

CRBW and CRSL were the competitive ratio of bread wheat and sweet lupine respectively.

PLERBW and PLERSL were a partial land equivalent ratio of bread wheat and sweet lupine, respectively.

ZBWSL and ZSLBW were a seed proportion of bread wheat intercropped with sweet lupine and the seed proportion of sweet lupine intercropped with Bread wheat respectively.

YBWIC and YSLIC were bread wheat and sweet lupine yields in an intercropping respectively and

YBWSC and YSLSC were bread wheat and sweet lupine yields in sole cropping respectively.

If CRBW is greater than one, bread wheat was a competitor. On the other hand, if CRBW is less than one, sweet lupine suppressed bread wheat production.

Aggressivity value and System productivity index

The Aggressivity value (A), which is computed using the formula below, was used to determine the competitive connection between the 2 crops (33):

$$Aab = \left(\frac{Yab}{Yaa \text{ x } Zab}\right) - \left(\frac{Ybb}{Ybb \text{ x } Zba}\right) \quad \text{.. (Eqn.6)}$$

$$Aba = \left(\frac{Yba}{Ybb \text{ x } Zba}\right) - \left(\frac{Yaa}{Yaa \text{ x } Zab}\right) \quad \text{.......(Eqn.7)}$$

Where ,

Aab = aggressivity of wheat, Aba = aggressivity of lupine, Yaa = pure culture yield of wheat, Ybb = pure culture yield of lupine, Yab = mixed culture yield of wheat, Yba = mixed culture yield of lupine, Zab = sown proportion of wheat and Zba = sown proportion of lupine.

The system productivity index (SPI) was developed using the formula below, which standardizes the yield of the secondary crop b in terms of the primary crop a (34).

$$SPI = \left(\frac{Sa}{Sb} Yb\right) + Ya \quad \text{..........................(Eqn.8)}$$

Where,

SPI = system productivity index; Sa and Sb were mean yields of wheat and lupine in sole cropping, respectively and Ya and Yb were mean yields of wheat and lupine in intercropping respectively.

Gross monetary value (GMV)

GMV of bread wheat and sweet lupine were calculated to evaluate the productivity and profitability of intercropping as compared to sole cropping of the associated component crops. The average prevailing market prices of each component crop at the time of harvesting were used to calculate GMV, with the lowest prices of wheat and lupine in the Adet district being 0.56 US dollars/kg in November and 0.63 US dollars/kg in December 2019/20 respectively. At the same time, the lowest prices of wheat and lupine in the Debre Tabor district were 0.47 US dollars/kg in November and 0.63 US dollars/kg in December 2019/20 respectively. Gross monetary value was calculated by multiplying the yields of the component crops by their respective current market price.

Data analysis for bread wheat and sweet lupine yields were conducted using the general linear model (GLM) procedure of SAS version 9.2 (SAS Institute, 2008) for each site and year. The data were combined over years since values for the error mean square of the 2 years were homogenous (35). Crop characteristics that showed significant differences (p<0.05) were further tested for mean separation.

Results

Grain yield of the component crops

Intercropping treatments had a substantial (P<0.01) impact on the grain yields of the component crops. The highest grain yield of wheat (3.75 t ha^{-1}, 3.67 t ha^{-1} and 3.53 t ha^{-1}) was recorded in 2 BW:1 SL (40 cm inter-row spacing of lupine + 20 cm intra-row spacing of lupine), 1 BW: 1 SL (20 cm inter-row spacing of lupine + 20 cm intra-row spacing of lupine and 3 BW): 1 SL (60 cm inter-row spacing of lupine + 20 cm intra-row spacing of lupine) at Adet experimental site respectively (Table 3). The highest grain yield of wheat (3.94 t ha^{-1}, 3.86 t ha^{-1} and 3.58 t ha^{-1}) was recorded in 2 BW: 1 SL (40 cm inter-row spacing of lupine + 20 cm intra-row spacing of lupine), 1 BW: 1 SL (20 cm inter-row spacing of lupine + 20 cm intra-row spacing of lupine) and 3 BW: 1 SL (60 cm inter-row spacing of lupine + 20 cm intra-row spacing of lupine) at Debre Tabor experimental site respectively (Table 3). On the other hand, the lowest grain yield of wheat was found in the intercropping of 2 BW: 1 SL + 5 cm (2.85 t ha^{-1}) and 1 BW: 1 SL + 5 cm (2.89 t ha^{-1}) at Adet and 2 BW: 1 SL + 5 cm (2.67 t ha^{-1}) and 1 BW: 1 SL + 5 cm (2.72 t ha^{-1}) at Debre Tabor experimental site (Table 3). Moreover, when the intra-row spacing of lupine was reduced from 20 to 5 cm in the 2BW:1SL arrangement, wheat grain yield was reduced by 24% and 32.2% in Adet and Debre Tabor respectively (Table 3). The grain yield of wheat decreased as the intra-row spacing of lupine decreased in the current study. The regression study of wheat yield and lupine intra-row spacing shown in Fig. 3a and 3b confirms this perspective.

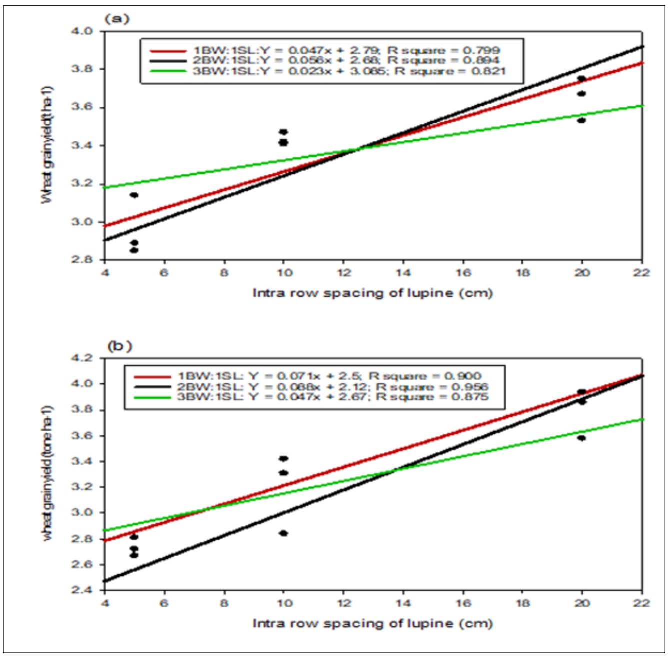

Fig.3. The relationships between wheat yield and intra-row spacing of lupine in bread wheat-sweet lupine intercropping at (**a**) Adet, (**b**) Debre Tabor.

Table 3. Effect of additive series intercropping practices on grain yields of the component crops in northwest Ethiopia

Intercropping treatments		Bread wheat grain yield (t ha^{-1})		Sweet lupine grain yield (t ha^{-1})	
IERL	IARL	Adet	Debre Tabor	Adet	Debre Tabor
	5cm	2.89c	2.72d	1.25b	1.39b
20 cm(1BW : 1SL)	10cm	3.47ab	3.42ab	0.89bc	1.32b
	20cm	3.67a	3.86a	0.25cd	0.9c
	5cm	2.85c	2.67d	0.94b	1.37b
40 cm (2BW : 1SL)	10cm	3.41ab	2.84cd	0.26cd	0.9c
	20cm	3.75a	3.94a	0.19d	0.45d
	5cm	3.14bc	2.81cd	0.88bc	1.22bc
60 cm (3BW : 1SL)	10cm	3.42ab	3.31bc	0.18d	0.43d
	20cm	3.53ab	3.58ab	0.17	0.41d
SBW	-	3.47ab	3.45ab	-	-
SSL	-	-	-	2.07a	1.85a
P-value		**	***	***	***
CV%		7.48	8.89	25	22
SE±		0.06	0.1	0.12	0.09

In Adet and Debre Tabor, the treatment combination 2BW : 1SL + 20cm IARL enhanced bread wheat grain production by 8.1% and 14.2 % respectively, compared to the sole crop (Table 3). In the current study, the sole cropping strategy produced significantly higher sweet lupine grain production in both locations (Table 3). Within the intercropping systems, the 1BW:1SL + 5cm IARL intercropping combination had the highest sweet lupine yields in both Adet (1.25 t ha^{-1}) and Debre Tabor (1.39 t ha^{-1}). In Adet (0.17 t ha^{-1}) and Debre Tabor (0.41 t ha^{-1}), however, the lowest grain yield of sweet lupine was obtained with a 3BW:1SL + 20 cm IARL intercropping combination as indicated in Table 3. Moreover, the 1BW:1SL + 5 cm gave 86.4% and 70.5% higher grain yield of sweet lupine compared to the 3BW:1SL +20 cm intercropping combination at Adet and Debre Tabor respectively. The grain yield of sweet lupine was negatively correlated with the intra-row spacing in wheat-sweet lupine intercropping in both locations (Fig. 4a and 4b), which supports the lupine grain yield results

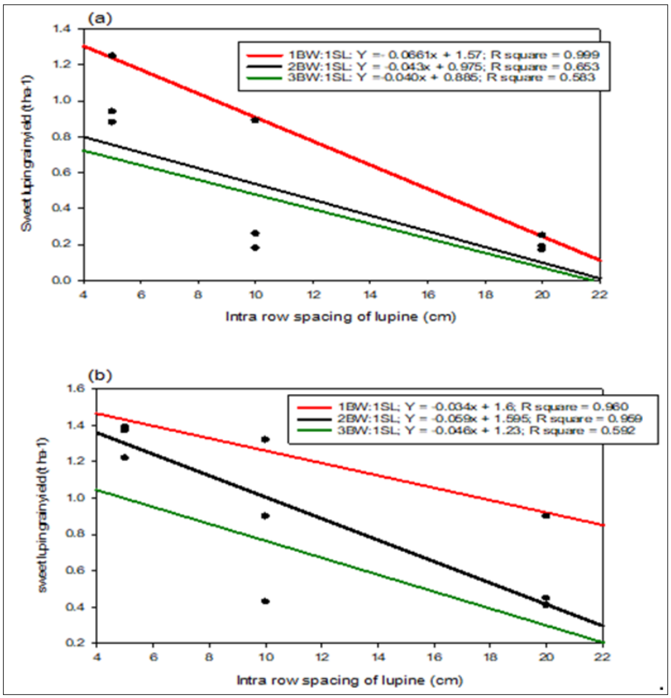

Fig.4. The relationships between sweet lupine yield and intra-row spacing of lupine in bread wheat-sweet lupine intercropping at (**a**) Adet, (**b**) Debre Tabor

obtained in the present study. As indicated in Fig. 5a and 5b, as wheat yield increased, the yield of sweet lupine in wheat-sweet lupine intercropping decreased in both experimental sites.

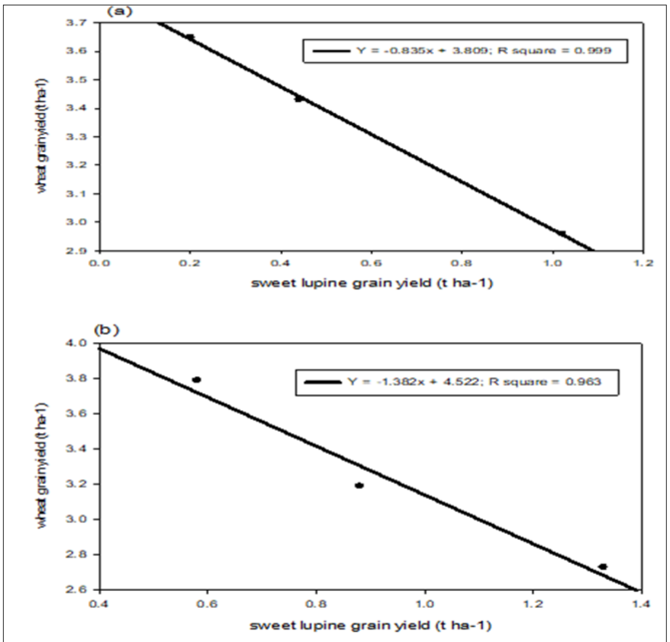

Fig.5. The relationships of wheat grain yield and sweet lupine grain yield in sheat-sweet lupine interfropping at (**a**) Adet, (**b**) Debre Tabor

Land use efficiency

In the present study, the partial land equivalent ratio of bread wheat (PLERBW) ranged from 0.82 to 1.08 in Adet and from 0.77 to 1.14 in Debre Tabor experimental sites. On the other hand, the partial land equivalent ratio of sweet lupine (PLERSL) ranged from 0.08 to 0.6 and 0.22 to 0.76 in Adet and Debre Tabor respectively (Table 4) where 1BW : 1SL + 5 cm at Adet and 1BW : 1SL + 5 cm ; 1BW : 1SL + 10 cm ; 2BW : 1SL +5 cm and 3BW : 1SL + 5 cm at Debre Tabor intercropping treatments scored greater than 0.5 PLERSL. While PLERBW in all intercropping treatments scored values greater than 0.5 in both experimental sites. All intercrops had a greater LER than sole crops, with the total LER of intercrops at Adet ranging from 1.07 to 1.43 and at Debre Tabor ranging from 1.19 to 1.71. The highest LER was recorded from intercropping systems of 1BW : 1SL + 5 cm (1.43) and 1BW : 1SL + 10 cm (1.43) followed by 3BW : 1SL + 5 cm (1.33) at Adet experimental site, while in Debre Tabor the highest LER was recorded in 1BW : 1SL + 10 cm (1.71) followed by 1BW : 1SL + 20 cm (1.61) (Table 4).

In the present study, total land equivalent ratios showed a positive relationship with the grain yields of bread wheat and sweet lupine at Adet and Debre Tabor in intercropping systems, as indicated (Fig. 6a and 6b).

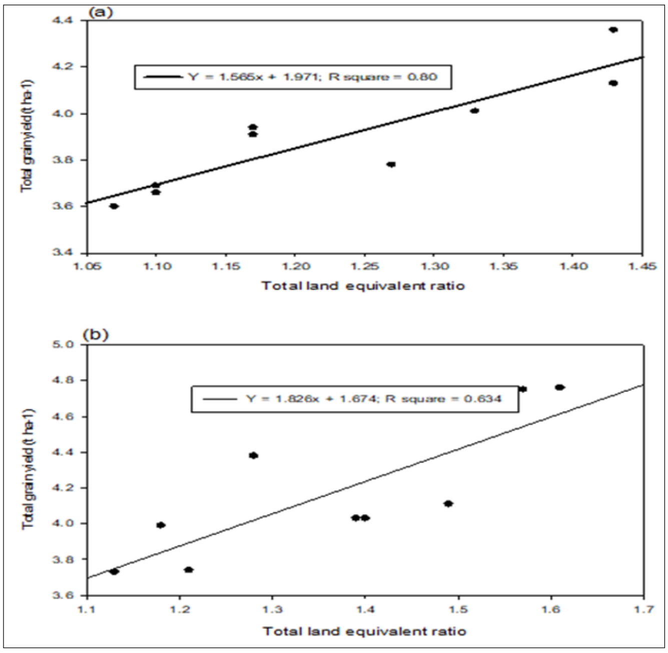

Fig. 6. The relationships between total land equivalent ratio and total grain yhields in bread wheat-sweet lupine intercropping at (a) Ader, (b) Debre Tabor

Therefore, the highest LER from intercropping systems of1BW : 1SL + 5 cm (1.43) and 1BW : 1SL + 10 cm (1.43) followed by 3BW : 1SL at Adet experimental site indicates 33-43% of more land is required for sole crops to attain the yield recorded from intercropping systems. In other words, intercrops can provide a yield benefit of 33 –43% over pure stands. While in Debre Tabor the highest LER from intercropping systems of 1BW : 1SL + 10 cm (1.71) followed by 1BW : 1SL + 20 cm (1.61) indicates 61–71% more land is required for sole crops to attain the yield recorded from intercropping systems.

Gross Monetary Values (GMV)

As indicated in Table 5, GMV was higher for the intercrops than sole crops of wheat and sweet lupine in Adet and Debre Tabor (Table 6), where GMV of sole wheat was greater than that of sole sweet lupine in both locations. The highest GMV (US$ 2511.26 ha^{-1}) of wheat in the Adet experimental site was recorded from the intercropping system of 1BW:1SL +10 cm (Table 5), which also recorded the highest total intercrop yield (4.36 t ha^{-1}) (Table 3). Similarly, the

Table 4. Effect of additive series intercropping treatments on land use efficiency in northwest Ethiopia

Wheat intercropping		Adet			Debre Tabor		
IERL	**IARL**	**PLERBW**	**PLERSL**	**LER**	**PLERBW**	**PLERSL**	**LER**
	5cm	0.83	0.60	1.43	0.79	0.76	1.54
20 cm (1BW : 1SL)	10cm	1	0.43	1.43	0.99	0.72	1.71
	20cm	1.06	0.12	1.17	1.12	0.49	1.61
	5cm	0.82	0.45	1.27	0.77	0.74	1.51
40 cm (2BW : 1SL)	10cm	0.98	0.12	1.10	0.83	0.48	1.31
	20cm	1.08	0.09	1.17	1.14	0.24	1.38
	5cm	0.90	0.42	1.33	0.81	0.66	1.47
60 cm (3BW : 1SL)	10cm	0.98	0.09	1.07	0.96	0.23	1.19
	20cm	1.02	0.08	1.10	1.04	0.22	1.26
SBW		1.00	-	1.00	1.00	-	1.00
SSL		-	1.00	1.00	-	1.00	1.00
SE ±		0.09	0.09	0.05	0.04	0.1	0.07

[a]Data were combined over the years (2019 and 2020 in Adet and Debre Tabor). **PLERBW** and **PLERSL**: partial land equivalent ratio of Bread wheat and sweet lupin, respectively, **LER**: total land equivalent ratio, **SBW**: sole bread wheat, **SSL**: sole sweet lupine, **1BW : 1SL**: one sweet lupine row was planted between every two rows of wheat, **2BW : 1SL**: SL was planted after two rows of bread wheat, **3BW : 1SL**: SL was planted after three rows of bread wheat, **IERL:** inter-row spacing of sweet lupine, **IARL**: Intra row spacing of sweet lupine, **SE**: the standard error.

Table 5. Competitive ratio, aggressivity value and system productivity index of bread wheat and sweet lupine intercropped at Adet, Ethiopia

Intercropping treatment		Adet		Aggressivity (A)		System productivity index (SPI)	Gross Monetary value(ETB ha^{-1})
IERL	**IARL**	**CRBW**	**CRSL**	**Wheat**	**SL**		
	5 cm	5.89	0.17	0.69	-0.69	4.96	76820.01
20 cm (1BW : 1SL)	10 cm	4.94	0.20	0.80	-0.80	4.96	80259.87
	20 cm	9.39	0.11	0.85	-0.85	4.07	70860.11
	5 cm	3.64	0.27	0.58	-0.58	4.43	70100.11
40 cm (2BW : 1SL)	10 cm	8.17	0.12	0.86	-0.86	3.83	66379.96
	20 cm	6.00	0.17	0.90	-0.90	4.07	71299.88
	5 cm	2.68	0.37	0.56	-0.56	4.60	73919.96
60 cm (3BW : 1SL)	10 cm	6.81	0.15	0.85	-0.85	3.72	65159.73
	20 cm	3.98	0.25	0.76	-0.76	3.82	66939.90
SBW		-	-	-	-	-	62460.07
SSL		-	-	-	-	-	41400.03
SE ±		0.7	0.03	0.04	0.04	0.16	3596.47

CRBW: competitive ratio of Bread wheat in intercropping, **CRSL**: competitive ratio of sweet lupin in intercropping, **SBW**: sole bread wheat, **SSL**: sole sweet lupine, **1BW:1SL**: one sweet lupine row was planted between every two rows of wheat, **2BW:1SL**: SL was planted after two rows of bread wheat, **3BW:1SL**: SL was planted after three rows of bread wheat, **IERL**: inter-row spacing of sweet lupine, **IARL**: Intra row spacing of sweet lupine, **SE**: the standard error, USD: U.S.dollar. Crop value in the systems was calculated by converting the Ethiopian birr (Ethiopian birr; 1USD = birr31.96) to US dollars. Data were combined over years (2019 and 2020) at both locations

Table 6. Competitive ratio, aggressivity value and system productivity index of wheat and sweet lupine intercropped at Debre Tabor, Ethiopia

Intercropping treatment		Adet		Aggressivity (A)		System productivity index (SPI)	Gross Monetary value (ETB ha^{-1})
IERL	**IARL**	**CRBW**	**CRSL**	**Wheat**	**SL**		
	5 cm	4.96	0.20	0.61	-0.61	4.96	76600.13
20 cm (1BW : 1SL)	10 cm	2.92	0.34	0.65	-0.65	4.96	87959.99
	20 cm	2.43	0.41	0.66	-0.66	4.07	87479.95
	5 cm	2.08	0.48	0.40	-0.40	4.43	75460.12
40 cm (2BW : 1SL)	10 cm	1.73	0.58	0.33	-0.33	3.83	69100.08
	20 cm	2.38	0.42	0.65	-0.65	4.07	79920.13

	5 cm	1.53	0.65	0.28	-0.28	4.60	74948.12
60 cm (3BW : 1SL)	10 cm	1.61	0.38	0.58	-0.58	3.72	68179.95
	20 cm	1.48	0.68	0.33	-0.33	3.82	72639.97
SBW		-	-	-	-	-	62099.97
SSL		-	-	-	-	-	39999.77
SE ±		0.35	0.05	0.05	0.15	0.19	36904.43

Data were combined over years (2019 and 2020) at both locations

CRBW: competitive ratio of Bread wheat in intercropping, **CRSL:** competitive ratio of sweet lupin in intercropping, **SBW**: sole bread wheat, **SSL**: sole sweet lupine, **1BW:1SL**: one sweet lupine row was planted between every two rows of wheat, **2BW:1SL**: SL was planted after two rows of bread wheat, **3BW:1SL**: SL was planted after three rows of bread wheat, **IERL**: inter-row spacing of sweet lupine, **IARL**: Intra row spacing of sweet lupine, **SE**: the standard error.

same intercropping system (1BW : 1SL +10 cm) with the highest total intercrop yield of 4.74 t ha^{-1} (Table 3) recorded the highest GMV of US$ 2752.19 ha^{-1} in Debre Tabor (Table 6).

Competition between bread wheat and sweet lupine intercropping system

Tables 5 and 6 show the competitive ratio and aggressivity parameters of component crops cultivated at both experimental sites. Accordingly, wheat was more competitive than sweet lupine at the Adet experimental site, where the CR of wheat (CRBW) ranged from 2.68 to 9.39 and the aggressivity value also ranged from 0.56 to 0.90 while CR of sweet lupine was between 0.11 and 0.37 and the aggressivity value was also between -0.90 to -0.56 (Table 5). Wheat was also competitive compared to sweet lupine, with CRBW ranging from 1.48 to 4.96 and the aggressivity value ranging from 0.28 to 0.66, while CRSL ranging from 0.20 to 0.68 and the aggressivity value ranging from -0.66 to -0.28 (Table 6).

The highest SPI of 4.96 and 5.88 at Adet and Debre Tabor, respectively, were obtained from 1BW:1SL +10cm intercropping (Tables 5, 6) in which the highest total yield, LER, and GMV were also recorded (Table 3-6). In intercropping system, wheat scored positive aggressivity values ranging from 0.04 to 0.90 and 0.05 to 0.66 at Adet and Debre Tabor respectively. On the contrary, sweet lupine scored negative values ranging from -0.90 to -0.56 and -0.66 to -0.28 at Adet and DebreTabor respectively (Table 5, 6).

Discussion

In the current study, wheat grain yield dropped as lupine intra-row spacing reduced (20 cm to 5 cm) or vice versa. The significantly greater wheat grain yield obtained on the broader intra-row spacing of sweet lupine (20 cm) intercropping condition compared to all other intercropping treatments might be due to less intra-row competition for plant growth resources between components crops. Under varying densities in an intercropping design, the influence of management, such as the crop combination of intercrops employed in the system, affects the yield (36). By limiting the shade effect of the component crops, the optimum plant population at this planting arrangement may benefit from more effective photosynthesis. Wheat grain output decreased when lupine intra-row spacing was reduced in the current study. The reduced wheat yield could be associated with the increase in the lupine population when the intra-row spacing is reduced from 20 to 5 cm which may create stiff competition for resources among the component crops. The findings of this study are congruent with an earlier work (37), who found that raising the legume planting ratio lowered the grain yield of the main crop due to plant growth resource competition between component crops.

Furthermore, the current findings are consistent with an earlier report in which it was found that cereal grain yields fell as the seed rate of legume crops increased (14). It was also showed that competition between component crops for nutrient usage is more pronounced in the intercropping system (38). In Adet and Debre Tabor, the treatment combination 2BW : 1SL + 20 cm enhanced bread wheat grain production by 8.1% and 14.2 % respectively, above sole cropping. This increase may be helped by transferring fixed nitrogen from legumes to cereal crops (8, 17). In both locations, the solo cropping system produced much higher sweet lupine grain yields, which could be attributed to the optimum plant population in sole cropping versus the intercropping system, which avoids interspecies competition for nutrients. In contrast to this finding, it was found that the legume produces considerably more when comparing grain–legume intercropping systems (39).

Increased plant population, which restricts weed growth and allows for more nitrogen fixation from the air, could explain the higher grain yield of sweet lupine in wheat-lupine intercropping with a lower intra-row spacing of sweet lupine (40). The yield of sweet lupine in wheat – sweet lupine intercropping declined as wheat yield increased. The findings of this study are congruent with an earlier report (37). They found that legume crop grain output was lower in cereal-legume intercropping with a lower seeding fraction of legume crops, obviously due to a lower plant population.

The comparison between the partial LER of the component crops indicates the competitiveness of the individual species, and the total LER is a measure of the relative yield advantage (41). The partial LER of bread wheat was greater than 0.5 in both experimental sites. On the other hand, the partial LER of sweet lupine was less than 0.5 except 1BW : 1SL + 5 cm at Adet and 1BW : 1SL + 5 cm, 1BW : 1SL + 10 cm, 2BW : 1SL + 5 cm, and 3BW : 1SL + 5 cm at Debre Tabor experiment sites. A higher partial LER for bread wheat than for sweet lupine was observed because it was the dominant crop, i.e., it was more competitive and aggressive than the lupine. The greater LER of intercrops than sole crops reported in this study shows that intercropping yields more overall production per unit area than a pure stand of each crop type. It was found that LER was superior in all intercrops, meaning that under the additive intercropping system, corn-soybean intercropping had a bigger relative yield advantage than sole cropping (41). The findings of the study corroborate with the earlier work, it was also found that all intercrops have greater overall yields and LER than sole crops (42). Different researchers observed similar results for several intercropping systems, including wheat-field bean (43) and wheat-lentil (44). In general, a greater LER does not always imply increased system productivity. Because the primary and sub crops' productivity may differ, in the present study, land equivalent ratios showed a positive relationship with total grain yields of bread wheat and sweet lupine at Adet and Debre Tabor in intercropping systems.

During the experimental period, improved productivity combined with higher wheat and lupine prices made wheat-sweet lupine intercropping more profitable in both experimental locations. The highest GMV of 2511.26 and 2752.19 USD ha^{-1} were obtained from 1BW : 1SL + 10 cm intercropping at both experimental sites. According to the economic analysis, intercropping wheat with sweet lupine was often more advantageous and profitable than monocropping individual crops. Results of the present study are consistent with another one (45); intercrops yield a larger cash return than solitary crops for smallholder farmers. The results are also corroborated with an earlier report (46), in which it was reported intercrops to have larger GMV than sole crops. Moreover, records are on the higher LER and GMV for cereal-legume intercropping systems compared to mono-cropping (47).

The competitive ratio of wheat was much higher than the CR of sweet lupine in all intercropping treatments at both experimental locations. The reason for the increased competitiveness of wheat compared to sweet lupine could be associated with the fact that sweet lupine in the present study was sown two weeks after wheat, which advances the growth of wheat and thus promotes its competitiveness. Contrary to the results in the present study, it was reported that a higher CR for legumes than the CR of cereal (37). There was also a negative association between the yield of the component crops at Adet as well as Debre Tabor (Fig. 6 a, b), which highlights some degree of competition between the main crop and sub-crop for space and resources. In agreement with this, reports are on the increased productivity in one crop as part of the system may result in lower yields in the other (4). Intercropping system had yield advantages, as shown in this study, which may be due to the deep root system of sweet lupine, which exploits water and nutrients from deeper soil strata than bread wheat. Besides, in the intercropping system with a legume, there may be nitrogen fixation under conditions of nodulation, which in turn is expressed in the form of a higher yield of intercrops than in the sole cropping (48). According to one study, competition rather than cooperation can be predicted in combinations containing species with similar morphology and physiology (49).

In the present study, intercropping has some synergistic effects on total productivity, where the total yield and SPI of 1BW : 1SL +10 cm intercropping exceeded the sole yield of either crop (Table 3, 5, 6) at both locations. On the other hand, the yield of the component crops at Adet and Debre Tabor (Fig. 5 a, b).

In the current study, all the A values of bread wheat were positive. At the same time, sweet lupine was negative at both locations, indicating wheat produced greater yield and wheat-dominated sweet lupine in the mixture. In agreement with these findings, reports are on the similar results in wheat-fababean intercropping (4). The highest SPI of 4.96 and 5.88 at Adet and Debre Tabor were obtained from 1BW : 1SL +10 cm intercropping. The SPI was highly determined mainly by the wheat intercrop, which was not much reduced by intercropping. Based on the findings of the current study, wheat dominates sweet lupine in the wheat-sweet lupine intercropping system while lupine was dominated in all experimental sites, in line with another report where it was claimed that a crop with a negative aggressivity value is considered to be dominated while a crop with a positive value is dominant, stated (33). The results of the present study contrast with the findings of an earlier report in which it was reported that the tef with weak-straw and to a lesser extent barley were dominated in their respective mixture with legumes (42).

Conclusion

The current study's findings clearly showed that wheat productivity may be improved by intercropping sweet lupine as an additive between wheat rows, as it produced a high land equivalent ratio and gross monetary value. The wheat-sweet lupine intercropping system outperformed the sole cropping system in terms of utilizing limited environmental resources, as the land equivalent ratio of all intercrop treatments exceeded that of the sole cropping system in the study areas. The highest system productivity index was obtained from 1BW : 1SL + 10 cm IRL intercropping in which the highest total yield, LER and GMV were also recorded at both locations. Based on the results of the present study, bread wheat-sweet lupine intercropping with a 1BW : 1SL + 10 cm IARL intercropping system could be recommended for improvement of wheat productivity and livelihoods of smallholder farmers in the study areas and areas with similar agroecology. Further studies should be focused on (i) the evaluation of wheat-sweet lupine intercropping at a different time of planting and (ii) the impact of the wheat-sweet lupine intercropping system on the grain quality of bread wheat as well as soil physical, chemical and biological properties.

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Authors contributions

BB conceived, planned, carried out experiments, gathered data, analyzed data and wrote the manuscript. The manuscript was supervised and edited by GA. The manuscript was co-supervised and edited by TT and MA.

Compliance with ethical standards

Conflict of interest: The authors do not have any conflicts of interest to declare.

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