**The effect of bi-cropping wheat *(Triticum aestivum*) and beans *(Vicia faba)* on forage yield and weed competition**

\*Nicola D Cannon, Donwell MA Kamalongo, John S Conway.

Royal Agricultural University, Cirencester, Gloucestershire, England, GL7 6JS.

Corresponding author: Nicola.cannon@rau.ac.uk

**Abstract**

Field experiments were conducted from April 2015 to September 2016 at the Royal Agricultural University, UK to explore the impact of drilling pattern and species mixtures on weed growth and forage yield. The bi-crops of spring field bean (*Vicia faba*) *cv.* Maris Bead and Fuego with spring wheat (*Triticum aestivum*) *cv.* Paragon were evaluated at four drilling patterns in a randomized complete block design with four replicates and compared against their respective sole crops. Weed DM was 59% higher in sole cropping systems than bi-cropping systems. Sole cropping systems outperformed bi-cropping systems for wheat (in 2016 only) and bean forage DM yield. However bi-cropping systems produced higher total forage DM yield than sole cropping systems. Weed DM was higher in broadcast than alternate rows. Bean forage DM was higher in alternate rows than broadcast by 74%. Wheat forage DM was not affected by the drilling patterns. Maris Bead had higher forage DM than Fuego (in 2016 only). In conclusion, bi-cropping can increase land productivity per unit area over sole cropping whilst improving forage DM yield and providing low cost integrated weed management. Alternate row drilling can improve bi-cropping productivity over broadcast practice.

**Key words**: bi-cropping, land equivalent ratio, resource-use efficiency,faba bean, forage yield, weed suppression.

# Introduction

Bi-cropping is a planned crop diversity strategy in space and time, which involves the growing of two dissimilar crops on the same production unit (Vandermeer et al.1998). There are various advantages of bi-cropping systems over sole cropping systems derived from ecological principles including; competition, complementarity and facilitation (Hauggaard-Nielsen et al. 2008). If the interspecific competition for growth resources is lower than the intraspecific competition, species share only part of the same niche resulting in reduced competition (Vandermeer 2011). Bi-cropping can offer benefits over sole cropping because it can increase production per unit area as a result of the more effective use of growth resources such as light, water and nutrients (Jalilian et al. 2017). Bi-cropping can offer higher yields than sole cropping due to better resource capture, which may occur when the grain legume component supplies nitrogen to other crops via biological nitrogen fixation (Corre-Hellou et al. 2011; Bedoussac and Justes 2010). Bi-cropping systems can also offer improved weed suppression due to more efficient capture and conversion of resources required for growth into crop biomass than in sole cropping systems (Khashayar et al. 2014). Bi-cropping has shown the capacity to improve sustainability in modern agricultural production systems over sole cropping by improving crop yields, reducing weeds and decreasing environmental deterioration (Malézieux et al. 2009).

With increasing restrictions on chemical weed control in European arable production systems, there has been a renewed interest to integrate non-chemical (cultural) weed control options, such as the use of competitive crop cultivars, resulting in reduced herbicide use and less detrimental to the environment (Food and Fairness 2008; Andrew et al*.* 2015) whilst suppressing weed seed production and help alleviate future weed infestation (Kumar et al. 2013). The use of crop height (Christensen 1995; Cosser et al. 1997), speed of crop development (Grime 2001) and efficient partitioning of resources (Stevanato et al. 2011) can play an important role in the reducing of weed growth and thereby improve long-term sustainability of organic based production systems (Andrew et al*.* 2015; Bahadur et al. 2015). Canopy architectural traits also contribute to integrated weed management strategy in bi-cropping production systems (Davies et al. 2004). Planophile crop cultivars were reported to be more suitable for cultural weed control over erectophile especially during the early growth stages (Eisele and Kopke 1997; Hoad et al. 2006; Davies et al. 2004). The use of competitive crop cultivars is rarely practised for weed control as it has not been the main focus for plant breeders (Andrew et al. 2015).

Bi-cropping can deliver higher forage yields than sole cropping whilst reducing weed growth by competing with the weeds for essential resources required for plant growth (Fernandez-Aparicio et al. 2010; Bahadur et al. 2015). Bicropping can improve soil fertility and combat low yield and quality (Askegaard et al. 2011) as well as mitigating risk of climate change (Brooker et al. 2015). It can prevent the proliferation of weeds by depriving them of critical growth resources without damaging the natural environment whilst obtaining higher forage yields (Liebman and Robichaux 1990; Rigby and Cáceres 2001). However, its effectiveness on the suppression of weeds can be influenced by a wide range of factors such as crop density, spatial arrangement and crop cultivars (Banik et al*.* 2006).

Bi-cropping using specified spatial arrangements is an intentional way of mixing dissimilar crops in the same production system in different geometrical arrangements such as; (i) alternate rows e.g. alternate single rows, alternate double rows and alternate triple rows, (ii) within rows, and (iii) broadcast among others (Musa et al*.* 2010). Spatial arrangements can play an important role in achieving interspecific complementarity on resources-use in crop mixtures with similar maturity periods (Klimek-Kopyra et al. 2015). Spatial arrangement can help to modify the crop canopy structure and micro-climate, which may lead to improved crop competitiveness against weeds, resource use efficiency and increased crop productivity (Sumathi et al. 2010; Olsen et al. 2012). Uniformly arranged bi-crops in alternate rows can increase spatial uniformity in leaf area index, promote early crop canopy closure, reduce the penetration of photosynthetically-active radiation through the crop canopy and increase crop dry matter yield (Olsen and Weiner 2007; Mashingaidze et al. 2009). According to Weiner et al.(2010) uniform spatial arrangement of bi-crops in alternate rows can help to delay the occurrence of intraspecific competition within the crop but can induce interspecific competition with weeds earlier in the growing season. However, randomly sown bi-crops have been reported less effective in weed control due to poor utilisation of growth resources (Bastiaans et al. 2008). Sowing the bi-crops within the same row can reduce the productivity of bi-cropping due to increased interspecific competition for growth resources (Chapagain 2014) but different crop mixtures can perform differently in different spatial arrangements by reducing the penetration of photosynthetically-active radiation into the crop canopy, weed suppression and the overall productivity of bi-cropping system, for example; barley/peas and oats/peas bi-cropping systems performed better when sown within rows (Chen et al. 2004; Lauk and Lauk 2008). However, Martin and Snaydon (1982) and Dubey et al. (1995) reported better performance of barley/beans and sorghum/soybean bi-cropping when sown in alternate rows.

Wheat/faba bean bi-cropping systems in the UK have been typically arranged in single alternate rows to aid large scale mechanised bi-cropping systems whilst developing sustainable feed for production systems for home-grown protein-rich forage (Bulson et al. 1997; Ghanbari-Bonjar 2000; Haymes and Lee 1999; Ghanbari-Bonjar and Lee 2003; Eskandari and Ghanbari-Bonjar 2010). It allows feasibility for mechanised drilling and combined harvesting of bi-crops (Bulson et al. 1997). When soil water is not limiting, the single alternate row spatial arrangement can improve leaf area index, light interception, weed suppression, aid direct nitrogen transfer due to closer proximity of bi-crop plants and physical root intermingling advantage (Musa et al. 2010; Mashingaidze et al. 2009). However, when soil water becomes limiting, the crop canopy competitiveness against weeds and the forage yield, can be reduced due to interspecific competition (Semere and Froud-Williams, 2001; Fanadzo et al*.* 2007).

The declaration by the European Parliament (2011), to promote self-sufficiency in home-grown forage for livestock in the European Union (EU) including the UK, encourages the development of more protein-rich spring faba bean varieties, which can be suitable for low input large scale bi-cropping (Häusling 2011). However, not all spring bean cultivars can achieve spatial complementarity on resource-use efficiency when sown in single alternate row spatial arrangement in mixture with spring wheat; this is due to their differences in morphology and growth rate traits. Most of these cultivars have been bred for sole cropping systems (Hill 1996), with the ability to exploit the environment solely for that crop and focus on increasing the availability and acquisition of limiting resources (White et al. 2013). Bi-crops components for bi-cropping are expected to have traits that can optimise complementarity or facilitation on the use of limited environmental resources (Costanzo and Barberi 2014).

The aims of this research were therefore to investigate:

(i) to what extend bi-cropping systems can improve weed control and increase forage DM yield over sole cropping,

(ii) to what extent manipulated spatial arrangements (drilling patterns) can influence interspecific complementarity on resource-use efficiency resulting in improved weed control and forage DM yield

(iii) to what extent the bean cultivars can influence resources-use efficiency resulting in improved weed control and forage productivity.

# Materials and methods

## *Site characteristics*

A field experiment was repeated for two years at the Steadings field at the Royal Agricultural University, Cirencester (51° 42' 33.6'' N 1° 59' 40.7'' W) in Gloucestershire, England during the 2015 and 2016 spring growing seasons. Previously, the land had been managed conventionally in a grass and clover ley but had received no inorganic fertiliser inputs. No fertiliser inputs or pesticides were used in the two years of this experiment, but the preceding ley was destroyed using glyphosate prior to ploughing. Climatic data during the two growing seasons of the experiments are presented in Table 1 and soil properties (0-20 cm) prior to sowing in Table 2.

Table 1. Monthly total rainfall and mean air temperature at Royal Agricultural University during the 2015, 2016 and 10-year mean growing seasons.

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| Months | Rainfall  (mm) | | 10-year mean (mm) |  | Mean temperatures (oC) | | 10-year mean (oC) |
|  | 2015 | 2016 | 2005-2014 |  | 2015 | 2016 | 2005-2014 |
|  | Site A | Site B |  | Site A | Site B |
| January | 93.1 | 106.8 | 79.5 |  | 3.8 | 5.0 | 4.1 |
| February | 51.9 | 80.7 | 56.4 |  | 4.4 | 4.6 | 3.8 |
| March | 34.2 | 111.3 | 54.4 |  | 6.3 | 5.3 | 6.4 |
| April | 13.9 | 55.0 | 43.2 |  | 9.1 | 7.7 | 9.2 |
| May | 71.0 | 78.9 | 72.0 |  | 11.5 | 12.6 | 11.8 |
| June | 41.8 | 106.1 | 62.1 |  | 14.3 | 15.2 | 14.8 |
| July | 56.3 | 27.1 | 78.9 |  | 17.1 | 16.9 | 16.4 |
| August | 75.7 | 52.1 | 66.1 |  | 15.6 | 17.4 | 16.0 |
| September | 62.0 | 42.8 | 49.7 |  | 12.7 | 16.1 | 15.2 |
| Totals | 499.9 | 660.8 | 562.4 | Mean | 10.5 | 11.2 | 10.9 |

Table 2. Characteristics of the soils (0-20 cm)\* at the beginning of the experiment in the 2015 and 2016 spring growing seasons.

|  |  |  |  |
| --- | --- | --- | --- |
| Properties | Spring growing seasons | | |
|  | 2015 | | 2016 |
|  | Site A | Site B | |
| **Chemical characteristics** | Values | | Values |
| pH 1:2.5 (soil: water ratio) | 7.8 | | 7.6 |
| Extractable Phosphorus (mg l-1) | 13.3 | | 17.0 |
| Organic matter (%) | 4.6 | | 3.6 |
| Total Nitrogen (%) | 0.43 | | 0.39 |
| Organic carbon (%) | 2.6 | | 2.1 |
|  |  | |  |
| **Physical composition** |  | |  |
| Sand (%) | 20.0 | | 21.0 |
| Silt (%) | 38.0 | | 37.0 |
| Clay (%) | 42.0 | | 42.0 |
| Textual class | Clay | | Clay |

\*Analyses conducted at Royal Agricultural University laboratory

## *Experimental design*

Field experiments were laid out as a randomised complete block design with four replications. Different, but adjoining land was used for each of the trial years. The cropping system was either sole crop wheat or beans, or a bi-cropping system. Two spring faba bean cultivars were evaluated in four drilling patterns comprised of (i) one row of wheat alternated with one row of beans (1 x 1); (ii) two rows of wheat alternated with two rows of beans (2 x 2); (iii) three rows of wheat alternated with three rows of beans (3 x 3) or (iv) broadcast, the beans bi-crop was randomly sown over and next to the drilled (in rows) wheat crop (Figure 1). The sole crops of wheat and beans were included as controls against their relative crops in mixtures. The two spring bean cultivars were; (i) Fuego with fast growth rate, short straw height, and (ii) Maris Bead with slower growth rate and tall straw height. The sowing density in bi-cropping plots was reduced to half of their respective sole cropping plots of wheat and beans (Snaydon 1991) as a strategy to achieve complementarity (Fradgley et al. 2013). The plot size was 2 m x 12 m (24 m2). Wheat and bean seeds were sown at the recommended density of 400 and 40 seeds m-2, respectively. The interrow distances for sole bean and wheat plots were 30 cm and 15 cm respectively. All bi-crop plots were sown at a uniform interrow distance of 15 cm apart except for the broadcast bi-cropping plots, where the bean seeds were randomly sown over the wheat crop established at an interrow distance of 15 cm apart.

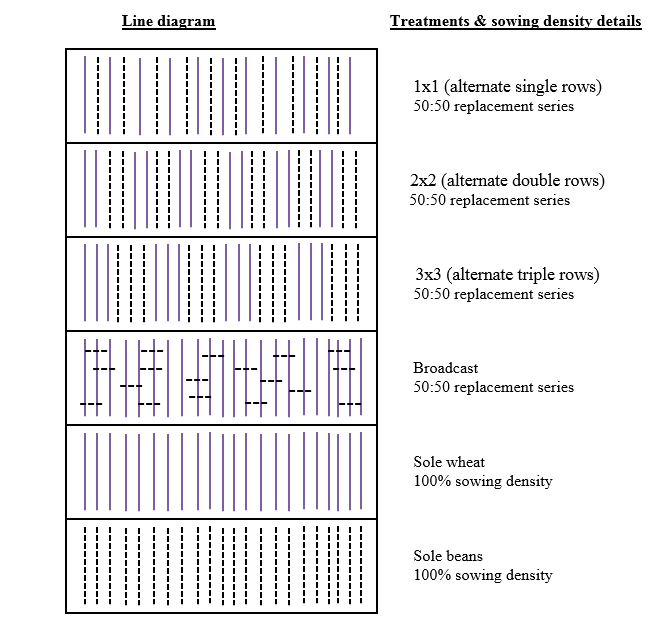


Figure 1. Schematic representation of drilling patterns in a wheat and faba bean bi-cropping systems.

## *Plot management*

In both spring seasons, prior to plot demarcation and sowing, the sites were sprayed with glyphosate and were then shallow disc harrowed. Wheat was drilled using a Winstersteiger Precision Seed Drill at the average soil depth of 2.5 cm. The beans in all plots (including the plots were the beans were broadcast) were hand sown at the average soil depth of 5.0 cm, because the plot drill specifications could not drill both crops simultaneously. Both wheat and beans were sown on the same day. The sowing dates for the 2015 and 2016 growing seasons were 9 April 2015 and 2 May 2016, respectively.

## *Measurements*

Forage yield and weed assessments were conducted at specific wheat and beans crop growth stages (GS) as defined by Zadoks et al.(1974) and PGRO (2016) respectively. Both crop and weed plant samples were hand harvested from 1 m2 quadrant area randomly placed at two points in the inner part of each plot, excluding the outer rows. Harvested plant samples were placed in air-tight plastic bags for total above-ground fresh weight determination. In the laboratory, plant samples were separated into weeds; wheat and bean for every plot and their respective total above-ground fresh weights recorded. The harvested wheat plants were further segregated into straw and ears before threshing. Similarly, the bean plants were separated into straw and pods before threshing. Sub samples of each of these categories of plant samples were oven dried for 48 hours at a constant temperature of 65 oC. After drying, the dry weight was recorded, and the total biomass yield determined.

***Land Equivalent Ratio (LER) and Partial Land Equivalent Ratio (PLER)***

The LER measures the effective use of environmental resources in bi-cropping systems compared to sole cropping systems. It measures the production efficiency of different systems by converting the production in terms of land area and can be used both for replacement and additive series of bi-cropping systems. LER was calculated according to Mead and Willey (1980), as follows:

Bi-crop yield of wheat

Bi-crop yield of beans

Sole crop yield of wheat

Sole crop yield of beans

+

LER =

## The LER values for two intercrop species in proportional replacement design were calculated as: LER = (PLER wheat + PLER beans), where PLER wheat = (Ywb/Yws), and PLER beans = (Ybb/Ybs), where Yws and Ybs were the yields of wheat and beans as sole crops respectively, and Ywb and Ybb were the yields of wheat and beans as bi-crops respectively. PLER is the partial equivalent ratio of each crop in mixture. The value of unity (1.0) is the critical value in assessing crop mixtures. A LER value greater than 1.0 indicates that bi-cropping systems favours the growth and yield of the cultivars; LER equal to 1.0 indicates no advantage of bi-cropping systems. When LER is lower than 1.0 the bi-cropping system negatively affects the growth and yield of the plants grown in mixtures (Dhima et al. 2007).

## *Statistical analysis*

The data were subjected to analysis of variance (ANOVA) using Genstat (Version 15.1, VSN International Ltd, U.K). The data on above-ground weed DM were subjected to square root transformation (√x + 0.5) to normalize the distribution. Statistical comparison of treatment means was conducted using standard error of the difference (sed) in accordance with Vijaya Bhaskar (2014).

# Results

Weed and bean forage DM yield was significantly higher in 2016 than in the 2015 growing season.

Table 3. The combined analysis of variance of weed, LER, wheat and bean forage DM yield influenced by cropping systems, drilling patterns and bean cultivars over two years (2015 and 2016) in wheat/faba bean bi-cropping.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Source of variation | Degrees of Freedom | Mean squares | | | |
| Weed  DM yield  (g m-2) | Wheat forage DM yield  (t ha-1) | Bean forage  DM yield  (t ha-1) | LER |
| Cropping systems (2) | 1 | 4.3182\*\*\* | 2.535\*\*\* | 7.924\*\*\* | 0.7959\*\*\* |
| Drilling patterns (4) | 3 | 7.383\*\*\* | 0.211ns | 1.94\*\*\* | 0.3254\*\*\* |
| Bean cultivars (2) | 1 | 4.7007\*\*\* | 0.001ns | 0.257ns | 0.0003ns |
| Year (growing season) (2) | 1 | 0.5299ns | 2.599\*\*\* | 5.563\*\*\* | 0.3075\*\*\* |
| Cropping system (2) x Year (2) | 1 | 0.2282ns | 0.6588ns | 0.4408ns | 0.0245ns |
| Drilling pattern (4) x Bean cultivar (2) | 3 | 0.1766ns | 0.200ns | 0.088ns | 0.0063ns |
| Drilling pattern (4) x Year (2) | 3 | 1.1838\* | 0.492\* | 0.906ns | 0.0524ns |
| Bean cultivar (2) x Year (2) | 1 | 0.1698ns | 0.030ns | 0.998\* | 0.0157ns |
| Drilling pattern (4) x Bean cultivar (2) x Year (2) | 3 | 0.1770ns | 0.144ns | 0.595ns | 0.0955ns |

Notes: Values in brackets under the source of variation column are the original experimental factor levels; DM, dry matter; LER, land equivalent ratio; \* =*p* < 0.05; \*\* = *p*< 0.01;\*\*\* = *p* < 0.001; ns= not significant at *p* < 0.05.

## *Weed DM*

There was no significant difference (*p* > 0.05) in the weed dry matter between 2015 and 2016 growing season (Table 3). However, weed DM was (*p* < 0.05) influenced by cropping systems over the growing seasons (Figure 2), with the overall mean for the sole cropping system (4.02 g m-2) producing 59% higher weed DM than the bi-cropping systems (2.53 g m-2). Over the two seasons, the sole bean cropping system (4.71 g m-2) had 41% higher weed DM than the sole wheat cropping system (3.33 g m-2).

Figure 2. The effects of drilling patterns and bean cultivars on weed biomass (g m-2) at different times (DAS) in the 2015 and 2016 spring growing seasons. The figures outside and inside the brackets represent time (DAS) and growing seasons respectively. Cropping systems with the same letter within the same time (DAS) are not significantly different at *p*< 0.05.

In the 2015 growing season, there was no significant differences between the drilling patterns in weed DM at 56 days after sowing (DAS) (Table 3 and Figure 3). However, at the later assessment at 87 DAS the drilling patterns affected weed DM, with the broadcast bi-cropping treatment (3.84 g m-2) producing 33.1% higher weed DM than the alternate row bi-cropping treatment (2.57 g m-2). Among the alternate rows bi-cropping treatments the 2 x 2 (2.35 g m-2) had significantly lower weed than the 1 x 1 (2.59 g m-2) and 3 x 3 (2.78 g m-2). In the 2016 growing season, the drilling patterns affected weed DM at both 51 DAS and 73 DAS and the weed DM was significantly higher in the broadcast bi-cropping treatment compared with the alternate rows bi-cropping treatments (Figure 3).

Figure 3. Weed biomass (g m-2) as affected by drilling patterns x year interactions at different times (DAS) in the 2015 and 2016 spring growing seasons. The figures outside and inside the brackets represent time (DAS) and growing seasons respectively. Drilling patterns with the same letter within the same time (DAS) are not significantly different at *p*< 0.05.

## *Forage DM yield and LER*

### *Wheat forage DM yield*

The wheat sole crop forage DM yield was significantly higher in the 2016 than in the 2015 growing season (*p* < 0.001) (Table 3). In the 2016 growing season, wheat forage DM yield was affected by the cropping system (*p* < 0.001) (Table 4), with the sole cropping system outperforming the bi-cropping system for wheat forage DM yield, but in 2015 there were no statistical yield differences. However, the total forage DM yield of wheat and bean was higher in the bi-cropping system than in the sole cropping system in both growing seasons. Wheat forage DM yield was not affected by the drilling patterns or bean cultivars (Table 4).

Table 4. The effects of cropping systems, drilling patterns and bean cultivars on forage DM yield (t ha-1) in the 2015 and 2016 spring growing seasons.

|  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  |  | | | Forage DM yield (t ha-1) | | | | | |
| Treatment | Mix-proportion | | 2015 growing season | | | | 2016 growing season | | |
| Drilling patterns | | | | Wheat | Bean | Total yield | Wheat | Bean | Total yield |
| 1x1 | | 50:50 | | 5.6 | 1.8 a | 7.4 a | 5.0 | 2.9 a | 7.9 a |
| 2x2 | | 50:50 | | 5.6 | 1.8 a | 7.4 a | 4.8 | 3.0 a | 7.8 a |
| 3x3 | | 50:50 | | 5.1 | 1.6 a | 6.7 b | 4.9 | 3.0 a | 7.9 a |
| Broadcast | | 50:50 | | 5.4 | 0.9 b | 6.3 c | 5.0 | 1.8 b | 6.8 b |
| SED (*p* < 0.05) | | - | | 0.294ns | 0.218\*\*\* | 0.383\*\*\* | 0.266 ns | 0.270\*\*\* | 0.365\*\*\* |
| Cropping systems | | | |  |  |  |  |  |  |
| Bi-crop mean | | 50:50 | | 5.4 | 1.5 b | 6.9 a | 4.8 b | 2.6 b | 7.4 a |
| Sole crop | | 100 | | 5.6 | 4.8 a | 5.2 b | 7.6 a | 5.6 a | 6.6 b |
| SED (*p* < 0.05) | | - | | 0.255ns | 0.172\*\*\* | 0.211\*\*\* | 0.230\*\*\* | 0.213\*\*\* | 0.197\*\*\* |
| Bean cultivars | | | |  |  |  |  |  |  |
| Fuego | | 50:50 | | 5.4 | 1.5 | 6.9 | 4.9 | 2.5b | 7.4 |
| Maris Bead | | 50:50 | | 5.3 | 1.5 | 6.8 | 4.8 | 2.9a | 7.6 |
| SED (*p* < 0.05) | | - | | 0.268ns | 0.244 ns | 0.349 ns | 0.243 ns | 0.302\* | 0.325 ns |
| Notes: Values with the same letter under the same parameter are not significantly different at *p* < 0.05; \* = *p* < 0.05; \*\* = *p* < 0.01; \*\*\*=*p*<0.001; ns= not significant at p < 0.05; SED, standard error of the difference of means. | | | | | | | | | |

### *Bean forage DM yield*

The bean forage DM yield was higher in 2016 than in 2015 growing season (*p* < 0.001) (Table 3). The bean forage DM yield was affected by cropping systems (*p* < 0.001) (Table 4) with the sole cropping system producing higher bean forage DM yield than the bi-cropping system in both growing seasons. The bean forage DM yield was also affected (*p* < 0.001) by the drilling patterns, with the alternate row bi-cropping treatments producing more than broadcast bi-cropping treatments in both seasons. In 2016, the bean cultivars influenced bean forage DM yield (*p* < 0.05) (Table 4), with Maris Bead producing higher bean forage DM yield than Fuego.

### *LER and PLER*

The growing seasons influenced the PLER and total LER (*p* <0.001) (Table 3) with higher LER recorded in 2015 than 2016 growing season. Cropping systems affected the LER in both growing seasons (*p* < 0.001) (Table 5) with higher wheat PLER in bi-cropping systems than in the sole cropping systems in both growing seasons. However, the bean PLER was lower in the bi-cropping system than the sole cropping system in the 2015 growing season. The ANOVA table showed no significant differences between cropping systems for bean PLER in 2016 growing season. The PLER for wheat bi-crops was higher than that for the bean bi-crops in both growing seasons, though the statistical significance of this difference was not determined. The total LER in bi-cropping systems exceeded the unitary value of 1.0 in sole cropping systems in both growing seasons.

The drilling patterns affected the total LER (*p* < 0.001) (Table 5) for all drilling patterns to values above the unitary value of 1.0. The alternate row bi-cropping treatments were significantly higher than broadcast bi-cropping treatments in both growing seasons. In 2015, the LER in the 3x3 alternate row bi-cropping treatment was significantly lower than that in alternate row bi-cropping treatments (1 x 1 and 2 x 2).

Table 5. LER as affected by cropping systems, drilling patterns and bean cultivars in wheat/faba bean bi-cropping systems in the 2015 and 2016 spring growing seasons.

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Treatment | Mix-proportion | | 2015 growing season | | | 2016 growing seasons | | |
|  |  | | PLER | | Total LER | PLER | | Total LER |
| Drilling patterns | | | Wheat | Bean |  | Wheat | Bean |  |
| 1x1 | | 50:50 | 0.99 | 0.38 a | 1.37 a | 0.66 | 0.51 a | 1.17 a |
| 2x2 | | 50:50 | 0.98 | 0.38 a | 1.36 a | 0.61 | 0.55 a | 1.16 a |
| 3x3 | | 50:50 | 0.88 | 0.34 a | 1.23 b | 0.63 | 0.54 a | 1.17 a |
| Broadcast | | 50:50 | 0.95 | 0.20 b | 1.15 c | 0.67 | 0.35 b | 1.02 b |
| SED (*p* < 0.05) | | - | 0.074ns | 0.048\*\*\* | 0.081\*\* | 0.0301ns | 0.055\*\*\* | 0.049\*\* |
| Cropping systems | | |  |  |  |  |  |  |
| Bi-crop mean | | 50:50 | 0.95 a | 0.32 b | 1.27 a | 0.65 a | 0.48 | 1.13 a |
| Sole crop | | 100 | 0.50 b | 0.50 a | 1.00 b | 0.50 b | 0.50 | 1.00 b |
| SED (*p* < 0.05) | | - | 0.035\*\*\* | 0.026\*\*\* | 0.091\*\*\* | 0.016\*\*\* | 0.030ns | 0.027\*\*\* |
| Bean cultivars | | |  |  |  |  |  |  |
| Fuego | | 50:50 | 0.96 | 0.32 | 1.28 | 0.67 | 0.46 | 1.13 |
| Maris Bead | | 50:50 | 0.94 | 0.32 | 1.26 | 0.63 | 0.51 | 1.14 |
| SED (*p* < 0.05) | | - | 0.058ns | 0.044ns | 0.074ns | 0.055ns | 0.051ns | 0.045ns |
| Notes: Values with the same letter under the same parameter are not significantly different at *p* < 0.05; \* = *p* < 0.05; \*\* = *p* < 0.01; \*\*\* = *p* < 0.001; s= not significant at *p* < 0.05; SED, standard error of the difference of means, PLER, partial land equivalent ratio. | | | | | | | | |

# Discussion

## *Weed DM*

### *Weed DM as affected by the cropping systems*

Weed control poses as a serious problem in organic and low input production systems (Baker and Mohler 2014). Bi-cropping systems have been widely reported to perform extra ecological services such as weed control besides increased food production over sole cropping systems (Altieri et al. 2011; Verret et al. 2017). Generally, visual field weed appraisal showed low infestations of weeds at the study sites. However, this study, averaged over two years showed lower weed DM in bi-cropping systems compared to sole cropping systems due to spatial interspecific complementarity. As bi-cropping systems reduced weeds in this study they may have out-competed weed species for the acquisition of environmental resources and left an inadequate supply, which impaired their growth and development, as also suggested by other studies Bedoussac et al. 2014; Choudhary et al. 2014). Past research has shown that the success of bi-cropping systems over sole cropping systems on biological weed control has been driven by two ecological mechanisms: (i) effectiveness in capturing growth resources from weeds species; and (ii) efficiency in the conversion of unexploited growth resources by weeds into harvestable materials (Khashayar et al. 2014; Stoltz and Nadeau 2014). A significant reduction of weed DM in bi-cropping systems over sole cropping systems demonstrated the capacity of the system to gradually reduce weed seed bank and the return of weed seeds as similarly reported by Röös et al. (2018) and Bastiaan et al. (2008). By smothering the weeds before reaching their reproductive growth stage in bi-cropping systems, it may help to ensure that no new weed seeds are added to the soil, hence reducing the seed bank.

The highest weed burden in the sole bean cropping system compared to the sole wheat cropping system during the early growth stage demonstrated poorer weed suppression effect of the mono-cropping systems. Similar findings were reported by Hauggaard-Nelson et al. (2008) who attributed this to a poor canopy ground cover of the bean plants, which may have led to more light reaching the ground, thereby stimulating greater weed seed germination, resulting in more weeds growths leading to a higher weed biomass. This weed competition implied that sole bean cropping system were less suitable for forage production because it may lower forage DM yield compared to bi-cropping systems. The sole wheat cropping system had lower weed DM compared to the sole bean cropping system. These findings support those of Sadeghpour et al. (2013), Eskandari and Ghanbari-Bonjar (2010) and Li et al. (2011), who found that dominance of cereal crops over weed species lead to a competitive advantage for resource acquisition, due to their fast growth rate and extractive root systems particularly during early stages of the crop growth.

### *Weed DM as affected by the drilling patterns*

At 56 DAS in 2015, there was no significant difference in the weed DM between the different drilling patterns and this was thought to be related to the prolonged dry weather conditions, which may have stunted the canopy development of the bi-crops, hence reduced effective weed suppression. At 87 DAS, improved canopy development along with a slight increase in rainfall, may have contributed to distinguished effects of the drilling patterns on weed DM. Higher weed DM in the 1 x 1 and 3 x 3 compared to 2 x 2 alternate row bi-cropping treatments may be attributed to below-ground competition between and within bi-crops for soil water, which was more limiting during the 2015 growing season. This finding concurred with Semere and Froud-Williams (2001) and Mariotti et al. (2009) who showed that below-ground competition for water can reduce leaf area of bi-crops, which may subsequently reduce light interception hence poor weed suppression (Bastiaans et al. 2008). The 2 x 2 alternate row bi-cropping treatment resulted in low weed DM, possibly due to minimised competition and maximised cooperation between bi-crops for limited resources. The findings support Bedoussac et al. (2015) and Devi et al. (2014) who reported that interspecific complementarity on efficient use of limited environmental resources in alternate rows spatial arrangement of bi-cropping systems, may lead to improved light interception, weed suppression, reduced inter-row evaporation.

During the 2016 growing season, the effect of drilling patterns on weed DM was evident at both 51 DAS and 73 DAS, possibly because soil water was not limiting, which promoted early canopy development. However, in both growing seasons the later weed assessment showed that the alternate row bi-cropping treatments showed improved weed suppression over broadcast bi-cropping treatment as a result of morphological and physiological complementarity. This finding agreed with Bedoussac et al. (2014) who also attributed better performance of alternate row than broadcast bi-cropping treatments to better use of ecological resources, particularly solar radiation and N. The findings of this study demonstrated that drilling wheat and beans as broadcast bi-cropping practice is unattractive for adoption by organic farmers because it may be vulnerable to inefficient use of resources and increased weed infestation, which is a challenge in organic production systems. Also, the maximum contact between the two bi-crops led to strong competitive effect of wheat towards faba bean, which resulted in poor performance of the legume bi-crop on weed suppression. The uniform spatial arrangement of bi-crops in alternate rows can improve the competitiveness of bi-crops and early canopy coverage, which in turn contribute to improve weed suppression as also reported by Evers and Bastiaans (2016). The concept of this study has shown the potential to improve weed management in organic production systems. However, considering the low levels of weed biomass at the study sites, which was partly caused by the previous crop management practices under conventional farming, it is imperative to repeat the study under organic conditions with more typical higher weed biomass levels.

### *Weed DM as affected by the bean cultivars*

This study showed that despite the bean cultivars differing in height and growth rates, they had similar effects on weed suppression when sown as bi-crops. This suggested that both bean varieties could effectively improve weed suppression when as sown as bi-crops in 50:50 replacements design because the reduction in their sowing density helped to achieve complementarity, which may have led to improve resource-use efficiency.

## *Forage DM yield*

### *Wheat and bean forage DM yield as affected by cropping systems*

Wheat forage DM yield was higher in sole cropping systems than bi-cropping systems, but only in the 2016 cropping season, due to differences in their respective sowing densities as the replacement strategy used for the sowing density for sole cropping systems was double the bi-cropping systems. The results of this study were in agreement with Fradgley et al. (2013) that the dry start to the growing season in 2015 may have partly contributed to low soil N and wheat forage DM yield, which resulted in non-significant differences between cropping systems. Even though the forage DM yield was low both in wheat and bean bi-crops, the bean had the lowest yield compared to wheat for two reasons; firstly, the beans plants were very sensitive to weed infestation and secondly, the wheat plants offered a strong competitive effect on resource acquisition which contributed to reduce bean forage DM yield. Cereals generally have higher forage dry matter over legumes with regard to forage DM yield (Lithourgidis et al. 2007; Sadeghpour et al. 2013) though this depends on the soil N status which maybe an issue in organic farming (Jensen et al. 2015).

Even though bi-cropping systems had lower forage DM yield than sole cropping systems, total forage DM yield of the two bi-crops in bi-cropping systems was higher than sole cropping systems, which demonstrated the superiority of bi-cropping systems over sole cropping systems. Similar findings were reported by Dusa and Stan (2013) in oat (*Avena sativa*)/pea (*Pisum sativum)*, Sadeghpour et al. (2013) in barley (*Hordeum vulgare*)/annual medic (*Medicago truncatula*), Pappa et al. (2012) in barley/pea and Dhima et al*.* (2016) in oat/faba bean (*Vicia faba*) mixtures. Contrary to this finding, Berkenkamp and Meeres (1987) reported higher total DM yield in the sole cropping system than the bi-cropping system in wheat/faba bean crop mixtures because the faba bean bi-crop was more competitive than the component wheat bi-crop.

### *Wheat and bean forage DM yield as affected by the drilling patterns*

Wheat forage DM yield was not affected by the drilling patterns possibly due to weaker interspecific competition than intraspecific competition. This was in agreement with the findings of Kim et al. (2018) in corn/soybean bi-cropping system who attributed this to lack of niche overlap for growth resources, which resulted in maximised resource consumption.

The bean forage DM yield was higher in the alternate rows than in the broadcast bi-cropping treatment possibly due to spatial interspecific complementarity, which may have led to efficient use of environmental resources. This finding confirmed those of Olsen et al. (2012) and Sherrwan and Kazhala (2014), who attributed higher forage yield in alternate rows to improved resource-use efficiency. Low bean forage DM yield in broadcast bi-cropping treatment was caused by system specific factors such as; the susceptibility of the bean crop to weed pressure, inefficient use of resources and the maximum contact between the bi-crop species, which favoured the wheat to execute strong competitive effect towards the bean bi-crop.

*LER and PLER as affected by cropping systems and drilling patterns*

The total LER for bi-cropping systems exceeded the unitary value of 1.0 in sole cropping systems, which demonstrated the advantage of cereal/legume crop mixtures compared to sole cropping systems due to efficient use of environmental growth resources such as light, water and nutrients. This finding was in agreement with Mead and Willey (1980) who reported that the LER value greater than 1.0 indicates the advantage of bi-cropping through more efficient use of environmental resources. This confirmed the reason for increased forage DM yield in bi-cropping systems over sole cropping systems. The higher LER of 1.27 and 1.13 from bi-cropping system in 2015 and 2016 growing seasons, implied that an extra 27% and 13% of land, respectively, would be required to produce similar forage DM yield to sole cropping system. Increased LER above 1.0 has been similarly reported by Dwomon and Quainoo (2012) and Jahanzad et al. (2011) indicating the benefits of cereal/grain legume bi-cropping, probably due to efficient use of environmental resources. The higher PLER for wheat over bean in the mixtures, probably showed the dominant growth attributes of wheat and its suppressive effect over the bean bi-crops on resource use. These results concurred with Sadeghpour et al. (2013), who attributed low legume bi-crop yield to its vulnerability to interspecific competition and natural sensitivity to weed infestation, which reduced efficient use of resources. The non-significant differences between cropping systems and the low PLER for beans in the 2016 growing season may have been partly attributed to faba bean rust (Uromyces viciae- fabae) disease, which infected the bean plants during reproductive growth stage. This may have affected the resource-use efficiency. This agreed with the findings of Mandal et al. (2009), which indicated that fungal diseases can significantly reduce primary photosynthetic pigments such as total chlorophyll and net photosynthetic hence resource use efficiency. Higher total LER for alternte row than broadcast bi-cropping treatments, may be an indication of better resource-use efficiency and reduced interspecific competition. This agreed with the findings of Adigbo (2013) which demonstrated that the efficient utilisation of growth resources in alternate rows, made it a suitable spatial arrangement for bi-cropping systems. These findings verified the reasons for increased performance of alternate rows over broadcast bi-cropping system on total forage DM yield.

**Conclusion**

This wheat/faba bean bi-cropping study was carried out to assess and identify suitable cropping systems, spatial arrangements and bean cultivars which can improve forage production and reduce weed resurgence in low input systems. The findings showed that bi-cropping practice can significantly minimise weed biomass and improve total forage yield over sole cropping practice with greater benefits realized in alternate row than broadcast practice. Therefore, spring wheat/faba bean bi-cropping can serve as a low cost sustainable feed production system.

**Acknowledgement**

The author is grateful to John Oldacre Foundation for financial support.

# Reference

Adigbo SO, Iyasere E, Fabunmi TO, Olowe VIO, Adejuyigbe CO. 2013. Effect of Spatial Arrangement on the Performance of Cowpea /Maize Intercrop in Derived Savannah of Nigeria. Am J Exp Agr. 3(4): 959-970.

Altieri MA, Lana MA, Bittencourt HV, Kieling AS, Comin, JJ, Lovato PE. 2011. Enhancing crop productivity via weed suppression in organic no-till cropping systems in Santa Catarina, Brazil.   J Sustain Agr. 35(8): 855-869.

Andrew IKS, Storkey J, Sparkes DL. 2015. A review of the potential for competitive cereal cultivars as a tool in integrated weed management. Weed Res. 55(3): 239-248.

Askegaard M, Olesen JE, Rasmussen IA, Kristensen K. 2011. Nitrate leaching from organic arable crop rotations is mostly determined by autumn field management. Agric. Ecosyst. Environ. 142:149-160.

Bahadur S, Verma S, Prasad SK, Madane AJ, Maurya SP, Verma VK, Sihag S. 2015. Eco-friendly weed management for sustainable crop production- Review. J. crop weed. 11(1): 181-189.

Baker BP, Mohler CL. 2014. Weed management by upstate New York organic farmers: Strategies, techniques and research priorities. Renew. Agr. Food Syst. 30: 418-427.

Banik P, Midya A, Sarkar BK, Ghosh SS. 2006. Wheat and chickpea intercropping systems in an additive series experiment: Advantages and weed smothering. Eur J Agron. 24: 325-33.

Bastiaans L, Paolini R, Baumann D. 2008. Focus on ecological weed management: what is hindering adoption? Weed Res. 48: 481-491.

Bedoussac L, Justes E, Journet EP, Hauggaard-Nielsen H, Naudin C, Corre-Hellou G, Prieur L, Jensen ES, Justes E. 2014. Eco-functional intensification by cereal-grain legume intercropping in organic farming systems for increased yields, reduced weeds and improved grain protein concentration. In: Bellon S, Penvern S, editors. Organic farming, prototype for sustainable agricultures: Prototype for sustainable agricultures. Berlin: Springer; p.47-63.

Bedoussac L, Journet EP, Hauggaard-Nielsen H, Naudin C, Corre-Hellou G, Jensen ES, Prieur L, Justes E. 2015. Ecological principles underlying the increase of productivity achieved by cereal-grain legume intercrops in organic farming. A review. Agron. Sustain. Dev. 35 (3): 911-935.

Bedoussac L, Justes E. 2010. Dynamic analysis of competition and complementarity for light and N use to understand the yield and the protein content of a durum wheat–winter pea intercrop. Plant Soil. 330:37-54.

Berkenkamp B, Meeres J. 1987. Mixtures of annual crops for forage in central Alberta. Can J Plant Sci. 67: 175–183.

Brooker RW, Bennett AE, Cong W, Daniell TJ, George TS, Hallett PD, Hawes C, Iannetta PPM, Jones HG, Karley AJ. 2015. Improving intercropping: a synthesis of research in agronomy, plant physiology and ecology. Research review. New Phytol. 206: 107-117

Bulson HAJ, Snaydon R N, Stopes CE. 1997. Effects of plant density on intercropped wheat and field beans in an organic farming system. J. Agric. Sci. 128: 59-71.

Chapagain T. 2014. Intercropping wheat and barley with nitrogen fixing legume species in low input organic systems. [dissertation]. Vancouver: The University of British Columbia.

Chen C, Westcott M, Neill K, Wichmann D, Knox M. 2004. Row configuration and nitrogen application for barley-pea intercropping in Montana. Agron J. 96: 1730–1738.

Choudhary VK, Dixit A, Kumar PS, Chauhan BS. 2014. Productivity, weed dynamics, nutrient mining, and monetary advantage of maize-legume intercropping in the Eastern Himalayan Region of India. Plant Prod Sci. 17(4): 342-352.

Christensen S. 1995. Weed suppression ability of spring barley varieties. Weed Res. 35: 241-247.

Corre-Hellou G, Dibet A, Hauggaard-Nielsen H, Crozat Y, Gooding M, Ambus P, Dahlmann C, von Fragstein P, Pristeri A, Monti M. 2011. The competitive ability of pea–barley intercrops against weeds and the interactions with crop productivity and soil N availability. Field Crops Res. 122(3): 264-272.

Cosser ND, Gooding MJ, Davies WP, Thompson AJ, Froud-Williams RJ. 1997. Cultivar and

Rht gene influence on the competitive ability, yield and bread making quality of organically grown winter wheat. In: Gooding MJ, Shewry PR, editors. Aspects of Applied Biology 50. Optimising Cereals Inputs: Its Scientific Basis. Warwick (UK). Association of Applied Biologists; p. 39-51.

Costanzo A, Barberi P. 2014. Functional agrobiodiversity and agroecosystem services in sustainable wheat production. A review. Agron. Sustain. Dev. 34: 327-348.

Devi KN, Shamurailatpam D, Singh TB, Singh H, Singh NG, Singh NB. et al. 2014. Performance of lentil (*Lens culinaris* M.) and mustard (*Brassica juncea* L.) intercropping under rainfed conditions. Aust. J. Crop Sci*.* 8(2):284-289.

Davies DHK, Hoad S, Maskell PR, Topp K. 2004. Looking at cereal varieties to help reduce weed control inputs crop protection in Northern Britain. Penicuik, Midlothian (UK): Scottish Agricultural College.

Dhima, K., Lithourgidis, A., Vasilakoglou, I., Dordas, C. 2007. Competition indices of common vetch and cereal intercrops in two seeding ratio. Field Crops Research 100: 249-256.

Dhima K, Vasilakoglou I, Gatsis T, Gougoulias N. 2016. Faba bean-barley intercrops for high productivity and corn poppy suppression. Exp. Agric. 54 (2): 163-180.

Dubey D N, Kulmi G S, Grish JHA. 1995. Performance of sorghum (*Sorghum bicolor*) as influenced by intercropping and planting geometry. Ind. J. Agronomy. 40: 353-356.

Dusa EM, Stan V. 2013. The effect of intercropping on crop productivity and yield quality of oat (*Avena sativa* L.) leguminous species pea (*Pissum sativum* L., lentil (*Lens culinaris*) cultivated in pure stand and mixtures, in the organic agriculture system. Eur Sci J. 9 (21): 69-78.

Dwomon IB, Quainoo AK. 2012. Effect of Spatial Arrangement on the yield of maize and groundnut Intercrop in the Northern Guinea Savanna Agro-Ecological Zone of Ghana. Int. J. LifeSc. Bt & Pharm. Res.1 (2): 78-85.

Eisele JA, Kopke U. 1997. Choice of variety in organic farming: New criteria for winter wheat ideotypes. Pflanzenbauwissen-schaften [German Journal of Agronomy]. 1(5): 19-24. German.

Eskandari, H., and Kazemi K. 2011. Weed control in maize-cowpea intercropping system related to environmental resources consumption. Notulae Scientia Biologicae, 3, 57-60.

Eskandari H, Ghanbari-Bonjar A. 2010. Effect of different planting pattern of wheat (*Triticum aestivum* L.) and bean (*Vicia faba*) on grain yield, dry matter production and weed biomass. Not Sci Biol. 2: 111-115.

European Parliament. 2011. The EU protein deficit: what solution for a long-standing problem. Brussels, Belgium: European Parliament. [accessed 2018 May 23]. <http://www.europarl.europa.eu/sides/getDoc.do?type=REPORT&reference=A7-2011-0026&language=EN>.

Evers JB, Bastiaans L. 2016. Quantifying the effect of crop spatial arrangement on weed suppression using functional-structural plant modelling. J. Plant Res.129: 339-351.

Fanadzo M, Mashingaidze AB, Nyakanda C. 2007. Narrow rows and high maize densities decrease maize grain yield but suppress weeds under dry-land conditions in Zimbabwe. Agron J. 6: 566-570.

Fernandez-Aparicio M, Emeran AA, Rubiales D. 2010. Inter-cropping with berseem clover (*Trifolium alexandrinum*) reduces infection by *Orobanche crenata* in legumes. Crop Prot. 29:867–871.

Food and Fairness. 2008. Which Pesticides are banned in Europe? Briefing No 1. [accessed 2018 March 30]. <https://www.pan-europe.info/old/Resources/Links/Banned_in_the_EU.pdf>.

Fradgley N, Winkler L, Doring T. 2013. Beans and wheat intercropping: a new look at an overlooked benefit. ORC Bulletin No. 112-spring/summer 2013. [accessed 2018 Jan 15]. <http://www.organicresearchcentre.com/manage/authincludes/article_uploads/Fradgley112.pdf>

Ghanbari-Bonjar A, Lee HC. 2003. Intercropped wheat and bean as whole crop forage: effect of harvest time on forage yield and quality. Grass Forage Sci. 58: 28-36.

Ghanbari-Bonjar A. 2000. Intercropping wheat (*Triticum aestivum* L.) and bean (*Vicia faba*) as a low input forage. [dissertation] Wye: University of London.

Grime JP. 2001. Plant Strategies: Vegetation Processes and Ecosystem Properties, 2nd ed. New York (NY): Wiley.

Hauggaard-Nielsen H, Jornsgaard B, Kinane J, Jensen ES. 2008. Grain legume-cereal intercropping: The practical application of diversity, competition and facilitation in arable and organic cropping systems. Renew Agr Food Syst. 23: 3-12.

Häusling M. 2011. Report. The EU protein deficit: what solution for a long‐standing problem? (2010/2111 (INI)). Committee on Agriculture and Rural Development. [accessed 2018 Mar 01]. <http://www.europarl.europa.eu/sides/getDoc.do?type=REPORT&reference=A7-2011-0026&language=EN>

Haymes R, Lee HC. 1999. Competition between autumn and spring planted grain intercrops of wheat (*Triticum aestivum* L.) and field bean (*Vicia faba* L.). Field Crops Res. 62:167-176.

Hill J.1996. Breeding components for mixture performance. Euphytica. 92:135-138.

Hoad SP, Davies DHK, Topp CFE. 2006. How to select for organic farming: science and practice. What will organic farming deliver? COR 2006. Asp. Appl. Biol. 79: 117-120.

Jalilian J, Najafabadi A, Zardashti MR. 2017. Intercropping patterns and different farming systems affect the yield and yield components of safflower and bitter vetch. J Plant Interact. 12(1): 92-99.

Jahanzad E, Sadeghpour A, Hashemi M, Zandvakili O. 2011. Intercropping millet with soybean for forage yield and quality. American Society of America, Northestern Branch Chesapeake, Maryland. June 26-29. Abstract.

Jensen ES, Bedoussac L, Carlsson G, Journet EP, Justes E, Hauggaard-Nielsen H. 2015. Enhancing yields in organic crop production by eco-functional intensification. Sustain. Agric. Res. 4 (3): 42–50

Khashayar R, Hamid RM, Mohammad RV. 2014. Effect of intercropping on resources use, weed management and forage quality. International Journal of Plant, Animal and Environmental Science. 4(2), 706-713.

Kim J, Song Y, Kim DW, Fiaz M, Kwon CH. 2018. Evaluating different interrow distance between corn and soybean for optimum growth, production and nutritive value of intercropped forages. J Anim Sci Technol. 60 (1): 1-6.

Klimek-Kopyra A, Kulig B, Oleksy A, Zajac T. 2015. Agronomic performance of naked oat (*Avena nuda* L.) and faba bean intercropping. Chil. J. Agr. Res. 75(2): 168-173.

Kumar V, Singh SR, Chhokar S, Malik RK, Brainard, DC, Ladha, JK.2013. Weed management strategies to reduce herbicide use in zero-till rice-wheat cropping systems of the Indo-Gangetic plains. Weed Technol. 27:241-254.

Lauk R, Lauk E. 2008. Pea-oat intercrops are superior to pea-wheat and pea-barley intercrops. Acta Agriculturae Scandinavica, Section B – Plant Soil. 58: 139-144.

Li QZ, Sun JH, Wei XJ, Christie P, Zhang FS, Li L. 2011. Over yielding and interspecific interactions mediated by nitrogen fertilization in strip intercropping of maize with faba bean, wheat and barley. Plant Soil. 339:147-161.

Liebman M, Robichaux RH. 1990. Competition by barley and pea against mustard: effects on resource acquisition, photosynthesis and yield. Agric Ecosyst Envir. 31:155-172.

Lithourgidis AS, Dhima KV, Vasilakoglou B, Dordas CA, Yiakoulaki MD. 2007. Sustainable production of barley and wheat by intercropping common vetch. Agron. Sustain. Dev. 27: 95-99.

Malézieux E, Crozat Y, Dupraz C, Laurans M, Makowski D, Ozier-Lafontaine H, Rapidel B, Tourdonnet de S, Valantin-Morison M.2009. Mixing plant species in cropping systems: concepts, tools and models. A review. Agronomy for Sustainable Development*.* 29, 43-62

Mandal K, Saravanan1 R, Maiti1 S, Kothari IL. 2009. Effect of downy mildew disease on photosynthesis and chlorophyll fluorescence in Plantago ovata Forsk. J.Plant Dis.Protect. 116 (4): 164-168.

Mariotti M, Masoni A, Ercoli L, Arduini I. 2009. Above-and below-ground competition between barley, wheat, lupin and vetch in a cereal and legume intercropping system. Grass Forage Sci. 64: 401- 412.

Martin MPLD, Snaydon RW. 1982. Intercropping barley and beans I. Effects of planting pattern. Exp Agr. 18: 139–148.

Mashingaidze AB, Van Der Werf W, Lotz LAP, Chipomho J, Kropff MJ. 2009. Narrow rows reduce biomass and seed production of weeds and increase maize yield. Ann Appl Biol. 155: 207-218.

Mead R, Willey WR. 1980. The concept of a land equivalent ratio and advantages in yields from intercropping. Exp Agr. 16: 217-22.

Musa M, Leitch MH, Iqbal M, Sahi FUH. 2010. Spatial arrangement affects growth characteristics of barley-pea intercrops. Int J Agric Biol.12: 685–690.

Olsen J, Weiner J. 2007. The influence of *Triticum aestivum* density, sowing pattern and nitrogen fertilization on leaf area index and its spatial variation. Basic Appl Ecol. 8: 252-257.

Olsen JM, Griepentrog HW, Nielsen J, Weiner J. 2012. How important are crop spatial pattern and density for weed suppression by spring wheat? Weed Sci. 60: 501-509.

Pappa VA, Rees RM, Walker RL, Baddeley JA, Watson CA. 2012. Legumes intercropped with spring barley contribute to increased biomass production and carry‐over effects. J. Agric. Sci. 150: 584-594.

[PGRO] Processors and Growers Research Organisation. 2016. [accessed 2018 Mar 11] <http://www.pgro.org/images/site/jan-2015/PGRO-AGRONOMY-GUIDE-2015.pdf>.

Rigby D, Cáceres D. 2001. Organic farming and the sustainability of agricultural systems. Agric Sys. 68: 21-40.

Röös E, Mie A, Wivstad M, Salomon E, Johansson B, Gunnarsson S, Wallenbeck A, Hoffmann R, Nilsson U, Sundberg C. et al. 2018. Risks and opportunities of increasing yields in organic farming. A review. Agron Sustain Dev. 38 (14): 1-20.

Sadeghpour A, Jahanzad E, Hashemi M, Esmaeili A, Herbert SJ. 2013. Intercropping annual medic with barley may improve total forage and crude protein yield in semi-arid condition.  Aus J Crop Sci. 7: 1822–1828.

Semere T, Froud-Williams R. 2001. The effect of pea cultivar and water stress on root and shoot competition between vegetative plants of maize and pea. J Appl Ecol. 38 (1): 137-145.

Sherwan IT, Kazhala RA. 2014. The role of intercropping wheat with legumes (chickpea or pea) in improving the yield and land equivalent ratio in rain fed regions. JZS-A. 16: 33-45.

Smitchger JA, Burke IC, Yenish, JP. 2012. The critical period of weed control in lentil (*Lens culinaris*) in the Pacific Northwest. Weed Sci. 60: 81-85.

Snaydon R. 1991. Replacement or additive designs for competition studies. J Appl Ecol. 28: 930-946.

Stevanato P, Trebbi D, Bertaggia M, Colombo M, Broccanello C, Conchert G, Saccomani M. 2011. Root traits and competitiveness against weeds in sugar beet. Int Sugar J. 113: 497-501.

Stoltz E, Nadeau E. 2014. Effects of intercropping on yield, weed incidence, forage quality and soil residual N in organically grown forage maize (*Zea mays* L.) and faba bean (*Vicia faba* L.). Field Crops Res. 169: 21-29.

Sumathi V, Subramanyam D, Koteswara RDS, Reddy DS. 2010. Effect of planting pattern and weed management on weed flora and yield of Rabi sunflower. Indian J. Weed Sci. 42:212-216.

Vandermeer J H. 2011. The ecology of agrosystems. Massachusetts (MA): Jones and Bartlett Publishers.

Vandermeer J, van Noordwijk M, Anderson J, Ong C, Perfecto I. 1998. Global change and multispecies agroecosystems: concepts and issues. Agric Ecosyst Environ 67:1-22.

Vandermeer J. 1989. The Ecology of Intercropping. Cambridge: Cambridge University Press.

Verret V, Gardarin A, Pelzer E, Médiène S, Makowski D, Valantin-Morison M. 2017. Can legume companion plants control weeds without decreasing crop yield? A meta-analysis. Field Crops Res. 204: 158-168.

Vijaya Bhaskar A V, Davies WP, Cannon ND and Conway JS. 2014. Weed manifestation under different tillage and legume undersowing in organic wheat.Biological Agriculture and Horticulture*.* 30:4, 253-263.

Weiner J, Andersen SB, Wille WKM, Griepentrog HW, Olsen JM. 2010. Evolutionary Agroecology: the potential for cooperative, high density, weed-suppressing cereals. Evol Appl. 3: 473-479.

Weiner J, Griepentrog HW, Kristensen L. 2001. Suppression of weeds by spring wheat (*Triticum aestivum*) increases with crop density and spatial uniformity. J Appl Ecol. 38: 784-790.

White PJ, George TS, Gregory PJ, Bengough AG, Hallett PD, McKenzie BM. 2013. Matching roots to their environment. Ann. Bot. 112:207–222.

Zadoks JC, Chang TT, Konzak CF. 1974. A decimal code for the growth stages of cereals. Weed Res. 14: 415-421.