Optimizing the Plant Population and Time of White Lupine Intercropping with Food Barley in Northwest Ethiopian Highlands

***Sewnet Getahun*[1], *Getachew Alemayehu*[2*] *and Kassaye Mulatu*[1]**

[1]Department of Plant Science, College of Agriculture and Natural Resource, Debre Markos University, Debre Markos, Ethiopia

[2]Chair of Agronomy, Department of Plant Science, College of Agriculture and Environmental Sciences, Bahir Dar University, Bahir Dar, Ethiopia

***Corresponding author:** getachew.64@gmail.com

Received: December 10, 2021 Accepted: December 19, 2021

Abstract: *Lupine has traditionally been intercropped with food barley in northwest Ethiopian highlands. But, there is no any documented information about the optimum plant population and time of white lupine intercropping with food barley in these areas. Hence, a field experiment was conducted on plant population and time of lupine intercropping with food barley in 2017 and 2018 main cropping season in Gozamin highland, northwest Ethiopia, to determine the optimum plant population and time of lupine intercropping for maximum productivity of food barley fields. Factorial combinations of three plant population (500000, 250000 and 166667 plants/ha) and four time of lupine additive series intercropping (simultaneously, two weeks, four weeks and six weeks after barley sowing) with food barley were laid out in randomized compete block design with three replications. Sole food barely and sole lupine were included as a comparison purpose. The results indicated that there was no significant difference among treatment combinations for biomass and grain yields of food barley. However, highly significant differences among treatment combinations were observed for biomass and grain yields of lupine. The highest land equivalent ratio (1.48), relative economic efficiency (42.61%), and net economic return (Birr 38,160/ha) with acceptable higher marginal rate of return (598.68%) were recorded in the combination of 166667 plants/ha plant population and simultaneous time of lupine additive intercropping with food barley.*

Keywords: Additive intercropping, economic efficiency, *Hordeum vulgare***,** land equivalent ratio, *Lupinus albus*, productivity efficiency

1. Introduction

Ethiopia is the second populous country in Africa after Nigeria and agriculture is the main stay of its economy (MoFED, 2016). Its highlands are especially important for human trafficking and crop production, while about 90% of the total human population and crop production of the country are found in these highlands (Hurni *et al*., 2010) that account only about 46% of the national surface area (Teklu, 2005). Subsistent smallholder crop-livestock mixed farming is the main agricultural system of Ethiopian highlands (Likawnt *et al*., 2010) and food barley (*Hordeum vulgare* L.) is one of the major food cereal crops grown in these highlands (Alemayehu *et al*., 2011; CSA, 2018). Since time immemorial, white lupine (*Lupinus albus* L.) has also been grown specially in northwest Ethiopian highlands as multipurpose legume crop used for reclaiming the crop soils especially after cereals, as well as for supplementing the household food security (as a good protein source) and incomes of farmers from its market sales (Hibstu *et al*., 2016; Akale *et al*., 2019). Lupine in most towns and cities of Ethiopia has also been used widely as a preferred snack food in both local and modern bear houses (Likawnt *et al*., 2011). On top of its high protein and fiber contents, lupine does have nutraceutical potential (combination of nutrition and pharmaceutical use) and have some health-protecting effects through preventing and controlling metabolic syndrome risk factors including abdominal obesity, increased triglyceride level, decreased HDL cholesterol concentration, hypertension, and hyperglycaemia (Hodgson and Lee, 2008; Sedláková *et al*., 2016; Villarino *et al*., 2016). This is due to causing the feeling of satiety (appetite suppression) and affecting the energy balance, affecting favorably glycaemia, improving the defecation and the levels of blood lipids, and having positive effect on hypertension (Hodgson and Lee, 2008; Tizazu and Emire, 2010).

Both food barley and white lupine productions in northwest Ethiopian highlands have however been facing big challenges of low productivity (CSA, 2018) and diminishing the cultivation area (Hibstu *et al*., 2016), respectively. On the one hand, productivity of barley fields in Ethiopia is low below the world average and beyond meeting the ever increasing food demand of rapidly growing highland population (CSA, 2018). As the result of high population growth, on the other hand, cultivated land in Ethiopian highlands has been becoming the scarcest resource for crop production and farmers have been forced to abandon crop rotation (Getachew *et al*., 2020) and give more priority to produce major cereals including food barley than white lupine, and thereby production of white lupine in northwest Ethiopian highlands has been declining steadily (Hibstu *et al*., 2016).

Hence, there is a need for enhancing the productivity of barley fields, as well as for expanding the production of white lupine in Ethiopian highlands, while beyond its food and economic contributions to poor smallholder farmers, white lupine plays a special role in raising the fertility of acidic crop soils of Ethiopian highlands effectively through its high symbiotic nitrogen fixation and soil phosphorous mobilization ability (Beneberu *et al*, 2019). Under the current circumstances of cultivated land and crop production in northwest Ethiopian highlands, increasing the productivity of barley fields and expanding the production of lupine in these areas can be possible through intercropping or mixed cropping of white lupine with food barley (Akale *et al*., 2019). Inter cropping/mixed cropping is the practice of cultivating two or more crops in the same piece of land at the same time or relayed (Yayeh *et al*., 2019), and it is commonly practiced by smallholder farmers mainly in the tropics (Panda, 2010; Seran and Brintha, 2010). Intercropping (in row planted crop fields) or mixed cropping (in broadcast planted fields) is among the most efficient land used systems adopted in tropical regions, where farmers have only limited access to agricultural inputs (Laurent *et al*., 2015).

Several authors described intercropping as an ecological intensification practice which has been widely used to boost crop productivity, increase crop diversity (Yayeh *et al*., 2014), enhance the land utilization ratio (Laurent *et al*., 2015), minimize crop failure due to adverse effects of biotic and abiotic factors (Dai *et al*., 2017), improve the use of limited resources (Tsubo *et al*., 2005), protect soil against erosion, improve soil fertility, increase stability of yield (Yayeh *et al*., 2020), reduce labor peaks, provide higher returns (Yayeh *et al*., 2019) and supply a balanced diet compared to sole cropping. This is mainly because of that intercropping is important to optimize the use of time, space and physical resources compared to sole cropping (Zhang and Li, 2003). Cereal-legume is the common combination used in most intercropping systems (Seran and Brintha, 2010), while legumes fix atmospheric nitrogen gas and make it available to plants on top of their other additional intercropping advantages.

Some low input farmers in northwest Ethiopian highlands have traditionally intercropped lupine with cereals mainly with food barley in additive design (ANRS Bureau of Agriculture, 2020), where the sole recommended plant density of the major crop barley is constant with varying the density of the minor crop lupine (Yayeh *et al*., 2020). Since farmers don't compromise the yields of major crops, proper additive intercropping can make the interest of farmers possible. Optimal additive intercropping enables farmers to get satisfactory additional yield from a secondary crop on top of a major crop yield obtained from its sole cropping. This is indeed possible when a secondary (minor) crop doesn't negatively affect the growth and yield of a major crop significantly apart from its economically sound additional yield gain (Yayeh *et al*., 2019, 2020). Hence, it is very essential to investigate the optimal plant density and time of intercropping of a secondary crop with a major crop in additive design for maximizing the productivity and profitability of the crop land (Akale *et al*., 2019). However, there is meager information on optimal plant density and time of lupine additive intercropping with food barley in the country. Therefore, the present study was devised to determine the optimum plant population and time of lupine additive intercropping with food barley in northwest Ethiopian highlands.

2. Materials and Methods

2.1. Description of the study site

A rain-fed field experiment was conducted during the main cropping season of 2017 and 2018 at trial-demonstration site of Debre Markos University in the main campus, in Gozamin District, Northwestern Ethiopia. Geographically, the study site is located at 10°21` N latitude and 37° 43`E longitude with an altitude of 2446 meter above sea level. It is found 300 kilometer northwest of Addis Ababa and 265 kilometer southeast of Bahir Dar. According to 36 years (1981-2016) recorded weather data (Debre Markos Meteorology Station, 2017), the mean annual rainfall of the experimental site is 1380 mm with average minimum and maximum temperatures of 15^{O}C and 22^{O}C, respectively (Figure 1).

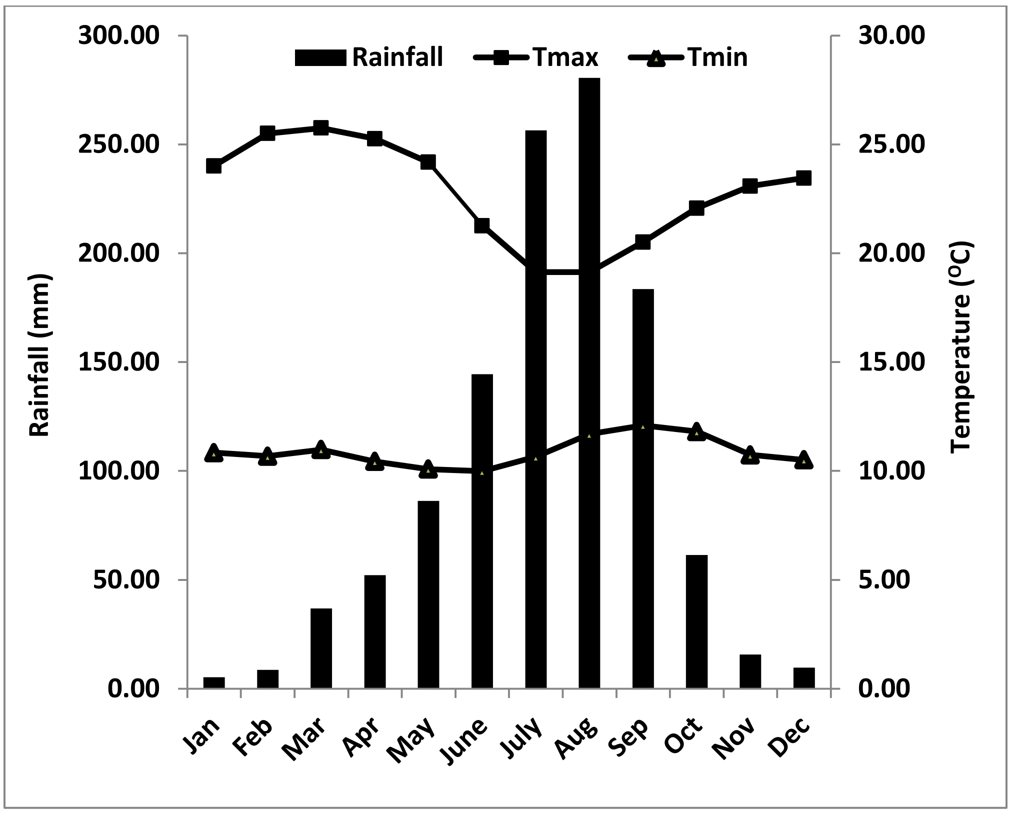

Figure 1: Average monthly rainfall, and minimum and maximum temperatures of the experimental site for 36 years from 1981 to 2016 (*Tmax = maximum temperature; Tmin = minimum temperature*)

To characterize the soil of the experimental site, a composite soil sample was taken before sowing and analyzed for important physicochemical properties. The composite soil sample was prepared by thorough mixing of seven soil samples collected randomly in a crisscross fashion of the whole experimental plot at a plow depth of 0-20 cm using an augur. It was then air dried up to attaining the constant weight and crushed with motorized grinder and sieved with a 2 mm diameter screen for further laboratory analysis that was done at Debre Markos Soil Laboratory. Particle size distribution (soil texture) was determined by hydrometer method (Bouyoucos, 1962; Gee and Bauder, 1986), while soil pH was measured using a digital pH meter in a 1:2.5 soil-water suspension as described by Panda (2010). Organic carbon (OC) was determined by wet digestion Walkley and Black method (Heanes, 1984). Determination of total nitrogen (TN) was carried out through micro-Kjeldahl digestion method (Bremner and Mulvaney, 1982). Available phosphorus (AP) was determined by calorimetrically using Olsen's method (Olsen *et al*., 1954), while cation exchange capacity (CEC) was determined using titration method (FAO, 2008). Lab analysis results of pH, CEC, OC, TN and AP status of the experimental soil before starting the experiment were rated according to Panda (2010), Landon (1991), Charman and Roper (2007), Havlin *et al*. (1999) and Tekalign *et al*. (1991) respectively, while texture of the soil was classified according to Brady and Weil (2017).

Laboratory analysis results of the experimental soil just before starting the study are presented in Table 1.

The soil laboratory results showed that texture of the experimental soil was clay as per the soil texture triangle matrix of Brady and Weil (2017). According to Panda (2010), the experimental soil was moderately acidic. Cation exchange capacity (CEC) of the soil was also moderate (Landon, 1991). Organic carbon (OC), total nitrogen (TN) and available phosphorous (AP) contents of the experimental soil were low as per rating made by Charman and Roper (2007), Havlin *et al*. (1999), and Tekalign *et al*. (1991), respectively (Table 1).

Table 1: Physicochemical properties of the experimental soil before starting the study

Soil properties	Value	Rating category	Rating reference
pH (H_2O)	5.67	Moderately acidic	Panda (2010)
CEC (cmol(+)/kg)	26.80	Moderate	Landon (1991)
Organic carbon (%)	1.56	Low	Charman and Roper (2007)
Total nitrogen (%)	0.16	Low	Havlin *et al*. (1999)
Available P (ppm)	30. 29	Low	Tekalign *et al*. (1991)
Particle distribution			Bouyoucos (1962)
Sand (%)	18.00		
Silt (%)	20.00		
Clay (%)	62.00		
Textural class	*Clay*		Brady and Weil (2017)

CEC = cation exchange capacity, P = phosphorus, pH = potential of hydrogen

2.2. Experimental planting materials

A six-row food barley variety of HB-1307 and local variety of white lupine were used as a test crops. The six-row food barley variety HB-1307 was developed and released by Holetta Agricultural Research Center in 2006. This variety has been released for mid and high altitude barley growing areas due to its superiority in grain yield performance, stability and wide adaptation. It has also good physical grain quality, resistance to leaf rust and scald, moderate resistance to net and spot blotch, lodging tolerance and good biomass yield. Local variety of white lupine is well adapted in mid and high altitude areas and currently grown in the study area, as well as its seed is also easily available in the local markets.

2.3. Experimental treatments, design and procedures

Factorial combinations of three plant population (500000, 250000 and 166667 plants/ha) and four time of lupine additive intercropping (simultaneously, two weeks, four weeks and six weeks after barley sowing) with food barley, as well as two sole cropping as comparison were laid out in randomized compete block design with three replications. Detail treatment combinations and sole crops used for the experiment are presented in Table 2. The gross plot size was 4.0 m x 3.2 m (12.8 m^2) with the net plot area of barley was 3.8 m x 2.8 m (10.64 m^2) both in the intercropping and sole cropping. The net plot size of lupine in the sole cropping was 3.8 m x 2.4 m (9.12 m^2), but in the intercropping it was variable depending on the plant population. Adjacent plots and blocks were separated with 0.5 m and 1.0 m wide paths, respectively.

Table 2: Intercropping treatment combinations and sole crops used for the experiment

Lupine plant population (plants/ha)	Time of lupine intercropping with food barley			
	Simultaneously (P1)	2WABS (P2)	4WABS (P3)	6WABS (P4)
500000 (R1)	R1P1 (T1)	R1P2 (T4)	R1P3 (T7)	R1P4 (T10)
250000 (R2	R2P1 (T2)	R2P2 (T5)	R2P3 (T8)	R2P4 (T11)
166667 (R3)	R3P1 (T3)	R3P2 (T6)	R3P3 (T9)	R3P4 (T12)
		Barley sole cropping (T13)		
		Lupine sole cropping (T14)		

WABS = weeks after barley sowing, T = treatment

In both experimental years of 2017 and 2018, the selected experimental plots were plowed repeatedly by oxen using local plowing tool “Maresha” as conventionally practiced by the surrounding farmers. Experimental plots were then prepared manually as per the design and treatments using necessary farm tools. After starting the reliable rainfall, seeds of food barley were drilled in 20 cm spaced rows at the recommended plant population of 100 kg/ha on 22 and 14 June 2017 and 2018, respectively. Lupine seeds in sole cropping were planted at 40 cm inter-row and 10 cm intra-row spacing on the same date of barley sowing, while lupine seeds in the intercropping were planted after every two rows of barley (equivalent to the recommended 40 cm inter-row spacing of sole lupine) at intra-row spacing of 5, 10 and 15 cm (equivalent to 500000, 250000 and 166667 plants/ha, respectively) on different dates as per the treatments. All experimental plots including sole lupine plots were received a basal application of NPS (19% N, 38% P_2O_5, 7% S) at the rate of 100 kg/ha during planting of barley. Urea (46% N) at the rate of 100 kg/ha was also applied in split into barley plots in such a way that one third of it was applied as basal during planting and the remaining two third as side-dressing at tillering growth stage. Beyond fertilizers applied to food barley, any additional fertilizers were not specifically applied to white lupine in the intercropping treatments. Other all remaining agronomic practices were also carried out as per their recommendations used for food barley and lupine productions in the study area (ARARI, 2003).

2.4. Crop yield data collection

After physiological maturity, both barley and lupine plants were allowed to dry as stand up and harvested manually with sickle at the ground level. The harvested pieces of bunches were further subjected to sun drying till their weight attained constant and the above-ground biomass of the component crops per net plot area was measured with sensitive weighing balance. Grains of the component crops were further recovered and weighed after threshing, winnowing and cleaning. The grain yields of barley and lupine were adjusted to 12% and 10% contents, respectively. Above ground biomass and grain yields obtained from the net plot areas were finally converted to hectare basis.

2.5. Crop yield data analysis

Data of biomass and grain yields of the component crops collected in 2017 and 2019 were separately subjected to analysis of variance (ANOVA) using general linear model (GLM) procedures of SAS version 9.4 (SAS, 2013). Since values for the error mean square of the two years were homogeneous, the data were combined over years (Gomez and Gomez, 1984). Year was considered as a random variable in the combined analysis. Whenever the combined ANOVA result showed significant difference between treatments for a parameter, further mean separation was done using Tukey test using the same statistical software.

2.6. Production efficiency assessments

Land equivalent ratio (LER), area time equivalent ratio (ATER), crop equivalent yield (CEY), relative production efficiency (RPE) and relative economic efficiency (REE) are some of the common methods used for assessing the production efficiency of cropping systems (Samant, 2015; Yayeh *et al*., 2020). LER is a measure of the efficiency of land use in an intercropping system. It indicates the efficiency of intercropping for using the resources of the environment compared with sole cropping (Yayeh *et* *al*., 2020; Zhang *et al*., 2014). The LER was calculated using the formula outlined by Yayeh *et al*. (2020):

$$LER = \sum_{i=1}^{n}(\frac{Yi}{Ym}) \quad [1]$$

Where, Yi and Ym were yields of component crops in intercrop and sole cropping, respectively, and n was the number of the crops involved.

The critical value of LER was one. When LER was one, there was complementarity between component crops. When the LER was greater than one, the intercropping favored the growth and yield of the component crops. In contrast, when LER was lower than one, the intercropping negatively affected the growth and yield of the component species.

ATER was also calculated using the formula sketched by Yayeh et al. (2020) as:

$$ATER = \frac{(PLERb*Tb)+(PLERl*Tl)}{T} \quad [2]$$

Where, PLERb and PLERl were partial land equivalent ratios of barley and lupine, respectively; Tb, Tl and T were the durations of barley and lupine maturity, as well as the total duration of the intercropping system, respectively.

Like that of LER, the critical value of ATER was one. When ATER was equal to one, there was complementarity between the component crops. When the ATER was greater than one, intercropping favored the growth and yield of the component crops. In contrast, when ATER was lower than one, intercropping negatively affected the growth and yield of the component crops.

To estimate CEY, the average yield of the component crops was primarily converted into the main crop barley equivalent yield (BEY) on a price basis following Samant (2015) and Yayeh *et al*. (2020).

$$\text{BEY (kg ha}^{-1}\text{)} = \text{LY (kg ha}^{-1}\text{)} * (\frac{Pl(ETB\ kg-1)}{Pb\ (ETB\ kg-1)}) \quad [3]$$

Where, LY was the lupine yield; Pl and Pb were prices of lupine and barley, respectively, in Ethiopian Birr per kg (ETB kg^{-1}).

The CEY was then the summation of barely yield and barley equivalent yield (BEY). RPE and REE were further estimated on the basis of CEY using the formulae sketched by Yayeh *et al*. (2020) as the followings:

$$RPE\% = (\frac{CEYi-CEYs}{CEYs}) \text{ x } 100 \quad [4]$$

$$REE\% = \left(\frac{NRi-NRs}{NRs}\right) x100 \quad [5]$$

Where, CEYi and CEYs were crop equivalent yields of intercropping and sole cropping systems, respectively; NRi and NRs were net returns of intercropping and sole cropping systems, respectively.

Positive results of RPE indicated the superiority of the new intercropping system of white lupine with food barley over the existing system of sole cropping. Whereas, negative results of RPE indicated inferiority of the new intercropping system under the existing sole cropping. Higher REE was inferred as the better cropping system.

2.7. Partial budget analysis

Partial budget analysis was used to assess the economic advantage of the cropping systems by estimating total variable cost, gross return, net return and marginal rate of return on hectare basis following the procedures described by CIMMYT (1988). Seeds of the component crops, soil fertilizers and labor (for land preparation, sowing, fertilize application, harvesting, threshing and cleaning) were the main variable costs of the experiment. Costs of barley and lupine seeds were estimated at the local market prices of Ethiopian Birr 20 and 15 per kg, while costs of labor and fertilizers (Urea and DAP) were estimated at Ethiopian Birr 100 per manday and 13 and 15 per kg, respectively. Barley and lupine grain yields were adjusted by reduction of 10% to reflect the actual productivity of farmers as described by CIMMYT (1988). Gross return was hence estimated as the multiple of the adjusted grain yields of the component crops (barley and lupine) and their farm gate prices of Ethiopian Birr 15 and 10 per kg, respectively. Net return was estimated by subtracting the total variable cost from the gross benefit, while marginal rate of return (MRR%) was estimated as the percentile ratio of the net return and variable cost differences of the intercropping treatments and the control (barley sole cropping). Mathematically, MRR was calculated as follow:

$$MRR(\%) = (\frac{(NRs-NRp)}{(TVCs-TVCp)})x100 \quad [6]$$

Where, NRs and NRp were the immediate succeeding and preceding net returns of the treatment combinations, while TVCs and TVCp were the immediate succeeding and preceding total variable costs of the treatment combinations, respectively, after putting the TVC in ascending orders.

Acceptability of intercropping by farmers is best judged by the marginal rates of return (MRR), which is considered as an appropriate indicator for maximum profit of the cropping systems (Kiwia *et al*., 2019) and it was used for ranking the intercropping treatments of the experiment. According to Kiwia *et al*. (2019), MRR less than 50% is considered low and unacceptable to farmers, while MRR > 100% is a higher cut-off value that has been recommended for the technology, which involves significant change from current farmer practices.

3. Results and Discussion

3.1. Grain and biomass yields

The results of analysis of variance showed that both grain and above ground biomass yields of food barley were not significantly ($P \geq 0.05$) influenced by both main and interaction of plant population and time of lupine additive intercropping. However, main and interaction of plant population and time of lupine additive intercropping with food barley highly significantly ($P<0.01$) affected both grain and above ground biomass yields of lupine (Table 3). In the intercropping treatments, the highest grain and biomass yields of lupine were recorded in the combination of 166667 plants/ha plant population (15cm intra-row spacing) and simultaneous planting of lupine on the same date of barley sowing. Simultaneous planting of lupine on the same date of barley sowing at its plant population of 250000 and 500000 plants/ha (10cm and 5cm intra-row spacing, respectively) gave the second and third highest grain and biomass yields of lupine in food barley-lupine intercropping systems (Table 3). Lupine grain and biomass yields were reduced consistently as its intercropping time after barley sowing prolonged and its plant population increased (Table 3).

Table 3: Average grain and biomass yields of the component crops as influenced by plant population and time of lupine additive intercropping with barley in 2017 and 18 in Gozamin highland

Lupine intercropping with barley		Food barley		Lupine	
SR (plants/ha)	Intercropping time	GY (ton/ha)	BY (ton/ha)	GY (ton/ha)	BY (ton/ha)
500000	SMPwB	1.78	7.49	1.46^{d}	1.95^{d}
	2WABS	1.87	7.53	0.64^{g}	1.12^{f}
	4WABS	2.02	7.70	0.53^{gh}	0.95^{fg}
	6WABS	2.10	7.84	0.27^{i}	0.88^{g}
250000	SMPwB	1.91	8.04	1.75^{c}	2.12^{c}
	2WABS	2.03	8.19	0.84^{f}	0.98^{fg}
	4WABS	2.17	8.26	0.80^{f}	0.91^{g}
	6WABS	2.21	8.32	0.44^{h}	0.87^{g}
166667	SMPwB	1.94	8.17	2.33^{b}	2.74^{b}
	2WABS	2.10	8.31	1.01^{e}	1.35^{e}
	4WABS	2.24	8.54	0.90^{ef}	1.18^{ef}
	6WABS	2.29	8.63	$0.56g^{h}$	0.86^{g}
Barley sole cropping		2.51	9.88	-	-
Lupine sole cropping		-	-	3.29^{a}	4.65^{a}
Sig. difference		NS	NS	**	**
SE±		0.09	0.88	0.03	0.05
CV (%)		7.82	10.64	5.02	5.89

SR = plant population; SMPwB = simultaneous planting with barley; 2WABS = two weeks after barley sowing; 4WABS = 4 weeks after barley sowing; 6WABS = six weeks after barley sowing; GY = grain yield; BY = above ground biomass yield; **highly significant at $P<0.01$; NS = not significant at $P\geq0.05$; means followed with the same letter are not significant at $P\geq0.05$.

The non-significant difference between the barley-lupine intercropping for the yield related parameters of barley indicated that the associated lupine did not cause severe competition for the limited growth resources on the main crop. On the contrary, both biomass and grain yield of lupine in the intercropping treatments were lessen below that of sole lupine cropping, indicating the growth dominance of barley over lupine in their intercropping systems. Similar results were also reported by Yeyeh *et al*. (2014), who showed that seed proportions in the lupine-barley intercropping did not affect all yield related parameters of barley. This is further supported by Adipala *et al*. (2002), who reported that maize yields were not significantly affected by the inclusion of cowpea in different time of planting in maize-cowpea intercropping experiment.

Consistent reduction of lupine grain and biomass yields with the prolong of lupine intercropping time after barley sowing would be associated to the increase of barley over shading effect, as well as to the progress of soil moisture stress as the advancement of drying season after August. Declining of lupine grain and biomass yields with the increase of lupine plant population in barley-lupine intercropping might related to the increase of intra-specific competition among lupine plants for light and moisture. These results are supported by other cereal-legume intercropping works (Tilahun, 2002; Egbe, 2010; Addo-Quaye *et al*., 2011). The present results clearly showed that delay intercropping of lupine after barley sowing was less advantageous than simultaneous intercropping with barley sowing, while lupine grows slower than barley. Besides, plant population of lupine in barley-lupine intercropping would be lower than the recommended plant population of sole lupine cropping.

3.2. Production efficiency

Influences of plant population and time of lupine additive intercropping with barley on various production efficiency measures including land equivalent ration (LER), area time equivalent ratio (ATER), crop equivalent yield (CEY), relative production efficiency (RPE) and relative economic efficiency (REE) are presented in Table 4. LER of intercropping treatment combinations was ranging from 0.84 to 1.48 (Table 4). Those intercropping treatments having <1 LER are disadvantageous than sole cropping, while those intercropping treatments having >1 LER are more advantageous than sole cropping. As shown in Table 4, several intercropping treatments resulted in the LER values of .05 to 1.48, indicating their yield advantages from 5% to 48%, respectively, over sole cropping. Compared the sole cropping, the treatment combination of 16667 plants/ha plant population and simultaneous intercropping of lupine with barley sowing (SMPwB) gave the highest yield advantage (48%), followed by the combination of 250000 plants/ha plant population and simultaneous intercropping of lupine with lupine sowing with 30% yield advantage. This revealed that sole cropping would require 48% and 30% more land area to equalize the yield obtained from these intercropping treatment combinations, On the contrary, the highest yield reduction (-16%) was recorded in the combination of 500000 plants/ha plant population and intercropping of lupine after six weeks of barley sowing (6WABS) compared to that of the sole cropping.

Table 4: Average production efficiency of barley-lupine intercropping as influenced by plant population and time of lupine additive intercropping in 2017 and 2018 in Gozamin highland

Lupine intercropping with barley		LER	ATER	CEY (t/ha)	RPE (%)	REE (%)
SR (plants/ha)	Intercropping time					
500000	SMPwB	1.15	0.88	2.75	9.84	-3.26
	2WABS	0.94	0.63	2.29	-8.45	-26.40
	4WABS	0.97	0.64	2.37	-5.29	-22.41
	6WABS	0.84	0.51	2.08	-16.90	-37.09
250000	SMPwB	1.30	1.00	3.08	23.04	19.62
	2WABS	1.05	0.75	2.56	1.99	-7.03
	4WABS	1.11	0.76	2.71	8.14	0.76
	6WABS	0.97	0.60	2.39	-4.46	-15.18
166667	SMPwB	1.48	1.19	3.49	39.28	42.61
	2WABS	1.15	0.82	2.77	10.71	6.45
	4WABS	0.97	0.69	2.34	-6.66	-15.54
	6WABS	0.97	0.62	2.37	-5.40	-13.94
Barley sole cropping		1.00	1.00	2.51	0.00	0.00
Lupine sole cropping		1.00	1.00	2.19	-12.50	-12.64

SR = plant population; SMPwB = simultaneous planting with barley; 2WABS = two weeks after barley sowing; 4WABS = 4 weeks after barley sowing; 6WABS = six weeks after barley sowing; LER = land equivalent ratio; ATER = area time equivalent ratio; CEY = crop equivalent yield; RPE = relative production efficiency; REE = relative economic efficiency

Except the combinations of 166667 and 250000 plants/ha plant population with simultaneous intercropping of lupine with barley, all other intercropping treatment combinations resulted in ATER values <1, indicating their yield disadvantages below the sole cropping. The intercropping treatment combination of 166667 plants/ha plant population and simultaneous planting of lupine with barley sowing resulted in the highest ATER (1.19). This showed that intercropping of lupine with barley in this treatment combination favored the growth and yield of the component crops by 19% over the sole cropping. The ATER value of lupine intercropping with barley at 166667 plants/ha plant population and simultaneous planting of lupine with barley sowing was one, indicating growth and yield complementarity between the component crops at this intercropping treatment combination.

The highest CEY (3.49 t/ha) was also recorded from the intercropping treatment combination of 166667 plants/ha plant population and simultaneous planting of lupine with barley sowing (Table 4). The intercropping treatment combination of 250000 plants/ha plant population and simultaneous planting of lupine with barley sowing gave also the second highest CEY (3.08 t/ha)). The CEY values of intercropping treatment combinations less than that of barley sole cropping (2.51 t/ha) indicated their yield inferiority performances below barley sole cropping. Several intercropping treatment combinations also generated negative RPE and REE, indicating their yield inferiority performances below barley sole cropping. Similar to LER and CEY, the highest positive RPE (39.28%) and REE (42.61%) were also recorded from the intercropping treatment combination of 166667 plants/ha plant population and simultaneous planting of lupine with barley sowing (Table 4). The second highest positive RPE (23.04%) and REE (19.62%) were also obtained from the intercropping treatment combination of 250000 plants/ha plant population and simultaneous planting of lupine with barley sowing. These and other few intercropping treatment combinations generated higher and positive RPE and REE showed their superiority over the existing sole cropping.

Results of the present study showed that additive intercropping of white lupine with food barley at its optimum plant population and intercropping time gave higher LER, ATER, CEY, RPE and REE than the existing sole cropping of the component crops. In agreement to these results, several additive intercropping studies such as pea-wheat (Naudin *et al*., 2010), cluster bean-beet root (Sankaranarayanan *et al*., 2011), white lupine-small grain cereals (Yayeh *et al*., 2014), and haricot bean/sweet lupine-finger millet (Yayeh *et al*., 2019, 2020) at the optimum plant populations of the secondary legume crops also showed higher LER, RPE and REE compared to the respective sole cropping of the main crops. All these results revealed that intercropping of suitable legumes with cereals at their optimum plant population and intercropping time are more efficient than the existing sole cropping of the component crops in crop production and resource utilization. Li *et al*. (2013) indicated that inter-specific interactions between legumes and cereals at their optimum plant population make cereals to acquire more soil nitrogen, which pushes the legumes to fix more nitrogen and thus improves the land use efficiency of the system.

3.3. Economic profitability

Similar to production efficiency measures, the highest NR (Ethiopian Birr 38,160/ha) with acceptable MRR (598.68%) was recorded at the combination of 166667 plants/ha plant population and simultaneous intercropping of lupine with barley sowing (Table 5). Similarly, several workers also reported that legume-cereal intercropping systems at their optimum plant population resulted in significantly higher NRs with acceptable MRRs (>100%) than the existing sole cropping of the component crops (Seran and Brintha, 2010; Yayeh *et al*., 2014; FAO, 2015; Alemayehu *et al*., 2016; Wang *et al*., 2017; Marcello, 2018; Yang *et al*.; 2018; Yayeh *et al*., 2019). According to FAO (2015), intercropping of suitable secondary crop species with main crops at their optimum plant populations is highly recommendable for small scale farms (which are of labor intensive) for maximizing crop productivity and return sustainably much better than that of sole cropping. As it wouldn't be easy for field management especially for inter-row movements, intercropping may not however suitable to large mechanized crop farms.

Table 5: Average economic profitability of barley-lupine intercropping as influenced by plant population and time of lupine additive intercropping in 2017 and 2018 in Gozamin highland

Lupine intercropping with barley		TVC	GR	NR	MRR (%)	Rank
PP (plants/ha)	Intercropping time	(ETB/ha)	(ETB/ha)	(ETB/ha)		
Barley SC		7100.00	33885.00	26785.00	-	-
166667	SMPwB	9000.00	47160.00	38160.00	598.68	1
	2WABS	9000.00	37440.00	28440.00	D	-
	4WABS	9000.00	38340.00	29340.00	D	-
	6WABS	9000.00	35955.00	26955.00	D	-
250000	SMPwB	9650.00	41535.00	31885.00	D	-
	2WABS	9650.00	34965.00	25315.00	D	-
	4WABS	9650.00	36495.00	26845.00	D	-
	6WABS	9650.00	33795.00	24145.00	D	-
500000	SMPwB	11300.00	37170.00	25870.00	D	-
	2WABS	11300.00	31005.00	19705.00	D	-
	4WABS	11300.00	32040.00	20740.00	D	-
	6WABS	11300.00	30780.00	19480.00	D	-

PP = plant population; SC = barley intercropping; SMPwB = simultaneous planting with barley; 2WABS = two weeks after barley sowing; 4WABS = 4 weeks after barley sowing; 6WABS = six weeks after barley sowing; TVC = total variable cost; GR = gross return; NR = net return; MRR = marginal rate of return; ETB = Ethiopian Birr; D = dominance

4. Conclusion

In all assessment methods employed in the study, 166667 plants/ha plant population at simultaneous intercropping time of lupine with barley gave the highest LER, CEY, RPE, REE and NR with 48%, 39.04%, 39.28%, 42.61% and 42.47% more advantages, respectively, than that of barley sole cropping. The plant population of 250000 plants/ha at simultaneous intercropping time of lupine with barley gave the second highest LER, CEY, RPE and REE with 30%, 22.71%, 23.04% and 19.62% more advantages, respectively, than that of barley sole cropping. At simultaneous intercropping time of lupine with barley, the plant population of 166667 plants/ha plant population of lupine additive intercropping with barley is hence suggested as the best recommendations to barley growing smallholder farmers in Gozamin highlands and similar areas in northwest Ethiopian highlands for enhancing the productivity of barley fields sustainably.

Acknowledgements

The authors sincerely acknowledge Bahir Dar University for its financial support to execute the field experiment. Debre Markos University is also duly acknowledged for its provision of experimental plot in its trial site at the main campus. Sincere acknowledgement is given to Dereje Ademe for his assistance in analyzing the data with SAS program.

Conflict of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

References

Addo-Quaye, A.A., Darkwa, A.A. and Ocloo, G.K. (2011). Yield and productivity of component crops in a maize-soybean intercropping system as affected by time of planting and spatial arrangement. *Journal of Agricultural and Biological Sciences*. 6(9): 50-57.

Adipala, E., Ocaya, C.P. and Osiru, D.S.O. (2002). Effect of time of planting cowpea (*Vigna unguiculata* L). Relative to maize (*Zea mays* L.) on growth and yield of cowpea. *Tropicultura*. 20(2): 49-57.

Akale, A.H., Alemu, M.W. and Asmamaw, M.B. (2019). Analyze production, utilization and its future trends of lupine in Ethiopia. *American Journal of Plant Sciences* 10: 1797-1812. https://doi.org/10.4236/ajps.2019.1010127

Alemayehu, A., Tamado, T., Nigusie, D., Yigzaw, D., Kinde, T. and Wortmann, C.S. (2016). Maize-common bean-lupine intercrops productivity and profitability in maize-based cropping system of Northwestern Ethiopia. *Ethiopian Journal of Science and Technology*. 9(2): 69–85. https://doi.org/10.4314/ejst.v9i2.1

Alemayehu, S.T., Dorosh, P. and Sinafikeh, A. (2011). Crop *production in Ethiopia: Regional patterns and trends*. *Ethiopia Strategy Support Program II (ESSP II) ESSP II Working Paper No. 0016*. Addis Ababa: International Food Policy Research Institute (IFPRI).

ANRS (Amhara National Regional State) Bureau of Agriculture. (2020). *Crop production in ANRS: Annual Report (2019/20)*. Bahir Dar: Bureau of Agriculture.

ARARI (Amhara Regional Agricultural Institute. (2003). Practical *crop production guide*. Bahir Dar, Ethiopia.

Beneberu, T., Likawent, Y., Nelson, M., Taylor, J., Mcnaughton, D., Sergeant, A. and Sanders, H. (2019). Farmers' decisions and determinants of crop rotations with lupine: The case of West Amhara Region, Ethiopia. *Review of Agricultural and Applied Economics*. 22: 24-31. https://doi.org/10.15414/raae.2019.22.01.24-31

Bouyoucos, A. (1962). Hydrometer method improved for making particle size analyses of Soils 1. *Agronomy Journal*. 54(5): 464–465. https://doi.org/10.2134/agronj1962.00021962005400050028x.

Brady, N.C. and Weil, R.R. (2017). *The Nature and poperties of soils, fifteenth ed., (eBook)*. Boston: Pearson.

Bremner, J.M. and Mulvaney, C.S. (1982). Nitrogen Total. In: A.L. Page (Ed.), *Methods of soil analysis - Agronomy No. 9, Part 2: Chemical and Microbiological Properties, second ed.,* (pp. 595–624). Madison, Wisconsin: American Society of Agronomy.

Charman, P. and Roper, R. (2007). Soil Organic Matter. In: P. Charman and B. Murphy (Eds.), *Soils, their properties and management, third ed.*, (pp. 276-285). Melbourne: Oxford University Press.

CIMMYT (International Maize and Wheat Improvement Centre). (1988). *From agronomic data to farmer recommendations. An economic training manual. Revised edition*. Mexico DF.

CSA (Central Statistical Agency). (2018). *Agricultural Sample Survey 2017/2018- Volume 1: Area and* production *of major crops*. Central Statistical Agency, Federal Democratic Republic of Ethiopia, Addis Ababa.

Dai, X., Pu, L. and Rao, F. (2017). Assessing the effect of a crop-tree intercropping program on smallholders' incomes in rural Xinjiang, China. *Sustainability*. 9: 1–19. https://doi.org/10.3390/su9091542

Debre Markos Meteorology Station. (2017). *Weather data records for 36 years from 1981 to 2016*. Debre Markos, Ethiopia.

Egbe, O. (2010). *Effects of plant density of intercropped soybean* with *tall sorghum on competitive ability of soybean and economic yield at Otobi, Benue State, Nigeria*.

FAO. (Food and Agriculture Organization of the United Nations). (2008). *Guide to laboratory establishment for plant nutrient analysis. FAO Fertilizer and Plant Nutrition Bulletin 19*. FAO, Rome, Italy.

FAO. (2015). *Maize-legume system: Save and grow farming systems fact sheet 7*. Rome, Italy.

Gee, G.W. and Bauder, W. (1986). Particle-size Analysis. In: A. Klute (Ed.), *Methods of soil analysis - Agronomy No. 9, Part 1: Physical and Mineralogical Methods, second ed*., (pp. 383-411). Madison, Wisconsin: American Society of Agronomy.

Getachew, A., Agegnehu, S., Enyew, A., Ash, F. and Freyer, B. (2020). Crop rotation and organic matter application restore soil health and productivity of degraded highland crop farms in northwest Ethiopia. *Cogent Food & Agriculture*. 6: e1831124. https://doi.org/10.1080/2331 1932.2020.1831124.

Gomez, K.A. and Gomez, A.A. (1984). *Statistical procedures for agricultural research*. New York: John Wiley and Sons.

Havlin, J.L., Beaton, J.D., Tisdale, S.L. and Nelson, W.L. (1999). Function and Forms of N in Plants. In: *Soil fertility and fertilizers, sixth ed*. New Jersey: Prentice Hall.

Heanes, D.L. (1984). Determination of total organic C in soils by an improved chromic acid digestion and spectrophotometric procedure. *Communications in Soil Science Plant Analysis*. 15: 1191–1213. https://doi.org/10.1080/0010 3628409367551.

Hibstu, A., Firew, M., Yigzaw, D., Zerihun, T. and Negussie, M. (2016). Challenges on production and utilization of white lupine (*Lupinus albus* L.) in Ethiopia: A strategic orphan crop. *American Journal of Experimental Agriculture*. 13: 1-14. https://doi.org/10.9734/AJEA/2016/27930

Hodgson, J. and Lee, Y.P. (2008). *Potential for benefit of lupine on obesity and cardiovascular disease risk in humans*. https:/www.researchgate.net/publication/21878 8489. Retrieved: October 8, 2016.

Hurni, H., Solomon, A., Amare, B., Berhanu, D., Ludi, E., Portner, B., Birru, Y. and Gete, Z. (2010). Land degradation and sustainable land management in the highlands of *Ethiopia*. In: H. Hurni and U. Wiesmann (Eds.), *Global change and sustainable development: a synthesis of regional experiences from research partnerships*, (Vol. 5, pp. 187–207). Bern: Geographica Bernensia.

Kiwia, A., Kimani, D., Harawa, R., Jama, B. and Sileshi, G. (2019). Sustainable intensification with cereal-legume intercropping in Eastern and Southern Africa. *Sustainability*, 11: 1–18. https://doi:10.3390/su11102891

Landon, J.R. (1991). *Booker Tropical Soil Manual: A hand book for soil survey and agricultural land evaluation in the Tropics and Subtropics*. UK: Longman Scientific and Technical Essex.

Laurent, B., Hauggaard-Nielsen, H., Naudin, C. and CorreHellou, G. (2015). Ecological principles underlying the increase of productivity achieved by cereal-grain legume *intercrops* in organic farming. A review. *Agronomy for Sustainable Development*. 35(3): 911–935. https://doi.org/10.1007/s13593-014-0277-7

Li, L., Long, Z. and Fusuo, Z. (2013). Crop mixtures and the *mechanisms* of over-yielding. In: S.A. Levin (Ed.), *Encyclopaedia of biodiversity*, *second ed*., (Vol. 2., pp. 382–395). Waltham, MA: Academic Press. https://doi.org/10.1016/B978-0-12-384719-5.00363-4

Likawent, Y., Kijora, C., Solomon, M., Anteneh, G. and Peters, K.J. (2010). White lupine (*Lupinus albus* L.), the neglected multipurpose crop: Its production and utilization in the mixed crop-livestock farming system of Ethiopia. *Livestock Research for Rural Development*. 22(4): Article # 74.

Likawnt, Y., Kijora, C., Wink, M. and Peters, K.J. (2011). Effect of a traditional processing method on the chemical composition of local white lupine (*Lupinus albus* L.) seed in northwestern Ethiopia. *Zeitschrift Naturforschung*. 66(3): 403-408.

Marcello, G., Giacomo, T., Beatrice, F. and Paolo, B. (2018). Sustainable management of nitrogen nutrition in winter wheat through temporary intercropping with legumes. *Agronomy for Sustainable Development*. 38: e31. https://doi.org/10.1007/s13593-018-0509-3

MoFED (Ministry of Finance and Economic *Development*). (2016). *Second five years (2016-2020) national growth and transformation plan*. Ministry of Finance and Economic Development, Federal Democratic Republic of Ethiopia, Addis Ababa.

Naudin, C., Corre-Hellou, G., Pineau, S., Crozat, Y. and Jeuffroy, M.H. (2010). The effect of various dynamics of N availability on winter pea–wheat intercrops: Crop growth, N partitioning and symbiotic N_2 fixation. *Field Crops Research*. 119: 2–11. https://doi.org/10.1016/j. fcr.2010.06.002

Olsen, S. and Cole, C. (1954). *Estimation of available phosphorus in soils by extraction with sodium bicarbonate.* Washington: USDA.

Panda, S.C. (2010). Agronomy. In: *Agrobios (India)*, (pp. 99-137). Jedhpur, India,

Samant, T.K. (2015). System productivity, profitability, sustainability and soil health as influenced by rice based cropping systems under mid central table land zone of Odisha. *International Journal of Agriculture Sciences*. 7: 746–749.

Sankaranarayanan, K., Nalayini, P., Sabesh, M., Rajendran ,K., Nachane, P., Mumbai, Q.E. and Gopalakrishnan, N. (2011). *Multi-tier cropping system for profitability and stability in Bt cotton production.* Technical *Bulletin No.2*, (pp. 1–19).

SAS (Statistical Analysis System) Institute. (2013). *SAS/AF® 9.4: Procedure guide, second ed*. Cary, NC, USA.

Sedláková, K., Straková, E., Suchý, P., Krejcarová, J. and Herzig, I. (2016). Lupine as a perspective protein plant for animal and human nutrition: A review. *ACTA VET. BRNO*. 85: 165-175. https://doi.org/10.2754/avb201685020165

Seran, T. and Brintha, I. (2010). Review on maize based *intercropping*. *Journal of Agronomy*. 9(3): 135-145.

Tekalign, M.T., Haque, I. and Aduayi, E.A. (1991). *Soil, plant, water, fertilizer, cattle manure and compost analysis manual. Plant division working document 13*. Addis Ababa, Ethiopia: ILCA.

Teklu, E. (2005). *Land preparation methods and soil quality of Vertisol area in the Central Highlands of Ethiopia*. Universitat Hohenheim, Stuttgart, Germany.

Tilahun, T. (2002). *Effect of planting densities and arrangement of component crops on productivity of maize/faba bean intercropping system* (M.Sc. thesis). Alemaya University, Alemaya, Ethiopia.

Tizazu, H. and Emire, S.A. (2010). Chemical composition, physicochemical and functional properties of lupine (*Lupinus albus*) seeds grown in Ethiopia. *African Journal of Food, Agriculture, Nutrition and Development*. 10(8): 187-207. https://doi.org/10.4314/ajfand.v10i8.60895

Tsubo, M., Walker, S. and Ogindo, H.O. (2005). A simulation model of cereallegume intercropping systems for semi-arid regions II. Model application. *Field Crops Research*. 93: 23–33. https://doi.org/10.1016/j.fcr.2004.09.003

Villarino, C.B.J., Jayasena, V., Coorey, R., Chakrabarti-Bell, S. and Johnson, S.K. (2016). Nutritional, health, and technological functionality of lupine flour addition to bread and other baked products: Benefits and challenges – critical reviews. *Food Science and Nutrition*. 56(5): 835-857. https://doi.org/10.1080/10408398.2013.814044

Wang, G.Z., Li, H.G., Christie, P., Zhang, F.S., Zhang, J.L. and Bever, J.D. (2017). Plant-soil feedback contributes to intercropping overyielding by reducing the negative effect of take-all on wheat and compensating the growth of faba bean. *Plant Soil*. 415: 1–12. https://doi.org/10.1007/s11104-016-3139-z

Yang, C., Fan Z. and Chai Q. (2018). Agronomic and economic benefits of pea/maize intercropping systems in relation to N fertilizer and maize density. *Agronomy* 8(4): 1–14. https://doi.org/10.3390/ agronomy8040052

Yayeh, B., Fetien, A. and Tadesse, D. (2014). Effect of lupine (Lupinus Spp.) intercropping and seed proportion on the yield and yield component of small cereals in North western Ethiopia. *African Journal of Agricultural Research* 9(30): 2287–2297. https://doi.org/10.5897/AJAR

Yayeh, B., Getachew, A., Enyew, A. and Alemayehu, A. (2019). Boosting land use efficiency, profitability and productivity of finger millet by intercropping with grain legumes. *Cogent Food & Agriculture* 5: 1–22. https://doi.org/10.1080/23311932.2019.1702826

Yayeh, B., Getachew, A., Enyew, A. and Alemayehu, A. (2020). Competition, production efficiency and yield stability of finger millet and legume additive design intercropping. *Renewable Agriculture and Food Systems* e00101: 1–12. https://doi.org/10.1017/S1742170520000101

Zhang, F. and Li, L. (2003). Using competitive and facilitative interactions in intercropping systems enhances crop productivity and nutrient-use efficiency. *Plant and Soil* 248: 305–312. https://doi.org/10.1023/A:1022352229863

Zhang, G., Zaibin Y. and Shuting D. (2014). Interspecific competitiveness affects the total biomass yield in an alfalfa and corn intercropping system. *Field Crops Research* 124: 66–73. https://doi.org/10.1016/j.fcr.2011.06.006