**Advantages of bi-cropping field beans (*Vicia faba*) and wheat *(Triticum aestivum*) on cereal forage yield and quality**

**Abstract**

# In organic production systems, penalties in cereal forage yield and low crude protein (CP) concentration are mainly caused by limited soil nitrogen (N) availability, which can be addressed by using cereal/grain legume bi-cropping systems. To confirm this, a bi-cropping experiment of spring wheat cv. Paragon and faba beans cvs*.* Fuego and Maris Bead was conducted in two years, using a randomised complete block design and sowing the crops in a replacement design series. In 2016, the wheat forage yield in sole cropping exceeded that in bi-cropping by 58%. In 2015, the wheat forage harvest index (HI) in bi-cropping was 14% higher than that in sole cropping, but in 2016 it was 7% lower. In both years, bi-cropping increased the CP and the grain N uptake in the wheat compared with that sole cropping, by 25% and 17%, respectively. The chlorophyll concentration index (CCI) in the wheat was 2.2 times higher in bi-cropping than in sole cropping and 34% higher in the alternate rows systems than in the broadcast system. In 2015, the efficiency of N use (NLER) in bi-cropping was 50.7% higher than that in sole cropping. Alternate row bi-cropping improved NLER over broadcast by 37.9%. Faba bean rust disease was more severe in Fuego than in Maris Bead. In conclusion, bi-cropping in uniform alternate row spacing can improve productivity and nutritional quality of wheat forage, compared with sole cropping. The bi-crop bean cultivars Fuego and Maris Bead can, improve wheat straw CP and reduce rust disease severity, respectively.

**Key words**: Bi-cropping, chlorophyll, crude protein, forage yield, N availability organic farming.

# Introduction

In organic production systems, the availability of soil N can compromise cereal forage yields and protein concentrations (Bilsborrow et al. 2013; Jensen et al. 2015). However, research has demonstrated that the use of cereal/legume bi-cropping systems can improve forage yields and increase cereal grain protein concentration compared with sole cropping systems (Lithourgidis et al. 2006; Gooding et al. 2007; Haq et al. 2018;). Bi-cropping can be defined as the simultaneous growing of two crop species in the same field for a significant period of time, but without necessarily sowing or harvesting both crop components at the same time (Vandermeer et al. 1998). The cereal component crop species in bi-cropping systems is grown mainly for forage or cash cropping, while the legume also provides other beneficial services such as biological nitrogen fixation (BNF) and improvement of soil fertility (Willey 1979; Malézieux et al. 2009).An effective bi-cropping system is assessed by its ability to produce greater total yields and more efficient use of ecological resources compared with that achieved in sole cropping (Inal et al.2007).

In arable production systems in Europe, bi-cropping was commonly practised until about 50 years ago when it was replaced by mono-cropping systems to produce higher grain yields by using conventional agricultural practices such as agrochemical inputs (Crew and Peoples 2004; Mueller et al. 2014). Currently, there is renewed interest in cereal/grain legume bi-cropping, as this has shown potential to offer multiple and sustainable ecological services that can address challenges affecting cereal forage yield and quality (Anil et al. 1998; Altieri 1999; Askegaard et al. 2011; Jensen et al. 2015). Bi-cropping systems are thought to be particularly appropriate for organic agriculture systems where mineral soil N bioavailability is often limiting and cannot be rectified by the application of externally sourced inorganic N (Andersen et al. 2004). Studies by Ghanbari-Bonjar and Lee (2002) demonstrated that without mineral fertiliser application, a wheat/faba bean bi-cropping system showed increased yield over the sole cropping system. Major agronomic advantages of bi-cropping over sole cropping in terms of improvement of forage yields and crude protein (CP) were noted when the interspecific competition was weaker than the intraspecific competition (Vandermeer 1990; Mariotti et al. 2006). This ecological mechanism promoted better utilisation of major environmental resources, including water, solar radiation and non-N-nutrients (Hauggaard-Nielsen et al. 2008).

The efficiency of bi-cropping over sole cropping can be evaluated using land equivalent ratio (LERs), which is defined as the relative land area required when growing a sole crop to produce the same yield as achieved in a bi-crop mixture (Mead and Willey 1980). Merkeb (2016) reported a mean LER of 1.20 from maize/pigeon pea crop mixtures and Fikadu et al. (2016) reported a mean LER value of 2.4 from wheat/faba bean intercropping systems. These bi-cropping cropping systems showed an advantage in terms of dry matter production over sole cropping systems as their LER values were greater than 1.0.

CP concentration of forage is a key criterion for assessing the forage quality (Anil et al. 1998; Malezieux et al. 2009). In a well-balanced forage diet, protein helps to improve microbial digestion of forage materials in the rumen to produce valuable products such as meat and milk (Eskandari et al. 2009). Cereal forage can produce high dry matter yield with relatively low concentration of CP (Sadeghpour et al. 2013), whilst grain legumes contain high concentrations of CP with relatively low dry matter yield (Eskandari et al. 2009). The integration of these crops in cereal/legume bi-cropping systems, e.g. cereal/faba beans, can improve the CP concentration and yield of the mixture compared with sole cropping systems and thus reduce the requirements for protein-rich supplements (Anil et al. 1998; Baghdadi et al. 2016). The integration of legumes and cereals is a low-tech method to increase the efficiency of the production system and to achieve higher forage dry matter yields and balanced nutrition for ruminants compared with their corresponding sole cropping systems (Eskandari et al. 2009).

According to Baghdadi et al. (2016), in a barley (*Hordeum vulgare* L.)/pea (*Pisum sativum*) bi-cropping system, the CP concentration was increased by 40 g kg-1 DM, compared with that in a sole cereal cropping system. Salawu et al. (2001) reported increased CP of 60 g kg-1 DM in wheat/common vetch (*Vicia sativa* L.) bi-cropping systems, compared with that in the sole cereal cropping systems. Recent studies by Haq et al. (2018), reported 42.6% higher CP in cereal (oats *Avena sativa*, barley *Hordeum vulgare* and common rye grass *Lolium multiflorum)/* legume (common vetch *Vicia sativum* and field pea *Pisum sativum)* crop mixtures, compared with the sole cereal cropping systems.

The most commonly used types of bi-cropping systems are complete mixtures of the components species within the rows, alternate rows of pure component species, and alternate blocks of two or more rows of pure component species or even cross-drilling rows of pure species at right angles to each other (Musa et al. 2010). In such spatial arrangements, the bi-crops may compete for growth resources influenced by the spatial proximity between them, as competition is a distant-dependent phenomenon (Sobkowicz and Tendziagolska 2015). It is for this reason that various researchers, including Chen et al. (2004), Li et al. (2011) and Sobkowicz and Tendziagolska (2015) have attempted to spatially separate the bi-crop components in alternate rows or separate strips to maximise cooperation and minimise competition for environmental resources-use. Bi-crop species that differ in canopy height and growth rate may affect utilisation of the growth resources compared with when they are grown as sole crop species (Bedoussac et al. 2014; Merkeb 2016). The row spatial proximity between bi-crops can also affect forage yield and quality (Fanadzo et al*.* 2007). Competition between bi-crops of similar maturity groups, such as spring wheat and beans, was found to be more severe because of their synchronised peak demand for growth resources (Yahuza 2011; Klimek-Kopyra et al. 2015) and this could be rectified only by an appropriate spatial arrangement.

There has been a lack of understanding of the commercial opportunities for whole crop forage production for livestock from cereal/legume bi-cropping systems, particularly with regards to the influence of the choice of legume species/variety, dry matter accumulation, harvest date requirements and nutritional status benefits (Ghanbari-Bonjar and Lee 2003) and this has led to a lack of adoption of bi-cropping practices by organic farmers (Yahuza 2011). For these reasons, earlier bi-cropping studies concentrated much effort on addressing the above-mentioned limitations, which may help to enhance adoption. Since the cultural practices required for improving production of forage in the wheat/bean bi-cropping system have not been evaluated all together in a single study, there is a need to explore agronomic opportunities, that may lead to improved sustainable forage production systems and achieve improved cereal yield and quality. Agronomic practices such as choice of suitable cultivars and changes to the spatial arrangements are some of the key adjustments that may be required to achieve a prototype low input sustainable feed production system for low-input and organic farmers. Therefore, the present study was undertaken to evaluate how the drilling pattern and the choice of bean cultivars influence the yield and the quality of the wheat forage in a wheat/faba bean bi-cropping systems, compared with a sole cropping system.

# Materials and methods

## ***Site characteristics***

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

[Tables 1 and 2 near here]

***Experimental design***

The field experiments were laid out as a randomised complete block design with four replications. Two spring faba bean cultivars were evaluated in four drilling patterns comprised of (i) one row of wheat alternated with one row of beans (1x1); (ii) two rows of wheat alternated with two rows of beans (2x2); (iii) three rows of wheat alternated with three rows of beans (3x3) and (iv) broadcast, the bean bi-crop was randomly sown over the precision drilled wheat. Sole crops of wheat and beans were included as controls against the relative crops in mixtures and these were used to calculate the biological efficiency of the mixed systems. The two spring bean cultivars were: (i) Fuego, with a relatively fast growth rate and a shorter straw height, and (ii) Maris Bead with a relatively slower growth rate and taller height. The sowing density in the 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 for both the sole and the bi-crop treatments was similar and measured 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 the sole wheat and all other bi-cropping plots was 15 cm, except for the broadcast bi-cropping plots where the bean seeds were randomly sown over the wheat crop, which was established at an interrow distance of 15 cm apart. The schematic description of drilling patterns is shown in Figure 1.

[Figure 1 near here]

## ***Plot management***

Before plot demarcation and sowing, shallow disc harrowing was performed. The wheat was drilled using a Winstersteiger precision seed drill at the average soil depth of 2.5 cm. The beans in all plots were hand sown at the average soil depth of 5.0 cm, as the plot drill specifications could not drill both crops simultaneously. Both wheat and beans were sown on the same day; 9 April in 2015 and 2 May in 2016. No additional inputs of fertilisers, pesticides or herbicides were used. The experimental site and design were previously described in Cannon et al. (2020), reporting on the effect of the bi-cropping system on the overall forage yield and weed competition.

## ***Measurements***

For this study, the forage yield and chlorophyll concentration index (CCI) were assessed only for the wheat component of crop and the assessments were made at specific growth stages (GS) of the wheat, as defined by Zadoks et al.(1974). Wheat forage dry matter yield was recorded per unit area of each plot, using a 1.0 m2 quadrant randomly placed at two points the plot. The agronomic assessments were conducted in the inner part of each plot excluding the outer rows, which did not represent the inner plant population samples. At every stage of plant sampling, wheat and bean plants were separated into their component crops for the bi-cropped plots. Chlorophyll, measured as CCI, was determined by a non-plant destructive method at GS39 using a hand-held chlorophyll meter (Model CCM 200 Plus, Opti-Sciences Inc., New Hampshire, USA). The wheat flag leaf and the 3rd leaf were consistently measured from ten representative wheat plants in each plot to eliminate the sources of variation that can occur due to differences in measurements. The readings were automatically recorded, stored and averaged to generate a mean reading for each plot (Mohsin et al. 2011). The wheat and the bean plants were hand harvested using garden shears. After harvest, total fresh above-ground yield of the wheat was recorded in the laboratory, segregating the yield into straw and ears before threshing. The same procedure was applied to the beans, where the pods were separated from the straw. Sub samples of each of the segregated categories were oven dried for 48 hours at a constant temperature of 65 oC for total above-ground dry matter determination after which the wheat ears were threshed to determine grain yield, adjusted to 15% moisture content. Thousand grain weight (TGW) was recorded after using an automatic grain feeder and counter (Farm-tec, Scunthorpe, UK). Harvest index (HI) was determined as the ratio of economic yield to the total biological yield (Wnuk 2013). Oven dried sub samples of wheat straw and grain were finely milled using (Cyclotec 1093) for total N analysis via an Elementar Cube CNS auto analyser (Elementar Analysensysteme GmbH, Hanua, Germany). The milled bean seeds were only used to determine N concentration (%) for the calculation of CP, as shown in Figure 2.

Total N uptake was calculated according to Mahama et al. (2016) as:

Total N uptake **=**

[N]DM

100

DMabove-ground

Xx

where N uptake was measured in kg ha-1. DMabove-ground indicated wheat above-ground dry matter yield (kg ha-1), and [N]DM was the N concentration (%) in the wheat dry matter yield.

CP was determined by using the Kjeldahl procedure method (Bremner 1965). CP values were determined by multiplying the N concentration in the wheat straw and grain by a conversion factor of 5.8 (Fujihara et al. 2008; AHDB 2015) and 6.25 for beans (Magomya et al. 2014).

The LER is the relative land area under sole crop that is required to produce the same yield as achieved in the bi-cropping system. The LER for N uptake (NLER) was calculated according to Mead and Willey (1980).

NLER = (NPLER wheat + NPLER beans), (2)

where NPLER wheat = (Ywb/Yws), and NPLER beans = (Ybb/Ybs) and where Yws and Ybs referred to the N accumulation in the dry matter yields of wheat and beans as sole crops respectively, and Ywb and Ybb were the N accumulation in the dry matter yields of wheat and beans as bi-crops, respectively.

The value of unity (1.0) is the critical value when assessing crop mixtures. NLER values greater than 1.0 indicate that bi-cropping outperformed sole cropping or interspecific facilitation was higher than interspecific competition, so that bi-cropping results in greater land-use efficiency. NLER values equal to 1.0 indicate no advantage of bi-cropping with regards to resource use efficiency. When NLER is lower than 1.0 this means that bi-cropping negatively affected the growth and yield of the plants grown in mixtures or interspecific competition was greater than interspecific facilitation (Dhima et al. 2007; Wahla et al. 2009).

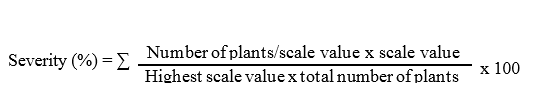
Aggressivity (A), is a measure of competitive relationships between two crops in intercropping (Willey 1979). The calculations were determined according to Dhima et al. (2007):

Awheat = (Ywb/Yws) – (Ybb/Ybs) and (3)

Abean = (Ybb/Ybs) – (Ywb/Yws), (4)

where Y represented crop dry matter yield per unit area; Yws and Ybs were the yields of wheat and beans as sole crops, respectively. Ywb and Ybb were the yields of wheat and beans as bi-crops, respectively. Thus, if Awheat = 0, both crops were equally competitive, if Awheat was positive, then wheat was dominant and if Awheat was negative, then wheat was weak, and bean was dominant. For any other situation, both crops will have the same numerical value, but the sign of the dominant species will be positive and that of the non-dominant will be negative. The greater the numerical value, the bigger the differences between actual and expected yields.

Faba bean rust disease (*Uromyces viciae-fabae*) severity was assessed according to Khare et al. (1993). The cereal forage yield and quality benefits of cereal/legume mixtures depend on a functional legume bi-crop, which can also be adversely affected by disease. A scale of 1-9 was used, where 1 meant no rust pustules visible and 9 meant rust pustules extensive on leaves, petioles and stems, and dead leaves and other plant tissues. The scores were then converted to percentage severity according to Chongo et al. (1999).



(5)

## ***Statistical analysis***

The data were subjected to a nested general analysis of variance (ANOVA) model, thus: cropping systems/(drilling patterns x bean cultivars) using the Genstat (Version 15.1, VSN International Ltd, U.K). This model was used because the drilling patterns and the bean cultivars could only be tested within the bi-cropping treatments and not in the sole crop treatment. Statistical comparisons of treatment means, at 5% level of probability, was done by using the standard errors of differences of means (SED) according to Gomez and Gomez (1984). Prior to statistical data analysis the data sets were checked for normal distribution and homogeneity of variance.

# Results

## ***Wheat forage yield parameters***

### *Straw, grain, 1000 grain weight, biomass yield and HI*

There was a significant interaction effect (*p* < 0.001) between the year and the cropping system on the wheat forage yield parameters (Table 3). In 2016, the grain yield and total biomass were significantly higher in the sole cropping than in the bi-cropping system, but in 2015 there were no differences between the cropping systems (Table 4) . In 2016, HI was significantly higher in sole cropping than in bi-cropping, but in 2015 the reverse was noted. In both growing seasons, the drilling patterns had no effect (*p* > 0.05) on the wheat forage yield parameters (Table 4), except for 1000 grain weight (TGW), which was significantly affected by the two-way interaction effect between year and drilling pattern (Table 5). In 2016, the TGW was 6.6% lower in the 3x3 alternate row bi-cropping treatment compared with the other bi-cropping treatments (alternate rows and broadcast) (Table 5).

[Tables 3, 4 and 5 near here]

## ***Wheat quality parameters***

### *CP concentration*

The CP concentration in the straw and grain was (*p* < 0.001) affected by the interaction between year and cropping system (Table 3), with higher CP recorded in 2016 compared to the 2015 growing season (Table 3 and Table 6). In 2016, the CP in the straw and the grain were 45% and 32% higher, respectively, than in 2015. In both growing seasons, the CP was significantly higher in the bi-cropping systems compared with that in the sole cropping system (Table 6 and Figure 2). In 2016, straw CP was (*p* < 0.05) affected by the bean cultivar (Table 6) and in the wheat forage grown with the bean cultivar Fuego the concentration of CP in the straw was 9% higher than that in the wheat forage grown with Maris Bead (Table 6).

### *Wheat N uptake*

The interaction between cropping systems and year greatly affected (*p* <0.001) N uptake (Table 3). Higher N uptake in the grain was recorded in the 2015 than 2016 growing season (Table 6). The cropping system (*p* <0.001) also affected N uptake (Table 6) and in both growing seasons, the N uptake in the grain in the bi-cropping system was higher than that in the sole cropping system. With regards to the N uptake in the straw, in 2016, the uptake was higher in sole cropping compared with that in bi-cropping. The drilling pattern, the bean cultivar and their interactions did not (*p* > 0.05) affect N uptake.

[Table 6 and Figure 2 near here]

## ***Biological efficiency***

## *LER for N uptake of cropping systems*

The LER for N (NLER) was (*p* <0.001) affected by the interaction between cropping system and year (Table 3). The NLER of 1.50 in 2015 was 38.8% higher compared to 1.08 recorded in the 2016 growing seasons (Figure 3). In 2015, the NLER was 37.9% higher in all alternate rows compared to broadcast and amongst the alternate rows, the NLER was 15.8% higher (*p* < 0.001) in the 1x1 and 2x2 than in the 3x3 alternate row bi-cropping treatment (Figure 3). In 2015, the NLER was also (*p <*0.001) affected by cropping systems, with 50.7% higher NLER values in the bi-cropping compared to sole cropping (Figure 3). No significant differences (*p* *>*0.05) due to treatments effects were observed on NLER in the 2016 growing season (Figure 3). The interactions among the study factors did not (*p* > 0.05) affect the NLER.

[Figure 3 near here]

***Chlorophyll concentration index (CCI)***

CCI was affected (*p* <0.001) by the interaction between cropping system and year (Table 3 and Table 7), with the CCI 36.7% higher in 2016 than in 2015. In both years, the cropping system also had a significant effect (*p* < 0.001) on the CCI, with a higher CCI in the bi-cropping systems than in the sole cropping system (Table 7). The drilling pattern also influenced (*p* <0.001) the CCI, with higher CCI in the alternate row patterns compared to broadcast bi-cropping treatment. In 2016, the CCI values were higher in the 1x1 and 2x2 treatments compared with the 3x3 alternate row treatment. (Table 7).

[Table 7 near here]

***Aggressivity (A)***

In both growing seasons, the aggressivity values for wheat bi-crops were positive, while the bean bi-crops had negative values (Table 8). In 2015, the 2x2 alternate row bi-cropping treatments had greater A values than other alternate rows. The A values were higher in 2015 than in 2016 growing season.

[Table 8 near here]

***Faba bean rust disease***

Faba beans rust disease severity at the reproductive growth stagewas affected (*p* < 0.001) by the drilling pattern (Table 9). The highest severity was recorded in the 1x1 (68.5%) and in the 3x3 (70.0%) alternate row treatments and the lowest severity was recorded in the 2x2 (57.5%) and broadcast (60.3%) bi-cropping treatments. The bean cultivar also influenced (*p* <0.001) the disease severity; with Fuego (84.7%) showing a higher severity of the disease than Maris Bead (44.6%) (Table 9).

[Table 9 near here]

# Discussion

## ***Wheat forage yield***

In this study, the wheat forage yield was higher in the sole cropping system than in bi-cropping systems and this was likely because the sowing density was twice as high in the sole cropping system compared with in the bi-cropping systems. The sowing density in bi-cropping systems were reduced by half of their sole cropping as a strategy to achieve complementarity and improved resource-use (Fradgleyet al.2013). Similar findings have been reported from other bi-cropping studies designed with 50:50 replacements (Jamshidi 2011; Sadeghpour and Jahanzad 2012). In 2016, the HI in the sole cropping was 8% higher than that in the bi-cropping system, demonstrating an advantage of the sole cropping in terms of wheat grain production rather than wheat dry matter production. Similar findings were reported by Ghanbari-Bonjar (2000) and Singh and Aulakh (2017) in wheat/faba bean and wheat/chickpea crop mixtures. In 2015, the HI in the sole cropping was12.5% lower than in the bi-cropping system. This was likely due to poor plant growth and development, which was attributed to soil N deficiency evidenced by the low CCI (Table 7), exacerbated by increased intraspecific competition for soil N at the 100% sowing density (Majumdar et al. 2016). Evidently, much of the energy was invested in vegetative production at the expense of grain production.

The results from this study, showed that there was no effect of the drilling patterns in the bi-cropping treatments on wheat forage yield and this was thought to be due to improved environmental resource-use that helped to minimise antagonistic interactions for major growth resources. The uniform inter-row spacing may have promoted greater availability and better distribution of the above and below-ground resource pools, resulting in equal effects on wheat grain yield. Similar effects of uniformly, inter-spaced alternate rows were reported by Eskandari and Ghanbari-Bonjar (2010). In contrast, studies by Muhammad and Ranamukhaarachchi (2012), showed that when the intra and inter-row distances within and between the cereal and legume bi-crops were varied, the cereal grain yield declined, because of inter and intra-specific competition. However, the finding from the study reported here showed that in 2015 a slightly lower (not statistically significant) biomass yield was recorded for the 3x3 pattern compared with other drilling patterns and a contributory factor was probably the above-ground interspecific competition for light, which was influenced by the crowdedness of the bi-cropped plants.

## ***CP concentration***

CP concentration is one of the most important parameters for assessing wheat forage and grain quality (Anil et al. 1998). This study showed improved wheat CP in the bi-cropping systems compared with that in the sole cropping system in both growing seasons. The CP in the bean was 2.4 times greater than that in the wheat in the crop mixture, as shown in Figure 2. Similarly Ghanbari-Bonjar (2000), Mariotti et al. (2006) and Chapagain (2014) reported, respectively, that the grain legume CP was 1.9, 2.4 and 1.9 times higher compared with that of the cereals, demonstrating the advantage of bi-cropping systems over sole cropping systems in terms of forage and grain quality. The use of wheat/bean bi-cropping systems can potentially help organic farmers to reduce dependency on imported non-forage protein-rich supplements and the protein enriched wheat forage and grain may help to achieve balanced feed for ruminants (Lithourgidis et al. 2011) and increase the volumes of high quality grain for bread, thus improve the economic value (Gooding et al. 2007).

In 2016, a seasonal effect might have partly influenced the higher N uptake in the wheat straw compared with that in 2015. The results suggested that the wet environmental conditions, unlike water stressed conditions, resulted in higher N offtake, especially in the sole wheat cropping system. This may have increased intraspecific competition for soil N at the 100% wheat sowing density, resulting in more N apportioned for vegetative production than for grain filling. Similar findings were reported by Majumdar et al. (2016). Improved wheat CP in bi-cropping systems compared to sole cropping systems was a result of a higher N uptake, which was also indicated by the higher CCI, as nitrogen and chlorophyll concentrations are known to be directly related (Koohi et al. 2014). This finding concurred with that of Gooding et al. (2007), who reported that bi-cropping can effectively enhance wheat grain protein quality compared with sole cropping by increasing the N concentration. Similarly, López-Bellido et al. (2001) demonstrated that the limited soil N availability in low input systems remained the main constraint for improving CP in wheat. The spatial interspecific complementarity in bi-cropping systems, may have played a greater role in improving N-use efficiency (Bedoussac and Jutes 2010; Bedoussac et al.2014; Chapagain 2014; Lithourgidis and Dordas 2010).

Assessing CCI in cereal/grain legume crop mixtures can play two significant roles in forage-based production systems; firstly, it can predict N availability and the ultimate forage quality, since N is a structural element of chlorophyll and protein molecules (Tucker 2004; Singh and Aulakh 2017). Secondly, it may help to assess the biological nitrogen fixation (BNF) abilities of the legume bi-crops through detection of chlorosis and deep green colours, which denote N deficiency and sufficiency, respectively, in cereal bi-crop leaves (Musa et al. 2010). The use of CCI values instead of converting them to chlorophyll (Chl) concentration was acknowledged as a limitation in this study.

The drilling patterns showed no effects on CP or N-uptake. However, the differences in spatial arrangements of bi-crop components between the alternate rows and broadcast resulted in contrasting effects on CCI outcome. The uniform inter-row spacing in alternate rows providing constant physical root intermingling that probably enhanced N transfer. The development of early total canopy ground cover due to the closer proximity of the plants, uniformly arranged in alternate rows, may have improved the interception of photosynthetically-active radiation, which is an indispensable energy source for nodulation and BNF in leguminous crops (Fan et al. 2006). The inconsistent inter-row spacing in the broadcast treatment, due to random sowing of bean bi-crops, provided sparse physical root intermingling, which may have limited N transfer. Also, poor canopy ground cover, may not have maximised photosynthetically-active radiation interception; hence low BNF, N transfer and CCI.

The suitability of the two different bean cultivars for sustainable bi-cropping was also assessed. In 2016, it was found that Fuego had a greater influence on wheat straw CP than Maris Bead, which was attributed to its geometrical leaf arrangement (erectophile) advantage. This may have led to greater light interception, enhanced nodulation and BNF, and hence improved CP (Fan et al. 2006).

In 2015, the LER for N (NLER) was above the unity value of 1.0 for the bi-cropping treatments (Figure 3), which revealed the advantages of practising bi-cropping compared to sole cropping, due to efficient acquisition of growth resources, particularly N (Rao and Willey 1980). The LER of 1.50 meant that bi-cropping was 1.5 times advantageous over sole cropping in terms of N-use efficiency. In 2016, there was no advantage of bi-cropping over the sole cropping and the NLER was near to the unity value of 1.0. The faba bean rust disease was thought to have been a contributory factor for the lower NLER in 2016, which occurred due to the warm and wet growing conditions (Putasso et al. 2012). This can further infer that fungal bean diseases can negatively affect the N-use in bi-cropping systems, as it affects the bean leaves, which are responsible for light interception, enhancing nodulation and BNF. The N-use efficiency gradually reduced as the number of rows were increased beyond the 2x2 alternate row spatial arrangements. This was probably due to antagonistic interactions on resource-use (Geno and Geno 2001). Even though Fuego had higher disease severity values, its faster growth rate attributes may have helped to escape the disease infestation and enable the plants to set seed before the peak disease infestation. This indicated that short and early maturing bean cultivars (e.g. Fuego) may provide a greater advantage for forage production in wheat/bean bi-cropping compared to tall and medium-late maturing bean cultivars (e.g. Maris Bead). The results of this study indicated greater aggressivity numerical values for the 2x2 alternate row treatments, which may have been due to the likelihood of interspecific complementarity for efficient utilisation of ecological resources (Wahla et al. 2009). This may have a direct bearing on improving fodder quality. The lower aggressivity values from the 1x1 and 3x3 alternate row treatments, may have resulted from the competitive response of the bi-crops to the negative treatment effect, possibly due to interspecific competition for available resources (Mariotti et al. 2009), which may compromise the quality of the fodder. The higher aggressivity values in 2015 than in 2016 demonstrated the advantage of bi-cropping under dry conditions (Semere and Froud-Williams 2001).

# Conclusion

The limited availability of N in organic farming systems can have a direct effect on cereal forage yields and CP concentrations, which are the key factors necessary to sustain livestock productivity. Therefore, the identification of agronomic practices that can improve the utilisation of N in low input wheat/faba bean bi-cropping systems, is fundamental. This study revealed advantages of bi-cropping compared to sole cropping in terms of improved wheat forage CP, wheat grain N uptake and NLER. The drilling patterns of the wheat bi-crops in the uniform inter-row spacing did not affect wheat forage yield, CP or N uptake, but had an effect on CCI, which was higher in the alternate rows patterns than in the broadcast pattern. The paired alternate rows (2x2) of wheat and beans showed an opportunity to improve NLER and reduce faba bean rust disease. In wheat/faba bean bi-cropping systems, the attributes of the bean cultivar Fuego were shown to improve wheat straw CP, whereas Maris Bead showed a lower severity of faba bean rust disease.

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

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| Months | Rainfall  (mm) | | 10-year mean (mm) |  | Mean temperatures (oC) | | 10-year mean (oC) |
|  | 2015 | 2016 | 2005-2014 |  | 2015 | 2016 | 2005-2014 |
| 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 |
| **Chemical characteristics** |  |  |
| 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 N (%) | 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 |

Note: \*Analyses conducted at Royal Agricultural University laboratory

Table 3. The combined analysis of variance (mean squares and F-probability values) for the wheat forage yield components, CP, N uptake, NLER and CCI influenced by cropping systems, drilling patterns and bean cultivars over two years (2015 and 2016) in wheat/faba bean bi-cropping.

|  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  |  | Mean Squares | | | | | | | | | | |
|  |  | Wheat forage yield | | | | | Wheat CP | | Wheat N uptake | | NLER | CCI |
| Source of variation | Degrees of Freedom | Straw  (t ha-1) | Grain  (t ha-1) | TGW  (g) | Total biomass  (t ha-1) | HI  (%) | Straw  (g kg-1 DM) | Grain  (g kg-1 DM) | Straw  (kg N ha-1) | Grain  (kg N ha-1) |  |  |
| Cropping systems (C) | 1 | 27.49 \*\*\* | 38.11 \*\*\* | 0.293 ns | 20.709 \*\*\* | 125.78 \*\* | 460.7 \*\*\* | 3135.5 \*\*\* | 3310.66 \*\*\* | 236.14 \*\*\* | 0.383 \*\*\* | 987.518 \*\*\* |
| C x Drilling patterns (D) | 3 | 0.319 ns | 2.3 ns | 3.091 ns | 1.239 ns | 42.94 \* | 14.7 ns | 174.7 ns | 19.51 ns | 3.84 ns | 0.206 \*\*\* | 135.714 \*\*\* |
| C x Bean cultivars (B) | 1 | 0.747 ns | 0.115 ns | 15.580 ns | 1.449 ns | 8.18 ns | 16.2 ns | 361.7 ns | 2.12 ns | 27.14 ns | 0.002 ns | 1.522 ns |
| C x Year (growing seasons) (Y) | 1 | 13.09 \*\*\* | 30.39 \*\*\* | 449.01 \*\*\* | 10.991 \*\*\* | 895.76 \*\*\* | 1773.1 \*\*\* | 14562.1 \*\*\* | 4699.80 \*\*\* | 90.83 \*\* | 2.421 \*\*\* | 164.1527 \*\*\* |
| C x D x B | 2 | 0.106 ns | 0.208 ns | 8.873 ns | 0.322 ns | 7.03 ns | 36.36 ns | 30.8 ns | 18.85 ns | 9.85 ns | 0.012 ns | 2.135 ns |
| C x Y x D | 3 | 0.229 ns | 1.006 ns | 15.45 \* | 1.036 ns | 7.21 ns | 14.92 ns | 103.5 ns | 26.85 ns | 71.30 ns | 0.037 ns | 2.274 ns |
| C x Y x B | 1 | 0.007 ns | 0.0193 ns | 8.067 ns | 0.107 ns | 33.95 ns | 92.6 ns | 333.9 ns | 3.07 ns | 0.05 ns | 0.060 ns | 0.935 ns |
| C x Y x D x B | 3 | 0.137 ns | 0.142 ns | 7.352 ns | 0.967 ns | 20.28 ns | 16.7 ns | 121.0 ns | 12.08 ns | 9.42 ns | 0.052 ns | 0.839 ns |
| Notes: DM, dry matter; \* = *p* < 0.05; \*\* = *p* < 0.01; \*\*\* = *p* < 0.001; ns = not significant at *p* < 0.05; HI, Harvest Index; CP, Crude Protein; NLER, Nitrogen Land Equivalent Ratio; DM, Dry Matter; CCI, Chlorophyll Concentration Index; N, nitrogen; TGW, total grain weight | | | | | | | | | | | | |

Table 4. The effects of drilling patterns and bean cultivars on wheat forage yield during the 2015 and 2016 growing seasons

|  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Treatments Mix-proportion | | |  | Straw yield  (t ha-1) | | Grain yield  (t ha-1) | | Total biomass yield  (t ha-1) | | HI  (%) | |
| Drilling patterns | |  | | 2015 | 2016 | 2015 | 2016 | 2015 | 2016 | 2015 | 2016 |
| 1x1 | 50:50 |  | | 2.6 | 2.8 | 2.4 | 1.6 | 5.6 | 5.0 | 48 | 37 |
| 2x2 | 50:50 |  | | 2.5 | 2.5 | 2.4 | 1.7 | 5.6 | 4.8 | 49 | 40 |
| 3x3 | 50:50 |  | | 2.3 | 2.7 | 2.2 | 1.6 | 5.1 | 4.9 | 50 | 38 |
| Broadcast | 50:50 |  | | 2.6 | 2.9 | 2.2 | 1.7 | 5.4 | 5.0 | 46 | 37 |
| SED (*p* <0.05) | - |  | | 0.210 ns | 0.191 ns | 0.167 ns | 0.151 ns | 0.294 ns | 0.266 ns | 2.2 ns | 2.0 ns |
|  |  |  | |  |  |  |  |  |  |  |  |
| Cropping systems | |  | |  |  |  |  |  |  |  |  |
| Bi-crop mean | 50:50 |  | | 2.5 b | 2.7 b | 2.3 | 1.7 b | 5.4 | 4.8 b | 48 a | 38 b |
| Sole crop | 100 |  | | 2.9 a | 5.6 a | 2.1 | 4.0 a | 5.6 | 7.6 a | 42 b | 41 a |
| SED (*p* <0.05) | - |  | | 0.182 \* | 0.166 \*\*\* | 0.144 ns | 0.131 \*\*\* | 0.255 ns | 0.230 \*\*\* | 1.9 \*\* | 1.8 \* |
|  |  |  | |  |  |  |  |  |  |  |  |
| Bean cultivars |  |  | |  |  |  |  |  |  |  |  |
| Fuego | 50:50 |  | | 2.5 | 2.78 | 2.3 | 1.68 | 5.4 | 4.9 | 48 | 39 |
| Maris Bead | 50:50 |  | | 2.4 | 2.75 | 2.3 | 1.59 | 5.3 | 4.8 | 49 | 37 |
| SED (*p* <0.05) | - |  | | 0.192 ns | 0.175 ns | 0.152 ns | 0.138 ns | 0.268 ns | 0.243 ns | 2.0 ns | 1.9 ns |

Notes: Values with the same letter within the same parameter and treatment factor are not significantly different at\*=*p* <0.05; \*\*=*p* <0.01; \*\*\*=*p* <0.001; ns= not significant at *p* < 0.05; SED, standard error of the difference of means; Total wheat yield biomass was calculated by summing up the ear and straw yield.

Table 5. The effects of year x drilling patterns interactions on wheat thousand grain weight (TGW) during the 2015 and 2016 growing seasons

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
|  |  |  |  |  | TGW (g) | | |
| Cropping systems | Year | Drilling patterns | Mix-proportions |  | Bean cv.  Fuego | Bean cv.  Maris bead | Effects of drilling patterns |
| Bi-cropping | 2015 | 1x1 | 50 |  | 40.0 | 40.8 | 40.4 a |
|  |  | 2x2 | 50 |  | 42.3 | 40.7 | 41.5 a |
|  |  | 3x3 | 50 |  | 45.1 | 40.1 | 42.5 a |
|  |  | Broadcast | 50 |  | 42.2 | 41.2 | 41.7 a |
| Seasonal mean |  | **-** | **-** |  | 42.4 | 40.7 | 41.5 A |
|  | 2016 | 1x1 | 50 |  | 35.6 | 34.0 | 34.8 a |
|  |  | 2x2 | 50 |  | 34.3 | 34.3 | 34.4 ab |
|  |  | 3x3 | 50 |  | 33.1 | 31.9 | 32.5 b |
|  |  | Broadcast | 50 |  | 34.5 | 36.1 | 35.3 a |
| Seasonal mean |  | **-** | **-** |  | 34.4 | 34.2 | 34.2 B |
| Sole cropping | 2015 | Sole wheat | 100 |  | - | - | 40.3 |
|  | 2016 |  | 100 |  | - | - | 35.9 |
| Mean |  |  | - |  | - | - | 38.1 |
| Effects of bi-cropping | | | 50 |  | 38.4 | 37.4 | 37.9 |
| SED Cropping Systems (C) 0.827 ns  SED Cropping x Year (Y) 1.17 \*\*\*  SED Cropping x drilling patterns (D) 0.955 ns  SED Cropping x bean (B) 0.872 ns  SED Cropping x year x drilling patterns (Y x D) 1.351 \*  SED Cropping x year x bean (Y x B) 1.233 ns  SED Cropping x drilling patterns x bean (D x B) 1.103 ns  SED Cropping year x drilling patterns x bean(Y x D x B) 1.560 ns | | | | | | | |

Notes: Values with the same letter within the same parameter and treatment factor are not significantly different at\* = *p* < 0.05; \*\* = *p* < 0.01; \*\*\* = *p* < 0.001; ns= not significant at *p* < 0.05; SED, standard error of the difference of means; g, grams; TGW, total grain weight. Letters in the uppercases compare the treatment means between cropping seasons while letters in lowercases compare the treatment means among the drilling patterns within each growing season.

Table 6. The effects of drilling patterns and bean cultivars on wheat forage quality parameters during the 2015 and 2016 growing seasons

|  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  | |  | | CP concentration (g kg-1 DM) | | | |  | N- uptake (kg N ha-1) | | | |
| Treatments Mix-proportion | | |  | Wheat straw | | Wheat grain | |  | Wheat straw | | Wheat grain | |
| Drilling patterns | |  | | 2015 | 2016 | 2015 | 2016 |  | 2015 | 2016 | 2015 | 2016 |
| 1x1 | 50:50 |  | | 25.4 | 40.7 | 94.0 | 134.0 |  | 13.2 | 27.2 | 41.5 | 35.3 |
| 2x2 | 50:50 |  | | 25.1 | 37.2 | 96.6 | 132.8 |  | 13.4 | 23.1 | 43.0 | 36.4 |
| 3x3 | 50:50 |  | | 25.5 | 41.0 | 96.2 | 140.3 |  | 11.4 | 26.2 | 39.0 | 37.9 |
| Broadcast | 50:50 |  | | 25.4 | 38.2 | 97.1 | 145.1 |  | 12.8 | 27.7 | 38.1 | 38.8 |
| SED (*p* <0.05) | - |  | | 1.891 ns | 2.119 ns | 3.142 ns | 10.150 ns |  | 1.73 ns | 3.81 ns | 2.39 ns | 3.00 ns |
|  |  |  | |  |  |  |  |  |  |  |  |  |
| Cropping systems | |  | |  |  |  |  |  |  |  |  |  |
| Bi-crop mean | 50:50 |  | | 24.8 a | 39.3 a | 96.0 a | 134.5 a |  | 12.7 | 26.0 b | 40.4 a | 37.1 a |
| Sole crop | 100 |  | | 18.8 b | 23.9 b | 86.1 b | 106.0 b |  | 12.5 | 69.6 a | 34.7 b | 31.4 b |
| SED (*p* <0.05) | - |  | | 1.638 \*\*\* | 2.119 \*\*\* | 2.74 \*\*\* | 11.710 \*\* |  | 1.50 ns | 3.30 \*\*\* | 2.07 \*\* | 2.19 \*\*\* |
|  |  |  | |  |  |  |  |  |  |  |  |  |
| Bean cultivars |  |  | |  |  |  |  |  |  |  |  |  |
| Fuego | 50:50 |  | | 24.2 | 40.9 a | 95.9 | 133.4 |  | 12.3 | 26.1 | 41.0 | 37.7 |
| Maris Bead | 50:50 |  | | 25.6 | 37.5 b | 96.1 | 142.7 |  | 13.1 | 26.0 | 39.8 | 36.6 |
| SED (*p* <0.05) | - |  | | 1.726 ns | 2.234 \* | 2.860 ns | 10.690 ns |  | 1.58 ns | 3.48 ns | 2.10 ns | 2.18 ns |
| Notes: Values with the same letter within the same parameter and treatment factor are not significantly different at\*=*p* < 0.05; \*\*=*p* < 0.01; \*\*\* = *p* <0.001;ns = not significant at *p* < 0.05*;* SED, standard error of the difference of means; DM, dry matte; N, nitrogen | | | | | | | | | | | | |

Table 7. The effects of cropping systems, drilling patterns and bean cultivars on CCI in wheat leaf in 2015 and 2016 cropping seasons.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Treatments | | Mix-proportion | CCI | | |
| Drilling patterns | | | 2015 | 2016 | |
| 1x1 | 50:50 | | 20.6 a | 24.7 a | |
| 2x2 | 50:50 | | 20.7 a | 25.0 a | |
| 3x3 | 50:50 | | 20.6 a | 23.7 b | |
| Broadcast | 50:50 | | 14.3 b | 19.2 c | |
| SED (*p* < 0.05) | - | | 0.461 \*\*\* | 0.422 \*\*\* | |
| Cropping systems |  | |  |  | |
| Bi-crop mean | 50:50 | | 19.0 a | 23.1 a | |
| Sole crop | 100 | | 6.6 b | 11.9 b | |
| SED (*p* < 0.05) | - | | 0.399 \*\*\* | 0.365 \*\*\* | |
| Bean cultivars |  | |  |  | |
| Fuego | 50:50 | | 19.0 | 22.9 | |
| Maris Bead | 50:50 | | 19.1 | 23.4 | |
| SED (*p* < 0.05) | - | | 0.421 ns | 0.385 ns | |
| Notes: Values with the same letter within the same parameter and treatment factor are not significantly different at \* =*p* < 0.05; \*\* =*p* < 0.01; \*\*\* =*p* < 0.001; ns= not significant at *p* < 0.05; SED, standard error of the difference; CCI, Chlorophyll concentration index. | | | | |

Table 8. Aggressivity (A) of wheat and beans in a bi-cropping system affected by drilling patterns and bean cultivars in 2015 and 2016 cropping seasons.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
|  | Aggressivity (A) | | | | System Aggressivity (A) | |
| Drilling patterns | Wheat  (Aw1) | Fuego  (AFG) | Wheat  (Aw2) | Maris Bead  (AMB) | Wheat  (Aw1+Aw2)/2 | Legume  (Afg+Amb)/2 |
| Spring 2015 | | | | |  |  |
| 1x1 | 0.729 | -0.729 | 0.754 | -0.754 | 0.742 | -0.742 |
| 2x2 | 0.759 | -0.759 | 0.818 | -0.818 | 0.789 | -0.789 |
| 3x3 | 0.652 | -0.652 | 0.673 | -0.673 | 0.663 | -0.663 |
| Broadcast | 0.547 | -0.547 | 0.600 | -0.600 | 0.537 | -0.537 |
| Spring 2016 | | | | |  | |
| 1x1 | 0.028 | -0.028 | 0.127 | -0.127 | 0.049 | -0.049 |
| 2x2 | 0.018 | -0.018 | 0.167 | -0.167 | 0.075 | -0.075 |
| 3x3 | 0.052 | -0.052 | 0.147 | -0.147 | 0.047 | -0.047 |
| Broadcast | 0.174 | -0.174 | 0.238 | -0.238 | 0.206 | -0.206 |

Notes AFG and AMB are Aggressivity indices for Fuego and Maris Bead bean cultivars in mixture with wheat (Aw).

Table 9. The effects of cropping systems, drilling patterns and bean cultivars on the severity (%) of faba bean rust (*Uromyces viciae-fabae*) at 205 DAS in 2016.

|  |  |  |
| --- | --- | --- |
| Treatments | Mix-proportion | Faba bean rust severity (%) |
| Drilling patterns |  |  |
| 1x1 | 50:50 | 68.5 a |
| 2x2 | 50:50 | 57.5 b |
| 3x3 | 50:50 | 70.0 a |
| Broadcast | 50:50 | 60.3 b |
| SED (*p* < 0.05) | - | 4.320 \*\* |
| Cropping systems | |  |
| Bi-crop mean | 50:50 | 64.7 |
| Sole crop | 100 | 67.0 |
| SED (*p* < 0.05) | - | 3.410 ns |
| Bean cultivars |  |  |
| Fuego | 50:50 | 84.7 a |
| Maris Bead | 50:50 | 44.6 b |
| SED (*p* < 0.05) | - | 4.830 \*\*\* |
| Notes: Values with the same letter within the same parameter and treatment factor are not significantly different at \* = *p* < 0.05; \*\* = *p* < 0.01; \*\*\* = *p* < 0.001; ns = not significant at *p* < 0.05; SED, standard error of the difference of means; DAS, days after sowing. | | |

|  |  |  |
| --- | --- | --- |
| **Drilling patterns** | **Details** | **Line diagram** |
| **Sole cropping** | Sole wheat and beans sown at 100% recommended sowing density.  Sole wheat crop  12 m  Sole bean crop  Beans randomly sown | 2m |
| **1 x 1**  (Replacement design) | Wheat and bean bi-crop densities maintained at 50% of their respective sole densities. One row of beans sown alternate with one wheat row spaced at 15 cm between wheat and bean rows. |  |
| **2 x 2**  (Replacement design) | Wheat and bean bi-crop densities maintained at 50% of their respective sole densities. Two rows of beans sown alternate with two rows of wheat spaced at 15 cm between rows. |  |
| **3 x 3**  (Replacement design) | Wheat and bean bi-crop densities maintained at 50% of their respective sole densities. Three rows of beans sown alternate with three rows of wheat spaced at 15 cm between rows. |  |
| **Broadcast** (Replacement design) | Wheat and bean bi-crop densities maintained at 50% of their respective sole densities. Beans randomly sown over wheat rows drilled at 15 cm apart. |  |

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

Figure 2. Effects of cropping systems on wheat grain and bean seed crude protein concentration across the cropping seasons. Bars with the same letter are not significantly different at *p* < 0.05.

Figure 3. LER values for N (NLER) as influenced by drilling patterns and year of wheat/bean bi-cropping during the 2015 and 2016 growing seasons. The error bars for NLER represent SED for drilling patterns x year interactions. These were calculated for each year comparing the bi-crops against the unitary (sole crop). The errors bars in the figure help to denote significant differences between treatment means at *p* < 0.05.