DOCTOR OF PHILOSOPHY

Improving sustainable production of home-grown forage for livestock

evaluating the potential of field bean (Vicia faba L.) and wheat (Triticum aestivum L.) variety mixtures as bi-crop opportunity

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Improving sustainable production of home-grown forage for livestock: Evaluating the potential of field bean (*Vicia faba* L.) and wheat (*Triticum aestivum* L.) variety mixtures as bi-crop opportunity

By

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DECLARATION

I declare that this research is the result of my own work and except where stated and referenced otherwise, all the written work and investigations are my own. This work has not been accepted or submitted for any comparable academic award elsewhere.

Kamalongo Donwell, M.A.

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ABSTRACT

Field experiments were carried out between 2015 and 2016 spring cropping seasons at the Royal Agricultural University farm, Cirencester, Gloucestershire, England (51° 42' 33.6" N 1° 59' 40.7" W) to evaluate spring faba bean cultivars in mixture with wheat towards improving sustainable production of home-grown forage for livestock. The four drilling patterns and two faba bean cultivars were evaluated against their corresponding sole crops of wheat and bean in a randomised complete block design replicated four times. The density of bi-crops was decided by substituting half the density of sole crops with additional crop. The cropping seasons significantly affected the treatments responses. Bi-cropping system significantly outperformed sole cropping system on various plant performances metrics across the two years. Bi-cropping increased land productivity up to 50% over sole cropping in 2015 with no land productivity advantage in 2016. Bi-cropping showed a significant increase in the Chlorophyll Concentration Index (CCI) over sole cropping system. Leaf Area Index (LAI), Intercepted Photosynthetic Active Radiation (IPAR) and Radiation Use Efficiency (RUE) were significantly higher in bi-cropping over sole cropping system by 71.4%, 14.8 and 35.7% respectively. Bi-cropping significantly outperformed sole cropping by 49.8% whilst giving better weed control, demonstrating its potential to counteract herbicide use. Sole bean had the lowest weed control effect compared to sole wheat. Dry matter yield and crude protein were significantly higher in bi-cropping than sole cropping. Bean N yield and wheat N harvest index was significantly higher in bi-cropping than sole cropping. Cropping system did not significantly affect bean crude protein. Fuego was more vulnerable to field biotic stress infestation than Maris Bead. Drilling patterns significantly influenced resource-use in bi-cropping systems. Alternate rows significantly influenced higher resource-use and land productivity over broadcast bi-cropping. Alternate rows arranged as 2x2 spatial configuration had the highest productivity in bi-cropping over other drilling patterns treatments. The seasonal variability significantly determined the performance of the 1x1 alternate rows treatment. The 3x3 reduced the productivity of bi-cropping. Contrasting bean morphological traits distinguished their ecological services on IPAR and weed control in the system. Fuego beans had higher wheat crude protein and N uptake than Maris Bead. Maris Bead had higher bean seed crude protein than Fuego. The 2015 growing season showed improved competitiveness of bi-crops on resource-use than in 2016 growing season. Bi-cropping treatments showed potential to mitigate greenhouse gas emissions and reduce use of synthetic fertilisers.

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ABBREVIATIONS

A	Aggressivity
ANOVA	Analysis of variance
AHDB	Agriculture and Horticulture Development Board
CAP	Common Agricultural Policy
CCI	Chlorophyll Concentration Index
Cm	Centimetres
DAS	Days after sowing
Df	Degrees of freedon
DM	Dry matter
EU	European Union
g	grams
GS	Growth Stages
HI	Harvest index
IPAR	Intercepted Photosynthetic Active Radiation
kg ha^{-1}	kilogram per hectare
LAI	Leaf Area Index
LER	Land Equivalent Ratio
m^2	square metres
MAFF	Ministry of Agriculture, Fisheries and Food
MJ	Megajoule
N	Nitrogen
NGR	National Grid Reference
Ns	No Signficant Differences
^oC	degrees Celcius (centigrade)
PGRO	Processors and Growers Research Organisation
RCC or K	Relative Crowding Coefficient
RUE	Radiation Use Efficiency
SED	Standard Errors of Differences of means
t	Tonnes

CHAPTER 1

1.1 General introduction

The increased demand for sustainable home-grown forage highlights the opportunity for low input bi-cropping systems and thus the importance of appropriately chosen faba bean cultivars and spatial arrangements thus creating an opportunity which will be explored in this study.

The current increasing global human population, urbanisation and income growth are the major factors which have influenced the increase in meat consumption. These factors are also expected to increase growth in the meat market and the production of protein-rich feeds for livestock (FAO, 2013; de Visser *et al.*, 2014).

In the United Kingdom and other European countries there is a growing interest in the promotion of increased production of home-grown protein-rich forage to sustain the domestic demand for beef and milk (Anil *et al.*, 1998). This stems from growing social, economic and environmental concerns regarding the importation of protein-rich feed materials from South America and the United States (European parliament, 2011; Hauslings, 2011).

Dependence on sole grass forage declining, in line with the growing competition on the grassland for the production of feed, food, biofuels and biodiversity, resulted in modifications to the feed production paradigm – moving from grass dependence to wholecrop cereal based forages such as wheat, maize and barley (Lüscher *et al.,* 2014; Powell, 2008). Wholecrop cereal based forage has the capacity to supply high amounts of energy-rich forage diets but contain low amounts of protein (Baghdadi *et al.*, 2016; Sadeghpour *et al.,* 2013). Low protein concentration in wholecrop cereal forage has been supplemented with costly protein-rich feed materials to balance the diet and sustain desirable levels of milk and beef production (Anil *et al.*, 1998).

The production of wholecrop cereal based forage for ruminants has relied mostly on conventional and monoculture farming systems using synthetic fertilizers and herbicides for greater forage dry matter yields and weed control (Motavalli *et al.,* 2013; Tilman *et al.,* 2011; Mousavi and Eskandari, 2011). The use of agrochemicals and intensive soil tillage has consequently resulted in on-site and off-site environmental externalities at the expense of obtaining greater wholecrop cereal forage dry matter yield (Altieri *et al.,* 2017). Increased cost of production is one of the negative economic implications associated with wholecrop cereal forage production in these systems (Keady *et al.,* 2002).

Organic based production systems were designed to produce optimum quantities of food of high nutritional quality by excluding all agricultural production practices detrimental to the environment and wildlife, such as the use of agrochemicals, to attain sustainability. It encourages biodiversity, biological cycles and soil biological activities (Röös, *et al.,* 2018; Seufert and Ramankutty, 2017; Soil Association, 2002). Pest control can be achieved by using appropriate cropping techniques, biological control and natural pesticides (mainly extracts from plants). Weed control is managed by appropriate rotations, mechanical cultivations, seeding timing, mulching and transplanting (Lutman *et al.,* 2013). However, there are some potential disadvantages such as limited soil nitrogen bioavailability, along with greater weed competition can lead to forage dry matter yield penalties and low cereal grain protein concentration (Bilsborrow *et al.,* 2013; Ponisio *et al.,* 2015; Gallandt, 2014). Requirements for additional labour and excessive cultivations as a method of weed control can also lead to soil compaction. The high carbon-to-nitrogen ratio for wholecrop cereals residues can slow the release of nitrogen to the system due to immobilisation, which may contribute to limit nitrogen availability (Jensen *et al.,* 2015. Therefore, the amount of soil nitrogen lost through plants' uptake can be higher than it can be replenished biologically (David *et al.,* 2005). This shows that the high demand for high quality forage cannot be met by wholecrop cereals alone due to the challenges involved with the production of these crops organically. This suggests that organically produced wholecrop cereal based feed for ruminants requires supplementation with protein-rich feed materials for a nutritionally balanced feed diet (Anil *et al.,* 1998). Alternative strategies have to be sought for organic farmers to combat the problem of low protein content of wholecrop cereal based forages. Such strategies must include systems that will sustain soil fertility, provide a balance between nitrogen fixing and nitrogen demanding crops and improve protein content of cereals whilst producing high quality feed to meet the annual requirements of livestock enterprise.

Since land is limited, the integration of cereals and grain legumes as bi-cropping is considered a potential alternative sustainable production strategy able to boost home-grown protein rich forage for livestock in low-N input production systems (Baghdadi *et al.,* 2016; Sadeghpour *et al.,* 2014; Eskandari *et al.,* 2009; Bulson *et al.,* 1997). This can improve nitrogen availability by balancing nitrogen exports from the system through biological nitrogen fixation by the legume bi-crop; improve forage dry matter yields through improved use of growth resources; improve the nutrition quality of cereal forage crops due to non-proportional competition for mineral and other plant growth. This system may also help livestock farmers to access low cost home-grown feeds of higher protein quality and reduce dependence on high cost non-forage feed materials (Askew, 2016; Pecetti and Piano, 2000). The reduction in pests and diseases result may not only lower production costs than those associated with herbicides and insecticides but also less environmental pollution (Mousavi and Eskandari, 2011). Ruminants fed with protein-rich feed retain more energy than those fed with low quality fodder (Poppi and McLennant, 2014). This may be attributed to increased feed intake, which is easy to chew with less resistance, increased breakdown of particles into smaller particles, which help to enhance digestion rate and clearance from the rumen than low quality fodder (Giordano *et al.*, 2014). Protein-rich feed diets can produce less methane than carbohydrates rich feeds per unit of feed intake (Sauvant and Giger-Reverdin, 2009). According to Van Dorland et al. (2007), this can be due to modification of fermentation patterns in the rumen towards propionate, which in turn is a hydrogen carrier and thus minimises the amount of methane produced.

Recent statistics indicate that increased faba bean production levels led to increased domestic use and potential opportunities for export (Askew, 2016; PGRO, 2017). The steady increase in domestic utilization and exports demonstrates the reliability and future prospects of faba bean in the livestock value chain. Jensen *et al.* (2010), Kopke and Nemecek (2010) reported that the faba bean has unique biological attributes which make it a suitable candidate for home-grown protein because of its capacity to biologically fix higher nitrogen amounts in the soil and higher concentrations of grain crude protein (Kopke and Nemecek, 2010). The faba bean adapts to a wide range of climatic and edaphic environmental conditions and is very compatible with cereal/legume crop mixtures (Jensen *et al.*, 2010). Faba beans in cereal/legumes crop mixtures can potentially facilitate various ecological services ranging from protein enhancement in wholecrop cereal based forage to enhanced ecological sustainability (Ghanbari-Bonjar and Lee, 2003; Strydhorst *et al.,* 2008; Jensen *et al.,* 2010; Chapagain, 2014).

The management of plant interaction in cereal/legume crop mixtures is crucial to maximise growth and productivity. Enhanced benefits are expected from bi-cropping systems when interspecific competition between bi-crops is minimised and interspecific co-operation is maximised with use of limited environmental resources (Geno and Geno, 2001). The choice of crop varieties, sowing densities and spatial arrangements are some of the determining factors for a functional and performing bi-cropping system (Naudin *et al.,* 2010; Dordas and Lithourgidis, 2011).

Currently, the choice of faba bean cultivars suitable for bi-cropping systems in low-N environment remains underdetermined. Farmers' choice of legume cultivars for bi-cropping systems has been based on the historical performance in sole cropping systems (O'Leary and Smith, 1999). Additionally, the botany of legumes and cereals differ which further challenges the selection of the appropriate cultivar (Tsubo *et al.,* 2004). The differences in morphology (straw height or leaf architecture) and growth rates (slowness and earliness of ripening) traits among the legume cultivars can determine the productivity of low input bi-cropping systems, influenced by the way limited environmental resources are utilised (Taylor and Cormack, 2002; Belel *et al.,* 2014).

The most commonly practiced bi-crop spatial arrangements include; a complete mixture of bi-crop species within the same row; alternate rows of each crop species; alternate blocks of two or more pure bi-crops species; and drilling rows of pure species at right angles to each other (Musa *et al.,* 2010). Spring faba beans and wheat have similar maturity groups (Yahuza, 2011b; Klimek-Kopyra *et al.,* 2015). Therefore the spatial rather than temporal manipulation of crop combinations due to synchronised maturity dates is the only option for the efficient and optimum use of limited environmental resources in spring bi-cropping systems (Martin and Snaydon, 1982).

The work on cereal/faba bean bi-cropping for forage production in the UK is not new. Previously, similar bi-cropping studies in low input environments have demonstrated its potential in the reduction of importation of protein-rich concentrates feed materials (Bulson *et al.,* 1997; Ghanbari-Bonjar, 2000, Ghanbari-Bonjar and Lee, 2002; Ghanbari-Bonjar and Lee, 2003; Pristeri *et al.,* 2006). The present study was therefore undertaken to address the knowledge gap in the productivity of spring wheat/faba bean bi-cropping as whole forage for organic based livestock systems by assessing the effects of different drilling patterns and contrasting faba bean cultivar combinations.

Currently, inadequate scientific knowledge regarding the choice of suitable faba bean cultivars for a specific drilling pattern for low input spring bi-cropping systems may be answered through this study towards improving sustainable production of home-grown protein-rich fodder for livestock production. The study builds on the outcomes of previous bi-cropping studies within the UK where the bi-crops' spatial arrangement in alternate rows maintained the one wheat row to one legume row (1:1) overtime as an initial solution to promote large scale bi-cropping systems under modern mechanised farming systems (Bulson *et al.*, 1997). However, the (1:1) spatial arrangement is not a one size bi-cropping practice to fit all faba bean cultivars because newly released faba bean cultivars may have different morphological and growth rates traits. Therefore the modification of alternate row spatial arrangements in the form of (1:1), (2:2) and (3:3) will not change the concept of alternate row drilling, originally designated to accommodate bi-cropping under for large scale mechanisation (Bulson *et al.* (1997), but rather explore further undiscovered opportunities for improving large scale bi-cropping for sustainable home-grown and high quality fodder production.

1.2 Research goal

Based on the above background, a study aimed at improving sustainable production of home-grown forage for livestock through evaluation of the potential of field bean (*Vicia faba* L.) and wheat (*Triticum aestivum* L.) variety mixtures as a potential bi-crop opportunity was proposed.

1.3 Study objectives

(i) To determine the effects of bean growth characteristics on crop canopy growth, light interception and weed suppression when sown as a bi-crop in wheat/bean bi-cropping systems.

(ii) To measure the effects of the spatial arrangement of wheat and beans bi-crop mixtures on resource-use efficiency, canopy growth and disease incidence in wheat/bean bi-cropping systems.

(iii) To determine the effects of spatial arrangements of wheat and faba beans bi-crop mixtures on biological yields; relative yield quality; and system productivity.

1.4 Study hypothesis

<u>Crop growth habits</u>

H_0: Faba bean growth habits can significantly influence ecological spatial interspecific *competition* on the use of limited growth resources when sown as bi-crops in wheat/faba bean bi-cropping system.

H_1: Faba bean growth habits can significantly influence ecological spatial interspecific *complementarity* on efficient use of limited growth resources when sown as bi-crops in wheat/faba bean bi-cropping systems.

Drilling Patterns (spatial arrangements)

H_0: Different drilling patterns can influence ecological spatial interspecific competition on the use of growth resources resulting in decreased productivity of wheat/faba bean bi-cropping systems.

H_1: Different drilling patterns can influence ecological spatial interspecific complementarity on efficient use of limited growth resources resulting in improved productivity of wheat/faba bean bi-cropping systems.

1.5 Conceptual framework

The conceptual framework (Figure 1.1) was designed in line with the production principles and species interactions in bi-cropping systems as described by Vandermeer (1989) and Zhang and Li (2003). The scenario $\mathbf{H_1}$ hypothesizes the likelihood of ecological interspecific complementarity and facilitation occurrence between species components reflected in the dependent variable as a result of *positive interaction* between independent variables.

The scenario $\mathbf{H_0}$ hypothesizes the likelihood occurrence of interspecific ecological competition between species components in bi-cropping systems reflected in the dependent variable as a result of *negative interaction* between independent variables. The larger phenological, morphological and physiological differences between bi-crops result in better use of growth resources.

1.6 Outline of the thesis

Chapter **Two:** Bi-cropping systems in temperate and tropical climates; management of bi-cropping systems, consequences of modern agricultural practices in the temperate on the environment; strengths and weaknesses of bi-cropping systems; drivers which led to promote home-grown protein-rich forage and problems associated with feed importation into the UK and other EU countries; the weaknesses and strengths of bi-cropping systems towards developing sustainable feed production systems; and biological strengths of faba bean on influencing feed quality and ecological sustainability of production systems.

Chapter **Three:** Outlines the materials and methods used for field and laboratory studies. It shows different kinds of equipment which supported data collection. It describes the statistical model and statistical software used in carryout statistical data analysis.

Chapter **Four:** Results for 2015 core experiment, presented in tables and graphs. Results represent different sectors of studies such as yield and components, weed studies, solar radiation, fodder quality, nitrogen uptake studies, competition indices, biological efficiency of the systems.

Chapter **Five:** Results for 2016 core experiment, presented in tables and graphs. Results represent different sectors of studies such as yield and components, weed studies, solar radiation, fodder quality, nitrogen uptake studies, competition indices, biological efficiency of the systems,

Chapter **Six:** Combined results for two cropping seasons showing the treatments responses between cropping seasons.

Chapter **Seven:** Assessed underground bean root studies. It outlines the introduction, study justification, materials and methods, results, discussion and conclusion.

Chapter **Eight:** Modelled the GHG mitigation potential of bi-cropping treatments. It outlines the introduction, justification, materials and methods, results, discussions and conclusion.

Chapter **Nine:** discusses the findings for the two cropping seasons to understand bi-cropping systems with regards to current context towards sustainable production of feed and livestock productivity.

Chapter **Ten:** Conclusions, limitations and recommendations.

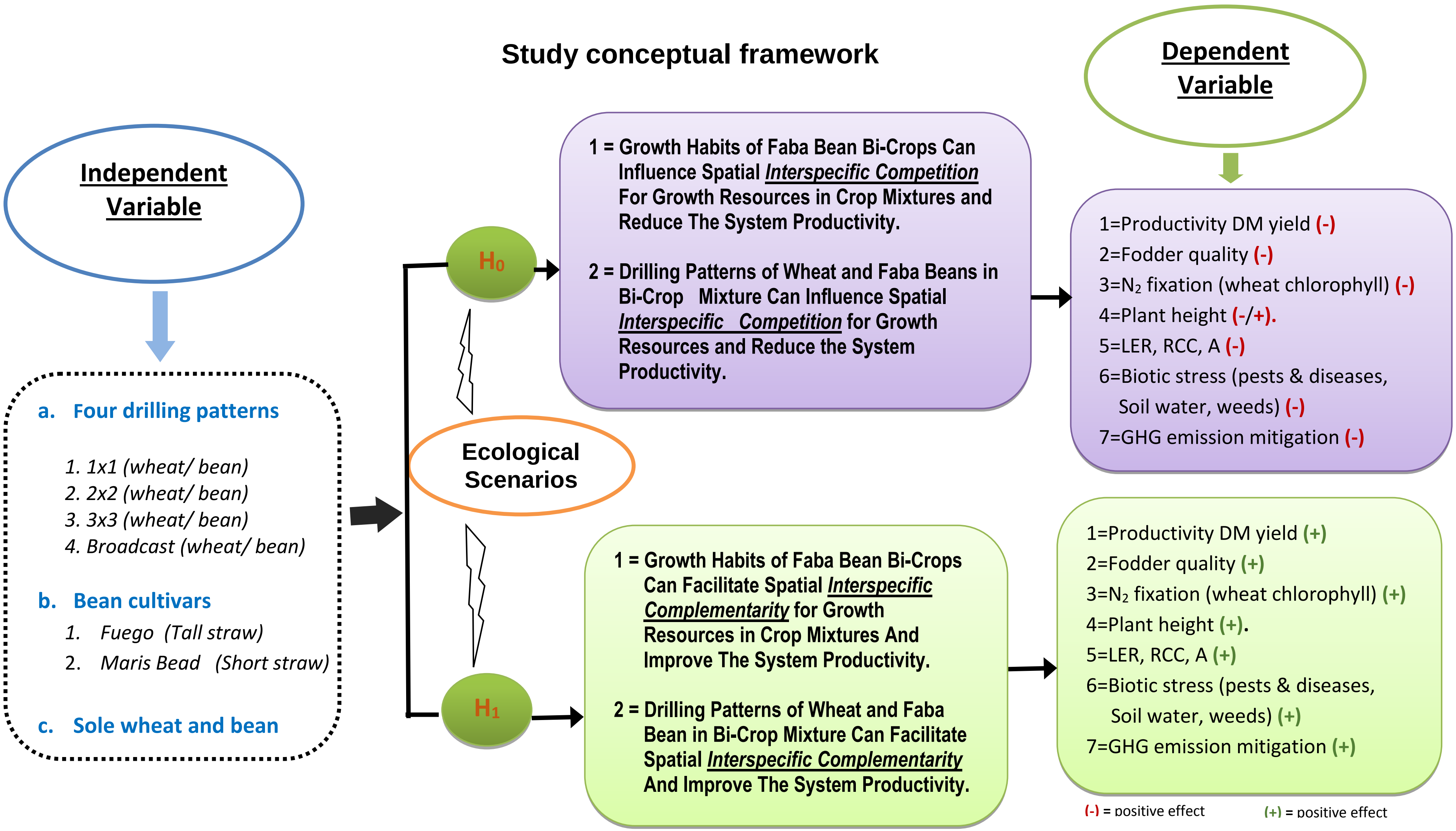

Figure 1.1: Conceptual diagram showing effects of study factors interaction on bi-cropping performance

Chapter 2

Literature review

2.1 Population growth and feed production systems

Current increases in human population have exerted much pressure on the limited land for the production of feed and food (Salter, 2017; Charles *et al.,* 2010). Global per capita meat consumption is expected to increase proportional to the increasing human population (de Visser *et al.,* 2014; FAO, 2013). Consequently, the market growth for meat due to the rise in population, urbanisation and income growth will directly increase the demand for protein-rich feed materials in the livestock production systems (De Haan *et al.,* 2010; de Visser *et al.,* 2014). Feed production in modern agriculture threatens the sustainability of agricultural production systems (Fritz, 2014; FAO, 2013). Modern agricultural production systems rely on conventional farming and monocropping systems of genetically identical plants (Mousavi and Eskandari, 2011). Such systems depend mostly on the use of agricultural chemical fertilizers and pesticides for higher crop yield and crop protection against field pests respectively (Mousavi and Eskandari, 2011). Conventional agriculture production systems have the capacity of producing higher yield per unit area and satisfying food security and nutritional demands for the increasing human population (Mousavi and Eskandari, 2011). However, over-reliance on use of agrochemicals in conventional production systems has caused serious on-site and off-site environmental externalities (Altieri *et al.,* 2017). Soil tillage has resulted in environmental degradation in the form of soil erosion, destruction of natural habitats and loss of biodiversity (Motavalli *et al.,* 2013; Altieri *et al.,* 2011). Therefore, establishing sustainable agricultural production systems remains an important option for sustainable feed production (Grethe *et al.,* 2011).

2.2 Protein shortage, importation and the environmental

The European Union (EU) livestock sector remains the largest in the world (EUROSTAT, 2012). It has been reported the largest importer of agricultural products such as feeds worldwide (Sawyer, 2006). Livestock based products are the major sources of protein for EU citizens (Anonymous, 2017). Livestock industry is important on the livelihoods and national economies of the EU countries. However, the protein deficit illustrated in Table 2.1 and Figure 1.0 was reported the major constraint across the livestock value chain (Hauling, 2011). The world-trade agreements contributed to this deficit of 70% in the EU because it promoted the imports of grain legumes into the EU which lowered the European production despite its increased consumption (Lüscher *et al.,* 2014). This also limited technology development for protein crops and made protein production unattractive for the EU farmers. High demand for protein-rich soya meal by monogastrics contributed to higher importations because they produce higher meat productivity per unit of feed than ruminants (Blue *et al.,* 2013). The importation of protein-rich soya to address the protein gap for both monogastrics and ruminants was associated with some limitations such as high costs, inconsistent availability and enhanced deforestation in producing countries (de Visser, 2013; Schrader and de Visser, 2014; Lessen *et al.,* 2011). Additionally, they were largely genetically modified (GM) in nature which was against the cultural values of the EU citizens (de Visser *et al.,* 2014).

Table 2.1: The European Union (EU) protein production (MT)

Sources: Schrader and de Visser (2014).

Source: de Visser *et al.,* (2014).

Figure 2.1: Import data for soya bean and soya bean meal and value per ton of meal imported.

2.3 Domestic protein production for self-sufficiency

In EU countries, the disadvantages of out-sourcing protein-rich feed materials outweighed its advantages because it was associated with risks such as high costs of dependence and the shortage of feed imports put the economic viability of the EU domestic meat production at risk (European Parliament, 2011). As a result, a Parliament motion was formally proposed calling for investing more efforts in plant breeding, research and development, and extension to increase home production of protein-rich feed materials (European Parliament, 2011; Hauling, 2011). However, addressing the aspects of sustainability of production systems and land shortage are key factors to the successful achievement of protein self-sufficiency in the EU. Currently, feed production practices are driven by intensive soil tillage and the use of agrochemicals substituting for higher value functional ecosystem services (Altieri *et al.,* 2017). As no more land is available for growing crops, increasing the area of protein-rich sole crops can reduce the production of carbohydrates crops (Jones *et al*., 2014; Alexandratos and Bruins, 2012). Moreover, the production of grain legume crops in crop rotation under organic, may result in low and unstable yields because they are susceptibility to water stress, competing weakly against the weeds (Bedoussac *et al.,* 2017). Spatial crop diversification of cereal and grain legumes crop mixtures under minimum tillage without agrochemicals, could be the possible intervention which may address land shortage problems and provide multiple ecosystem services (Kremen and Miles, 2012) include: increased biodiversity; improved soil quality; improved nutrient management; improved water holding capacity; improved weed, pest and disease control; reduction of global warming potential; resilient to climate change; improved fodder yield, stability and quality (Dobermann and Nelson, 2013; FAO, 2014).

Additionally, the domestic production of GM-free protein forage crops under low input production systems, may help to enhanced widespread adoption and utilisation across the EU livestock feed industry due to government restrictive approaches towards GM crops (de Visser *et al.,* (2014). Also, on cultural aspect, it can increase the interest in local feed systems among the EU citizens and increase market demand for GM-free feed supply chain (Martinez *et al.,* 2010). Protein self-sufficiency cannot be sustained under organic based production systems because of higher incidences of weeds which limit nitrogen bioavailability to the crop (Corre-Hellou and Crozat, 2005). Organic based production systems are limited to soil nitrogen as a result dry matter yield and protein concentration cannot be attained at optimum (Andrew *et al.,* 2003; Jensen *et al.,* 2015)

2.4 Bi-cropping: potential protein production system and environmental sustainability

Bi-cropping is an agronomic practice which involves the simultaneous growing of two crops on the same piece of land (Ofori and Stern, 1987). It has, and continues to be a major part of traditional farming systems in the developing continents including Africa, Asia and Latina America (Walker *et al.,* 2011). About 50 to 80% of rainfed crops are sown as bi-crops in most parts of developing world (Wang *et al.,* 2014). Bi-cropping practices have contributed greatly to Chinese crop production considering that the country contains 22% of the world's population with only 9% available arable land (Tong, 1994). In recent years, its' practise has been limited in industrialized nations due to the challenges of weed control and herbicide use in conventional farming systems (Crew and People, 2004). Annual bi-crop mixtures are currently rare in the EU cropping systems except for animal feed (Anil *et al.,* 1998). Nevertheless, numerous ecological service benefits from bi-cropping systems have renewed interest in cereal/legume mixtures preferably in low-N input environments (Malezieux *et al.,* 2009). In developing countries, bi-cropping is influenced by higher levels of subsistence agriculture which is mostly practiced in low-input and low-yield farming systems under fragmented small landholdings (Ngwira *et al.,* 2012). Bi-cropping in developing countries is practised as a strategy to mitigate against crop failure and market fluctuations; meet food preference and demands; protect and improve soil quality, and increase income (Rusinamhodzi *et al.*, 2012).

In developed countries, bi-cropping is a sustainable and efficient practice for improved fodder production (Table 2.2) (Anil *et al.,* 1998). It is also being practised as a remedial intervention to counteract the use of external non-renewable inputs and improve overall farm sustainability after cereal/legume crop rotations (Clement, *et al.,* 1996; Lithourgidis *et al.,* 2011). Crop mixtures in agricultural system attempt to mimic the natural ecosystems which can potentially address the challenges associated with organic systems in developed nations (Walker *et al.,* 2011). In developed nations such as the EU, livestock industry plays a bigger role of economic growths and livelihoods of citizens (Häusling, 2011). Therefore, bi-cropping systems may help in the improvement of fodder quality and balance livestock feed (Eskandari *et al.,* 2009). In the UK the use of cereal based crude protein feed is of primary importance because non-forage protein feed supplements are costly (Anil *et al.,* 1998). Therefore, the integration of cereals forage crops containing low protein contents with grain legumes with higher protein content can make a low cost intervention of balanced protein supply (Eskandari *et al.,* 2009).

The higher level of mechanisation practiced in developed countries necessitates the need to restrict the number of bi-crops in mixed cropping systems to two (cereal and legume) which may help in the designing of suitable mechanised planters for large scale bi-cropping systems. This explains why the term 'bi-cropping' is consistently used in this research. Contrary to developing countries under smallholder farming, more than two crops mixtures are sown in the same production unit to achieve food security and insurance against crop failure; hence the term 'intercropping' applies. If bi-cropping is becomes an integral part of modern production system in developed countries, mechanisation may play a significant role in future mechanised farming systems (Bulson *et al.,* 1997). The implementation of mechanized bi-cropping is viable in developed countries (Tisdall and Adem, 1990). However, wide adoption can be promoted if benefits are assessed by a wider suite of metrics, and via wider 'systems thinking' through the enactment of schemes, such as payment for ecosystem services (Swinton *et al.,* 2007).

Table 2.2: Examples of annual crop mixtures in temperate regions and their relative ultimate goal of production

Temperate region	Crop mixtures	Purpose	Reference
UK	Triticale/lupins (*Lupinus albus*)	Forage	Azo *et al*.(2012)
UK	Maize/kale (*Brassica oleracea*)	Forage	Anil *et al.* (1996)
UK	Wheat *Triticum aestivum*)/white clover (*Trifolium repens*)	Forage	Balsdon *et al.* (1997)
Canada	Triticale/peas (*Pisum stivum*)	Forage	Berkenkamp and Meeres (1987)
Turkey	Barley/vetch(*Vicia sativa)*	Hay	Yasar and Ugur (2003)
USA	Maize/soybean (*Glycine max*)	Forage	Sawyer (2006)
Spain	Maize/soybean	Forage	Reta Sánchez *et al.* (2010)
USA	Wheat/pea	Forage	Machado (2009)
Australia	Wheat/peas	Forage	Jacobs and Ward (2013)
Bulgaria	Clover /grass	Forage	Viliana (2016)
USA	Maize (*Zea mays*)/beans (*Lablab spp.)*	Forage	Armstrong *et al.* (2008)

Globally, different crop families can be mixed in bi-cropping systems, not necessarily poaceae and fabaceae crop families (Aziz *et al.*, 2015). Such crop mixtures can include annual and perennial crops species (Table 2.3). The poaceae and fabaceae crop families are the most dominant crop mixtures in global cropping systems. For instance; in Latin America, small-holder farmers grow 70-90% of beans with maize (Francis, 1989). In Africa 98% of cowpeas are sown as bi-crops with cereal and 90% of beans in Colombia are also sown as bi-crops with cereals (Francis, 1989). In the UK, before the demise of bi-cropping in 1940s, mixtures of oats (*Avena sativa*), barley (*Hordeum vulgare*) with vetch (*Vicia sativa*) were commonly grown for forage (Anil *et al.*, 1998). Agroforestry (a form of bi-cropping) which involves the integration of leguminous plant species with cereals, has increased over a billion hectares (Zomer *et al.*, 2009).

Table 2.3: Bi-cropping systems in different parts of the world

Country	Component crops		Reference
United Kingdom	Wheat	Faba bean	Gooding *et al*. (2007)
Malawi	Maize	Gliricidia	Akinnifesi *et al*.(2010)
Uganda	Coffee	Banana	Asten *et al*. (2011)
Ethiopia	Tef	Sunflower	Bayu *et al*. (2007)
Bangladesh	Wheat	Chickpea, Lentil	Das *et al.* (2011*)*
Iran	Barley	Annual Medic	Esmaeili *et al.* (2011)
India	Soybean	Pigeon Pea	Ghosh *et al.* (2006)
Kenya	Sorghum	Cowpea	Karanja *et al.* (2014)
China	Wheat	Maize	Gao and Wu (2014)
Iran	Canola	Faba Bean	Gharineh and Moosavi (2010)

Bi-cropping, as a planned crop biodiversity, involves intentionally introducing bi-crops in space and time which in turn provides long term ecological sustainability and productivity of the cropping systems (Jensen *et al.*, 2010; Kopke and Nemecek, 2010). The bi-crops in the same field are neither necessarily sown at the same time nor harvested at the same time, but are grown simultaneously for a majority of their growing periods (Lithourgidis *et al.*, 2011). Maximum ecological benefits from bi-cropping systems are expected when bi-crop species are from heterogeneous rather than homogenous crop families e.g. poaceae and fabacaea mixtures (Malezieux *et al.*, 2009). One of the component crops in mixture is either sown mainly for food or cash while the other providing other facilitation beneficial services such as weed suppression, N_2 fixation, soil fertility and moisture retention (Willey, 1979). An effective bi-cropping system is assessed by its ability to produce greater total yield on a piece of land and uses ecological resources more efficiently than would be used when each crop was sown in monoculture system (Inal *et al.*, 2007).

The appropriate management of intra and interspecific competition for above and belowground resources is a major concern in bi-crop mixtures for the maximisation of crop growth and productivity (Brooker *et al.*, 2015; Zhang and Li, 2003). The replacement (or substitutive) and additive designs were developed to understand the competition and complementarity in bi-cropping studies through management of plant sowing densities

(Snaydon, 1994). The replacement design, involves the reduction of bi-crops plant density to one half of their respective sole crop densities while the total relative density of 100% is maintained in the habitat (de Wit and van den Bergh, 1965). In additive designs, the total relative density of bi-crop species in mixtures can exceed 100% with the main reason to induce a most productive bi-cropping system (Snaydon, 1991). Both designs are used in bi-cropping field research in different regions of world depending on the objective of a particular study (Table 2.4a). However, a review by Raseduzzaman and Jensen *et al.* (2017) revealed that about 72% of bi-cropping experiments use replacement designs with only 28% use additive bi-cropping experiments because replacement designs give more stable yields than additive designs.

Table 2.4: Examples of cereal/legume bi-cropping designs used across different parts of the world

Country	Bi-crop design	Bi-crop components	Bi-crop arrangements	References
Malawi	Replacement	Cereal-legume	Temporal	Akinnifesi *et al.* (2010)
South Africa	Additive	Cereal-legume	Temporal	Chimonyo *et al.* (2016)
UK	Replacement	Cereal-legume	Spatial	Eskandari and Ghanbari-Bonjar (2010)
Malawi	Additive	Cereal-legume	temporal	Ngwira *et al.* (2012)
Nigeria	Replacement	Cereal-legume	Spatial	Oseni and Aliyu (2010)
Iran	Additive	Cereal-legume	Spatial	Reza *et al.* (2011)
Sweden	Additive	Cereal-legume	Spatial	Stoltz and Nadeau (2014)
China	Replacement	Cereal-cereal	Temporal	Wang *et al.* (2015)
Serbia	Additive	Cereal-cereal	Temporal	Dolijanović *et al*. (2013)

Bi-cropping research has not received so much attention compared to sole cropping because of limited methods for statistical analysis of combined yields of both bi-crops and sole crops; and also researchers face challenge to understand the processes and mechanisms which underpins a functional bi-cropping and the good it delivers (Brooker *et al.,* 2015). According to Singh (1983), a measure of bi-cropping advantage against sole cropping can either be short term (a single season) or long term (over number of years). In bi-cropping systems yield of component crops are not simply added or compared directly with each other; different methods have to be used (Willey, 1979). There are many different methods for assessing output yield advantages from intercrops yields as detailed by Willey (1979). The first method compares the component yields against their respective sole crop yield for every crop in the mixture and adds the ratios together. Another possible method compares the land area needed to obtain similar component yields in sole and intercrops (Reddy, 1990). However, the indices for assessing the efficacy of bi-cropping systems are grouped in two categories based on the functions they perform. The Land Equivalent Ratio (LER) and its related Relative Yield Total (RYT) verifies the effectiveness of bi-cropping systems on biological use of environmental resources compared to sole cropping systems (Mead and Willey, 1980). The LER greater than 1.0 shows that benefits of bi-cropping systems are more than growing the same bi-crops in sole cropping systems. The LER less than 1.0 shows less benefit of bi-cropping systems than sole cropping systems. The partial land equivalent ratios (L) (de Wit, 1960), the aggressivity coefficient (A) (McGilchrist, 1965); the relative crowding coefficient (K) proposed by Hall (1974); and Competitive Ratio (CR) (Willey and Rao, 1980) have been developed to describe the competition and possible economic advantages of bi-cropping systems (Ghosh, 2004). The LER is widely used because it shows the patterns of competition outcomes in a bi-cropping system (Bedoussac and Justes, 2011) while other indices are limited to assess the productivity of bi-cropping system (Bedoussac and Justes, 2011).

2.5 Categories of bi-cropping

The categories of bi-cropping systems practiced in different parts of the world are summarised in Table 2.5 according to Andrew and Kassam (1979) and Vandermeer (1989).

Table 2.5 bCategories of bi-cropping systems practiced in different parts of the world.

Bi-cropping systems	**Description**
Row bi-cropping	It is the simultaneous growing of two crops within the same row.
Strip bi-cropping	It is the simultaneous growing of two crops in different strips permitting independent cultivation of each crop but narrow enough for the crops to interact agronomically. It allows different crop management practices to different crops. This category of bi-cropping can be used in agroforestry systems as alley cropping where annual crop are grown in between two adjacent of tree hedge rows or shrubs (Rao *et al.,* 1997);
Relay bi-cropping	It is the growing of two crops together, in which different species share the same area for part of their life cycle. Usually, the second crop is planted after the first crop has attained its physiological maturity but before it is ready for harvest. This system is mostly practised in areas where the growing season is too short to permit the cultivation of two crops in sequence (Flesch, 1994);
Mixed bi-cropping	It is the simultaneous growing of two crops in no distinct row arrangements. This type of bi-cropping can be used to classify the grass-legume mixtures in pastures used in intensive livestock husbandry (Sinoquet and Cruz, 1993).

2.6 Advantages of bi-cropping

The advantage of bi-cropping system is derived from the “competitive interference principle” (Vandermeer, 1989), where the interspecific competition between bi-crop component species is less than the intraspecific competition in sole cropping systems (Vandermeer, 1989). A large body of literature reported more advantages of bi-cropping systems than sole cropping systems (Jensen, 2006). The component crops species in bi-cropping systems often causes yield advantages due to increased capture and efficient use of biophysical resources as compared to sole cropping systems (Sadeghpour *et al.,* 2011; Gao *et al.,* 2014). Greater advantages of bi-cropping systems over mono-cropping systems results because of morphological, physiological and phenological differences between bi-crops on rooting and canopy architectural characteristics; and nutrient requirements (Vandermeer, 1989; Lithourgidis *et al.,* 2011). The advantages of bi-cropping systems are influenced by interspecific complementarity and niche differentiation effects as summarised in Table 2.6 below.

Table 2.6: Advantages of bi-cropping sytems over sole cropping systems

Bi-cropping benefit	Crop combinations	Region	Results	References
Light interception	Durum wheat-winter pea	France	Bi-cropping intercepted solar radiation 10% greater than sole cropping.	Bedoussac and Justes (2011)
	Maize-cowpea	Iran	Bi-cropping intercepted greater solar radiation than sole maize.	Ghanbari-Bonjar *et al*. (2010)
	Maize/legume	Greece	Bi-cropping intercepted greater solar radiation than sole cropping.	Bilalis *et al.* (2010)
	Wheat/pea	Canada	Bi-cropping increased radiation use efficiency than sole wheat.	Szumigalski and van Acker (2008)
	Maize/soybean	Kenya	Bi-cropping intercepted solar radiation 84.5% greater than sole soybean.	Matusso *et al.* (2014).
Nutrient use efficiency and availability	Maize/faba bean	China	Bi-cropping enhanced phosphorus recovery over sole cropping	Xia *et al.* (2013)
	Wheat/faba bean	UK	Bi-cropping improved nutrient uptake than sole cropping.	Eskandari and Ghanbari-Bonjar, 2010; Bulson *et al.* (1997)
	Barley –pea	Scotland	Bi-cropping reduced nitrate leaching 5.67 times higher than sole cropping.	Pappa *et al*. (2011)
	Pea/barley	Denmark	Pea bi-crops increased 40-80% N fixation over sole pea.	Hauggaard-Nielsen *et al.* (2001b)
	Multiple	Multiple	Higher residual soil nitrogen content of 15% realised from annual bi-crops habitats with 156% from perennial leguminous bi-crops habitats as *Faidherbia albida* than respective sole cropping.	Garrity *et al.* (2010); Li *et al.* (2013)
Climate change mitigation	Barley/pea	Scotland	Bi-cropping reduced NO_2 emissions by 30% over sole barley crop.	Pappa *et al.* (2011)
Weed control	Barley/chickpea	Iran	Bi-cropping reduced weed density and its biomass by 66% and 90% over sole cropping.	Hamzei and Seyedi (2015)
	Pea/false flax	Germany	Higher weed suppression in bi-cropping weeds over sole pea by 63% and 52% in 2003 and 2004 respectively.	Saucke and Ackermann (2006)
	Wheat/faba bean	UK	Bi-cropping provided higher weed suppression than sole crops in additive series.	Bulson *et al.* (1997)
Disease control	Various crop mixtures	Various	Populations of natural enemies of pests were higher in the bi-cropping systems compared to sole cropping in 53% of studies, and	Lithourgidis *et al.* (2011

			lower in 9%. Data from a review of 2009 field studies	
	Spring barley/Faba bean/lupin	Denmark	Bi-cropping reduced brown spot disease on lupin by 80% over sole cropping	Hauggaard-Nielsen *et al.* (2008)
Yield advantages	Maize/faba bean	China	Bi-cropping increased total grain yield by 24.8% over sole cropping.	Xia *et al.* (2013)
	Faba bean/triticale	Greece	Bi-cropping increased forage dry matter yield by 37% over sole cropping.	Dordas and Lithourgidis (2011)
	Barley/faba bean	Ethiopia	Bi-cropping increased productivity and profitability over sole cropping.	Legesse *et al.* (2015)
	Maize/ Potato (*Solanum tuberosum* L.)	Ethiopia	Bi-cropping in additive series increased yield, LER and MAI over sole cropping.	Bantie *et al.* (2015)
Yield quality	Maize/legume	Iran	Bi-cropping increased crude protein yield than sole cropping.	Javanmard *et al.* (2009)
	Oat-faba bean	Greece	Bi-cropping provided higher total dry matter and protein yields than those of faba bean sole crops in 50:50 sowing ratio in additive series.	Dhima *et al.* (2014)
	Corn/soybean	Malaysia	Forage quality in terms of crude protein improved in bi-cropping (13.7%) than sole corn (10.8%)	Baghdadi *et al.* (2016)
	Barley/faba bean; Annual medic/Barley	Canada; Iran	Higher protein yields have reported in bi-cropping than sole cropping.	Strydhorst *et al.* (2008)
Runoff quality	Sorghum-cowpea	Burkina Faso	Bi-cropping reduced run-off by 20-30% and 45-55% compared with sorghum and cowpea sole crops, respectively; soil loss was reduced with bi-cropping by more than 50%.	Zougmore *et al.* (2000)

2.7 Ecological principles of bi-cropping systems

Competition and facilitation/complementarity ecological concepts determine the outcome of species interactions in bi-cropping systems (Vanadermeer, 1989). These principles embrace the concepts of ecology, agronomy and plant protection (Brooker *et al.,* 2015). The 'competition' concept is an ecological situation in which one organism can negatively affect the environment for another organism through allelopathy and competition (Trinder *et al*. 2013). The 'Facilitation' concept is an ecological situation in which one organism may positively affect the environment for another organism and such ecological examples include: mutualism and complementarity (Brooker *et al.,* 2015). Nitrogen fixation in cereal/legume crop mixture is a typical example of facilitation concept.

2.8 Crop species interaction in bi-cropping systems

Competition and complementarity/facilitation are the most important ecological interactions that occur in bi-cropping systems (Gebru, 2015). Competition is a negative interspecific interaction which occurs when a shared available growth resource is in limited supply (Jensen, 2006). Interspecific competition and complementarity take place simultaneously in many bi-cropping systems (Geno and Geno, 2001). According to Vandermeer (1989) obtaining the net LER >1 in bi-cropping systems means that complementarity facilitation is contributing more to species interaction than the competitive interference. Similarly, a net LER <1 means that interspecific competition effects dominates over complementarity facilitation effects. However, competition can improve biological nitrogen fixation in cereal/legume crop mixtures (Hauggaard-Nielsen *et al.,* 2008; Fujita *et al.,* 1992). Ecologists differentiated competition as 'intra-specific competition' which occurs between crop species of the same family of plants and the negative impacts are severe because of identical resource needs and niches (Yoda *et al.,* 1963; Beets, 1982) and 'inter-specific competition' takes place between dissimilar crop species in a habitat (Beets 1982; Park *et al.,* 2003). According to Willey (1979) three competitive relationships which take place between crop components in bi-cropping systems include: 'mutual inhibition' a competitive relationship where the actual yield of each crop species is less than expected; 'mutualism' a competitive relationship where the yield of each species is greater than expected; and 'compensation' a competitive relationship where the yield of one crop is less than expected, but the yield of the other crops(s) and total yield of bi-crop are greater than expected.

On the other hand, complementarity facilitation interaction contributes more than competition interference in the bi-cropping habitat towards improving land use efficiency (Geno and Geno, 2001). Temporal and spatial complementarities are the key features of bi-cropping habitats because they are responsible for the improvement of yield gains and ecological services benefits (Willey, 1979; Jensen, 1996). Complementarity facilitation benefit is widely reported especially on its significant impact on nutrient-poor soils in agroecosystems (Hauggaard-Nielsen *et al.*, 2005). Similarly, phosphorus liberalisation for plant uptake from insoluble P complexes with Calcium (Ca^{2+}), Aluminium (Al^{3+}) and Iron (Fe^{3+}) is achieved with complementarity facilitation (Maliha *et al.*, 2004). The temporal complementarity effect, distinguishes the growth patterns between bi-crops in time which directly influence crops' environmental use at different times (Gebru, 2015). The spatial complementarity effect on below and aboveground morphological differences on root patterns and canopy architecture may facilitate better use of available resources in bi-cropping systems. The crop components may ably exploit the soil layers or canopy heights at different times in the same bi-cropping habitat (Gebru, 2015). In a moisture limiting environment, bi-crops species with different root systems may minimise the degree of competition for water (Francis, 1989). Spatial complementarity effects in bi-cropping systems may improve water use over sole cropping systems through increased water availability and increased water partitioning into the economical part of the crop (Willey, 1990). Benefits of symbiotic interaction, mediated by Vesicular Arbuscular Mycorrhiza (VAM) fungi in association with roots of bi-crops can improve exploration of immobile phosphorus and soil moisture for plant use due to spatial complementarity effects (Dakora, 2003). Physiological differences between bi-crops can facilitate improved biological nitrogen fixation due to differences in nutrient requirements (Jensen, 1996). The trait complementarity effects in tropical crop mixture system termed as 'three sisters' comprising of maize (*Zea mays*), beans (*Phaseolus vulgaris*) and squash (*Cucurbita spp*) has been reported by Postma and Lynch (2012). The squash acts as groundcover during the early season, reducing competition with early-season weeds and water losses by evaporation. The subsequent growth of maize and beans maintains canopy humidity during the later season and maximizes the utilization of solar radiation.

2.9 Challenges for bi-cropping systems

There is lack of practical management options for using agrochemicals, irrigation and harvesting in bi-cropping systems (Anil *et al.,* 1998). The advanced mechanisation designed for monocropping systems cannot be used efficiently in bi-cropping systems (Gebru, 2015). Excretion of toxic substances by one of the component bi-crops as a territorial defensive mechanism for limited growth resources can negatively affects optimum performance of the companion bi-crop (Muller, 1996). Reduction in yield may occur in bi-cropping systems due to intense competition (Thole, 2007). Due to the challenges of evaluating bi-cropping experiments, the number of crop scientist to investing in bi-cropping research to improve the system is limited (Parkhurst and Francis, 1986).

2.10 Aspects for consideration in bi-cropping systems

The choice of bi-crops with different maturity dates may provide interspecific complementarity benefits and subsequent higher yields opportunities due to distinct differences in growing periods and demands for growth resources (Dong *et al.,* 2018). This may separate the maximum demand periods for nutrients, water, and aerial space between bi-crops (Jensen, 2005). Reddy and Reddi (2007) reported the peak light demand for maize at 60 days after planting while at the same time the green gram (*Phaseolus aureus)* bi-crop beans was ready for harvesting in maize/green gram bi-cropping system. Li *et al.* (2011) reported an effective decreasing in soil mineral nitrogen accumulation and increasing crop nitrogen use efficiency in wheat/faba bean and maize/faba bean mixtures with different maturity dates. The selection of suitable crop varieties for bi-cropping systems may help in the reduction of the competition between bi-crops not only by spatial arrangement, but also by their ability to exploit soil growth resources (Seran and Brintha, 2010). The mixture of cereals and legumes could be more valuable because the component crops can utilize different sources of nitrogen (Jensen, 1996). However, certain bi-crop combinations can have negative effects on the yield of the bi-crops. For instance, Mucuna (*Mucuna utilis*) can reduce maize yields when sown as a bi-crop while cowpeas (*Vigna sinensis*) and green gram (*Phaseolus aureus*) had much less effect on maize when sown as bi-crops (Agboola and Fayemi, 1971). The time of planting may influence the performance of bi-crops in mixture. In Ghana, sowing maize and soybean bi-crops at the same resulted in significantly higher values for leaf area index (LAI), crop growth rate (CGR) and net assimilation rate (NAR) compared to delayed planting treatments

(Addo-Quaye *et al.,* 2011). The seed rate or sowing density can determine the performance of bi-cropping system. Sowing full seed rate of each bi-crop may result in intense overcrowding hence competition (Seran and Brintha, 2010). Morgado and Willey (2003) reported a reduction in maize dry matter yield of individual maize bi-crop plant with increased plant population of the bean bi-crops. Bulson *et al.* (1997) reported significant increase in nitrogen content of the wheat grain and whole plant biomass with increased bean bi-crop density which was reflected in significant increase in grain protein at harvest. However, the total N accumulated by the wheat, decreased with increased bean density due to a reduction wheat biomass.

2.11 Cereal/grain legume bi-cropping systems

Cereal/grain legume crop mixtures is the most commonly practised among the annual crops. It is the most efficient and successful crop mixture (Francis, 1989). Its greater efficiency is attributed to resource use complementarity in the utilisation of different sources of nitrogen by bi-crop components in mixture (Jensen, 1996; Bedoussac and Jutes, 2011). It offers various ecological facilitation services especially under low-N environments which contribute to successful performance of bi-cropping systems (Altieri, 1999). The provisions of multiple ecological services under low-N environments, makes it more attractive and suitable for organic farming systems where use of agrochemicals is strictly forbidden (Jensen, 1996; Hauggaard-Nielsen *et al.,* 2008). The grain legume bi-crop remains the backbone crop for the successful organic farming production systems because it satisfies the nutrition, economic and environmental sustainability concerns (Malezieux *et al.,* 2009; Gomiero *et al.,* 2011). In the temperate regions, the cereal/grain legume crop mixture in low input systems has the potential to increase protein-rich fodder and sustainability of agroecosystems (Anil *et al.,* 1998). The potential grain legumes evaluated under low N-input in temperate regions in combination with small grains cereals crops (wheat/barley/oats) include: faba bean (*Vicia faba* L.; Tosti and Guiducci, 2010; Dordas and Lithourgidis, 2011; Dhima *et al.,* 2014; Chapagain, 2014; Agegnehu *et al*., 2006; Ghanbari-Bonjar, 2000); pea (*Pisum sativum;* Ghaley *et al.,* 2005; Subedi, 1997); lentil, (*Lens culinaris* L.; Dusa, 2009) and lupin (*Lupinus albus* L.; Azo *et al* 2012).

2.12 Significance of grain legume bi-crops

2.12.1 Nitrogen effects on bi-cropping systems

Nitrogen is the most important macronutrient for most crops (Hauggaard-Nielsen *et al.,* 2009). Inorganic nitrogen fertiliser application to the cereal bi-crop in cereal/grain legume bi-cropping system particularly during early growth stages can strongly affect species complementarity resulting in reduced amount of N fixed, reduced legume yield and increase cereal yield (Molaaldoila *et al.,* 2017). Late nitrogen application may have no effect on overall symbiotic nitrogen fixation and yield of the legumes but can increase protein accumulation of the cereal crop (Stark and Tindall, 1992; Zebarth *et al.,* 2007; Bedoussac *et al.,* 2014). Highest cereal fodder dry matter and lowest cereal crude protein yields can result at higher rates of nitrogen while contrasting results can occurred with no nitrogen fertilizer application (Zebarth *et al.,* 2007). The cereal crude protein yield reduction at higher nitrogen rates was influenced by the dilution effect on the nitrogen in the cereal (Foster and Malhi, 2013). Reduction in biological nitrogen fixation potential of the grain legume bi-crop with application of higher rates of nitrogen rates has been widely reported (Stern, 1993; Hauggard-Nielsen *et al.,* 2009; Sarr *et al.,* 2015). However, inorganic nitrogen application up to 100 kgN ha^{-1} was recommended to sustain productivity in wheat/faba bean bi-cropping systems (Ghanbari-Bonjar and Lee, 2002).

The overall efficiency of the cereal/legume bi-cropping system depends on low levels of soil nitrogen, an edaphic condition which favour higher fixation of atmospheric N_2 by the legume bi-crop and reduced competition for soil nitrogen with the cereal component (Hauggaard-Nielsen *et al.,* 2008). The productivity of bi-cropping systems with regard to yield advantage is greater under low input (Ghambari-Bonjar, 2000; Jensen *et al.,* 2010). Studies by Rao *et al.* (1987) reported comparable yields between unfertilised cereal bi-crops and fertilised sole cereal crop. Application of inorganic fertiliser to the cereal bi-crop may depress the yield of the component legume bi-crops (Ananthi *et al.,* 2017; Corre-Hellou *et al.,* 2011). Similar findings were reported by Ghanbari-Bonjar (2000) as shown in Table 2.7. A review by Hiebsch and McCollum (1987) showed that 472 bi-cropping field experiments had greater advantage when the cereal bi-crops were under low input than if optimum nitrogen was applied.

Table 2.7: The effect of nitrogen rates and cropping system on percentage of bean total dry weight.

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Source: Ghanbari-Bonjar (2000).

2.12.2 Nitrogen transfer between legumes and cereals in bi-cropping systems

In cereal/grain legume bi-cropping systems, nitrogen transfer to the non-legume companion crop species is facilitated by improved soil fertility; biological nitrogen transfer through root exudates and root connections between the donor (N_2-fixing plant) and a receiver (non N_2-fixing plant) (Aminifar and Ghanbari, 2014; Johansen and Jensen, 1996). Direct and indirect N transfers are the two main pathways through which N is transferred between bi-crop plants determining the benefit of bi-cropping system (Dwivedi *et al.*, 2015). The direct N-transfer involves the activities of mycorrhizae and their hyphal network connecting the donor and receiver plants, known as common mycorrhizal networks (CMN) (Newman, 1988). The process involves extension of the hyphae from the roots of mycorrhizal plants to the roots of non-mycorrhizal species in a bi-cropping habitat (He *et al*. 2003). The indirect N-transfer however, is related to the release of soluble nitrogen in the form of ammonia (NH_4^+) and nitrates (NO_3^-) from the legumes to the soil and subsequent movement to the roots of receiver cereal plants through mass flow or diffusion mechanisms (San-nai and Ming-pu, 2000). Nitrogen inter-plant N transfer can occur within the same cropping season (Chapagain, 2014). However, the extent to which this is true is still a subject of intense debate (Francis, 1989) because much evidence has been reported to occur on mixed grass/legume swards because of their long time co-existence in the field and closer root proximity than most bi-cropping systems whose root close proximity is determined by component crop densities (Giller *et al.,* 1991; Fujita *et al.,* 1996) and spatial arrangements. According to Høgh-Jensen and Schjoerring (2000), direct nitrogen transfer on cereal/grain legumes is evident under controlled studies.

Nitrogen transfer in cereal/grain legumes mixtures is more evident and successful in poor soils and low input agroecosystem environments (Hauggaard-Nielsen *et al.,* 2005; Brooker *et al.,* 2015; Dwivedi *et al.,* 2015). The greater facilitation of nitrogen transfer by grain legumes in such environmental conditions elucidates the significance of crop diversification of modern farming systems as a global response to the challenges of future agriculture (Altieri 1999; Malézieux *et al.,* 2009). Grain legumes are globally considered backbone of organic agricultural and food systems for their ability to reclaim degraded ecological services in agroecosystems (Kopke and Nemecek, 2010; Jensen *et al.,* 2010). Low input cereal/grain legume bi-cropping systems can potentially increase cereal grain protein (Table 2.8) over sole cereal cropping systems (Mariotti *et al.,* 2011). Crude protein enhancement in cereal bi-crops under low input cereal/legume mixtures is driven by low competitiveness of the grain legume for mineral soil nitrogen in the system compared to the monocropped cereal. Additionally, interspecific competition for light, water and other nutrients restrict biomass production for the cereal bi-crops compared to sole crops (Gooding *et al.,* 2007). Inorganic nitrogen fertilizer application, may reduce wheat grain crude protein content due to dilution effects. Applied nitrogen fertiliser end up in a greater accumulation of cereal dry matter, vegetative biomass and grain yield without necessarily being translated into improved wheat grain protein content (Lemaire and Gastal, 1997). Grain legumes assimilate more of its total fixed N_2 to the grain justifying why they contain higher grain crude protein content (Hauggaard-Nielson *et al.,* 2006). If the grain legume over-dominates the cereal bi-crop in mixture, it makes the systems less advantageous on enhanced N_2 fixation and transfer to the cereal bi-crop (Jensen, 1996).

Table 2.8: The effect of barley/grain legume crop mixtures on crude protein concentration comapred to barley sole cropping.

Source: Strydhorst *et al.* (2008).

2.13 Faba bean (*Vicia faba* L.)

Faba bean (*Vicia faba* L.) also known as broad bean and horse bean belongs to the genus of *Vicia* of the leguminoseae within the popilunoideae sub-family (Singh *et al.*, 2010). It is one of the earliest domesticated food legume crops in the world (Osman *et al.*, 2010). The Far East is believed to be its origin before spread to Europe, along the coast of North Africa to Spain, along the Nile River to Ethiopia (secondary centre of origin), and to India from Mesopotamia (Long *et al*. 1989). It is the commonly cultivated among the five species of the genus *Vicia* (Duc, 1997). It is cultivated for human consumption in developing countries because of its protein quantity (25-37%) and quality (Table 2.9; Rubiales, 2010). These attributes make it a suitable substitute for meat and skimmed-milk. It is a source of livestock and poultry feed in developed countries (Table 2.9; Flores *et al.*, 2012). The trend of cereal/faba bean research and purpose over time in developed regions is shown in Table 2.10. Antinutritional factors are commonly associated with pulses (Norton *et al*., 1985). Oligosaccharides, tannins, and vicine-convicine are the major elements of concern in faba bean (Norton *et al*., 1985). Oligosaccharides contribute to gases accumulation in the alimentary canal, tannins impart a bitter flavour to the seed, and vicine-convicine aglycone derivatives inflict the rare genetic disorder favism (Crepon *et al.*, 2010). The oligosaccharides, tannin and vicine-convicine are mainly concentrated within mature seeds, the seed coat, and cotyledons of the developing seed respectively. To date, faba bean in Europe ranks second in area and production after pea (Baddeley *et al.*, 2013). It is a very promising protein value crop compared to other grain legumes (Strydhorst *et al.*, 2008; Jensen *et al.*, 2010; Multari *et al.*, 2015). The suitability of faba bean for bi-cropping systems was verified by multi-locational agronomic exploratory field experiment replicated across Europe between 2003 and 2005 (Table 2.11) (Pristeri *et al.*, 2006).

Table 2.9: The distribution of cereal/faba bean production systems and its utilisation in different regions of the world

Crop combination	Country	Utilisation	Reference
Wheat /Faba bean	Egypt	Food	Abdel-Wahab and Elmanzalawy (2016)
Wheat/Faba bean	Ethiopia	Food	Agegnehu *et al.* (2008)
Wheat and field beans	UK	Forage	Bulson *et al.* (1997)
Durum wheat/faba bean	Italy	Forage	De Stefanis *et al.* (2017)
Faba bean/oat/wheat	Greece	Forage	Dordas and Lithourgidis, (2011)
Wheat or maize/Faba bean	China	Forage	Fan *et al.* (2006)
Wheat/Faba bean	Ethiopia	Food	Fikadu *et al.* (2017)
Wheat /Field bean	Denmark	Forage	Ghaley *et al.* (2005)
Wheat /Faba bean	UK	Forage	Ghanbari-Bonjar and Lee (2002)
Barley/Faba bean	Denmark	Forage	Knudsen *et al.* (2004)
Barley/Faba bean	Ethiopia	Food	Legesse *et al.* (2015)
Faba bean/Maize	China	Forage and food	Mei *et al.* (2012)
Faba bean/lupin	Canada	Forage	Strydhorst *et al.* (2008)
Wheat /Faba bean	Morocco	Food	Wahbi *et al.* (2016)

Table 2.10: The trend of cereal/faba bean research and purpose over time in developed countries

Cropping system	Country	Purpose	Author
Maize/faba bean	USA	Forage	Murphy *et al.* (1984)
Wheat/faba bean	Canada	Forage	Berkenkamp and Meeres (1987)
Oats/faba bean	Canada	Forage	Berkenkamp and Meeres (1987)
Burley/faba bean	Canada	Forage	Jedel and Helm (1993)
Wheat/faba bean	UK	forage	Bulson *et al.* (1997)
Wheat/faba bean	UK	forage	Ghanbari-Bonjar and Lee (2003)
Wheat/faba bean	UK	Forage	Eskandari and Ghanbari-Bonjar (2010)
Maize/faba bean	Sweden	Forage	Stoltz and Nandeau (2014)
Oat/faba bean	Greece	Forage	Dhima *et al.* (2014)
Barley/faba bean	Italy	Forage	Mariotti *et al.* (2015)

Table 2.11: Grain yield (g m^{-2}) and LER of faba bean and wheat in additive, replacement series and sole crop (SC) in UK 2003-2005

	Grain Yield (g m^{-2})		LER yield		
Treatments	Faba bean	wheat	Faba bean PLER	Wheat PLER	Total LER
Spring sowing					
F100 W100	123±37	179±7	0.58	0.86	1.44
F50 W50	98±17	172±10	0.46	0.83	1.29
Sole crop	211±13	208±10			
Winter sowing					
F50W50	275±67	96±10	0.82	0.46	1.28
Sole crop	336±38	210±38			

Source: Pristeri et al. (2006). F50W50 stands for a 50:50 sowing ratios of faba bean and wheat in a replacement series. F100W100 stands for a 1:1 sowing ratios of faba bean and wheat in an additive series. PLER, Partial Land Equivalent Ratio; LER, Land Equivalent Ratio

2.13.1 Strengths of faba bean in bi-cropping systems

Previously, pea, common vetch and lupin were the common legume bi-crop components with wheat, barley and oat in cereal/legume bi-cropping systems (Berkenkamp and Meeres, 1987;

Caballero *et al.,* 1995; Lithourgidis *et al.,* 2007; Hauggaard-Nielsen *et al.,* 2007; Bedoussac and Justes, 2011). Recent cereal/faba bean bi-cropping studies, proved faba bean a superior bi-crop legume compared to peas mainly due to its wide adaption to cereal-growing areas of the world (Robertson, 1996), tolerance to broomrape *Orobanche crenata*, a parasitic weed (Robertson 1996) and *Aphanomyces,* a soil borne disease (Jensen *et al*., 2010), higher grain protein and tall stem strength advantage (Ghanbari-Bonjar and Lee, 2003; Strydhorst *et al.,* 2008; Lithourgidis and Dordas, 2010; Jensen *et al.*, 2010).

Faba bean can facilitate ecological sustainability of agroecosystems, offer nutritional values (foods and feeds) and economic benefits (Kopke and Nemecek, 2010). It is adapted to a wide range of climatic and edaphic diversity (Jensen *et al.,* 2010). It can potentially fix up to 648 kg N/ha, more than other grain legumes as demonstrated in Figure 2.2 (Briggs *et al.,* 2005) and this is one of the fundamental agronomic advantages which makes it suitable for organic farming systems. About 96% of its total Nitrogen fixed comes from Biological Nitrogen Fixation activity (Peoples *et al.*, 2009). A wide range of N_2 fixed (15 to 648 kg N ha^{-1}) is a result of variations in environmental conditions; genotype types and methods of evaluating Nitrogen fixation (Kopke, 1987). The overall grain yield of faba bean shows a high correlation with nitrogen fixation (Kopke and Nemecek, 2010). Because of its higher N_2 fixation capacities, fertilization of a cereal following faba bean can be significantly reduced up to 30-50 kg N ha^{-1} without yield loss compared to a cereal-cereal rotation (Prew and Dyke, 1979; Kopke and Nemecek, 2010). It can tolerate to soil mineral nitrogen levels up to 20 kg N ha^{-1} before the negative effects can impact on its growth and physiological performance (Mwengi, 2011). The substantial amount of nitrogen available in the bean seed influences its tolerance to soil nitrogen during early growth stages (Richards and Soper, 1982). It may facilitate higher biological weed suppression in bi-cropping systems than sole bean cropping systems which can result in complete reduction on reliance on herbicide use (Ghanbari-Bonjar, 2000; Chapagain, 2014). Most of the livestock production systems have for a long time depend heavily on off-farm purchase of protein feed concentrates (Kopke and Nemecek, 2010; Anil *et al.*, 1998). Faba bean in crop mixture can facilitate cereal grain protein quality and make it potential for higher market value (Gooding *et al.,* 2007). Faba bean as a bi-crop in low input system, with substantial amounts of crude grain protein, can help to counteract external sources of protein rich feeds and reduce expenditures associated with importation (Hauggaard-Nielsen, 2006; Anil *et al.*, 1998).

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2.14 Sustainability of bi-cropping systems

FAO (2014) defined sustainable agriculture as the ability of the agroecosystem to maintain productivity in spite of major disturbances that are caused by intense or large perturbation. Modern agriculture practices are accountable for the negative environmental externalities such as soil erosion; environmental pollution; loss of natural habitat and biodiversity; and overall loss of ecological services in agroecosystems (Horrigan *et al*., 2002). Bi-cropping, in low input environments in interaction with indirectly associated biodiversity shown in Figure 2.3 form major attributes which increase the complexity of bi-cropping system to performing sustainable ecological services outside the mandate of food production (Malézieux *et al.,* 2009; Altieri, 1999). Such ecological services which are in line with sustainability include: minimise use of external non-renewable inputs for crop production, improves soil fertility through decomposition, nutrient recycling and biological nitrogen fixation (Jensen *et al.,* 2010); improves resilience and stability of agricultural systems against environmental degradation (Altieri *et al.*, 2015); improves soil buffer against extreme soil pH and nutrient availability (Dordas and Lithourgidis, 2011); weed suppression (Hauggaard-Nielsen *et al.*, 2007) facilitates biological control against pests and diseases (Trenbath, 1993); increase microbial diversity for enhanced the facilitation of water and nutrient transfer by vesicular arbuscular mycorrhizae (He *et al.*, 2003). Bi-cropping system at food system level, may sustainably offer improved protein important for human health and livestock feed (Tharanathan and Mahadevamma, 2003). At production system level, bi-cropping systems is low input due to high N_2 fixation by the beans bi-crops and may contribute towards mitigating greenhouse gases emissions (Lemke *et al.*, 2007). At cropping system level, bi-cropping systems, due to crop diversification can sustainably contribute towards breaking the life cycles of pest and diseases and also help to balance the deficit in plant protein production in many areas of the world, including Europe (Jensen *et al.*, 2010).

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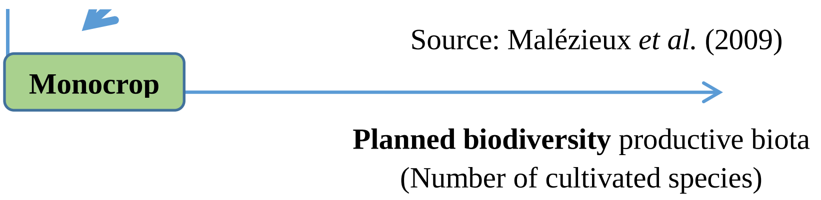

Source: Malézieux *et al.* (2009)

Figure 2.3: Relationship between planned biodiversity (plant species introduced and cultivated intentionally by the farmer) and associated biodiversity (species that colonise the agroecosytem).

2.15 Spatial arrangements

Spatial arrangement and sowing density are the main factors which may influence yield and quality of bi-crops in mixture (Aziz *et al.,* 2015). Reducing interspecific competition is one of the major concerns to realise advantages of bi-cropping systems (Baidoo *et al.,* 2012). Spatial arrangement through manipulation of row orientation of bi-crops is one way of reducing interspecific competition by promoting resource complementarity which allows bi-crop components to acquire limited resources from different spaces, at different times or utilize different forms of the resources (Bulson *et al.*, 1997) resulting in increased dry matter yield (Bedoussac *et al.,* 2015). The alternate row spatial arrangement is suitable to attain ecological spatial interspecific complementarity for bi-crops with similar maturity groups such as spring crops (Martin and Snaydon, 1982; Klimek-Kopyra *et al.,* 2015). Complete mixing of the crop species within the rows, alternate rows of pure crop species, alternate blocks of two or more rows of pure crop species or even cross-drilling rows of pure crop species at right angles to each other are the commonly practiced spatial arrangements in bi-cropping systems (Musa *et al.,* 2010). However different crop combinations may perform differently to a given similar spatial arrangement due to differences in crop morpho-physiological plant characteristics (Musa *et al.,* 2010). Lauk and Lauk (2008) and Aynehband *et al.* (2010), reported better performance of barley/peas, oats/peas and maize/amaranth bi-crop mixtures for within row spatial arrangement. On the other hand, Martin and Snaydon (1982) and Dubey *et al.* (1995) reported highest yield performance of barley/beans and sorghum/soybean bi-cropping systems for alternate row spatial arrangement. Langat *et al.* (2006) and Megawer *et al*. (2010) reported better performance of 2:2 alternate rows for sorghum/groundnuts and barley/lupin crop mixtures respectively. Spatial arrangement may help to achieve spatial complementarity for bi-crop mixtures with synchronised peak demand for nutrients, water and solar radiation (Klimek-Kopyra *et al.,* 2015). The facilitation variability effects of different spatial arrangements for different bi-crop combinations is summarised in Table 2.12.

Table 2.12: The influence of geometrical row configurations on bi-cropping systems' performance

Bi-cropping system	Country	Row configuration	Outcome	Reference
Barley /annual medic	Iran	1:1	Improved forage yield and quality	Sadeghpour *et al.* (2013)
Barley /annual medic	Iran	6:6	Reduced forage yield and quality	Sadeghpour *et al.* (2013)
Barley/faba bean	Ethiopia	1:1	Increased bean seed than	Legesse *et al.* (2015)
Barley/faba bean	Ethiopia	3:3	Reduced bean seed yield	Legesse *et al.* (2015)
Barley/Lupin	Egypt	1:1	Induced competition	Megawer *et al.* (2010)
Barley/Lupin	Egypt	2:2	Induced complementarity	Megawer *et al.* (2010)
Barley/pea	Canada	1:1	Increased productivity by 50%	Chapagain and Riseman (2014)
Barley/pea	Canada	1:1	Improved soil nutrient balances	Chapagain and Riseman (2014)
Maize/cowpea	Nigeria	1:1	Highest total maize grain	Iderawumi (2014)
Maize/groundnuts	Srilanka	2:2	Higher LER over sole crop	Sutharsa and Srikrishnah (2015)
Maize/haricot bean	Ethiopia	1:1	Higher grain maize yield	Hirpa (2014)
Maize/Soybean	China	1:3	Improved silage quality	Htet *at al.(*2016)
Sorghum/ cowpea	India	2:2	Higher protein forage and yield	Mishra *et al*. (1997)
Sorghum/groundnuts	Kenya	2:2	Improved productivity (LER=2.1)	Langat *et al.* (2006)
Maize/groundnuts	Ghana	1:1	Increased productivity	Konlan *et al*. (2013)
Wheat/faba bean	Iran	1:1	Reduced soil temperature	Eskandari & Ghanbari-Bonjar, (2009)
Wheat/faba bean	UK	1:1	Increased LER (1.27)	Ghanbari-Bonjar (2000)
Wheat/Gram	Pakistan	10:10	Reduced wheat grain yield	Munir *et al*. (2004)
Wheat/Gram	Pakistan	4:4	Increased wheat grain	Munir *et al*. (2004)
Wheat/Lentil	Bangladesh	1:1	Increased LER (1.17)	Akter *et al.* (2004)

2.16 Bi-cropping in the United Kingdom (UK)

The wholecrop cereals grown for forage are important in the rations of ruminants in the UK because they can supply high proportions of energy-rich forage in their diets (Anil *et al.,* 1998). Unfortunately, they contain lower crude protein contents (Sadeghpour *et al.* 2013; Anil *et al.*, 1998). The problems associated with the importation of protein-rich feed materials from South America and the United States of America raised an interest to invest in the cereal/grain legume bi-cropping system as a strategy to achieve sustainable home-grown protein supply (Hauslings, 2011).

Previously, cereal/legumes bi-cropping systems were traditionally practiced in the UK over the past 50 years ago (Crew and Peoples, 2004). During that time, most of the European cropping systems sustained as much as 50% of the soil nitrogen facilitated by biological fixation capacities of legume bi-crops (Peoples *et al.,* 2009). The introduction of combined harvesters and the differences in maturity dates between cereal and legume bi-crops in mixture led to the demise of the practice (Bulson *et al.*, 1997; Yahuza, 2011b). Recently, the availability of early maturing bean varieties may allow simultaneous harvesting of both the cereal and legume bi-crops which can either be separated using cleaning equipment or be fed to livestock as a mixture (Bulson *et al.*, 1997).

Faba bean was considered a potential grain legume bi-crop based on its strength on protein quality and quantity; and its sustainability attributes through multiple ecological services delivery (Jensen *et al.,* 2010). In view of these attributes, faba bean as a bi-crop remains the backbone for the successful performance and productivity of low input bi-cropping systems. The biological strengths of faba bean can potentially contribute to increase local on-farm protein production and reduce the out sourcing of protein purchases (Anil *et al.*, 1998).

The domestic demand and utilisation of faba bean is increasing in the UK (Askew, 2016). The domestic use of faba bean as livestock feed in the UK has increased by 265% (Askew, 2016). Major drivers to such an increased growth include: increased domestic demand for use in feed formulations because of its relatively low prices as compared to soymeal and rape meal availability of market opportunities for export within the EU and other countries outside Europe for human consumption (Askew, 2016). Between 2015 and 2016, the UK exported 224 Kt volumes of faba bean due to increased production levels and its relative production area (Figure 2.5) supported by the Common Agricultural Policy reflected in the CAP Reform of 2014- 2020 (Askew, 2016; PGRO, 2016). According to PGRO (2017), the faba bean has potential markets in Scotland and Norway for de-hulled feed beans for fish feed; North Africa and Egypt for human consumption while domestic bean demand is potentially dominated by the ruminant compound feed millers.

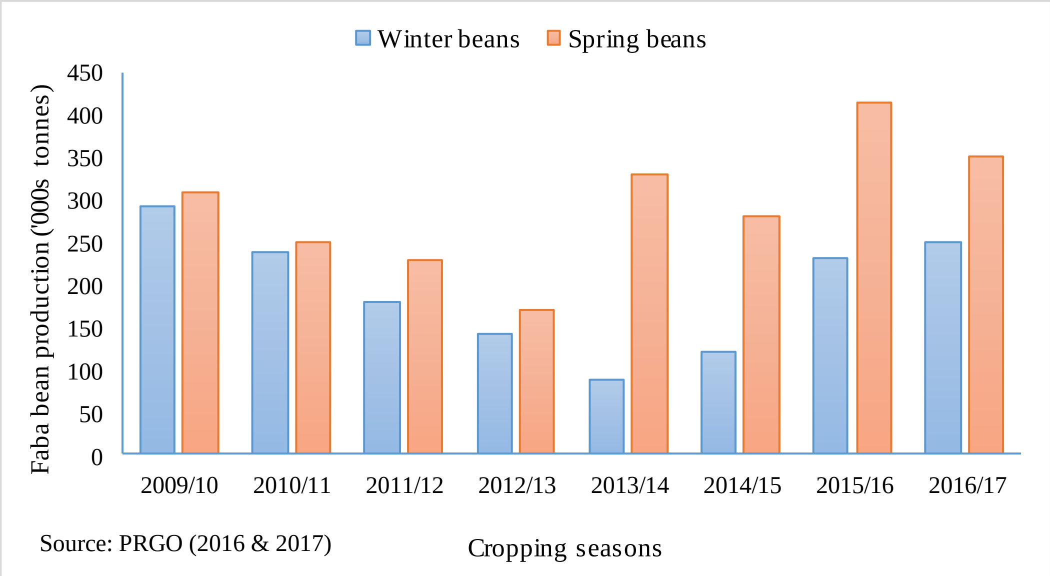

Figure 2.4: Faba bean production (000's tonnes) trend in the UK between 2009 and 2016

Beans are grown for their high protein concentrations while wheat is a valuable cash crop. Therefore, their combination in a production system can improve fodder quality, yield and economic benefits (Fradgley *et al.*, 2013). Both the spring wheat and beans crops have similar maturity period and they can be harvested together and either separated using a seed dresser or used as a mixed livestock feed (Gooding and Davies, 1997). Alternatively, bi-crops can be used for whole crop silage depending on the crop varieties used in bi-cropping (Ghanbari-Bonjar and Lee, 2002).

The benefit of bi-cropping system is greater when the growth duration between the bi-crops differ widely suggesting a temporal facilitation effect than when the bi-crops synchronise their duration period to maturity (Yahuza, 2011b). The success of any given bi-cropping system largely depends on whether or not the component crops can be simultaneously managed agronomically (Vandermeer, 1989). The spring wheat and faba beans bi-crops can be managed largely depending on the interspecific spatial facilitation effects than temporal facilitation effect because their sowing dates cannot be staggered. In cereal/legume cropping systems where bi-crops have synchronised maturity dates, the spatial arrangement in the form of row orientation remains the only agronomic practice which can favourably counteract the interspecific competition (Martin and Snaydon, 1982). Studies by Ennin et *al.*, (2002) demonstrated low productivity of bi-cropping systems due to similarity in maturity dates resulting in increased inter and intraspecific competition for growth resources. Spatial arrangement (spatial effect) can also influence positive or negative ecological interspecific competition under different environmental conditions and determine the ultimate productivity of crop mixtures. According to Musa *et al.*, (2010) there is little information on the planting arrangements of the various combinations of small grains and legumes and the literature is inconclusive as to the most efficient arrangement.

In the UK, for the past 28 years ago (1982-2010) cereal/faba bean bi-cropping research was consistently evaluated using the 1x1 alternate row spatial arrangement (Table 2.13) as a system design to respond to problems associated with compatibility of mechanisation at large scale bi-cropping systems (Bulson *et al.,* 1997). With the burgeoning thrust to promote local production of protein crops under low input bi-cropping systems (Anil *et al.,* 1998), the availability of early maturing spring faba bean varieties require further assessment to establish suitable information about their suitability in bi-cropping systems based on their morphological and growth rates traits (Bedoussac *et al.*, 2014). The bean cultivars currently on the market were selected based on their performance under sole bean cropping systems (Davis and Woolley, 1993) regardless of their differences in morphology and growth traits. Despite the 1x1 alternate rows spatial arrangement provide an opportunity to accommodate mechanisation in bi-cropping systems, further evaluation of alternate rows is indispensable to accommodate morphological and growth traits heterogeneity of released bean cultivars. Spatial manipulation is the only available option to determine interspecific complementarity for spring wheat and beans. According to Haymes and Lee (1999) the 1x1 alternate row spatial arrangements was intended to provide a solution to cross drilling bi-cropping practise which was mostly practised by commercial farmers. In this practice (cross drilling), the bi-crops were sown without a definite inter row spacing which made it difficult to understand competitive interactions between the crop components in their crop mixtures. The alternate rows spatial arrangement were introduced as a better agronomic approach to standardize interrow distances to better understand and evaluate the interactions between crop components in a wheat/faba bean bi-cropping systems. According to Bulson *et al.* (1997), the aim of introducing alternate rows in bi-cropping systems was to reduce interspecific crop competition and facilitate the convenience of using combined harvesters in bi-cropping systems. Recent wheat/faba bean bi-cropping studies by Yahuza (2012) the 1x1 alternate row spatial arrangements were maintained. Therefore, various spatial drilling options against the commonly practiced 1x1 alternate row spatial arrangement need to be evaluated to improve fodder productivity in wheat/faba bean bi-cropping systems. This knowledge gap led to the development of this study aimed at evaluating faba bean cultivars with heterogeneous morphological and growth rate traits at different spatial drilling patterns in wheat based bi-cropping system.

Table 2.13: The trend of wheat/faba bean bi-cropping research under single row alternate spatial arrangement in the UK

Bi-cropping system	Country	Research focus	Reference
Barley/ Faba bean	UK	Improving productivity of wheat/faba bean bi-cropping system.	Martin and Snaydon (1982)
Wheat/ Faba bean	UK	Sowing densities and practical compliance of bi-cropping system under mechanisation.	Bulson *et al.* (1997)
Wheat/ Faba bean	UK	Resource competition between autumn and spring bi-cropping systems.	Haymes and Lee (1999)
Wheat/ Faba bean	UK	Effect of harvest time on forage yield and quality.	Ghanbari-Bonjar and Lee (2002)
Wheat/ Faba bean	UK	Effects of different planting patterns.	Eskandari and Ghanbari-Bonjar (2010)
Wheat/faba bean	UK	Improving productivity of wheat/bean bi-cropping systems.	Yahuza (2012)

Chapter 3

MATERIAL AND METHODS

The methodologies used in the present study were consistent between experiments; and are combined in this chapter to avoid repetitions.

3.1. Experimental site

Field experiments were carried out during 2015 and 2016 spring cropping seasons under rainfed conditions at the Royal Agricultural University farm (51° 42' 33.6" N 1° 59' 40.7" W) in Gloucestershire, England. Two sites (A and B) were utilised during the 2 year study period. The physiochemical soil properties of the experimental sites are presented in Table 3.1.

Table 3.1: Initial physiochemical soil properties* of top soil profile (0-20 cm) of the experimental sites during 2015 and 2016 spring cropping seasons

Soil properties	**Spring cropping seasons**	
	Site A 2015	Site B 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 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

3.1.1. Meteorological conditions

Meteorological data for the study sites was collected from the Royal Agricultural University (RAU) Meteorological station (NGR SP 42 004 011). The meteorological measurements for 2015 and 2016 spring cropping seasons were reported in comparison against the 10-year average (Figures 3.1 and 3.2; Appendix 1.1 & 1.2).

Between the months of January and August, the mean air temperatures for 2015, 2016 and 10-year average were 10.3 ^{o}C, 10.6 ^{o}C and 10.2 ^{o}C respectively (Figure 3.1). In April, 2016, the monthly mean temperature was relatively lower which resulted in delayed sowing until May, 2016 when the optimum mean temperature conducive for sowing was attained. The monthly mean temperatures in April, 2015 and the 10-year average period were relatively higher, which resulted in timely sowing within the normal sowing window in the month of April (Figure 3.1).

The 10-year average period had the seasonal mean precipitation of 513 mm with the standard deviation mean 152. The 2016 cropping season received the total seasonal precipitation of 618 mm which was higher than the 2015 cropping season (438 mm) and the 10 year average (513 mm). However, the precipitation values for the 2015 cropping season (438 mm) was below the 2016 cropping season and the 10-year average (Figure 3.2). The total seasonal precipitation for 2016 did not occur by chance or erroneously because similar seasonal precipitation events occurred four times in the past (2007, 2008, 2012 and 2014). The total season precipitation for the 2015 cropping season was relatively lower than the 10-year average which also occurred in six years (2005, 2006, 2009, 2010, 2011 and 2013). The differences in seasonal precipitation between cropping seasons had a direct implication on soil conditions, crop establishment, crop growth and development (Figure 3.2)

The seasonal variation for mean soil temperature trends for 2015, 2016 and 7-year average were different at all soil depths (Figure 3.3). Within the sowing soil depth of 10 cm and during the sowing window in the month of April; the monthly mean temperatures for 2015 cropping season and the 7-year average were relatively warmer than 2016 cropping season (Figure 3.3). The differences in monthly mean soil temperatures between cropping seasons (2015 and 2016) determined their respective sowing dates. The mean soil temperatures increased with increasing number of days after sowing (DAS) at all soil depths and declined between the months of July and August across the cropping seasons.

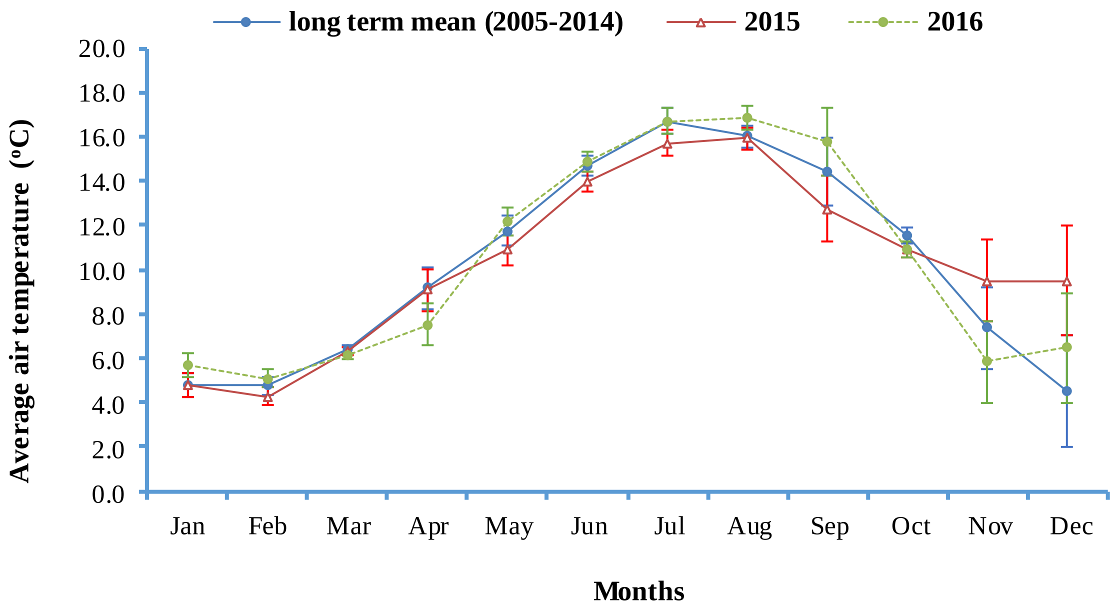

Figure 3.1: Average air temperatures during spring 2015 and 2016 crop seasons in comparison with the 10-year average. Royal Agricultural University meteorological station (NGR SP 42 004 011)

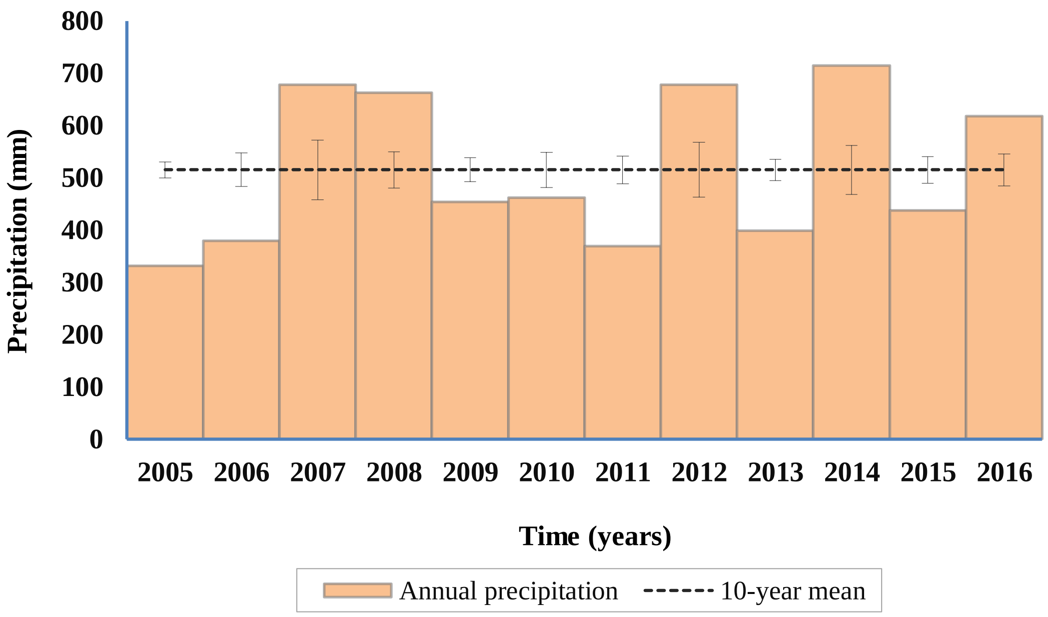

Figure 3.2: Amount of precipitation (mm) shown in histogram during January-August, 2015 and 2016 crop seasons in comparison with the 10-year trend. Royal Agricultural University meteorological station (NGR SP 42 004 011)

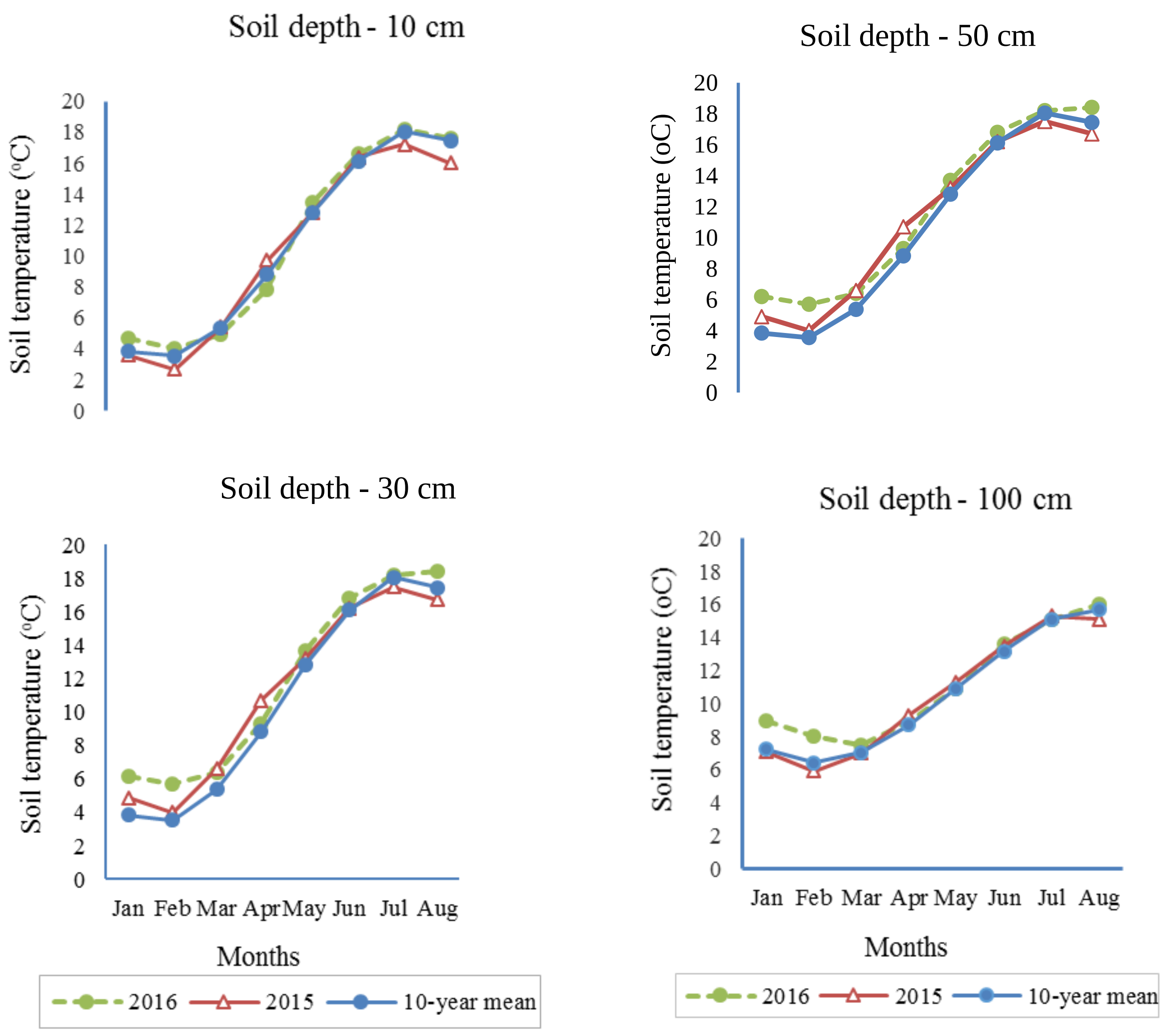

Figure 3.3: Soil temperatures at 10 cm, 30 cm, 50 cm and 100 cm soil depths for experimental sites during 2005 to 2016 cropping seasons. Royal Agricultural Meteorological station site (NGR SP 42 004 011)

3.2. Experimental design and treatments

For both spring cropping seasons, field trials followed a completely randomised block design with four replications (Figure 3.4 and 3.5). The experiments were not sown in autumn in order to maintain spring data consistency, which can easily necessitate across season analysis than if cropping seasons were different. The total experimental area of 1056 m^2 was equally divided into four replications/blocks each measuring 264 m^2. Each block was further divided into eleven (11) equal parts each measuring 24 m^2 forming experimental units where treatments combinations were allocated and fully randomised to minimise variations within each experimental unit and maximise variation between replications (Gomez and Gomez, 1984). The study evaluated four different spatial arrangements inform of drilling patterns and two different spring faba bean cultivars bi-crops against three corresponding sole crops (thus: two bean cultivars and one sole wheat crop). Therefore the treatment structure of the study was: *4 Blocks x* **(***4 drilling patterns x 2 bi-crop bean cultivars + 3 sole crops***)**

Plot no.	1	2	3	4	5	6	7	8	9	10	11
Block 1	Wheat Fuego 3x3	Sole Fuego	Wheat M Bead 1x1	Wheat M Bead 3x3	Wheat Fuego 1x1	sole wheat	Wheat M Bead Broadcast	Wheat M Bead 2x2	Wheat Fuego Broadcast	Wheat Fuego 2x2	Sole M Bead
Trt no.	5	8	2	6	1	7	11	4	10	3	9

Plot no.	12	13	14	15	16	17	18	19	20	21	22
Block 2	Wheat M Bead 3x3	Wheat M Bead 2x2	Sole M Bead	Sole Fuego	Wheat Fuego 2x2	Wheat Fuego 3x3	Wheat M Bead Broadcast	Wheat Fuego Broadcast	Wheat M Bead 1x1	Wheat Fuego 1x1	sole wheat
Trt no	6	4	9	8	3	5	11	10	2	1	7

Plot no.	23	24	25	26	27	28	29	30	31	32	33
Block 3	Wheat M Bead 1x1	sole wheat	Wheat M Bead 3x3	Wheat Fuego 2x2	Wheat Fuego 3x3	Wheat Fuego 1x1	Sole Fuego	Wheat M Bead Broadcast	Sole M Bead	Wheat Fuego Broadcast	Wheat M Bead 2x2
Trt no	2	7	6	3	5	1	8	11	9	10	4

Plot no.	34	35	36	37	38	39	40	41	42	43	44
Block 4	Wheat M Bead 1x1	Wheat M Bead Broadcast	Wheat Fuego 3x3	Wheat Fuego 2x2	Wheat M Bead 3x3	Wheat M Bead 2x2	Wheat Fuego 1x1	Sole M Bead	Sole Fuego	sole wheat	Wheat Fuego Broadcast
Trt no.	2	11	5	3	6	4	1	9	8	7	10

Trt no. = treatment number

Figure 3.4: Field trials design and treatments randomisation for 2015 cropping season

Plot no.	1	2	3	4	5	6	7	8	9	10	11
Block 1	Wheat Fuego Broadcast	Wheat M Bead 2x2	Sole M Bead Bean	Wheat Fuego 3x3	Wheat Fuego 2x2	Wheat M Bead 1x1	sole wheat	Wheat Fuego 1x1	Sole Fuego Bean	Wheat M Bead Broadcast	Wheat M Bead 3x3
Trt no.	10	4	9	5	3	2	7	1	8	11	6

Plot no.	12	13	14	15	16	17	18	19	20	21	22
Block 2	Wheat M Bead Broadcast	Wheat Fuego 1x1	Wheat Fuego Broadcast	Wheat M Bead 2x2	Wheat M Bead 3x3	Sole M Bead Bean	Wheat Fuego 2x2	Wheat M Bead 1x1	Wheat Fuego 3x3	sole wheat	Sole Fuego Bean
Trt no.	11	1	10	4	6	9	3	2	5	7	8

Plot no.	23	24	25	26	27	28	29	30	31	32	33
Block 3	Wheat M Bead 3x3	Wheat Fuego Broadcast	Wheat Fuego 2x2	Wheat Fuego 3x3	Sole Fuego Bean	Wheat M Bead Broadcast	sole wheat	Sole M Bead Bean	Wheat M Bead 1x1	Wheat M Bead 2x2	Wheat Fuego 1x1
Trt	6	10	3	5	8	11	7	9	2	4	1

Plot no.	34	35	36	37	38	39	40	41	42	43	44
Block 4	Wheat Fuego 3x3	Wheat Fuego 1x1	Wheat M Bead 3x3	Wheat M Bead 1x1	Sole Fuego Bean	Wheat Fuego Broadcast	Sole M Bead Bean	Wheat M Bead Broadcast	Wheat M Bead 2x2	sole wheat	Wheat Fuego 2x2
Trt no.	5	1	6	2	8	10	9	11	4	7	3

Trt no. = treatment number

Colour codes:		Treatment description
	=	Broadcast
	=	1 x 1 - Drilling pattern
	=	2 x 2 - Drilling pattern
	=	3 x 3 - Drilling pattern
	=	Sole crops (*wheat and beans*)

Figure 3.5: Field trials design and treatments randomisation for 2016 cropping season

3.2.1. Details of experimental treatments

3.2.1.1. Drilling patterns

Four different drilling patterns are elaborated below and in Appendix 2.0.

- 1x1 drilling pattern: one row of spring wheat alternated with one rows of spring faba bean

- 2x2 drilling patterns: two rows of spring wheat alternated with two rows of spring beans.
- 3x3 drilling patterns: three rows of spring wheat alternated with three rows of spring beans.
- Broadcast: Bean bi-crops were randomly sown over the precisely drilled wheat crop. This mimic commercial farmers as commonly practiced in Scotland

3.2.1.2. Spring bean cultivars

Two spring faba bean cultivars with two contrasting growth habits and morphological characteristics were selected for evaluation. The spring bean cultivars were Fuego and Maris Bead whose details are described the Table 3.2 below.

Table 3.2: Description of spring faba bean cultivars

Spring bean	Hilum colour	Shortness of straw	Earliness of ripening	Protein content (%DM)	Yield as %control (5.39 t ha^{-1}) 5 year mean	Year of release
Fuego bean	Pale	6	7	27.5	99	2005
Maris Bead	Black	4	6	29.0	83	1964

A scale of 1-9, a high value indicates that the variety shows the character to a high degree. Source: PGRO (2017).

3.2.1.3. Sole crops

The sole crops of beans and wheat were included as controls for comparison against their companion bi-crops' performance on various parametric assessments and also assisted in assessing the efficiency of bi-cropping treatment combinations. Spring wheat *cv.* Paragon was used in the experiment.

Varietal choice

Fuego, a spring bean variety released in 2005, has taller growth habits and matures early compared to Maris Bead. It has a mean protein content of 28.0%, with a white hilum an indication of the suitability of the bean for human consumption and export. It has relatively bigger seed size than to Maris Bead, paled coloured (Plate 1.0) with low level of bruchid beetle infestation in storage (PGRO, 2015). Faba bean seed was supplied by the PGRO.

Maris Bead, spring bean variety released in 1964, has relatively shorter straw height and matures later than Fuego. It has a mean protein content of 29.0%, small seeded (Plate 3.0) with a black hilum an indication of the suitability of the bean for feed formulation or livestock feeding for domestic sales and export (PGRO, 2015). Paragon, a spring wheat variety (Plate 3.0) was chosen for the following traits; taller height (87 cm) with stiff straw, good standability, relatively high and stable protein content of 13.9% which does not change with untreated trials (NABIM 2014); its dual end use which include milling and baking purposes (AHDB, 2015); ability to withstand early season environmental stress (NABIM 2014). Its fast growth rate and height advantage, gives good compatibility in mixture with legumes (Kankanen *et al.*, 2001).

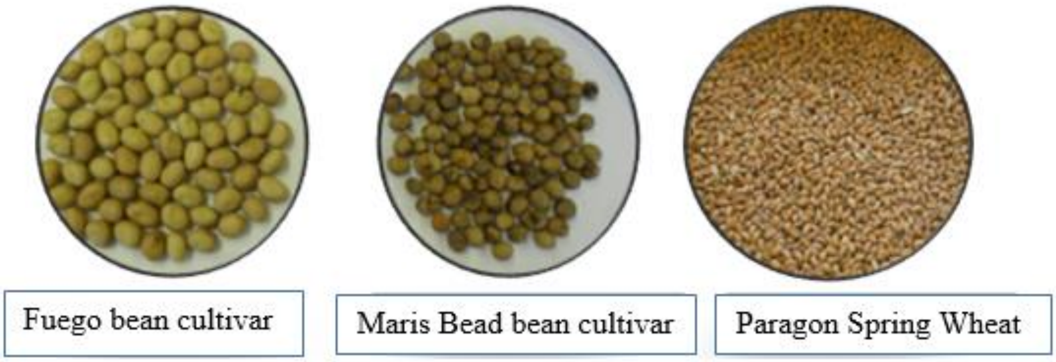

Plate 1: Physical characteristics of spring bean and wheat seeds

<u>Sowing date</u>

Grain yield and other characteristics of wheat and bean both in sole and bi-crops can be influenced by variations in sowing dates (Hayward, 1990). In this study, the sowing dates were influenced by each seasonal weather characteristics. The extent to which precipitation stops in the month of March between the two seasons, determined the time taken for soil to dry to obtain the right soil moisture ideal for sowing in subsequent months of April and May. The sowing dates for 2015 and 2016 cropping seasons were 09/04/2015 and 02/05/2016 respectively.

<u>Sowing density</u>

Sowing density (weight of seeds drilled per unit area) can influence the crop performance and final crop yield (Dehdashti and Riahinia, 2008). Both high and low seed rates can have negative and positive implications on the final crop performance (Hayward, 1990). Optimum sowing density is ideal because it may increases crop yield due to availability of environmental resources (Gooding et al., 2002). However higher densities does not usually increase crop performance and yields because it influence inter and intraspecific competition for soil moisture, light and N. It also reduces individual plant growth and the production of tillers in wheat (Gooding and Davies, 1997).

Seed rates are determined by soil types, climatic conditions and crop cultivars (AHDB, 2015). According to Lithourgidis *et al.,* (2006), spring wheat has low tillering ability than winter wheat hence to produce optimum number of wheat competitive plants and compensate low tillering potential, a higher seed rate of 500 seeds m^{-2} is ideal. Lampkin *et al.,* (2011) reported that most UK organic growers use >400 seeds m^{-2} of spring wheat under organic farming systems because germination is assumed neither predictable nor consistent due to variations in the seed bed conditions and lack of seed dressing.

In this study, in both experimental growing seasons, the spring wheat and bean seeds with a mean germination above 90 percent (Appendix 8.1, 8.2, 8.3 and 8.4) were sown at the recommended plant density of 400 wheat seeds m^{-2} and 40 bean seeds m^{-2} respectively. This translated into 220 kg/ha for Paragon wheat variety, 283 kg/ha for Fuego bean cultivar and 195 kg/ha for Maris Bead bean cultivar. The sowing density of sole and bi-cropped treatments followed the replacement design (Snaydon, 1991) where the density of bi-cropped treatments of each spring crop was reduced to one half of their respective spring sole crop densities. In replacement designs, the total relative density of 100% is held constant while the relative proportion of each species is varied based on the recommended density (De Wit and van den Bergh, 1965). This differs from the additive designs where total relative density of crop species in mixtures can exceed 100%. The main reason of such a design is to induce a most productive bi-cropping system (Fukai and Trenbath, 1993; Snaydon, 1991). Replacement (or substitutive) designs have been universally considered the only valid type of experimental design used in studies of plant competition because it eliminates most problems of additive designs (Harper, 1977). Despite other studies like Bulson *et al.* (1997) used additive design with a uniform spatial arrangement, considering the factors involved in this study, varying densities (in additive design) could have masked the effects of drilling patterns. This explains why the recommended density of both crops in a replacement design was used.

Plot size, row spacing and sowing depth

Each experimental plot was 2 metres wide and 12 metres long (24.0 m^2). The plot width of 2 metres was deliberately designed in order to fit the width of the plot drill (Plate 2a). Spring wheat and beans in their respective sole experimental units were drilled at the inter-row spacing of 15 cm and 30 cm respectively. Bi-crop experimental units of spring beans and wheat in mixtures were sown at the standard inter-row spacing of 15 cm apart. Spring wheat crop in sole and bi-crop plots was sown using a Winstersteiger Precision Seed Drill (Plate 2*a*). Spring beans in sole and bi-crop experimental units were hand sown because the Winstersteiger Precision Seed Drill was not designed to simultaneously drill wheat and bean seeds. The approach to drill wheat in sole and alternate rows experimental units differed. Sole wheat experimental units were drilled with all the driller's pipes inserted in the soil in all the rows (Plate 1*a*). For beans bi-crops, alternate rows were blocked with a bucket to leave empty rows for hand sowing beans (Plate 1*d*).

The success of seed germination and crop emergence depends on the sowing depth among other factors (Nsowah, 1986). Shallower and very deeper sowing depth may prevent negatively affect germination resulting in low crop establishment and reduced final crop yield (Calvino and Sandras, 1999). In this study, wheat was drilled at the uniform average depth of 2.5 cm which was within the recommended sowing depth of 2-4 cm (AHDB, 2016) and the sowing depth varies depending on the soil type and soil conditions (AHDB, 2016). The beans seeds were hand sown at an average uniform sowing depth of 5 cm irrespective of the cropping systems i.e. sole bean or bi-cropping system. In order to establish a better seed-bed contact with the seeds for better germination and reduce the risk of birds eating the sown seed, a roller had run over the site soon after seed sowing.

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Plate 1 *a*. Winstersteiger Precision Seed Drill

Plate 2 Electric fence unit

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Plate 1 *b*. Sole wheat drilling

Plate 1 *c*. Drilling instructions

Plate 1 *d*. Alternate rows drilling

3.3. Aboveground assessments

3.3.1 Developmental stages

The timing for wheat plant sampling and final harvest was guided by the decimal code growth stages (GS) defined by Zadoks *et al.* (1974) in Appendix 3.1. Timing for bean plant sampling and final harvest was guided by the bean growth stages (GS) reported by PGRO (2015) in Appendix 3.2. Details of the dates and development stages for each crop assessment are presented in Tables 3.3 & 3.4. All agronomic assessments were conducted in the inner rows of each experimental unit, excluding the outer rows which did represent the inner plant population due to external influences (Gomez *et al.*, 1984).

Table 3.3: Growth stages for aboveground crop assessments during 2015 spring cropping season

Assessments	Approximate crop growth stage (GS)	
	Wheat	**Beans**
Crop establishment (plants m^{-2})	On/or before GS15	On/or before GS101
Wheat tillers count (tillers m^{-2})	On/or before GS21	-
Weed biomass (g m^{-2})	On/or before GS31, GS69 and GS92	On/or before GS201, GS207 and GS410
Wheat leaf chlorophyll (CCI)	On/or before GS32, GS71, and GS83	-
IPAR (%) and LAI	On/or before GS69, GS71, GS83 and GS89	On/or before GS103, GS105, GS201, GS204, GS205 and GS207
Wheat biomass and final biological harvest (t ha^{-1})	On/or before GS21, GS31, GS69 and GS92	-
Bean biomass and final biological harvest (t ha^{-1})	-	On/or before GS103, GS201, GS207 and GS410
Wheat plant height (cm)	On/or before GS69 and GS87	-
Bean plant height (cm)	-	On/or before GS201 and GS209

IPAR, intercepted photosynthetic active radiation; CCI, chlorophyll concentration index; LAI, leaf area index.

Table 3.4: Dates and growth stages for above and belowground crop assessments during 2016 spring cropping season

Assessments	Approximate crop growth stage (GS)	
	Wheat	**Beans**
Crop establishment (plants m^{-2})	On/or before GS21	On/or before GS101
Wheat tiller count (tillers m^{-2})	On/or before GS25	-
Weed biomass (g m^{-2})	On/or before GS35 and GS69	On/or before GS105 and GS207
Wheat chlorophyll (CCI)	On/or before GS 31, GS44, GS69, GS77 and GS80	-
IPAR (%) and LAI	On/or before GS35, GS40, GS69, GS75 and GS80	On/or before GS103, GS105, GS205, GS206 and GS207
Underground bean assessments	-	On/or before GS207
Wheat biomass (t ha^{-1})	On/or before GS21, GS35, GS69 and GS92	-
Bean biomass (t ha^{-1})	-	On/or before GS103, GS105, GS207 and GS410
Wheat plant height (cm)	On/or before GS92	-
Bean plant height (cm)	-	On/or before GS204

IPAR, intercepted photosynthetic active radiation; CCI, chlorophyll concentration index; LAI, leaf area index.

3.3.2. Assessments

3.3.2.1 Plant establishments

The numbers of emerged plants were recorded from a randomly placed 1 m^2 quadrant area replicated twice within the central part of every experimental unit at GS15 and GS21.

3.3.2.2 Wheat tiller numbers

The total numbers of wheat tillers were recorded from a randomly placed 1 m^2 quadrant replicated twice within the central part of every experimental unit at GS21 and GS29.

3.3.2.3 Growth assessments

Four growth destructive analysis (GDA) (Ciampitti, 2012) assessments were conducted during vegetative, flowering, physiological maturity and at final harvest. The harvest of aboveground plant materials was done using a pair of scissors or secateurs which was suitable at experimental plot level. Harvested plant materials were determined from the central part of an experimental using a 1 m^2 quadrant replicated twice. The number of random plant sampling replications was restricted to two because the quadrant was large enough to accommodate simultaneous plant sampling of both crops throughout the crop growth cycle and perform other canopy assessment such PAR and LAI against the limited plot size of 12m x 2 m. Plant sampling in 100% sown sole crops and the 50:50 sown bi-crop mixture experimental units were conducted the same. The harvested aboveground plant samples comprised of wheat, beans and weeds were quickly put inside well labelled air tight sealed plastic bags to reduce moisture loss before subsequent processing in the laboratory. At every stage of aboveground plant harvesting, wheat and beans were separated into their component crops for bi-cropping experimental treatments. The sampled wheat, beans and weeds plants were separated and recorded their respective fresh weights using a digital weighing balance. Dry weights were recorded after oven dried aboveground plant samples for 48 hours at a constant temperature of 65 ^{o}C.

3.3.2.4 Weed assessments

Weed dry matter (g m^{-2}) and weed smothering efficiency (%) (WSE) were the two experimental variables used to assess the efficacy of cropping systems on biological weed control.

Weed dry matter (g m^{-2}) was assessed as described in section 3.3.2.3 above.

Weed smothering efficiency (WSE) was calculated according to Choudhary *et al.* (2014):

$$\text{WSE (\%)} = \frac{\text{Mdw} - \text{Bdw}}{\text{Mdw}} \times 100$$

Where; Mdw = Dry weight of weeds in the sole crop plot (g m^{-2}), Bdw = Dry weight of weeds in bi-crop plots (g m^{-2}).

3.3.2.5 Plant height

Wheat plant height of the main wheat shoot was measured in centimetres using a calibrated two metre ruler from the ground level to the tips of the wheat ear (AHDB, 2015). Ten representative wheat plants were randomly measured and averaged to get the mean plant height for each experimental unit. Similarly, ten representative bean plants were randomly measured from the ground level to the end growing point of the plant (Nadeem *et al.*, 2015). Measured bean plants were averaged to get the mean bean plant height for each experimental unit. Wheat and bean plants were assessed at GS92 and GS204 respectively when no further plant took place.

3.3.2.6 Field pests and disease assessments

Black bean aphids (*Aphis fabae*) and Ascochyta bright (*Ascochyta fabae)* biotic stresses were assessed at GS 201 and GS207 respectively. Their incidence was calculated by using the number of infected plants (m^{-2}), expressed as a percentage of the total number of plants from 1.0 m^2 quadrant (Hailu *et al.*, 2014; ICARDA, 1986).

Faba bean rust disease (*Uromyces viciae-fabae*) severity assessment method in the field was adopted from Khare *et al*. (1993); using a scale of 1-9, where 1 meant no pustules visible and 9 meant pustules extensive on leaves, petioles and stems, and killing leaves and other plants. These scores were then converted to percentage severity according to Chongo *et al.* (1999): The number of affected bean plants was randomly assessed from 1.0 m^{-2} within the central part of every experimental unit.

$$\text{Rust severity (\%)} = \sum \frac{\text{Number of plants/scale value x scale value}}{\text{Highest scale value x total number of plants}} \times 100$$

The experimental sites in both seasons were fenced at GS15 with an electric fence against the rabbits which were feeding fed on the young wheat plants (Plate 2.0)

3.3.2.7 Leaf chlorophyll content

Nitrogen is a structural element of chlorophyll and protein molecules (Tucker, 2004). Assessing chlorophyll in the wheat bi-crops gives an indication of legumes' nitrogen facilitation in cereal bi-crops. The chlorophyll content in the wheat bi-crop leaves reported as

Chlorophyll Concentration Index (CCI) was determined with non-plant destructive method using a hand held chlorophyll meter (Model CCM 200 Plus, Opti-Sciences Inc., New Hampshire, USA). Ten representative wheat plants from each experimental unit were measured. The wheat flag leaf and the 3rd leaf were consistently measured from each of the selected wheat plants to eliminate the sources of variation which could occur due to differences in measurements. The readings were automatically recorded, stored and averaged to generate one mean reading for each experimental unit (Mohsin *et al*., 2011).

3.3.2.8 Leaf Area Index (LAI) determination

The LAI is an important variable for analysing the interactions between crop species and the atmosphere, estimating the amount of radiation intercepted by crop canopy; estimating the photosynthetic activity of cropping systems and guides on how to optimise dry matter production (Confalonieri *et al.,* 2013). The SunScan canopy analysis system device (Delta-T, Burwell, and Cambridge, UK) which does not involve plant destruction was used to determine LAI. The readings were consistently measured between 10.00 am and 2.00 pm British Local Time (BLT). The SunScan probe, 1 m long was placed under the crop canopies at standard height of 7.5 cm from the soil surface at five representative points of each experimental unit (Figure 3.6).

3.3.2.9 Photosynthetic active radiation (PAR) determination

PAR describes the spectral range of solar radiation from 400 to 700 nm in which photosynthetic organisms are able to use light and facilitate photosynthesis (McCree, 1972 and Figure 3.7). Measuring PAR in agronomic studies helps to understand the influence of amount and quality of PAR absorption by crop canopies on photosynthesis and the productivity of cropping systems (Yahuza, 2011a). PAR was determined by using the SunScan canopy analysis system device (Delta-T, Burwell, and Cambridge, UK). The system had a single quantum sensor (the bean fraction) and a linear sensor (the SunScan probe, 1 m long with 64 photodiodes equally spaced along its length) for measuring PAR above and beneath plant canopies, respectively (Figure 3.6). The PAR which transmitted through the crop canopies was measured with linear sensor (the SunScan probe) at a standard height of 7.5 cm from the soil surface to avoid sources of errors that could occur due to different heights. Five representative points were randomly selected for PAR measurement in each experimental unit. Readings were taken between 10.00 am and 2.00 pm British Local Time (BLT). The PAR intercepted was calculated by measuring both incident and transmitted light through the canopy simultaneously (Matusso *et al.* (2014). Intercepted PAR is the amount of the incident that was not transmitted through the canopy. The PAR intercepted was calculated according to Goudriaan (1988) and Campiglia *et al*. (2014): where the subscript *i* designated intercepted PAR; subscript *a* and *b* designates PAR readings measured above and below the plant canopy respectively.

$$\% \, PAR_i = \frac{(PAR_a - PAR_b)}{PAR_a} \times 100$$

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Figure 3.6: Direct PAR and indirect LAI measurement with the SunScan canopy analysis system device (Delta-T Devices, Cambridge, UK)

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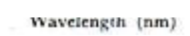


Source: Koning (1994).

Figure 3.7: Solar radiation spectrum showing where PAR and photosynthesis takes place

3.3.2.10 Radiation use efficiency (RUE)

The RUE measures the ability of the crop to produce dry matter per unit of radiation intercepted or absorbed (Monteith, 1972; Awal and Ikeda, 2003). Assessing the radiation use efficiency for each bi-crop is difficulty due to canopy intermingling. In bi-cropping systems, if the canopy is either horizontally or vertically stratified, it worthwhile to use intercepted radiation and biomass to calculate RUE value for each of the component crops compared with sole crops (Marshall and Willey, 1983; Yahuza, 2011b).

On the other hand, if the canopy is not stratified completely, it would be better to calculate RUE value for the whole bi-cropping system by dividing the total biomass of both components by the total amounts of radiation intercepted by the complete system (Azam-Ali and Squire, 2002).

Since the canopy structure for the wheat/faba bean bi-cropping system do not show compete stratification, that would not necessitate the computation of the RUE for each crop (Hongo, 1995; Haymes and Lee, 1999), the computation of the total RUE for the whole bi-cropping systems may be more valid, by dividing the total biomass of both components crops by the total radiation intercepted by the complete bi-cropping systems (Azam-Ali and Squire, 2002).

3.3.2.11 Final biological harvest

Final harvest was determined from a randomly placed 1 m^2 quadrant area replicated twice with the central part of each experimental plot. The field experiments were hand harvested using a pair of scissors or secateurs. Wheat was harvested when the spikelets changed to straw-coloured and 80% of the grains of the spike were in the hard-dough stage (Chapagain, 2014). The beans were harvested when the stems and pods turned black with seeds dry (PGRO, 2016). All the harvested wheat plant materials were separated into ears and straw by cutting off ear at the peduncle to determine the total number of ears harvested per unit area. Bean pods were separated from the straw by hand to determine the total number of pods harvested per unit area. Both wheat and bean plant samples were oven dried at a constant temperature of 105 ^oC overnight to determine the dry weight. Wheat ears and bean pods were hand threshed and the extracted grain was weighted to obtain total grain weights and yield which was corrected to 15% grain moisture content. Thousand grain weight (TGW) was recorded after an automatic grain feeder and counter determined the number (Farm-tec, Scunthorpe). Harvest index (HI) was determined as the ratio of economical yield to biological yield (Wnuk, 2013).

3.3.2.12 Plant N content

To determine the N content, all the plant samples were course milled and then sub sampled and further micro-milled (0.5 mm sieve) (Cyclotec 1093 Sample Mill) to obtain a sample with fine particle size distribution. A sub sample of 25 mg (±0.05 mg) of the ground material plus 50 mg of tungsten oxide were placed into aluminium boats and weighed on a five decimal place analytical balance. Encapsulate samples were then analyse on an Elemental Cube CNS auto analyser (Eelemental Analysen systemse GmbH). Total N uptake calculations for wheat, beans and weeds were computed according to Mahama *et al.* (2016).

(a) N uptake in the plant tissues (crops and weeds):

$$\mathbf{N}\text{ uptake} = \mathbf{DM}_{\text{aboveground}} \times \frac{[\mathbf{N}]_{\text{DM}}}{100}$$

Where: N uptake is measured in kilograms per hectare (Kg N ha^{-1}), $DM_{aboveground}$ indicates aboveground dry matter (kg ha^{-1}), and $[N]_{DM}$ is the N concentration (%) in dry matter.

(b) N uptake in the grain:

$$\text{Grain N uptake} = \text{Yield} \times \frac{[\text{Grain } \mathbf{N}]}{100}$$

Where: grain N uptake is measured in kilograms per hectare (Kg N ha^{-1}), Yield indicates grain yield (kg ha^{-1}), and [Grain N] indicates grain N concentration (%).

(c) Nitrogen harvest index

$$\text{Nitrogen harvest index} = \left(\frac{\text{Grain N uptake}}{\text{Grain N + Straw N uptake}} \right) \times 100$$

(d) Grain crude protein

Grain nitrogen values were converted to crude protein content by multiplying grain N% by 5.7 for wheat (Osborne, 1907) and 6.25 for beans (Magomya *et al.*, 2014). Nitrogen yield was obtained by multiplying the crude protein content by dry matter yield (Mariotti *et al.*, 2006). This measured of how much N was taken up by the crop and also how much nitrogen was removed from the field with harvest (Dordas and Lithourgidis, 2011).

3.4 Biological efficiency assessments

3.4.1 Land Equivalent Ratio (LER)

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 acreage. It can be used both for replacement and additive series of bi-cropping systems. It was calculated according to Mead and Willey (1980).

The LER values for two intercrop species in proportional replacement design were calculated as: LER = ($PLER_{wheat}$ + $PLER_{beans}$), where $PLER_{wheat}$ = (Y_{wb}/Y_{ws}), and $PLER_{beans}$ = (Y_{bb}/Y_{bs}) where Y_{ws} and Y_{bs} are the yields of wheat and beans as sole crops respectively, and Y_{wb} and Y_{bb} are 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. When the LER is 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).

3.4.2 Land savings

Assessing the advantages of crop mixtures in terms of land savings is one of the major purposes of bi-cropping systems in addition to LER which was described by Mead and Willey (1980). Land savings in crop mixtures was calculated using the formula described by Willey (1985). % Land savings = 100-1 / LER x 100. The productivity coefficient of 25% was established as the minimum value in assessing per cent land saving in crop mixtures (Adetiloye *et al.*, 1983).

3.5 Competition indices

The competitive behaviour of component crops in bi-cropping systems was determined by Relative Crowding Coefficient (RCC or K) and aggressivity (A) which are suitable in a 50:50 replacement designs.

3.5.1 The Relative Crowding Coefficient (RCC or K)

The RCC or K measures the relative dominance of one crop species over the other in a bi-crop mixture as proposed by de Wit (1960) which was calculated as follows:

K = (K_{wheat} x K_{beans}), where $K_{wheat} = Y_{wb} / (Y_{sw} – Y_{wb})$, and $K_{beans} = Y_{bb} / (Y_{sb} –Y_{bb})$, where Y represent crop yield per unit area; Y_{sw} and Y_{sb} are the yields of wheat and beans as sole crops respectively, and Y_{wb} and Y_{bb} are the yields of wheat and beans as bi-crops respectively.

The bi-crop component in mixture with a higher coefficient (K) is considered to be dominant over the other. If the product of the two coefficients (K) is greater than 1.0, there is a yield advantage whereas if K obtained in the system equals to 1.0, there is no yield advantage, and if K in the system is less than 1.0, there is a yield disadvantage (Dhima *et al.*, 2007).

3.5.2 Aggressivity (A)

Aggressivity is a measure of competitive relationships between two crops in bi-cropping systems (Willey, 1979). The calculations were determined according to Dhima *et al.* (2007) based on the following formula: $A_{wheat} = (Y_{wb}/Y_{sw}) – (Y_{bb}/Y_{sb})$ and $A_{bean} = (Y_{bb}/Y_{sb}) – (Y_{wb}/Y_{sw})$, where Y represent crop yield per unit area; Y_{sw} and Y_{sb} are the yields of wheat and beans as sole crops respectively, and Y_{wb} and Y_{bb} are the yields of wheat and beans as bi-crops respectively. If $A_{wheat} = 0$, both crops are equally competitive, if A_{wheat} is positive, then the wheat bi-crop is dominant over bean bi-crop and if A_{wheat} is negative, then the wheat bi-crop is weak and the bean bi-crop is 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 dominated negative. The greater the numerical value, the bigger the differences between actual and expected yields.

3.6 Soil assessments

3.6.1 Soil chemical analysis

3.6.1.1 Field sampling

Before sowing, soil samples were sampled at the depth of 0-20 cm using a soil auger at ten randomly selected sampling points within each block in a W sampling pattern. The soil samples for each block were bulked up in a plastic bucket, mixed thoroughly and obtained a composite sample for each block. The composite soil samples were placed in sealed labelled bags and transferred to the laboratory. In the laboratory, each composite soil sample was sub sampled, air dried, sieved, and passed through a <2 mm Laboratory Test Sieve (ENDECOTTES Ltd) for physiochemical analysis according to the British system of soil classification (MAFF, 1988). Sub soil samples for the determination of total soil nitrogen and total soil organic carbon using an Elemental Cube CNS auto analyser (Eelemental Analysen systemse GmbH) were further milled and sieved through 0.5 mm sieve.

3.6.1.2 Soil pH

The soil pH was measured in water (1: 2.5; soil to water ratio). A 20 g of sieved (<2 mm) air dried soil replicated three times was put into 100 ml pre-labelled plastic bottles, 50 ml of deionised water was added and shaken gently for 15 minutes at a speed of 120 oscillations per minute using a shaker unit (Gerhardt Germany) and allowed the soil solution to settle. A pH electrode of the Soil pH Digital pH Meter was immersed in the soil solution, swirling a couple of times before allowing the pH to stabilise before taking readings (Faithfull, 2002). Before pH measurements, calibration of the pH Digital meter (Omega Engineering, USA) was performed according to manufacturer's instructions using buffers of pH 10.0 and 4.0 to cover the pH range of the soil samples.

3.6.1.3 Soil phosphorus

Soil phosphorus (P) was determined using the Olsen Method (Olsen *et al.*, 1954). From each composite sample, three analytical samples of 5 g of (± 0.05 g) of sieved (<2 mm) air-dry soil were weighed and transferred into pre-labelled 150 ml shaking bottles. About 1 g of powdered charcoal and 100 ml of sodium bicarbonate (NaHCO3) reagent at pH 8.5, was added to the bottles and shaken vigorously using a shaker unit (Gerhardt, German) for 15 minutes at an oscillation speed of 120 per minute and allowed to settle for 15 minutes after shaking. The soil solution was filtered through a Whiteman No 2 filter paper. From the extraction, 5 ml was pipetted into 100 ml of conical flask slowly adding 1 ml of 1.5 M sulphuric acid. When the frothing ceased from releasing carbon dioxide, 20 ml of ammonium molybdate (1.2% m/v) ascorbic acid solution was added and allowed to stand for 30 minutes. Working standard solutions of 0.25, 0.5,1,2,3,4,5 and 6 ug P ml-1 were used to obtain P equivalent ug P ml-1 of the samples and two blanks were used as controls. Eventually, the absorbance of the samples, standards and blanks were measured using a spectrophotometer (Cecil Instruments Ltd., UK) at the wavelength of 880 nm.

3.6.2 Physical soil analysis

3.6.2.1 Soil texture

Soil texture was determined following the Bouyoucos Hydrometer method (Bouyoucos, 1962). From each composite sample, three analytical samples of 50 g (± 0.05) of sieved (<2 mm) air-dry soil were placed into 250 ml shaking bottles. 100 ml of Calgon solution was added and shaken for 400 minutes. The solutions were transferred into 1000 ml measuring cylinders and diluted to 1000 ml with deionised water. The top of the 1000 ml cylinder was further sealed with parafilm to prevent water spillage when the cylinder was being frequently inverted upside down. The cylinder was inverted for 20 times; placed on the bench and timed immediately with a stop watch. A hydrometer was inserted into each cylinder without disturbing the solution approximately 20 seconds prior to taking a reading; then removed and rinsed immediately. Readings were taken at 40 seconds, 4 minutes, 37 minutes and 2 hours. To correct the readings for temperature and density, readings were calibrated against the hydrometer in the Calgon-water control solution and subtracted from all the readings. The percentage of sand, silt and clay fractions was plotted on the texture triangle chat in Appendix 4.0 to determine the texture class (MAFF, 1988).

3.7 Statistical analysis

Statistical analyses were carried out on all the data collected using the general analysis of variance (ANOVA) model in Genstat (15^{th} Edition version VSN International Ltd, Hemel, Hempstead, U.K) to establish differences between cropping system, drilling patterns and bean cultivars. Significant main effects and their interactions were separated by Standard Error of Difference of means (SED) tests at $P<0.05$. The results of the ANOVA (Gomez and Gomez, 1984) were reported quoting treatment means degrees of freedom (df), Standard Error of Difference (SED) and the *p*-value (significant level of $P<0.05$). Analytical results were presented in tables and graphs. Significant differences between and among treatment means at $P<0.05$; $P<0.01$ and $P<0.001$ were respectively denoted by: *, **, and *** while *ns* denoted non-statistical differences at $P<0.05$. In each column values with the same letter are not statistically different at $P<0.05$. The data sets for weed dry weights and weed nitrogen uptake were subjected to square root transformation using the formula $\sqrt{(x+0.5)}$ as suggested by Gomez and Gomez (1984) to normalize their distribution and conform to the assumptions underlying the ANOVA.

Chapter 4

RESULTS FOR 2015 CORE EXPERIMENT

4.1 Wheat

4.1.1 Crop establishment

Cropping systems had a greater (P<0.001) effect on wheat establishment (Table 4.1.), and the sole cropping system (313 plants m^{-2}) had a higher number of established wheat plants than the bi-cropping system (160 plants m^{-2}). The drilling patterns and the bean cultivars did not affect the number of established wheat plants.

Table 4.1: The Effects of cropping systems, drilling patterns and spring bean cultivars on spring wheat establishment (plants m^{-2}) and the number of tillers (tillers m^{-2}) in 2015 cropping season

Treatments	Mix-proportion	Wheat establishment (Plants m^{-2})	Wheat tillers (Tillers m^{-2})		
Drilling patterns					
1x1	50:50	150	199^{b}		
2x2	50:50	153	193^{b}		
3x3	50:50	158	223^{a}		
Broadcast	50:50	177	233^{a}		
SED (3 df)	-	22.140ns	13.25***		
P-value	-	0.134	0.001		
Cropping systems					
Bi-crop mean	50:50	160^{b}	212^{b}		
Sole crop	100	313^{a}	420^{a}		
SED (1 df)	-	19.170***	11.43***		
P-value	-	0.001	ns 0.001	ns	***
Bean cultivars					
Fuego	50:50	161	216		
Maris Bead	50:50	157	208		
SED (1 df)	-	20.210ns	12.50ns		
P-value	-	0.723	ns 0.251		***ns

*Values with the same letter in each parameter are not significantly different at P<0.05, *=P<0.05, **=P<0.01, ***=P< 0.001, and ns= not significant at (P<0.05); SED, standard error of difference of means; df, degrees of freedom.*

4.1.2. Number of wheat tillers

Cropping systems had a greater (P<0.001) effect on the number of wheat tillers at GS 21 (Table 4.1), and the sole cropping system (420) had a higher number of tillers than the bi-cropping system (212). The number of tillers was (P<0.001) affected by drilling patterns, and the highest number of tillers were achieved in the 3x3 (223) and broadcast (233) while the lowest was achieved with the 1x1 (199) and 2x2 (193) bi-cropping treatments.

4.1.3 Chlorophyll Concentration Index (CCI)

The CCI was (P<0.001) affected by cropping systems, and the bi-cropping system (19.10) increased CCI than the sole cropping system (6.70) by 184.6% revealing the advantage of bi-cropping systems than sole wheat cropping systems. (Table 4.2).

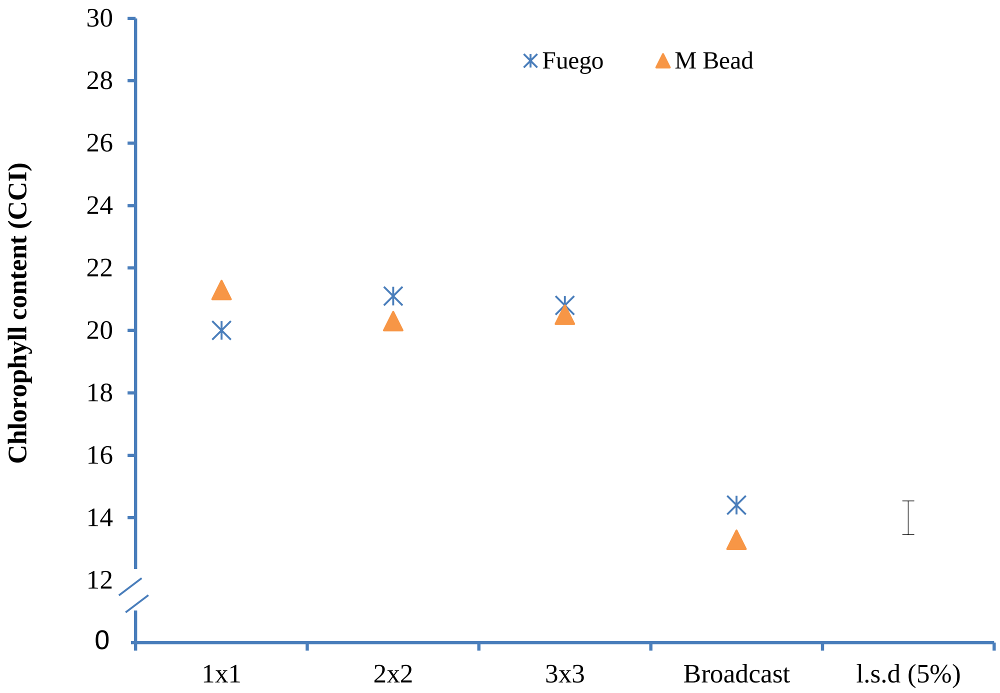
The drilling patterns had a greater (P<0.001) effect on CCI, and the alternate rows bi-cropping treatments (20.60) increased CCI than broadcast bi-cropping treatment (14.32) by 43.8% (Table 4.2: Figure 4.1).

Across the drilling patterns, the influence of the bean cultivars did not affect CCI.

Table 4.2: The effects of cropping systems, drilling patterns and bean cultivars on mean chlorophyll content (CCI) on the wheat leaf in 2015 cropping season

Treatments	Mix-proportion	Chlorophyll content (CCI)
Drilling patterns		
1x1	50:50	20.63[a]
2x2	50:50	20.70[a]
3x3	50:50	20.62[a]
Broadcast	50:50	14.32[b]
SED (3 df)	-	0.467***
P-value	-	<0.001
Cropping systems		
Bi-crop mean	50:50	19.10[a]
Sole crop	100	6.70[b]
SED (1 df)	-	0.405***
P-value	-	<0.001
Bean cultivars		
Fuego	50:50	19.09
Maris Bead	50:50	19.10
SED (1 df)	-	0.427ns
P-value	-	0.886

*Values with the same letter 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; df, degrees of freedom; CCI, chlorophyll concentration index.*



Error bars representing average LSD (*P≤0.05*)

Figure 4.1: The effects of drilling patterns x bean cultivars interactions on mean chlorophyll content in wheat leaf in 2015 cropping season

4.1.4. Leaf Area Index (LAI)

Cropping systems had a greater (P<0.001) effect on LAI, and bi-cropping systems (1.89) increased LAI than sole cropping systems (1.74) by 8.3%. The bean sole cropping system (2.11) increased LAI than the sole wheat cropping system (1.38) by 52.8%. (Table 4.3).

The LAI was (P<0.001) affected by drilling patterns (Table 4.3), and the alternate rows bi-cropping treatments (1.99) increased LAI than broadcast bi-cropping treatments (1.63) by 22.0%. The 2x2 alternate row bi-cropping treatments (2.03) had the highest LAI over other drilling patterns (1.85).

Across the drilling patterns, the bean cultivars had a greater (P<0.001) effect on LAI, and Fuego (1.92) increased LAI than Maris Bead (1.83) by 4.9% (Table 4.3a).

Table 4.3: The effects of cropping system, drilling patterns and bean cultivars on mean leaf area index (LAI) in 2015 cropping season

Treatments	Mix-proportions	LAI
Drilling patterns		
1x1	50:50	1.95[b]
2x2	50:50	2.03[a]
3x3	50:50	1.97[b]
Broadcast	50:50	1.63[c]
SED (3 df)	-	0.047***
P-value	-	<0.001
Cropping systems		
Bi-crop mean	50:50	1.89[b]
Sole crop (wheat)	100	1.38[c]
Sole crop (beans)	100	2.11[a]
SED (1 df)	-	0.035***
P-value	-	<0.001
Bean cultivars		
Fuego	50:50	1.92[a]
Maris Bead	50:50	1.83[b]
SED (1 df)	-	0.058***
P-value	-	<0.001

*Values with the same letter are not significantly different at P< 0.05; *=P<0.05; **=P<0.01; ***=P<0.001; SED, standard error of difference of means; df, degrees of freedom; LAI, Leaf area Index.*

4.1.5.1 Intercepted Photosynthetic Active Radiation (IPAR)

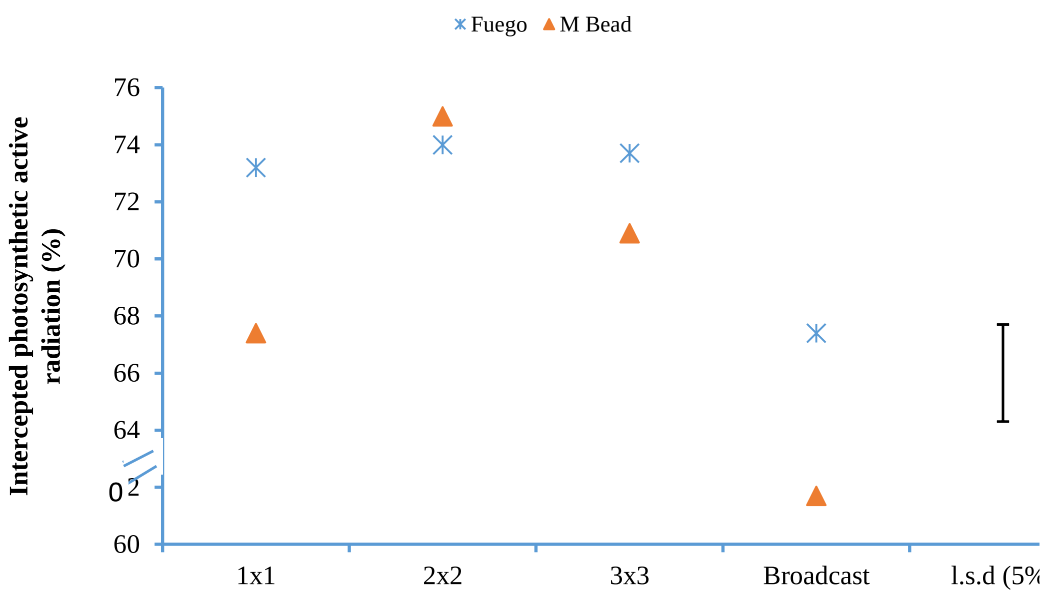
The IPAR was (P<0.001) affected by cropping systems (Table 4.4). It was difficult to determine how much of the IPAR was used by each of the component bi-crops. As such, IPAR was determined from both crops which formed the bi-cropping system. Bi-cropping systems had higher IPAR (70.42%) than sole cropping systems (wheat and beans). The sole bean cropping system (68.0%) outperformed the sole wheat cropping system (58.90%) on IPAR by 15.5% (Table 4.4 and Figure 4.2a).

The IPAR was (P<0.001) affected by the drilling patterns (Table 4.4). The alternate rows (71.5%) had the highest IPAR than broadcast bi-cropping treatments (64.6%). Among the drilling patterns, the highest and lowest IPAR resulted from the 2x2 (74.51%) and the broadcast (64.6%) bi-cropping treatments respectively. The trend of drilling patterns performance on IPAR was 2x2>3x3>1x1>broadcast>sole wheat (Table 4.4). The IPAR was (P<0.05) affected by the bean cultivars, and Fuego had higher IPAR (72.10%) than Maris Bead (68.70%) by 4.9%.

Table 4.4: The effects of cropping systems, drilling patterns and bean cultivars on mean per cent IPAR in 2015 cropping season

Treatments	Mix-proportion	IPAR (%)
Drilling patterns		
1x1	50:50	70.30[c]
2x2	50:50	74.51[a]
3x3	50:50	72.30[b]
Broadcast	50:50	64.60[d]
SED (3 df)	-	0.956***
P-value	-	<0.001
Cropping systems		
Bi-crop mean	50:50	70.42[a]
Sole crop (wheat)	100	58.90 [c]
Sole crop (bean)	100	68.00[b]
SED (1 df)	-	0.861***
P-value	-	<0.001
Bean cultivars		
Fuego	50:50	72.10[a]
Maris Bead	50:50	68.70[b]
SED (1 df)	-	1.170***
P-value	-	<0.001

*Values with the same letter are not significantly different at P<0.05; *=P<0.05; **=P<0.01; ***=P<0.001; SED, standard error of the difference; df, degrees of freedom; IPAR, Intercepted Photosynthetic Active Radiation.*



Error bars representing average LSD (*P≤0.05*)

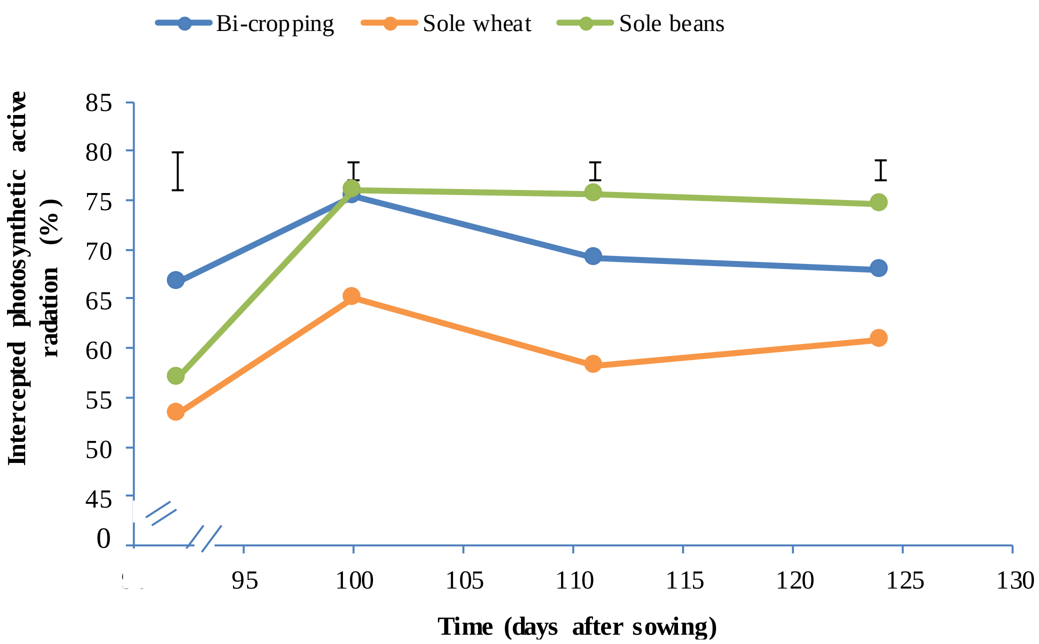
Figure 4.2a: Mean per cent intercepted photosynthetic active radiation influenced by the bean cultivars bi-crops x drilling patterns in 2015 cropping season

4.1.5.2 The effects of time on IPAR

The time of IPAR measurements had a greater (P<0.001) effect on the IPAR across cropping systems (Figure 4.2b). The maximum IPAR (74.6%) occurred at 100 days after sowing (DAS) with steady reduction of 69.3% at 111 DAS and 68.5% at 124 DAS.

The bi-cropping system had the higher IPAR of 75.4% between 92-100 DAS before the IPAR ability reduced by 8.2% and 10.9% at 111 and 124 DAS respectively. During the same period (92-100 DAS) the sole wheat cropping system lost 22% IPAR to soil. Across the growing season, 17% of the total incident solar radiation was lost under the sole wheat cropping system which predicted subsequent low biomass production.

The sole bean cropping system increased IPAR than bi-cropping and sole wheat cropping systems after 100 DAS due to differences in growth development stages between bean and wheat crops. During early growth stages (92 DAS), the sole bean cropping system had lower IPAR (57.1%) which was 16.8% lower than the bi-cropping systems (66.7%). The sole bean cropping system (75.9%) and the bi-cropping system (75.4%) had equal IPAR interception at 100 DAS (Figure 4.2b).



Error bars representing average LSD (*P≤0.05*)

Figure 4.2b: The effects of time (DAS) on IPAR (%) for different cropping systems in spring 2015.

4.1.5.3 Total radiation use efficiency (RUE)

The total RUE was (P<0.01) affected by cropping systems (Table 4.5). The bi-cropping system (0.721 g MJ^{-1} m^{-2}) increased total RUE than sole cropping system (0.423 g MJ^{-1} m^{-2}). The bi-cropping system was 70.4% more efficient than the sole cropping on the conversion of each unit of light intercepted into dry matter production.

Table 4.5: The effects of cropping systems, drilling patterns and bean cultivars on total radiation use efficiency (g MJ^{-1} m^{-2}) in 2015 cropping season

Treatments	Mix-proportion	Total radiation use efficiency (g MJ^{-1} m^{-2})
Drilling patterns		
1x1	50:50	0.758
2x2	50:50	0.700
3x3	50:50	0.729
Broadcast	50:50	0.698
SED (3 df)	-	0.083ns
P-value	-	0.790
Cropping systems		
Bi-crop mean	50:50	0.721^{a}
Sole crop	100	0.423^{b}
SED (1 df)	-	0.071***
P-value	-	<0.001
Bean cultivars		
Fuego	50:50	0.742
Maris Bead	50:50	0.700
SED (1 df)	-	0.075ns
P-value	-	0.609

*Values with the same letter 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; df, degrees of freedom; RUE, radiation use efficiency.*

4.1.6 Dry matter accumulation

The wheat dry matter accumulation was (P<0.001) affected cropping systems only at 42 DAS and 92 DAS, and the sole wheat cropping system had higher wheat dry matter accumulation than the bi-cropping system (Table 4.6).

The wheat dry matter accumulation was (P<0.01) was affected by the drilling patterns x bean cultivars interactions (Figure 4.3).

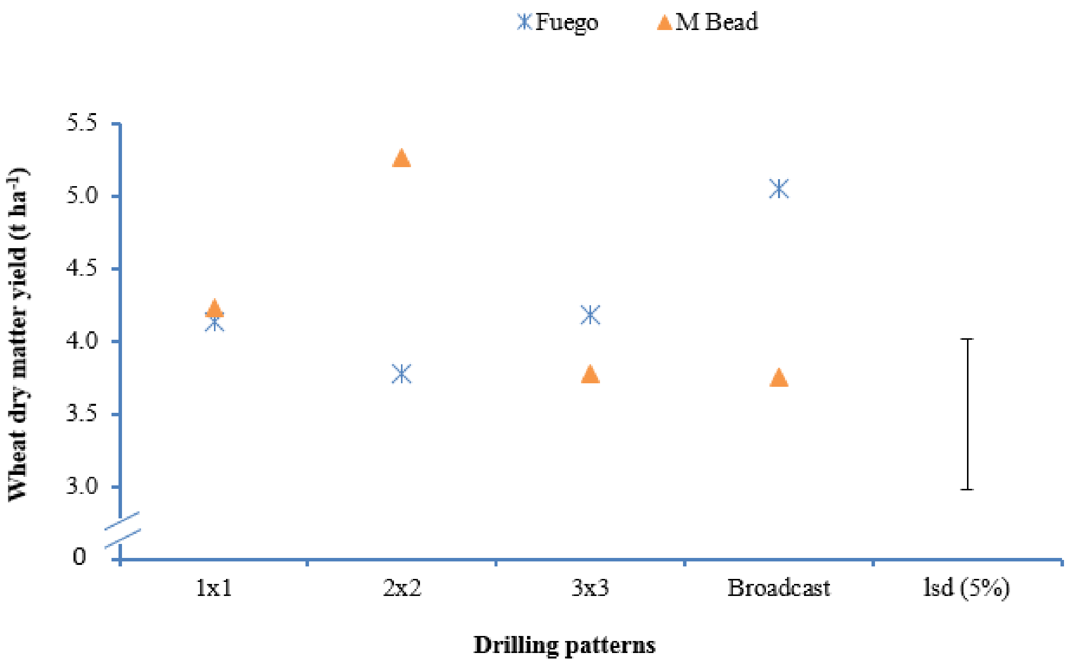
4.1.7 The effects of time (DAS) on wheat dry matter accumulation across the cropping season

There was (P<0.001) effect of time (DAS) on wheat dry matter accumulation (Figure 4.4). The sole wheat cropping system yielded higher dry matter than the bi-cropping system across the season. Both cropping systems gave the highest wheat dry matter between 40 and 60 DAS with significant reduction between 60 and 92 DAS. The wheat dry matter accumulation was not affected between 92 and final harvest (141DAS).

Table 4.6: The effects of cropping systems, drilling patterns and bean cultivars on wheat dry matter yield (t ha^{-1}) at different times of the 2015 cropping season

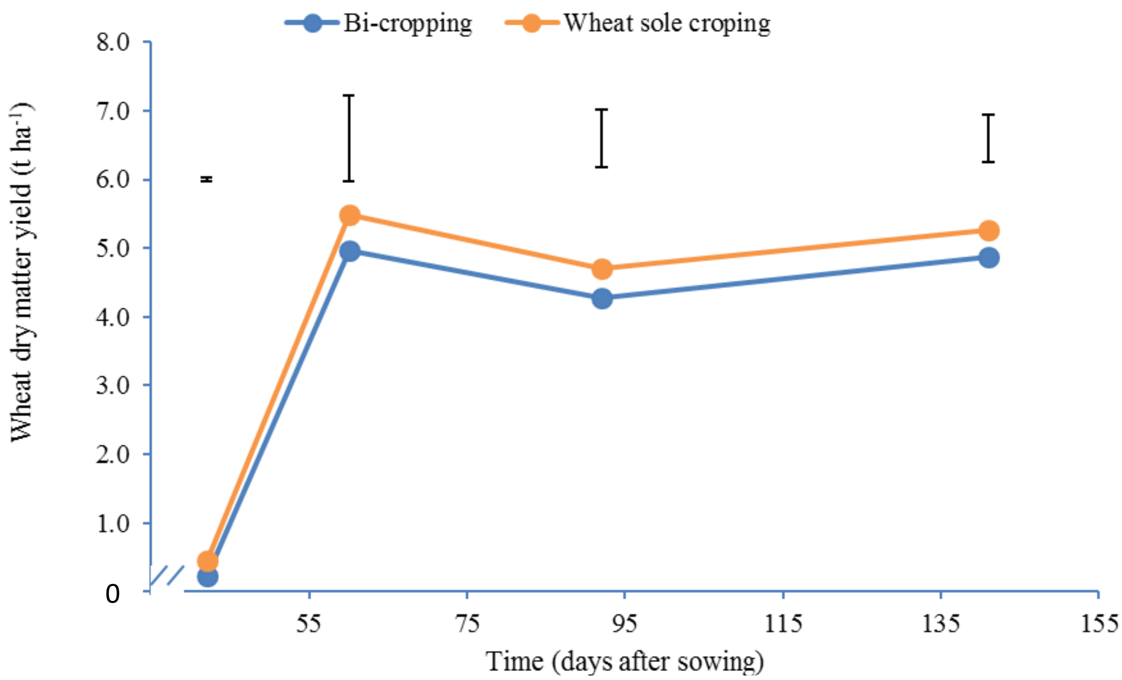
Treatments	Mix-proportion	Wheat dry matter (t ha^{-1}) DAS			
		42	60	92	141
Drilling patterns					
1x1	50:50	0.216	5.08	4.18	5.33
2x2	50:50	0.218	4.42	4.57	4.84
3x3	50:50	0.251	4.48	3.98	4.42
Broadcast	50:50	0.251	5.89	4.40	4.89
SED (3 df)	-	0.043ns	0.727ns	0.388ns	0.392ns
P-value	-	0.623	0.427	0.601	0.263
Cropping systems					
Bi-crop mean	50:50	0.234	4.97	4.28	4.87
Sole crop	100	0.458	5.48	4.71	5.26
SED (1 df)	-	0.037***	0.629ns	0.414***	0.340ns
P-value	-	<0.001	0.071	<0.001	0.068
Bean cultivars					
Fuego	50:50	0.227	5.06	4.31	4.93
Maris Bead	50:50	0.242	4.88	4.25	4.81
SED (1 df)	-	0.039ns	0.663ns	0.409ns	0.358ns
P-value	-	0.558	0.687	0.867	0.576

*Values with the same letter are not significantly different at P<0.05; *=P<0.05; **=P<0.01; ***=P<0.00; ns= not significant at (P<0.05); SED, standard error of difference of means; df, degrees of freedom; DAS, days after sowing.*



Error bars representing average LSD ($P \leq 0.05$)

Figure 4.3: The interaction effects of drilling patterns x bean cultivars on wheat dry matter yield (t ha^{-1}) in 2015 cropping season



Error bars representing average LSD ($P \leq 0.05$)

Figure 4.4: The effects of time (DAS) on wheat dry matter yield (t ha^{-1}) on two different cropping systems in spring 2015

4.2 Bean

4.2.1 Plant establishment

Cropping systems had a greater (P<0.001) effect the number of bean plants established per metre square at GS103 (Table 4.7). The sole cropping system (27.88 plants m^{-2}) had a higher number of bean plants established than the bi-cropping systems (15.48 plants m^{-2}).

The number of bean plants established was (P<0.001) affected by drilling patterns. The alternate rows bi-cropping treatments had the highest (15.75 plants m^{-2}) number of bean plants established than broadcast bi-cropping treatment (13.31 plants m^{-2}). Among the alternate rows, the 3x3 alternate row bi-cropping treatments had significantly higher number of bean plants established per square metre compared to 1x1 and 2x2 alternate row bi-cropping treatments.

The bean cultivars had a greater (P<0.001) effect on the number of bean plants established. Maris Bead (17.00 plants m^{-2}) outperformed Fuego (13.28 plants m^{-2}) on the number of established bean plants.

Table 4.7: The Effects of cropping systems, drilling patterns and spring bean cultivars on spring bean establishment (plants m^{-2}) in 2015 cropping season

Treatments	Mix-proportion	Bean plant establishment (plants m^{-2})
Drilling patterns		
1x1	50:50	13.56[b]
2x2	50:50	14.50[b]
3x3	50:50	19.19[a]
Broadcast	50:50	13.31[b]
SED (3 df)	-	1.184***
P-value	-	<0.001
Cropping systems		
Bi-crop mean	50:50	15.48[b]
Sole crop	100	27.88[a]
SED (1 df)	-	0.936***
P-value	-	<0.001
Bean cultivars		
Fuego	50:50	13.28[b]
Maris Bead	50:50	17.00[a]
SED (1 df)	-	1.324***
P-value	-	<0.001

*Values with the same letter under each 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 difference of means; df, degrees of freedom.*

4.2.2 Bean dry matter yield

The bean dry matter yield was (P<0.001) affected by time of sampling across the cropping season (Table 4.8; Figure 4.5). The bean dry matter yield increased with time except at 92 DAS possibly in part due to prolonged dry weather conditions 15th June, 2015 and 27th June, 2015. The cropping systems had a greater (P<0.001) effect on bean dry matter yield. The sole cropping system consistently outperformed the bi-cropping system across the season (Table 4.8; Figure 4.5). The drilling patterns had a greater (P<0.001) effect on bean dry matter yield (Table 4.8). The alternate row bi-cropping treatments had higher bean dry matter yield than broadcast bi-cropping treatments. The 2x2 alternate row bi-cropping treatment gave the highest bean dry matter yield at 60 and 92 DAS. The bean dry matter yield was (P<0.01) affected by the bean cultivars at 42 and 92 DAS. Fuego out yielded Maris Bead on bean dry matter yield.

Table 4.8: The effects of cropping systems, drilling patterns and bean cultivars on spring bean dry matter yield (t ha^{-1}) at different times of the 2015 cropping season

		Bean dry matter (t ha^{-1})			
Treatments	Mix-proportion	DAS			
		42	60	92	144
Drilling patterns					
1x1	50:50	0.056^b	2.04^b	1.28^b	1.93^a
2x2	50:50	0.069^a	2.68^a	1.55^a	1.83^a
3x3	50:50	0.063^a	2.09^b	1.16^c	1.71^a
Broadcast	50:50	0.023^c	0.71^c	0.82^d	1.03^b
SED (3 df)	-	0.006***	0.360***	0.221***	0.196***
P-value	-	<0.001	<0.001	<0.001	<0.001
Cropping systems					
Bi-crop mean	50:50	0.053^b	1.88^b	1.20^b	1.62^b
Sole crop	100	0.098^a	3.72^a	2.70^a	4.56^a
SED (1 df)	-	0.004***	0.284***	0.174***	0.154***
P-value	-	<0.001	<0.001	<0.001	<0.001
Bean cultivars					
Fuego	50:50	0.062a	1.87	1.31^a	1.68
Maris Bead	50:50	0.044^b	1.89	1.09^b	1.57
SED (1 df)	-	0.007***	0.402ns	0.247*	0.219ns
P-value	-	<0.001	0.583	0.142	0.966

*Values with the same letter under each 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 difference of means; df, degrees of freedom; DAS, days after sowing.*

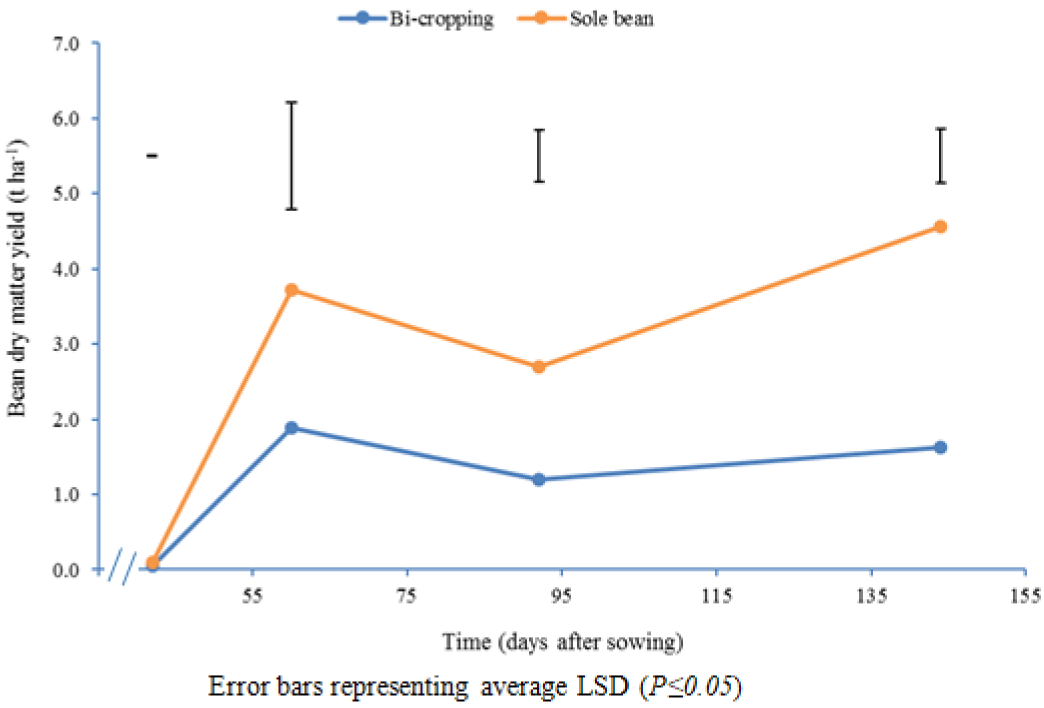


Figure 4.5: Mean bean dry matter yield (t ha^{-1}) as influenced by time (DAS) during 2015 spring cropping season

4.3 Weed biomass

4.3.1 Effects of cropping systems, drilling patterns and bean cultivars on transformed mean weed dry weight (g m^{-2}) and weed nitrogen uptake (kgN ha^{-1}) at 56 DAS in 2015 seasons

The results on weed dry weight are presented in Table 4.9a. Cropping systems had a greater ($P<0.001$) effect on transformed weed dry matter at 56 DAS. Bi-cropping systems (1.90 g m^{-2}) had lower weed dry weight than sole cropping systems (3.12 g m^{-2}). Bi-cropping systems had a greater weed suppression potential of 64.2% over sole cropping systems. During the early vegetative growth stage (56 DAS) the drilling patterns and the bean cultivars had no effect on transformed weed dry weight (Table 4.9a & 4.9b). The weed flora identified at the site at 56 DAS are summarised in Table 4.9c. Transformed weed nitrogen uptake was ($P<0.05$) effected by cropping systems (Table 4.9a). Sole cropping systems (1.47 kgN ha^{-1}) had higher transformed weed nitrogen uptake than bi-cropping systems (1.24 kgN ha^{-1}) by 18.5%. The sole wheat cropping system had lower (0.89 kgN ha^{-1}) transformed weed nitrogen uptake than sole bean cropping (2.08 kgN ha^{-1}).

Table 4.9a: The effects of drilling patterns and bean cultivars on transformed weed dry weight (g m^{-2}) and weed nitrogen uptake (kgN ha^{-1}) at 65 DAS in 2015 spring seasons.

Treatments	Mix-proportion	Weed dry weight (g m^{-2})	Weed shoot N uptake (kgN ha^{-1})
Drilling patterns			
1x1	50:50	1.55[2.54]	1.02 [1.09]
2x2	50:50	2.20[5.22]	1.44 [2.22]
3x3	50:50	1.96[3.96]	1.28 [1.71]
Broadcast	50:50	1.89[4.48]	1.23 [1.89]
SED (3 df)	-	0.328ns	0.214ns
P-value	-	0.609	0.620
Cropping systems			
Bi-crop mean	50:50	1.90^{c}[4.05]	1.24^{c}[1.87]
Sole crop (wheat)	100	2.55^{b}[8.00]	0.86^{b}[0.78]
Sole crop (beans)	100	3.12^{a}[11.10]	2.08^{a}[4.78]
SED (1 df)	-	0.243**	0.158*
P-value	-	0.007	0.007
Bean cultivars			
Fuego	50:50	1.83[3.83]	1.20[1.63]
Maris Bead	50:50	1.97[4.27]	1.29[1.83]
SED (1 df)	-	0.402ns	0.262ns
P-value	-	0.310	0.332

*Values with the same letter under each parameter are not significantly different at P< 0.05; *=P<0.05; **=P< 0.0; ***=P<0.001; ns = not significant at P<0.05; SED, standard error of the difference of means; Data was subjected to square root √(x+0.5) transformation and figures in parenthesis are the means of original values; df, degrees of freedom*

Table 4.9b: The effects of drilling patterns and bean cultivars on weed smothering efficiency (%) at 65 DAS in 2015 spring seasons

Treatments	Mix-proportion	Weed smothering efficiency (%)
Drilling patterns		
1x1	50:50	76.60
2x2	50:50	68.2
3x3	50:50	61.90
Broadcast	50:50	77.00
Bi-crop mean	50:50	70.90
SED (3 df)	-	8.120ns
P-value	-	0.218
Bean cultivars		
Fuego	50:50	73.90[a]
Maris Bead	50:50	68.00[b]
SED (1 df)	-	5.740*
P-value	-	0.042

*Values with the same letter under each 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; df, degrees of freedom; DAS, days after sowing.*

Table 4.9c: Botanical classification of weed species identified at the study site at 56 DAS in 2015 cropping season

Common name	Category	Scientific name	Family	Genus
Bindweed	Broad leaf	*Convolvulus arvensis* (L.)	Convolvulaceae	*Convolvulus*
Black Mustard	Broad leaf	*Brassica nigra* (L.)	Brassicaceae	*Brassica*
Common orache	Broad leaf	*Atriplex patula* (L.)	Aamaranthaceae	*Atriplex*
Prickly sow thistle	Broad leaf	*Sonchus asper (*L.) Hill	Asteraceae	*Sonchus*
Cow parsley	Broad leaf	*Anthriscus sylvestris* (L.) Hoffm	Apiaceae	*Anthriscus*
Creeping thistle	Broad leaf	*Cirsium arvense* (L.) Scop.	Asterraceae	*Cirsium*
Fool's Parsley	Broad leaf	*Aethusa cynapium* (L.)	Apiaceae	*Aethusa*
Rape seed	Broad leaf	*Brassica napus* (L.)	Brassicaceae	*Brassica*

4.3.2 The Effects of cropping systems, drilling patterns and bean cultivars on transformed mean weed dry weights (g m^{-2}) and weed nitrogen uptake (kgN ha^{-1}) at 87 DAS in 2015 seasons

Cropping systems had a greater (P<0.001) effect on the transformed weed dry matter and nitrogen accumulation at 87 DAS (Table 4.10a). Bi-cropping systems (2.88 g m^{-2}) had lower transformed weed dry weight than sole cropping systems (5.54 g m^{-2}) by 69.7%. The sole wheat cropping system (4.24 g m^{-2}) had significantly lower transformed weed dry weight compared to the sole bean cropping system (5.54 g m^{-2}). The drilling patterns had a greater (P<0.001) effect on the transformed weed dry matter weight (Table 4.10a). The alternate row bi-cropping treatments (2.57 g m^{-2}) had lower weed dry matter than broadcast bi-cropping treatments (3.84 m^{-2}) by 49.2%. Similarly the alternate row bi-cropping treatments (74.3%) had a higher WSE than broadcast bi-cropping treatments (42.8%) (Table 4.10 b). The bean cultivars had no effect on transformed weed dry weights.

The weed N uptake was (P<0.001) affected by cropping systems and drilling patterns (Table 4.10a). The sole cropping system had higher weed N uptake than the bi-cropping system by 69.3%. The sole bean cropping system had 26.2% higher transformed weed nitrogen uptake than the sole wheat cropping system. The alternate row treatments (1.29 kgN ha^{-1}) had (P<0.001) lower transformed weed N uptake than broadcast bi-cropping treatments (1.92 kgN ha^{-1}) by 48.0%. The 2x2 alternate row treatments had the lowest transformed weed N uptake compared to other drilling patterns. The lower transformed weed N accumulation values meant better weed suppression than higher values. The weed flora identified at the experimental site were summarised in Table 4.10c.

Table 4.10a: The effects of drilling patterns and bean cultivars on transformed weed dry weight (g m^{-2}) and weed nitrogen uptake (kgN ha^{-1}) at 87 DAS in 2015 spring seasons

Treatments	Mix-proportion	Weed dry weight (g m^{-2})	Weed shoot N uptake (kgN ha^{-1})
Drilling patterns			
1x1	50:50	2.59^{b}[6.91]	1.26^{c}[1.65]
2x2	50:50	2.35^{b}[5.61]	1.17^{d}[1.39]
3x3	50:50	2.78^{b}[7.88]	1.45^{b}[2.18]
Broadcast	50:50	3.84^{a}[15.13]	1.92^{a}[3.80]
SED (3 df)	-	0.2486***	0.143***
P-value	-	0.002	<0.001
Cropping systems			
Bi-crop mean	50:50	2.88^{c}[8.88]	1.45^{c}[2.18]
Sole crop (wheat)	100	4.24^{b}[18.42]	2.17^{b}[4.76]
Sole crop (beans)	100	5.54^{a}[30.88]	2.74^{a}[7.63]
SED (1 df)		0.184***	0.106***
P-value		<0.001	<0.001
Bean cultivars			
Fuego	50:50	2.99[9.58]	1.49[2.39]
Maris Bead	50:50	2.78[8.18]	1.41[2.13]
SED (1 df)	-	0.3044ns	0.175ns
P-value	-	0.089	0.819

*Values with the same letter under each 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; [ ] Data was subjected to square root √(x+0.5) transformation and figures in parenthesis are the means of original values; df, degrees of freedom.*

Table 4.10b: The effects of drilling patterns and bean cultivars on weed smothering efficiency (%) at 87 DAS in 2015 spring seasons

Treatments	Mix-proportion	Weed smothering efficiency (%)
Drilling patterns		
1x1	50:50	73.90[a]
2x2	50:50	79.10[a]
3x3	50:50	70.00[b]
Broadcast	50:50	42.80[c]
Bi-crop mean	50:50	66.50
SED (3 df)	-	6.740***
P-value	-	<0.001
Bean cultivars		
Fuego	50:50	64.10
Maris Bead	50:50	68.80
SED (1 df)	-	4.770ns
P-value	-	0.340

*Values with the same letter under each 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; df, degrees of freedom.*

Table 4.10c: Botanical classification of weed species identified at the study site during 2015 spring cropping season at 87 DAS

Common name	Category	Scientific name	Family	Genus
Bind weed	Broad leaf	*Convolvulus arvensis* (L.)	Convolvulaceae	*Convolvulus*
Common orache	Broad leaf	*Atriplex patula* (L.)	Aamaranthaceae	*Atriplex*
Nipple worth	Broad leaf	*Lapsana communis* (L.)	Asteraceae	*Lapsana*
Prickly sow thistle	Broad leaf	*Sonchus asper (*L.) Hill	Asteraceae	*Sonchus*
Creeping thistle	Broad leaf	*Cirsium arvense* (L.) Scop.	Asterraceae	*Cirsium*
Fool's Parsley	Broad leaf	*Aethusa cynapium* (L.)	Apiaceae	*Aethusa*
Rape seed	Broad leaf	*Brassica napus* (L.)	Brassicaceae	*Brassica*

4.4 Plant heights (cm)

4.4.1 Wheat plant height

The wheat plant height was (P<0.001) affected by cropping systems (Table 4.11). The bi-cropping systems (72.65 cm) increased wheat plant heights than the sole cropping systems (56.15 cm) with a mean difference of 16.50 cm between cropping systems (Table 4.11).

The wheat plant height was (P<0.001) affected by drilling patterns (P<0.001) (Table 4.11). The effect of drilling patterns on wheat plant height in descending order was: 2x2 > 3x3 > 1x1 > broadcast> sole wheat. However, among the alternate rows, the 1x1 and 3x3 treatments had the shortest plant height and had significantly (P>0.05) similar plant heights. The bean cultivars did not affect wheat plant height.

Table 4.11: Mean wheat plant height (cm) as affected by cropping systems, drilling patterns and bean cultivars during 2015

Treatments	Mix-proportion	Wheat plant height (cm)
Drilling patterns		
1x1	50:50	73.89^{b}
2x2	50:50	75.53^{a}
3x3	50:50	74.36^{b}
Broadcast	50:50	66.91^{c}
SED (3 df)	-	0.841***
P-value	-	<0.001
Cropping systems		
Bi-crop mean	50:50	72.65^{a}
Sole crop	100	56.15^{b}
SED (1 df)	-	0.693***
P-value	-	<0.001
Bean cultivars		
Fuego	50:50	72.98
Maris Bead	50:50	72.37
SED (1 df)	-	0.746ns
P-value	-	0.611

*Values with the same letter under each 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; df, degrees of freedom.*

4.4.2 Bean plant heights

The bean plant heights was (P<0.001) affected by cropping systems (Table 4.12). The sole cropping system (77.81 cm) increased bean plant height than the bi-cropping system (75.52 cm) by 3.0%.

The bean plant height was (P<0.001) affected by the drilling patterns (Table 4.12). The tallest and shortest bean plant heights were recorded from the 2x2 alternate row bi-cropping treatments (77.40 cm) and broadcast bi-cropping treatments (73.30 cm) respectively. The 1x1 (76.08 cm) and the 3x3 (75.66 cm) treatments had the shortest bean plant heights than other alternate rows treatments. However, bean plant heights for the 2x2 alternate row bi-cropping treatment (77.40 cm) and sole bean cropping systems (77.81 cm) were similar an indication of interspecific complementarity.

Maris Bead (77.04 cm) had a taller (P<0.001) bean plant height than Fuego (74.93 cm) by 20.2% (Table 4.12).

Table 4.12: Mean bean plant height (cm) affected by cropping systems, drilling patterns and bean cultivars in 2015 cropping season

Treatments	Mix-proportion	Bean plant height (cm)
Drilling patterns		
1x1	50:50	76.08^{b}
2x2	50:50	77.40^{a}
3x3	50:50	75.66^{b}
Broadcast	50:50	73.30^{c}
SED (P<0.05)	-	0.648***
P-value	-	<0.001
Cropping systems		
Bi-crop mean	50:50	75.52^{b}
Sole crop	100	77.81^{a}
SED (P<0.05)	-	0.480*
P-value	-	0.024
Bean cultivars		
Fuego	50:50	74.93^{a}
Maris Bead	50:50	77.04^{b}
SED (P<0.05)	-	0.697***
P-value	-	<0.001

*Values with the same letter under each 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.*

4.5 Field pests and diseases

4.5.1 Black bean aphid (*Aphis fabae*)

The distribution of the Black bean aphid *(Aphis fabae)* on the bean plants at GS 207 was (P<0.001) affected cropping systems, drilling patterns and the bean cultivars (Table 4.13). The bi-cropping system (4.74%) reduced pest incidence than the sole cropping system (6.5%) by 37.1%.

The drilling patterns had a greater (P<0.001) effect on the incidence of the Black bean aphid *(Aphis fabae)* irrespective of the bean cultivars bi-crops. The lowest and highest incidence was recorded from broadcast (1.98%) and alternate row (5.67%) bi-cropping treatments respectively. Among the alternate rows, the highest and lowest incidence was recorded from the 1x1 (4.74%), and 3x3 (6.45%) respectively. The 2x2 (5.82%) had the moderate incidence.

The bean cultivars (P<0.05) affected the Black bean aphid incidence irrespective of the cropping system and drilling patterns (Table 4.13), and Fuego (5.86%) had the highest incidence than Maris Bead (4.33%).

Table 4.13: The effects of drilling patterns and bean cultivars on transformed black bean aphid (*Aphis fabae*) incidence (%) during bean flowering stage (GS 207) at 55 days after sowing in 2015 cropping season

Treatments	Mix-proportions	Black bean aphid incidence (%)
Drilling patterns		
1x1	50:50	4.74[c] [27.60]
2x2	50:50	5.82[b] [37.10]
3x3	50:50	6.45[a] [42.60]
Broadcast	50:50	1.98[d] [7.90]
SED (3 df)	-	0.097*
P-value	-	0.011
Cropping systems		
Bi-crop mean	50:50	4.74[b] [28.80]
Sole crop	100	6.50[a] [45.50]
SED (1 df)	-	0.019***
P-value	-	<0.001
Bean cultivars		
Fuego	50:50	5.86a [36.60]
M Bead	50:50	4.33b [21.10]
SED (1 df)	-	0.015**
P-value	-	0.003

*Values with the same letter under each 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; df, degrees of freedom. Data was subjected to square root √(x+0.5) transformation and figures in parenthesis are the means of original values.*

4.5.2 Ascochyta blight *(Ascochyta fabae)* disease incidence

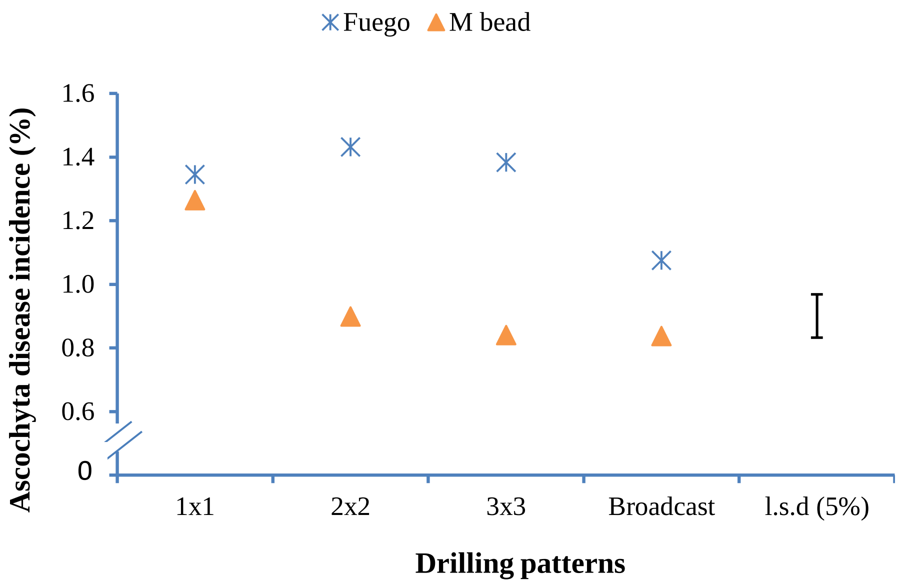
Cropping systems had no effect (P>0.05) on transformed Ascochyta blight disease incidence (Table 4.14). The drilling patterns had a greater (P<0.001) effect on transformed Ascochyta blight disease incidence on the bean plants in both sole and bi-cropping systems (Table 4.14). The highest and lowest transformed disease incidence of 1.31% and 0.96% was recorded from the 1x1 alternate row and broadcast bi-cropping treatments respectively. The 2x2 (1.11%) and the 3x3 (1.17%) alternate row bi-cropping treatments had statistically similar reaction to the disease.

Ascochyta blight disease incidence was (P<0.001) affected by the bean cultivars. Fuego (1.31%) had higher transformed disease incidence than Maris Bead (0.91%) (Figure 4.6). By increasing the number of rows to crop ratio increased the disease incidence for Fuego while at the same time reduced the disease incidence for Maris Bead (Figure 4.6).

Table 4.14: The effects of cropping systems, drilling patterns and bean cultivars on transformed mean Ascochyta blight disease incidence (%) at 125 days after sowing in 2015 cropping season

Treatments	Mix-proportions	Ascochyta blight disease incidence (%)
Drilling patterns		
1x1	50:50	1.31[a] [27.5]
2x2	50:50	1.17[b] [19.7]
3x3	50:50	1.11[b] [18.3]
Broadcast	50:50	0.96[c] [10.3]
SED (3 df)	-	0.097**
P-value	-	0.005
Cropping systems		
Bi-crop mean	50:50	1.14 [19.0]
Sole crop	100	1.07 [18.6]
SED (1 df)	-	0.076ns
P-value	-	0.914
Bean cultivars		
Fuego	50:50	1.31[a] [25.3]
M Bead	50:50	0.91[b] [12.7]
SED (1 df)	-	0.108***
P-value	-	<0.001

*Values with the same letter under each 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; df, degrees of freedom. [ ] Data was subjected to square root √(x+0.5) transformation and figures in parenthesis are the means of original values*



Error bars representing average LSD (*P≤0.05*)

Figure 4.6: The interaction effects of drilling patterns and bean cultivars on mean Ascochyta blight disease incidence (%) at 125 days after sowing in 2015 cropping season.

4.6 Grain yield and components

4.6.1 Wheat

4.6.1.1 Total grain yield

Cropping systems, drilling patterns, bean cultivars and their interactions had no effect on total wheat grain yield. The overall wheat grain yield of 2.35 t ha^{-1} was obtained. Similarly, main experimental factors did not affect the total ear weight, 1000 seed weight, and total biomass except on wheat straw yield (Table 4.15).

4.6.1.2 Wheat straw yield

Wheat straw yield was (P<0.05) was affected by cropping systems (Table 4.15), and the sole cropping system (2.9 t ha^{-1}) had higher straw yield than the bi-cropping system (2.5 t ha^{-1}) by 16%. The influence of drilling patterns and bean cultivars had no effect on wheat straw yield.

4.6.1.3 Wheat harvest index (HI)

The wheat HI was ($P<0.01$) affected by cropping systems (Table 4.15). The bi-cropping system (43%) outperformed the sole cropping system (38%) by 13.1% higher. The drilling patterns, bean cultivars and their interaction had no effect on HI.

Table 4.15: The effects of cropping systems, drilling patterns and bean cultivars on mean wheat yield and components during 2015 cropping season

Treatments	Mix-proportion	Wheat yield components					
		Total wheat ear weight (t ha-^{1})	Total wheat straw yield (t ha-^{1})	Total wheat grain yield (t ha-^{1})	1000 seed weight (g)	Total wheat biomass yield (t ha-^{1})	Wheat harvest index (%)
Drilling patterns							
1x1	50:50	3.0	2.6	2.4	40.4	5.6	43
2x2	50:50	3.1	2.5	2.4	41.5	5.6	43
3x3	50:50	2.8	2.3	2.2	42.6	5.1	43
Broadcast	50:50	2.8	2.6	2.2	41.7	5.4	41
SED (3 df)	-	0.197ns	0.210ns	0.167ns	1.455ns	0.332ns	2.2ns
P-value	-	0.230	0.100	0.138	0.483	0.422	0.841
Cropping systems							
Bi-crop mean	50:50	2.9	2.5[b]	2.3	41.5	5.4	43[a]
Sole crop	100	2.7	2.9[a]	2.1	40.3	5.6	38[b]
SED (1 df)	-	0.171ns	0.182*	0.144ns	1.675ns	0.287ns	1.9**
P-value	-	0.306	0.022	0.203	0.377	0.382	0.008
Bean cultivars							
Fuego	50:50	2.9	2.5	2.3	42.4	5.4	0.43
Maris Bead	50:50	2.9	2.4	2.3	40.7	5.3	0.43
SED (1 df)	-	0.179ns	0.192ns	0.152ns	1.529ns	0.303ns	2.0ns
P-value	-	0.880	0.262	0.713	0.084	0.111	0.244

*Values with the same letter under each 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; df, degrees of freedom. The total biomass was calculated as the sum of total ear weight and total straw yield (t ha^{-1}).*

4.6.2 Bean

4.6.2.1 Bean seed yield

The bean seed yield was ($P<0.001$) affected by cropping systems (Table 4.16). The sole cropping system (2.7 t ha^{-1}) increased bean seed yield than the bi-cropping system (0.814 t ha^{-1}). The bean seed yield was ($P<0.001$) affected by the drilling patterns. The alternate rows bi-cropping treatments (0.937 t ha^{-1}) outperformed broadcast bi-cropping treatments (0.447 t ha^{-1}) by 52.2%. The 2x 2 alternate rows bi-cropping treatments had significantly the highest bean yield compared to other drilling patterns.

4.6.2.2 The 100 bean seed weight

There was ($P<0.001$) effect of cropping systems on 100 bean seed weight (Table 4.16). The sole cropping system had higher (56.9 g) bean seed weight than the bi-cropping system (48.6 g). The drilling patterns did not affect ($P>0.05$) the 100 bean seed weight. The bean cultivars ($P<0.001$) had an effect on the 100 bean seed weight, and Maris Bead (67.1 g) had higher 100 bean seed weight than Fuego (45.5 g) by 47.4%.

4.6.2.3 Bean straw yield

The bean straw yield was ($P<0.001$) affected by cropping systems. The sole cropping system had higher straw yield of 1.3 t ha^{-1} while the bi-cropping system had a lower yield of 0.494 t ha^{-1}. The drilling patterns and bean cultivars as independent factors did not affect the straw yield (Table 4.16).

4.6.2.4 Total Bean biomass yield

The total bean biomass yield was ($P<0.001$) affected by cropping systems (Table 4.16). The sole cropping system (4.8 t ha^{-1}) increased total bean yield than the bi-cropping systems (1.5 t ha^{-1}). The drilling patterns had a greater ($P<0.001$) effect on the total biomass yield, and the alternate row bi-cropping treatments (1.7 t ha^{-1}) had higher total bean biomass yield than broadcast bi-cropping treatment (0.9 t ha^{-1}).

Bean harvest index

The bean HI was ($P<0.001$) affected by the bean cultivars, and Fuego had higher HI over Maris Bead (Table 4.16).

Table 4.16: The effects of cropping systems, drilling patterns and bean cultivars on mean bean yield and components during 2015 cropping season

Treatments	Mix-proportion	Total bean Pod yield (t ha^{-1})	Total bean straw yield (t ha^{-1})	Total bean seed yield (t ha^{-1})	100 bean seed weight (g)	Total bean biomass yield (t ha^{-1})	Bean harvest index (%)
Drilling patterns							
1x1	50:50	1.3^{a}	0.491	0.970^{a}	59.1	1.8^{a}	53
2x2	50:50	1.2^{a}	0.587	0.977^{a}	54.5	1.8^{a}	52
3x3	50:50	1.1^{a}	0.522	0.863^{a}	59.3	1.6^{a}	51
Broadcast	50:50	0.6^{b}	0.377	0.447^{b}	54.5	0.9^{b}	50
SED (3 df)	-	0.165***	0.084ns	0.119***	3.490ns	0.218***	2.4ns
P-value	-	<0.001	0.102	<0.001	0.313	<0.001	0.586
Cropping systems							
Bi-crop mean	50:50	1.1^{a}	0.494^{b}	0.814^{b}	56.8^{a}	1.5^{a}	52
Sole crop	100	3.4^{b}	1.3^{a}	2.7^{a}	48.6^{b}	4.8^{b}	55
SED (1 df)	-	0.131***	0.067***	0.094***	2.760 **	0.172***	3.9ns
P-value	-	<0.001	<0.001	<0.001	0.004	<0.001	0.085
Bean cultivars							
Fuego	50:50	1.1	0.490	0.826	67.1^{a}	1.5	53
Maris Bead	50:50	1.0	0.498	0.802	46.5^{b}	1.5	50
SED (1 df)	-	0.185ns	0.094ns	0.133ns	3.900 ***	0.244ns	2.7***
P-value	-	0.678	0.051	0.892	<0.001	0.234	0.002

*Values with the same letter under each 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; df, degrees of freedom. Total bean biomass was calculated as the sum of total pod and straw yields.*

4.7 Biological efficiency of cropping systems

4.7.1 Partial land equivalent ratio (PLER) for wheat

The $PLER_w$ were not affected by the drilling patterns and bean cultivars (Table 4.17). However, the wheat PLER were above 0.5 indicated the advantage of bi-cropping systems than sole cropping systems. The PLER were compared against 0.5 because bi-crop species in mixture were sown at half density of the sole crop species (Bedoussac and Justes, 2010). The PLER value above 0.5 it indicates the advantage of the bi-cropping system over the sole cropping system and vice versa.

PLER for bean cultivars

The $PLER_b$ were ($P<0.05$) affected by the drilling patterns (Table 4.17). The $PLER_b$ values were less than 0.50 which indicated that the bean bi-crops were dominated by the wheat bi-crop on growth resource acquisition. The PLER value above 0.5 indicated that the bi-crops in mixture produced more than a sole crop and vice versa. The alternate row bi-cropping treatments (0.38) had higher $PLER_b$ than broadcast bi-cropping treatments (0.19). However, among the alternate rows, the $PLER_b$ decreased with increasing number of rows.

4.7.2 Land equivalent ratio (LER)

Across the bean cultivars, the drilling patterns had a greater ($P<0.01$) effected on LER (Table 4.17). The LER values for the bi-crops were above 1.0 which indicated the advantage of bi-cropping systems over sole cropping systems on environmental resources use efficiency. The alternate row bi-cropping treatments (1.58) had higher LER than broadcast bi-cropping treatment (1.29). Across the drilling patterns and the bean cultivars, the overall LER for bi-cropping treatments was 1.50. The highest (1.64) and lowest (1.4) LER was recorded from the 2x2 and the 3x3 alternate row bi-cropping treatments respectively. The LER decreased with increased number of rows among the alternate row treatments. The alternate rows bi-cropping treatments (33.6%) showed higher land saving advantage than broadcast bi-cropping treatment (22.5%) over sole cropping (Table 4.17). According to Adetiloye *et al.* (1983), 25% is the minimum productivity coefficient value to validate land saving advantage in bi-cropping systems. The 2x2 alternate row bi-cropping treatments (38.8%) had higher land saving advantages compared to other drilling pattern treatments (33.0%).

Table 4.17: Biological efficiency of bi-cropping on nitrogen use efficiency influenced cropping systems, drilling patterns and bean cultivars, in 2015 cropping season

		Partial Land Equivalent Ratio ($PLER_N$)		Total Land Equivalent Ratio (LER_N)	Land savings (%)
Treatments	Mix-proportion (%)	Wheat ($PLER_{wheat}$)	Bean ($PLER_{bean}$)	($PLER_{wheat}$+$PLER_{bean}$)	
Drilling patterns					
Sole crop	100	0.50	0.50	1.00	-
1x1	50:50	1.21	0.40 [a]	1.61[a]	37.8
2x2	50:50	1.25	0.39 [a]	1.64 [a]	38.8
3x3	50:50	1.14	0.36 [a]	1.49 [b]	33.1
Broadcast	50:50	1.10	0.19 [b]	1.29 [c]	22.5
SED (3 df)	-	0.055 [ns]	0.071**	0.085**	-
P-value	-	0.061	0.023	0.002	
Bean cultivars					
Fuego	50:50	1.19	0.34	1.11	-
Maris Bead	50:50	1.15	0.32	1.05	-
SED (1 df)	-	0.081[ns]	0.0498ns	0.0620ns	-
P-value	-	0.382	0.795	0.433	

*Values with the same letter under each 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;* $PLER_N$*, partial land equivalent ratio for nitrogen;* LER_N*, land equivalent ratio for nitrogen;* $PLER_{wheat}$ *and* $PLER_{beans}$ *partial land equivalent ratio for wheat and beans.*

4.8. Competition indices

4.8.1 Aggressivity (A)

The competitive ability of the component crops in bi-cropping system is determined by its aggressivity value. Results in Table 4.18 showed positive signs for the wheat bi-crops and a negative signs for the bean bi-crops which indicated that the wheat dominated the bean in bi-cropping systems. The alternate rows bi-cropping treatments had higher aggressivity value than broadcast bi-cropping treatment. Among the alternate rows bi-cropping treatments, the highest (0.759) and lowest (0.652) aggressivity values under the wheat/Fuego bi-cropping system was recorded from the 2x2 and the 3x3 treatments respectively. Similarly, the highest (818) and lowest (0.673) aggressivity values under the wheat/Maris Bead bi-cropping system was recorded from the 2x2 and the 3x3 alternate row bi-cropping treatments respectively. However, the low aggressivity values for the 1x1 and the 3x3 alternate row bi-cropping treatments were consistent with the wheat and bean plant heights results in Tables 4.11 and 4.12 which showed negative interactions between bi-crops. The lowest aggressivity values indicated a sign of negative interspecific interactions. Highest aggressivity values indicated better interspecific complementarity on resource use efficiency (McGilchrist, 1965; Bakar *et al.*, 2014; Choudhary 2014; Gosh *et al.*, 2006).

Table 4.18: Aggressivity (A) as influenced by drilling patterns and faba bean cultivars in a wheat/bean based bi-cropping systems in 2015 cropping season

	Aggressivity (A)				System Aggressivity (A)	
Treatments	Wheat	Fuego	Wheat	Maris Bead	Wheat	Legume
	(A_{w1})	(A_{FG})	(A_{w2})	(A_{MB})	($A_{w1+}A_{w2}$)/2	($A_{fg+}A_{mb}$)/2
Drilling patterns						
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

Broadcast: *Direct sowing of bean bi-crops, randomly over precisely drilled wheat row.* A_{FG} *and* A_{MB} *are Aggressivity indices for Fuego and Maris Bead bean cultivars in mixture with wheat* (A_w)

4.8.2 Relative Crowding Coefficient (RCC or K)

The Relative Crowding Coefficient measures the relative dominance of one bi-crop species over the other in bi-cropping system to determine inter and intraspecific competition between them (De Wit, 1960). The results in Table 4.19 showed that the partial *K* coefficient values of wheat were consistently higher than the partial *K* coefficient values for the beans. If the coefficient *K* derived from the product of bi-crop components species (wheat*beans) is greater than unitary value of 1.0, it shows that all bi-cropping treatments combinations irrespective of the drilling patterns and the bean cultivars had positive yield advantage over sole cropping. Despite that the values were above the unitary value of 1.0, the highest product *K* coefficient values were obtained from 1x1 under wheat/Fuego bi-cropping (18.20) and from the 2x2 under wheat/Maris Bead bi-cropping (26.95) which showed great advantage of bi-cropping systems over sole cropping systems. Similarly, broadcast bi-cropping treatment had the lowest product *K* coefficients values of 12.12 and 6.35 for wheat/Fuego and wheat/Maris Bead bi-cropping systems respectively. The alternate row bi-cropping treatments had a higher product *K* coefficient value over broadcast and indication relative bi-cropping benefits of alternate rows than broadcast compared to sole cropping.

Table 4.19: Relative Crowding Coefficient (K) of wheat/bean bi-cropping systems as influenced by drilling patterns and faba bean cultivars in 2015 cropping season

	Relative Crowding Coefficient (K)					
Drilling patterns	Wheat (K_{w1})	Fuego (K_{FG})	System ($K_{w1}*K_{FG}$)	Wheat (K_{w2})	Maris Bead (K_{MB})	System ($K_{w2}*K_{MB}$)
1x1	7.121	2.557	18.205	8.813	1.980	17.449
2x2	4.607	3.137	14.451	9.564	2.791	26.695
3x3	7.887	1.578	12.449	4.011	2.425	9.727
Broadcast	14.853	0.816	12.120	3.906	1.628	6.359

Broadcast: *Direct sowing of bean bi-crops, randomly over precisely drilled wheat row.* K_{FG} *and* K_{MB} *are relative crowding coefficients of crop Fuego and Maris Bead bean cultivars bi-cropped with wheat (*K_w*).*

4.9 Forage quality

4.9.1 Wheat crude protein content

4.9.1.1 Crude protein content

Cropping systems had a greater (P<0.001) effect on crude protein content in wheat grain and straw (Table 4.20). The highest wheat grain and straw crude protein content of 96.01 g kg^{-1} DM and 24.8 g kg^{-1} DM were respectively recorded from bi-cropping systems. The lowest wheat grain and straw crude protein content of 86.06 g kg^{-1} DM and 18.8 g kg^{-1} DM were respectively obtained from sole cropping systems. The crude protein content gain in the wheat grain and straw over sole wheat due to the effect of bi-cropping system was 11.5% and 31.9% respectively.

The drilling patterns, the bean cultivars and their interactions had no effect wheat the crude protein content levels (Table 4.20).

4.9.1.2 Protein yield

The wheat grain and straw protein yield was (P<0.01) affected by cropping systems (Table 4.20). The highest wheat grain, straw and total biomass yields of 227.0 kg ha^{-1}, 62.6 kg ha^{-1} and 289.3 kg ha^{-1} were respectively recorded from bi-cropping systems. The lowest wheat grain and straw protein yield of 188.0 kg ha^{-1}, 55.1 kg ha^{-1} and 243.1 kg ha^{-1} were respectively obtained from sole cropping systems. The wheat/bean bi-cropping system outperformed the sole cropping system on wheat grain, straw and total biomass by 13.6%, 20.7% and 19.0% respectively. The cropping systems had no effect on wheat protein yield harvest index.

Both the drilling patterns and bean cultivars did not affect wheat protein yield for grain, straw, total biomass and harvest index.

Table 4.20: Wheat crude protein content (g kg^{-1} DM) and protein yield (kg ha^{-1}) adjusted at 15% moisture content, for fodder production influenced by cropping systems, drilling patterns and bean cultivars, in 2015.

Treatments	Mix-proportion	Wheat crude protein content (g kg^{-1} DM)		Wheat protein yield (kg ha^{-1})			
Drilling patterns		Wheat straw	Wheat grain	Wheat Straw	Wheat grain	Total Biomass	HI (%)
1x1	50:50	25.36	94.04	65.8	232.5	298.3	78
2x2	50:50	25.11	96.62	64.4	240.2	304.6	79
3x3	50:50	24.48	96.24	55.4	216.5	271.6	80
Broadcast	50:50	24.50	97.14	64.6	219.1	283.7	77
SED (3 df)	-	1.891ns	3.142ns	7.93ns	14.39ns	19.02ns	1.90ns
P-value	-	0.920	0.644	0.369	0.170	0.176	0.456
Cropping systems							
Bi-crop mean	50:50	24.86	96.01	62.6 ^{a}	227.0^{a}	289.3^{a}	78
Sole crop	100	18.79	86.06	55.1^{b}	188.0^{b}	243.1^{b}	77
SED (1 df)	-	1.638***	2.721***	6.86***	12.46**	16.47**	1.65ns
P-value	-	<0.001	<0.001	<0.001	0.005	0.009	0.511
Bean cultivars							
Fuego	50:50	24.16	95.92	62.7	228.9	291.6	78
Maris Bead	50:50	25.56	96.11	62.4	225.2	287.7	78
SED (1 df)	-	1.726ns	2.860ns	7.23ns	13.14ns	17.36ns	1.74ns
P-value	-	0.212	0.919	0.954	0.664	0.724	0.751

*Values with the same letter under each 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; df, degrees of freedom; N, nitrogen; HI, harvest index*

4.9.2 Beans crude protein

4.9.2.1 Crude protein content

Cropping systems did not affect bean crude protein content in the bean straw and grain (Table 4.21).

The bean crude protein content was ($P<0.05$) affected by the drilling patterns on only in the bean seed (Table 4.21). The highest bean seed crude protein content values of 279.2 g kg^{-1} DM and 275.3 kg^{-1} DM were obtained from the 2x2 alternate rows and broadcast bi-cropping treatments respectively. The lower bean crude protein content values of 266.0 g kg^{-1} DM and 268.3 g kg^{-1} DM were obtained from the 1x1 and 3x3 alternate row bi-cropping treatments (Table 4.21).

The bean seed crude protein content was ($P<0.001$) affected by the bean cultivars (Table 4.21). The highest and lowest bean seed protein content of 282.9 g kg^{-1} DM and 261.5 g kg^{-1} DM resulted from Maris Bead and Fuego cultivars respectively.

4.9.2.2 Protein yield

There was a highly ($P<0.001$) effect of cropping systems on bean protein yield for bean straw, seed and total biomass (Table 4.21). The highest bean protein yield in straw (89.7 kg ha^{-1}), bean seed (817.0 kg ha^{-1}) and total biomass (727.0 kg ha^{-1}) were obtained from sole cropping systems. The lowest bean protein yield in the bean straw (35.0 kg ha^{-1}) bean seed (241.0 kg ha^{-1}) and total bean biomass (276.0 kg ha^{-1}) were obtained from bi-cropping systems.

The bean straw protein yield was not effected by drilling patterns. The bean seed protein yield was ($P<0.05$) affected by the drilling patterns. Similarly, total bean biomass protein yield was ($P<0.01$) affected by the drilling patterns (Table 4.21). On both variables, the alternate row bi-cropping treatments outperformed broadcast bi-cropping treatments.

The bean cultivars had no effects on protein yield for bean seed, straw and total bean biomass (Table 4.21b). The experimental factors did not affect the bean protein yield harvest index (Table 4.21).

Table 4.21: Bean crude protein content (g kg^{-1} DM) and protein yield (kg ha^{-1}) adjusted at 15% moisture content for fodder production influenced by cropping systems, drilling patterns and bean cultivars, in 2015 cropping season

Treatments	Mix-proportion	Bean crude protein content (g kg^{-1} DM)		Bean protein yield (kg ha^{-1})			
Drilling patterns		Bean straw	Bean seed	Bean Straw	Bean seed	Total biomass	HI (%)
1x1	50:50	65.70	266.00^{b}	32.1	291.0^{a}	324.0^{a}	88
2x2	50:50	76.80	279.20^{a}	44.6	271.0^{a}	315.0^{a}	85
3x3	50:50	73.10	268.20^{b}	38.6	269.0^{a}	307.0^{a}	85
Broadcast	50:50	68.20	275.30^{a}	42.6	133.0^{b}	175.6^{b}	84
SED (3 df)	-	5.33ns	5.82*	8.31ns	43.30**	43.11**	3.10ns
P-value	-	0.184	0.046	0.121	0.008	0.007	0.624
Cropping systems							
Bi-crop mean	50:50	70.90	272.20	35.0^{b}	241.0^{b}	276.0^{b}	86
Sole crop	100	68.10	271.50	89.7^{a}	727.0^{a}	817.0^{a}	88
SED (1 df)	-	4.210ns	4.6ns	6.57***	34.30***	37.30***	2.45ns
P-value	-	0.512	0.884	<0.001	<0.001	<0.001	0.248
Bean cultivars							
Fuego	50:50	74.00	261.50^{b}	36.7	216.0	252.7	85
Maris Bead	50:50	67.90	282.9^{a}	33.2	255.0	258.2	86
SED (1 df)	-	7.530ns	6.500***	9.29ns	48.5ns	52.7ns	3.47ns
P-value	-	0.130	<0.001	0.201	0.422	0.332	0.969

*Values with the same letter under each 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; df, degrees of freedom; N, nitrogen; HI, harvest index; DM, dry matter.*

4.10 N uptake

4.10.1 Wheat N uptake

Cropping systems had a greater (P<0.001) effect of on N uptake in the wheat grain and total wheat biomass (Table 4.22a). The bi-cropping systems (40.44 kgN ha^{-1}) outperformed the sole cropping system (34.73 kgN ha^{-1}) on wheat grain N uptake by 16.4% demonstrating the advantage of bi-cropping systems over sole cropping systems. Similarly, the bi-cropping system (53.19 kgN ha^{-1}) outperformed the sole cropping system (47.24 kgN ha^{-1}) on total biomass N uptake by 12.5%.

Both the drilling patterns and bean cultivars did not affect N uptake in the wheat grain and total wheat biomass (Table 4.22a).

Table 4.22a: The effects of cropping systems, drilling patterns and bean cultivars on wheat nitrogen yield (kgN ha^{-1}) in 2015 spring cropping seasons

Treatments	Mix-proportion	Total straw N yield (kgN ha^{-1})	Total grain N yield (kgN ha^{-1})	Total biomass N Yield (kgN ha^{-1})	Wheat N harvest index (%)
Drilling patterns					
1x1	50:50	13.22	41.59	54.80	75
2x2	50:50	13.42	43.05	56.47	76
3x3	50:50	11.49	39.01	50.50	77
Broadcast	50:50	12.85	38.13	50.98	74
SED (3 df)	-	1.738ns	2.396ns	3.484ns	4.4ns
P-value	-	0.531	0.068	0.126	0.552
Cropping systems					
Bi-crop mean	50:50	12.74	40.44^{a}	53.19^{a}	76
Sole crop	100	12.51	34.73^{b}	47.24^{b}	74
SED (1 df)	-	1.505ns	2.075**	3.017*	3.8ns
P-value	-	0.878	0.011	0.050	0.280
Bean cultivars					
Fuego	50:50	12.34	41.07	53.41	76
Maris Bead	50:50	13.15	39.82	52.97	75
SED (1 df)	-	1.586ns	2.187ns	3.181ns	4.0ns
P-value	-	0.432	0.378	0.828	0.194

*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; df, degrees of freedom; N, nitrogen.*

4.10.2 Bean N uptake

Cropping systems had a greater (P<0.001) effect on N uptake in the bean straw, seed and total bean biomass (Table 4.22b). The sole cropping system increased N uptake than the bi-cropping system in the bean seed and total bean dry matter. The sole cropping system had higher N uptake of 16.2 kgN ha^{-1}, 123.4 kgN ha^{-1} and 139.5 kgN ha^{-1} for bean straw, seed and total biomass respectively. The bi-cropping system had a lower N uptake values of 6.2 kgN ha^{-1}; 39.8 kgN ha^{-1} and 46.0 kgN ha^{-1} for bean straw, seed and total biomass respectively.

The drilling patterns had a greater (P<0.001) effect on N uptake by the bean (Table 4.22b). The alternate rows (45.6 kgN ha^{-1}) outperformed broadcast bi-cropping treatments (23.2 kgN ha^{-1}) on bean seed N uptake. Similarly, the alternate rows bi-cropping treatments (52.3 kgN ha^{-1}) outperformed broadcast bi-cropping treatment (26.9 kgN ha^{-1}) on N uptake in the total bean biomass. Even though the drilling patterns had no effect, the trend of N uptake gradually reduced with increasing number of rows.

The bean cultivars did not affect the N uptake by the bean plants.

Table 4.22b: The effects of cropping systems, drilling patterns and bean cultivars on bean nitrogen yield (kgN ha^{-1}) in 2015 spring cropping seasons

Treatments	Mix-proportion	Total straw N yield (kgN ha^{-1})	Total seed N yield (kgN ha^{-1})	Total biomass N Yield (kgN ha^{-1})	N harvest index (%)
Drilling patterns					
1x1	50:50	5.75	48.90^{a}	54.65^{a}	88
2x2	50:50	7.69	44.00^{a}	51.69^{a}	85
3x3	50:50	6.90	43.90^{a}	50.80^{a}	86
Broadcast	50:50	4.44	22.40^{b}	26.84^{b}	84
SED (3 df)	-	1.600ns	8.490*	9.140*	3.110ns
P-value		0.221	0.020	0.018	0.511
Cropping systems					
Bi-crop mean	50:50	6.20^{b}	39.80^{b}	46.00^{b}	86
Sole crop	100	16.12^{a}	123.40^{a}	139.52^{a}	88
SED (1 df)	-	1.265***	6.720***	7.230***	2.400ns
P-value		<0.001	<0.001	<0.001	0.380
Bean cultivars					
Fuego	50:50	6.59	42.20	48.79	86
Maris Bead	50:50	5.81	37.40	43.21	85
SED (1 df)	-	1.788ns	9.500ns	10.220ns	3.4ns
P-value		0.445	0.576	0.623	0.883

*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; df, degrees of freedom; N, nitrogen.*

Chapter 5

RESULTS FOR 2016: CORE EXPERIMENT

5.1 Wheat

5.1.1 Crop establishment

The number of established wheat plants was (P<0.001) affected by cropping systems, and the sole cropping system (447 plants m^{-2}) had the highest number of establishment wheat plants than the bi-cropping system (224 plants m^{-2}) (Table 5.1). The drilling patterns and bean cultivars did not affect the number of established wheat plants.

Table 5.1: The Effects of cropping systems, drilling patterns and spring bean cultivars on spring wheat establishment (plants m^{-2}) and the number of tillers (tillers m^{-2}) in 2016

Treatments	Mix-proportion	Wheat establishment (Plants m^{-2})	Wheat tillers (Tillers m^{-2})
Drilling patterns			
1x1	50:50	203	277
2x2	50:50	213	297
3x3	50:50	253	306
Broadcast	50:50	232	307
SED (3 df)	-	21.330ns	18.230ns
P-value	-	0.831	0.531
Cropping systems			
Bi-crop mean	50:50	224	297
Sole crop	100	447	305
SED (1 df)	-	18.470***	15.790ns
P-value	-	<0.001	0.598
Bean cultivars			
Fuego	50:50	227	300
Maris Bead	50:50	224	293
SED (1 df)	-	19.470ns	16.640ns
P-value	-	0.171	0.179

*Values with the same letter 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 difference of means; df, degrees of freedom.*

5.1.2. Number of wheat tillers

The number of wheat tillers was not affected by cropping systems, drilling patterns and bean cultivars (Table 5.1).

5.1.3. Chlorophyll Concentration Index (CCI)

CCI in the wheat leaf was (P<0.001) affected by cropping systems, and bi-cropping systems (23.2 CCI) increased CCI than sole cropping systems (11.9 CCI) by 48.7% (Table 5.2).

CCI was (P<0.001) affected by drilling patterns, and the alternate rows bi-cropping treatments (24.4 CCI) had higher CCI than broadcast bi-cropping treatments (19.2 CCI) by 27.2% (Table 5.2). Among the alternate row bi-cropping treatments, the 3x3 alternate row bi-cropping treatments significantly the lowest CCI values compared to others. The bean cultivars had no effects on the CCI on the wheat leaves.

Table 5.2: The effects of cropping systems, drilling patterns and bean cultivars on mean chlorophyll content (CCI) on the wheat leaf in 2016 cropping season

Treatments	Mix-proportion	Chlorophyll content (CCI)
Drilling patterns		
1x1	50:50	24.7[a]
2x2	50:50	24.9[a]
3x3	50:50	23.7[b]
Broadcast	50:50	19.2[c]
SED (3 df)	-	0.385***
P-value	-	<0.001
Cropping systems		
Bi-crop mean	50:50	23.2[a]
Sole crop	100	11.9[b]
SED (1 df)	-	0.365***
P-value	-	<0.001
Bean cultivars		
Fuego	50:50	22.9
Maris Bead	50:50	23.4
SED (1 df)	-	0.788ns
P-value	-	0.056

*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; df, degrees of freedom; CCI, chlorophyll concentration index.*

5.1.4. Leaf Area Index (LAI)

LAI was (P<0.001) affected by cropping systems, and the bi-cropping system increased LAI over the sole cropping by 14.6% showing its advantage sole cropping system. LAI in the bean sole cropping system (3.56) was higher than in the sole wheat cropping system (2.30) by 54.7% (Table 5.3).

The drilling patterns showed a greater (P<0.001) effect LAI (Table 5.3). The alternate row bi-cropping treatments increased LAI than broadcast bi-cropping treatments by 23.4%. Among alternate rows, the 3x3 had significantly the lowest LAI compared to other alternate row bi-cropping treatments.

LAI was (P<0.001) affected by the bean cultivars, and Fuego increased LAI than Maris Bead bean by 5.4% (Table 5.3).

Table 5.3: The effects of cropping systems, drilling patterns and bean cultivars on mean leaf area index (LAI) in 2016 cropping season

Treatments	Mix-proportion	Leaf area index (LAI)
Drilling patterns		
1x1	50:50	3.62[a]
2x2	50:50	3.60[a]
3x3	50:50	3.37[b]
Broadcast	50:50	2.86[c]
SED (3 df)	-	0.069***
P-value	-	<0.001
Cropping systems		
Bi-crop mean	50:50	3.36[b]
Sole crop (wheat)	100	2.30[c]
Sole crop (beans)	100	3.56[a]
SED (1 df)	-	0.051***
P-value	-	<0.001
Bean cultivars		
Fuego	50:50	3.66 [a]
Maris Bead	50:50	3.47[b]
SED (1 df)	-	0.0848***
P-value	-	<0.001

*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; SED, standard error of difference of means; df, degrees of freedom; LAI, Leaf area Index*

5.1.5. Intercepted Photosynthetic Active Radiation (IPAR)

Cropping systems had a greater (P<0.001) effect of on IPAR (Table 5.4). It is difficult to determine how much of the IPAR was intercepted by each of the component crop. Instead, IPAR was determined based on the total crop canopy from each experimental plot. The bi-cropping systems had higher IPAR (82.3%) than the sole cropping system (75.35%). Between the sole cropping systems, the sole bean cropping system had higher IPAR (77.5%) than the sole wheat cropping system (73.2%) by 5.8%.

The drilling patterns had a greater (P<0.001) effect on IPAR (Table 5.4). The alternate row bi-cropping treatments (85.5%) had higher IPAR than the broadcast bi-cropping treatments (75.5%). Among the drilling patterns treatments, the 2x2 alternate rows bi-cropping treatment (86.8%) had the highest IPAR than other drilling patterns (81.8%) which include; the 1x1, 3x3 and broadcast. Among the alternate rows treatments, the 1x1 and 3x3 bi-cropping treatments had lower IPAR compared to the 2x2 alternate row treatments (Table 5.4).

There was (P<0.001) effect of the bean cultivars on IPAR (Table 5.4), and Maris Bead had higher IPAR (83.1%) than Fuego (81.5%).

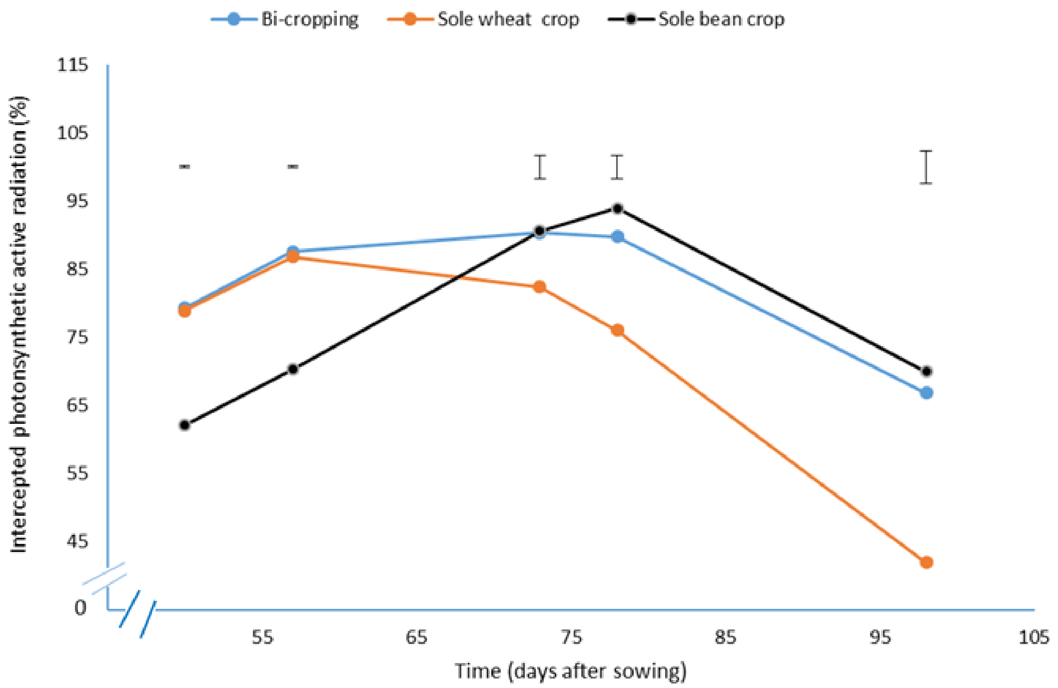
Table 5.4: The effects of cropping systems, drilling patterns and bean cultivars on mean per cent intercepted photosynthetic active radiation (IPAR) in 2016 cropping season

Treatments	Mix-proportion	IPAR (%)
Drilling patterns		
1x1	50:50	85.0[b]
2x2	50:50	86.8[a]
3x3	50:50	84.9[b]
Broadcast	50:50	75.5[c]
SED (1 df)	-	0.628***
P-value	-	<0.001
Cropping systems		
Bi-crop mean	50:50	82.3[a]
Sole crop (wheat)	100	73.2[c]
Sole crop (beans)	100	77.5[b]
SED (1 df)	-	0.395***
P-value	-	<0.001
Bean cultivars		
Fuego	50:50	81.5[b]
Maris Bead	50:50	83.1[a]
SED (1 df)	-	0.769***
P-value	-	<0.001

*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; SED, standard error of the difference; df, degrees of freedom; IPAR, Intercepted Photosynthetic Active Radiation.*

The effects of time (DAS) on IPAR

The days after sowing had a greater (P<0.001) effect on IPAR. An annual IPAR of 81.1% of the total annual incident was recorded across cropping systems, drilling patterns and bean cultivars (Figure 5.1). Higher IPAR for the bi-cropping system occurred between 51 and 73 DAS which declined between 78 and 98 DAS. The maximum IPAR for the sole wheat cropping system occurred during booting stage at 57 DAS afterwards the canopy became less dense allowing more PAR to the soil surface. The sole bean cropping system initially had lowest IPAR than the sole wheat cropping system. It had equal IPAR with bi-cropping at 73 DAS before reached its maximum IPAR at 78 DAS. Similarly, the sole wheat cropping system had equal IPAR with the bi-cropping system only between 50 and 57 DAS afterwards the sole wheat canopy (at booting stage) became less dense allowing more PAR to the soil surface. However, at 51 DAS the bi-cropping system had 27.6% PAR than the sole bean cropping systems revealing the advantage of bi-cropping systems and the weakness of sole bean cropping systems on light interception during early stages of growth.



Error bars representing average LSD ($P \leq 0.05$)

Figure 5.1: The effects of time (DAS) on IPAR (%) for different cropping systems in spring 2016

5.1.6. Total radiation use efficiency (RUE)

Cropping systems had a greater (P<0.05) effect on total RUE. The bi-cropping system had a higher total RUE value of 0.668 g MJ^{-1} m^{-2} compared to 0.600 g MJ^{-1} m^{-2} from the sole cropping system by 11.3% (Table 5.5).

The drilling patterns had a greater (P<0.001) effect on total radiation use efficiency (Table 5.5). The 3x3 alternate row treatment (0.560 g MJ^{-1} m^{-2}) reduced total radiation use efficiency compared to other drilling pattern (0.704 g MJ^{-1} m^{-2}) by 25.7%.

Total RUE was (P<0.001) affected by the bean cultivars (Table 5.5). Fuego had a higher total RUE value (0.739 g MJ^{-1} m^{-2}) than Maris Bead (0.597 g MJ^{-1} m^{-2}) by 23.7%.

Table 5.5: The effects of cropping systems, drilling patterns and bean cultivars on total radiation use efficiency (g MJ^{-1} m^{-2}) in 2016 cropping season

Treatments	Mix-proportion	Total radiation use efficiency (g MJ^{-1} m^{-2})
Drilling patterns		
1x1	50:50	0.693[a]
2x2	50:50	0.741[a]
3x3	50:50	0.560[b]
Broadcast	50:50	0.678[a]
SED (3 df)	-	0.091***
P-value	-	<0.001
Cropping systems		
Bi-crop mean	50:50	0.668[a]
Sole crop	100	0.600[b]
SED (1 df)	-	0.050*
P-value	-	0.046
Bean cultivars		
Fuego	50:50	0.739[a]
Maris Bead	50:50	0.597[b]
SED (1 df)	-	0.083*
P-value	-	0.031

*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; SED, standard error of the difference of means; df, degrees of freedom; RUE, radiation use efficiency.*

5.1.7. Dry matter accumulation

5.1.7.1. Wheat

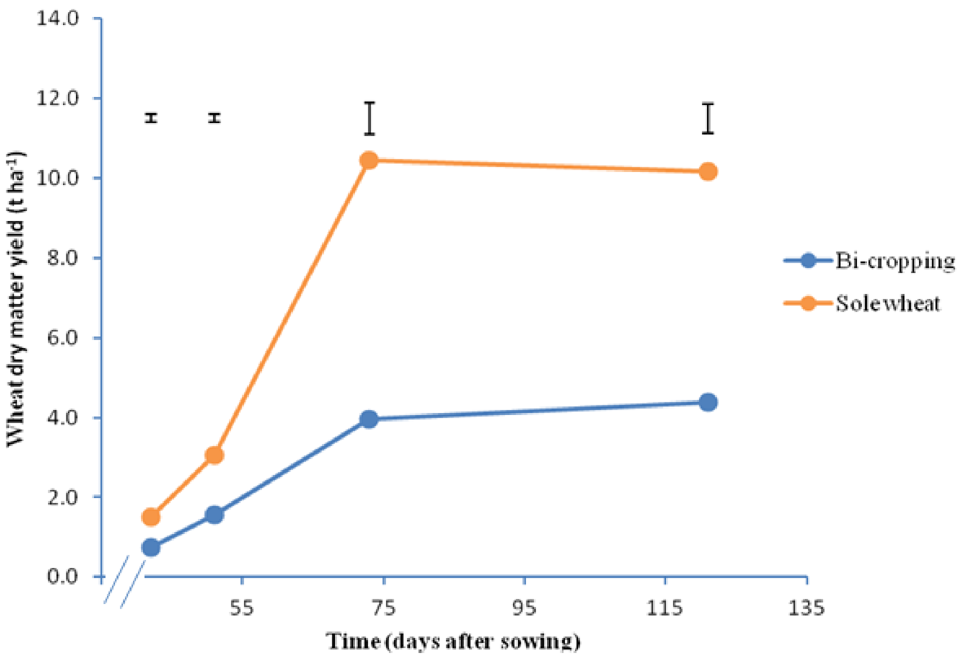
The wheat dry matter yield across the DAS was ($P<0.001$) affected by cropping systems (Table 5.6). The sole cropping system accumulated increased amount of wheat dry matter yield than the bi-cropping system across the DAS (Table 5.6; Figure 5.2).

The drilling patterns and the bean cultivars as independent factors had no effect on wheat dry matter yield differences.

Table 5.6: The effects of cropping systems, drilling patterns and bean cultivars on wheat dry matter yield (t ha^{-1}) at different times of the 2016 cropping season

Treatments	Mix-proportion	Wheat dry matter (t ha^{-1}) DAS 42	51	73	121
Drilling patterns					
1x1	50:50	0.765	1.61	4.12	4.53
2x2	50:50	0.751	1.42	3.85	4.24
3x3	50:50	0.680	1.57	3.66	4.10
Broadcast	50:50	0.808	1.61	4.46	4.69
SED (3 df)	-	0.113ns	0.122ns	0.452ns	0.427ns
P-value	-	0.130	0.099	0.511	0.061
Cropping systems					
Bi-crop mean	50:50	0.751^{b}	1.54^{b}	4.02^{b}	4.38^{b}
Sole crop	100	1.502^{a}	3.11^{a}	10.46^{a}	10.17^{a}
SED (1 df)	-	0.097***	0.106***	0.392***	0.370***
P-value	-	<0.001	<0.001	<0.001	<0.001
Bean cultivars					
Fuego	50:50	0.791	1.59	3.86	4.55
Maris Bead	50:50	0.750	1.55	4.08	4.24
SED (1 df)	-	0.103ns	0.112ns	0.413ns	0.390ns
P-value	-	0.540	0.815	0.423	0.055

*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 difference of means; df, degrees of freedom; DAS, days after sowing.*



Error bars representing average LSD (*P≤0.05*)

Figure 5.2: The effects of time (DAS) on wheat dry matter yield (t ha^{-1}) by two different cropping systems in 2016 cropping season

5.2 Bean performance

5.2.1 Plant establishment

Cropping systems had a greater (P<0.001) effect on the number of bean plants established at GS103 (Table 5.7), and the sole cropping system had a higher (38.09 plant m^{-2}) number of established bean plants than the bi-cropping system (15.95 plants m^{-2}).

The drilling patterns had a greater (P<0.001) effect on the number of established bean plants at GS103 (Table 5.7). The highest and lowest number of bean plants established was recorded from the 3x3 and (1x1 & 2x2) respectively.

Table 5.7: The Effects of cropping systems, drilling patterns and spring bean cultivars on spring bean establishment (plants m^{-2}) in 2016 cropping season

Treatments	Mix-proportion	Bean plant establishment (plants m^{-2})
Drilling patterns		
1x1	50:50	14.88^{c}
2x2	50:50	14.50^{c}
3x3	50:50	18.30^{a}
Broadcast	50:50	16.30^{b}
SED (3 df)	-	2.309**
P-value	-	0.002
Cropping systems		
Bi-crop mean	50:50	15.95^{b}
Sole crop	100	38.09^{a}
SED (1 df)	-	1.825***
P-value	-	<0.001
Bean cultivars		
Fuego	50:50	36.94
Maris Bead	50:50	39.25
SED (1 df)	-	2.581ns
P-value	-	0.108

*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 difference of means; df, degrees of freedom.*

5.2.2 Bean dry matter yield

The bean dry matter yield at different DAS was (P<0.001) affected by cropping systems (Table 5.8). The higher bean dry matter yield of 0.61 t ha^{-1} and 5.60 t ha^{-1} from the sole cropping system than 0.25 t ha^{-1} and 2.72 ha^{-1} from the bi-cropping system was recorded at 42 and 121 DAS respectively.

The bean dry matter accumulation was (P<0.01) affected by drilling patterns at 42 and 121 DAS (Table 5.8). At 42 DAS, the 2x2 alternate row treatments (0.32 t ha^{-1}) influenced highest bean dry matter yield compared to for other drilling patterns (0.22 t ha^{-1}). Broadcast bi-cropping treatment had the lowest bean dry matter yield of 0.17 t ha^{-1} compared to other drilling patterns. Among the alternate row treatments, the bean dry matter yield for the 1x1 and the 3x3 treatments was lower compared to the 2x2 alternate row bi-cropping treatments.

At 122 DAS, the alternate row bi-cropping treatments (2.85 t ha^{-1}) had higher bean dry matter yield than broadcast treatment (1.77 t ha^{-1}) by 62.5%.

The bean cultivars had no effect on the bean dry matter yield.

Table 5.8: The effects of cropping systems drilling patterns and bean cultivars on mean bean dry matter yield (t ha^{-1}) at different DAS, for forage production, spring 2016

Treatments	Mix-proportion	Bean dry matter (t ha^{-1}) DAS			
		42	51	73	121
Drilling patterns					
1x1	50:50	0.26^{b}	0.57	1.73	2.74^{a}
2x2	50:50	0.32^{a}	0.52	2.24	2.85^{a}
3x3	50:50	0.24^{b}	0.58	1.91	3.04^{a}
Broadcast	50:50	0.17^{c}	0.38	1.38	1.77^{b}
SED (3 df)	-	0.031***	0.094ns	0.370ns	0.360**
P-value	-	<0.001	0.146	0.174	0.009
Cropping systems					
Bi-crop mean	50:50	0.25^{b}	0.51	1.97	2.72^{b}
Sole crop	100	0.61^{a}	1.47	5.29	5.60^{a}
SED (1 df)	-	0.024***	0.074***	0.297***	0.28***
P-value	-	<0.001	<0.001	<0.001	<0.001
Bean cultivars					
Fuego	50:50	0.25	0.56	1.82	2.43
Maris Bead	50:50	0.24	0.46	1.81	2.76
SED (1 df)	-	0.034ns	0.105ns	0.421ns	0.404ns
P-value	-	0.137	0.294	0.363	0.230

*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; df, degrees of freedom; DAS, days after sowing.*

5.3 Weeds

5.3.1 Weed biomass

Transformed weed dry weight (g m^{-2}) and weed nitrogen uptake (kg ha^{-1}) at 51 DAS

At 51 DAS, weed dry matter accumulation was (P<0.001) affected by cropping systems (Table 5.9a). Sole cropping systems (wheat and beans) had the highest transformed weed dry weights (3.91 g m^{-2}) than bi-cropping systems (2.34 g m^{-2}). Between the sole cropping systems, the sole bean cropping system (5.18 g m^{-2}) had the highest transformed weed dry weight than the sole wheat cropping system (2.65 g m^{-2}).

Transformed weed dry weight was (P<0.001) affected by drilling patterns (Table 5.9a). The alternate row bi-cropping treatments (2.13 g m^{-2}) outperformed broadcast treatment (2.95 g m^{-2}) by 38.2% on the reduction of transformed weed dry weights. However, the alternate row bi-cropping treatments had (>0.05) similar effect on transformed dry weight.

Transformed weed nitrogen uptake was (<0.001) affected by cropping systems (Table 5.9a). The sole cropping systems (2.06 kgN ha^{-1}) had the highest transformed weed nitrogen uptake (1.23 kgN ha^{-1}) than bi-cropping systems. The capacity of the bi-cropping system to minimised nitrogen loss from the system through weeds was 67.4% higher than the sole cropping system (Table 5.9a).

Transformed weed nitrogen uptake was (<0.001) affected by drilling patterns (Table 5.9a). The alternate rows bi-cropping treatments (1.1 kgN ha^{-1}) had the higher capacity than broadcast bi-cropping treatment (1.56 kgN ha^{-1}) on reducing nitrogen loss from the system through weeds by 41.8%.

Table 5.9a: The effects of drilling patterns and bean cultivars on transformed weed dry weight (g m^{-2}) and weed nitrogen uptake (kg ha^{-1}) at 51 DAS in 2016 cropping seasons

Treatments	Mix-proportion	Weed dry weight (g m^{-2})	Weed shoot N uptake (kg ha^{-1})
Drilling patterns			
1x1	50:50	2.04^{b} [4.36]	1.08^{b}[1.25]
2x2	50:50	2.09^{b} [4.52]	1.02^{b}[1.26]
3x3	50:50	2.27^{b} [5.28]	1.20^{b}[1.49]
Broadcast	50:50	2.95^{a} [9.24]	1.56^{a}[2.66]
SED (3 df)	-	0.2224*	0.126***
P-value	-	0.041	<0.001
Cropping systems			
Bi-crop mean	50:50	2.34^{c} [5.85]	1.23^{c}[1.52]
Sole crop (wheat)	100	2.65^{b}[7.07]	1.39^{b}[1.97]
Sole crop (beans)	100	5.18^{a} [27.24]	2.73^{a}[7.69]
SED (1 df)	-	0.164***	0.093***
P-value	-	<0.001	<0.001
Bean cultivars			
Fuego	50:50	2.46[6.35]	1.30[1.81]
Maris Bead	50:50	2.22[5.35]	1.17[1.52]
SED (1 df)	-	0.2724ns	0.155ns
P-value	-	0.993	0.098

*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; DAS, days after sowing.*
[ ] *Data was subjected to square root √(x+0.5) transformation and figures in parenthesis are the means of original values; df, degrees of freedom.*

Transformed mean weed dry weight (g m^{-2}) and weed N uptake (kg ha^{-1}) at 73 DAS

At 73 DAS, transformed weed dry weight was (P<0.001) affected by cropping systems (Table 5.9b). Sole cropping systems (3.89 g m^{-2}) higher transformed weed dry weights than bi-cropping systems (3.01 g m^{-2}).

The drilling patterns had a greater (P<0.001) effect on transformed weed dry weight (Table 5.9b). The alternate row bi-cropping treatments (2.33 g m^{-2}) outperformed the broadcast bi-cropping treatment (5.03 g m^{-2}) by 115.8% on the ability to reduce transformed weed dry weights in production system. Despite alternate rows were not different statistically, the 3x3 alternate row bi-crop treatments had relatively lower effect than other alternate rows.

Transformed weed N uptake was (P<0.001) affected by cropping systems (Table 5.9b). The sole cropping system had highest transformed weed N uptake (1.9 kgN ha^{-1}) than the bi-cropping system (1.5 kgN ha^{-1}). Bi-cropping systems showed higher abilities to minimise N loss through weeds than sole cropping by 26.6%. Between the sole cropping systems, the sole bean cropping system had the highest transformed weed N uptake (2.19 kgN ha^{-1}) than the sole wheat cropping system (1.70 kgN ha^{-1}).

The drilling patterns had a greater (P<0.001) effect on transformed weed N uptake (Table 5.9b). The alternate rows reduced (1.1 kgN ha^{-1}) transformed weed N uptake than broadcast bi-cropping treatment (2.5 kgN ha^{-1}). The weed species identified on the study site are summarised in Table 5.9c.

Table5.9b: The effects of drilling patterns and bean cultivars on transformed weed dry weight (g m^{-2}) and weed nitrogen uptake (kg ha^{-1}) at 73 DAS in 2016 cropping season

Treatments	Mix-proportion	weed dry weight (g m^{-2})	Weed shoot N uptake (kg ha^{-1})
Drilling patterns			
1x1	50:50	2.11^{c}[5.00]	1.05^{b}[1.24]
2x2	50:50	2.22^{bc}[5.07]	1.11^{b}[1.30]
3x3	50:50	2.67^{b}[7.30]	1.34^{b}[1.86]
Broadcast	50:50	5.03^{a}[27.13]	2.51^{a}[6.83]
SED (3 df)	-	0.489***	0.249***
P-value	-	<0.001	<0.001
Cropping systems			
Bi-crop mean	50:50	3.01^{c}[11.12]	1.50^{c}[3.16]
Sole crop (wheat)	100	3.42^{b}[12.22]	1.70^{b}[3.00]
Sole crop (beans)	100	4.36^{a}[20.75]	2.19^{a}[5.37]
SED (1 df)	-	0.362**	0.185**
P-value	-	0.005	0.016
Bean cultivars			
Fuego	50:50	3.07[11.68]	1.54[3.25]
Maris Bead	50:50	2.94[10.57]	1.47[3.39]
SED (1 df)	-	0.598ns	0.306ns
P-value	-	0.375	0.323

*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; DAS, days after sowing. [ ] Data was subjected to square root $\sqrt{(x+0.5)}$ transformation and figures in parenthesis are the means of original values; df, degrees of freedom.*

Table 5.9c: Botanical classification of weed species identifies at the study site during 2016 spring cropping season

Common name	Weed type	Scientific name	Family	Genus
Black bind weed	Broad leaf	*Convolvulus arvensis* (L.)	Convolvulaceae	*Convolvulus*
Common orache	Broad leaf	*Atriplex patula* (L.)	Aamaranthaceae	*Atriplex*
Nipplewort	Broad leaf	*Lapsana communis* (L.)	Asteraceae	*Lapsana*
Smooth sow thistle	Broad leaf	*Sonchus oleraceus (*L.)	Asteraceae	*Sonchus*
Fool's Parsley	Broad leaf	*Aethusa cynapium* (L.)	Apiaceae	*Aethusa*
Oilseed rape	Broad leaf	*Brassica napus* (L.)	Brassicaceae	*Brassica*

5.3.1 Weed smothering efficiency (WSE) (%)

Results in Table 5.10, showed no effect of the drilling patterns on WSE at 73 DAS (Table 5.10). At 51 DAS, the alternate rows bi-cropping treatments (82.9%) outperformed (P<0.01) broadcast (66.9%) by 23% on WSE. The bean cultivars had a greater (P<0.001) effect on WSE. At 51 DAS, Maris Bead (80.6%) had higher WSE than Fuego (76.8) by 4.9%. At 73 DAS, Fuego had higher WSE effect (82.0%) than Maris Bead (75.3%) by 8.8% (Table 5.10).

Table 5.10: The effects of drilling patterns and bean cultivars on weed smothering efficiency (%) at 51 and 73 DAS in 2016 cropping season

Treatments	Mix-proportion	Weed smothering efficiency (%)	
Drilling patterns		51 DAS	73 DAS
1x1	50:50	84.1[a]	78.1
2x2	50:50	83.1[a]	78.1
3x3	50:50	80.5[a]	81.9
Broadcast	50:50	66.9[b]	76.5
Bi-crop mean	50:50	78.7	78.6
SED (3 df)	-	4.600 **	5.650ns
P-value	-	0.004	0.798
Bean cultivars			
Fuego	50:50	76.8[b]	82.0[a]
Maris Bead	50:50	80.6[a]	75.3[b]
SED (1 df)	-	3.250*	4.000*
P-value	-	0.027	0.048

*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; DAS, days after sowing.*

5.4 Plant heights

5.4.1 Wheat plant height

The wheat plant height was (P<0.001) affected by cropping systems (Table 5.11). The wheat plants in bi-cropping systems (93.29 cm) were taller than wheat plants (89.21 cm) in sole cropping systems by 4.5%.

The wheat plant height was (P<0.001) affected the drilling patterns (Table 5.11). The 3x3 alternate row bi-cropping treatments had the tallest wheat plant height (100.00 cm) compared to other drilling patterns treatments (91.0 cm) by 9.9 cm. The wheat plant height for the 1x1 (90.46 cm), 2x2 (91.62) and broadcast treatment (90.68 cm).

The bean cultivars did affect the plant height for the wheat bi-crops. The wheat plant height was (P<0.01) affected by the drilling patterns x bean cultivars (Figure 5.3).

Table 5.11: Mean wheat plant height (cm) as affected by cropping systems, drilling patterns and bean cultivars in 2016 cropping season

Treatments	Mix-proportion	Wheat plant height (cm)
Drilling patterns		
1x1	50:50	90.46[a]
2x2	50:50	91.62[a]
3x3	50:50	100.00[b]
Broadcast	50:50	90.68[a]
SED (3 df)	-	2.237***
P-value	-	<0.001
Cropping systems		
Bi-crop mean	50:50	93.29[a]
Sole crop	100	89.21[b]
SED (1 df)	-	1.937*
P-value	-	0.037
Bean cultivars		
Fuego	50:50	92.56
Maris Bead	50:50	94.01
SED (1 df)	-	2.042ns
P-value	-	0.262

*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; df, degrees of freedom.*

5.4.2 Bean plant heights

The bean plant height was (P<0.001) affected by cropping systems (Table 5.12). The sole cropping system (133.02 cm) increased plant height compared to the bi-cropping system (119.03 cm) by 11.7%.

The drilling patterns had a greater (P<0.001) effect on bean plant height (Table 5.12). The 3x3 alternate row bi-cropping treatment (126.09 cm) had the tallest plant height. The 1x1 alternate row bi-cropping treatments (107.27 cm) had the shortest plant height. The effect of drilling patterns on bean plant height occurred in the following descending order was: 3x3> 2x2> broadcast> 1x1.

There was (P<0.05) effect of the bean cultivars on bean plant heights (Table 5.12). Maris Bead (122.37 cm) was taller than Fuego (115.69 cm) by 5.4%.

Table 5.12: Mean bean plant height (cm) as affected by cropping systems, drilling patterns and bean cultivars in 2016 cropping season

Treatments	Mix-proportion	Bean plant height (cm)
Drilling patterns		
1x1	50:50	107.27^{c}
2x2	50:50	120.53^{b}
3x3	50:50	126.09^{a}
Broadcast	50:50	122.23^{b}
SED (3 df)	-	2.638***
P-value	-	<0.001
Cropping systems		
Bi-crop mean	50:50	119.03^{b}
Sole crop	100	133.02^{a}
SED (1 df)	-	2.086***
P-value	-	<0.001
Bean cultivars		
Fuego	50:50	115.69^{b}
Maris Bead	50:50	122.37^{a}
SED (1 df)	-	2.949**
P-value	-	0.002

*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; SED, standard error of the difference of means; df, degrees of freedom.*

5.5 Field pests and diseases

5.5.1 Faba bean rust disease (*Uromyces viciae-fabae)* severity (%)

Faba bean rust disease severity was (P<0.01) affected by the drilling patterns during the reproductive growth stage of faba beans (Table 5.13). The 1x1 (68.5%) and the 3x3 (70.0%) alternate row bi-cropping treatments had (P<0.01) high disease severity. The 2x2 alternate row (57.5%) and broadcast bi-cropping treatments (60.3%) had (P<0.01) low percentage disease severity. The disease severity for the 1x1 (68.5%) was equal to the sole bean cropping systems (67.0%).

The bean cultivars had a greater (P<0.001) effect on the disease severity (Table 5.12), and Fuego (84.7%) had the highest disease severity than Maris Bead (44.6%).

Table 5.13: The effects of cropping systems, drilling patterns and bean cultivars on the severity (%) of faba bean rust (*Uromyces viciae-fabae*) at 205 DAS during spring, 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 (3 df)	-	4.320**
P-value	-	0.019
Cropping systems		
Bi-crop mean	50:50	64.7
Sole crop	100	67.0
SED (1 df)	-	3.410ns
P-value	-	0.393
Bean cultivars		
Fuego	50:50	84.7[a]
Maris Bead	50:50	44.6[b]
SED (1 df)	-	4.830***
P-value	-	<0.001

*Values with the same letter under the same parameter are not significantly different at P<0.05; *=P<0.05; **=P<0.0; ***=P<0.001; ns=not significant at (P<0.05); SED, standard error of the difference of means; df, degrees of freedom.*

5.6 Grain yield and components

5.6.1 Wheat yield

5.6.1.1 Total grain weight

The wheat total grain yield was (P<0.001) affected by cropping systems (Table 5.14). The sole cropping system (4.0 t ha^{-1}) had higher wheat grain yield than the bi-cropping system (1.7 t ha^{-1}) by 2.3 times higher. The drilling patterns and bean cultivars had no effect on wheat grain yield.

5.6.1.2 1000 seed weight

The seed index or 1000 wheat seed weight was (P<0.05) affected by cropping systems (Table 5.14). The sole cropping system (35.9 g) was 4.9% higher than the bi-cropping system on influencing 1000 wheat seed weight. The drilling pattern (P<0.01) effected 1000 the wheat seed weight. The 3x3 alternate row treatments (32.5 g) had the lowest 1000 wheat seed weight compared to other drilling patterns.

5.6.1.3 Wheat straw yield

The wheat straw yield was (P<0.001) affected by cropping systems (Table 5.14). The sole cropping system (5.6 t ha^{-1}) had 2.0 times higher wheat straw yield than the bi-cropping system (2.7 t ha^{-1}). The drilling patterns and bean cultivars did not affect the wheat straw yield.

5.6.1.4. Total wheat biomass yield

The total wheat biomass yield was (P<0.001) affected by cropping systems (Table 5.14). The sole cropping system (7.6 t ha^{-1}) had higher total wheat biomass yield than the bi-cropping system (4.8 t ha^{-1}). The drilling patterns and bean cultivars had no effect on total biomass yield.

5.6.1.5 Wheat Harvest index (HI)

The wheat harvest HI was (P<0.05) affected by cropping systems (Table 5.14). The wheat cropping system (53%) had higher HI than the bi-cropping system (35%).

Table 5.14: The effects of cropping systems, drilling patterns and bean cultivars on mean wheat yield (t ha^{-1}) and components during 2016 cropping season

Treatments	Mix-proportion	Total wheat ear weight (t ha^{-1})	Total wheat straw yield (t ha^{-1})	Total wheat grain yield (t ha^{-1})	1000 seed weight (g)	Total wheat biomass yield (t ha^{-1})	Harvest index (%)
Drilling patterns							
1x1	50:50	2.2	2.8	1.6	34.8^{a}	5.0	32
2x2	50:50	2.3	2.5	1.7	34.1^{a}	4.8	35
3x3	50:50	2.2	2.7	1.6	32.5^{b}	4.9	33
Broadcast	50:50	2.1	2.9	1.7	35.4^{a}	5.0	34
SED (3 df)	-	0.116ns	0.191ns	0.151ns	0.922**	0.266ns	2.0ns
P-value	-	0.729	0.074	0.891	0.002	0.091	0.175
Cropping systems							
Bi-crop mean	50:50	2.1	2.7^{b}	1.7^{b}	34.2^{b}	4.8^{b}	35^{b}
Sole crop	100	2.0	5.6^{a}	4.0^{a}	35.9^{a}	7.6^{a}	53^{a}
SED (1 df)	-	0.141ns	0.166***	0.131***	0.799*	0.230***	1.8*
P-value	-	0.241	<0.001	<0.001	0.037	<0.001	0.047
Bean cultivars							
Fuego	50:50	2.2	2.78	1.68	34.4	4.9	34
Maris Bead	50:50	2.1	2.75	1.59	34.0	4.8	33
SED (1 df)	-	0.148ns	0.175ns	0.138ns	0.842ns	0.243ns	1.9ns
P-value	-	0.135	0.825	0.075	0.494	0.094	0.075

*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= significant at P>0.05; SED, standard error of the difference of means; df, degrees of freedom. The total biomass was calculated as the sum of total ear weight and total straw yield (t ha^{-1}).*

5.6.2 Bean yield

5.6.2.1 Total bean seed yield

The total bean yield was ($P<0.01$) affected by cropping systems (Table 5.15). The highest and lowest total bean seed yield of 1.3 t ha^{-1} and 1.01 t ha^{-1} resulted from sole cropping and bi-cropping systems respectively.

The total bean yield was ($P<0.05$) affected by drilling patterns (Table 5.15). The alternate row bi-crop treatments (1.17 t ha^{-1}) had higher influenced higher yield than broadcast bi-cropping treatment (0.86 t ha^{-1}) by 35.6%.

The bean cultivars had no effect on bean yield (Table 5.15). The faba bean rust disease outbreak during pod filling might have partly contributed to this outcome.

5.6.2.2 100 bean seed weight

The cropping systems and drilling patterns had no effect on 100 seed weights (Table 5.15).

The bean cultivars had a greater ($P<0.001$) effect on 100 bean seed weight (Table 5.15). Fuego (35.1g) had a higher 100 bean seed weight than Maris Bead (29.9 g) by 17.3%.

5.6.2.3 Bean straw yield

The bean straw yield was ($P<0.001$) affected by cropping systems (Table 5.15). The highest and lowest bean straw yield of 4.30 t ha^{-1} and 1.61 t ha^{-1} resulted from sole and bi-cropping systems respectively.

The bean straw yield was ($P<0.05$) affected by the drilling patterns (Table 5.15). The alternate row bi-cropping treatments (1.82 t ha^{-1}) had higher bean straw yield than broadcast bi-cropping treatment (0.96 t ha^{-1}) by 1.89 times higher.

5.6.2.4 Total Bean biomass yield

Cropping systems had a greater ($P<0.001$) effect on bean total biomass yield (Table 5.15). The sole cropping system influenced higher total bean biomass yield of 5.60 t ha^{-1} than 2.60 t ha^{-1} recorded from the bi-cropping system.

The total bean biomass yield was ($P<0.01$) affected by the drilling patterns (Table 5.15). The alternate row bi-cropping treatments (2.99 t ha^{-1}) had higher total bean biomass yield than broadcast bi-cropping treatment (1.83 t ha^{-1}).

The total bean biomass yield was ($P<0.01$) affected by the bean cultivars, and Maris Bead (2.89 t ha^{-1}) had higher total bean biomass yield than Fuego bean cultivar (2.50 t ha^{-1}) (Table 5.15).

5.6.2.5 Harvest index (HI)

Bean HI was ($P<0.001$) affected by cropping systems (Table 5.15). The bi-cropping (42%) outperformed the sole bean cropping system (24%) on HI by 75%.

Table 5.15: The effects of cropping systems, drilling patterns and bean cultivars on bean yield and components (t ha^{-1}) for forage production, 2016 spring season

Treatments	Mix-proportion	Total bean straw yield (t ha^{-1})	Total bean seed yield (t ha^{-1})	100bean seed weight (g)	Total bean biomass yield (t ha^{-1})	Bean harvest index (%)
Drilling patterns						
1x1	50:50	1.76^{a}	1.09^{a}	32.2	2.86^{a}	43
2x2	50:50	1.80^{a}	1.28^{a}	32.2	3.08^{a}	46
3x3	50:50	1.90^{a}	1.13^{a}	32.9	3.04^{a}	40
Broadcast	50:50	0.96^{b}	0.86^{b}	32.7	1.83^{b}	44
SED (3 df)	-	0.269**	0.102**	0.785ns	0.270**	4.3ns
P-value	-	0.003	0.002	0.772	<0.001	0.337
Cropping systems						
Bi-crop mean	50:50	1.61^{b}	1.01^{b}	32.5	2.60^{b}	42^{a}
Sole crop	100	4.30^{a}	1.30^{a}	32.8	5.60^{a}	24^{b}
SED (1 df)	-	0.212***	0.080*	0.620ns	0.213***	3.4***
P-value	-	<0.001	0.014	0.655	<0.001	<0.001
Bean cultivars						
Fuego	50:50	1.51	1.01	35.1	2.50^{b}	42
Maris Bead	50:50	1.71	1.19	29.9	2.89^{a}	43
SED (1 df)	-	0.300ns	0.114ns	0.877***	0.302*	4.8ns
P-value	-	0.181	0.051	<0.001	0.044	0.494

*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= significant at P<0.05; SED, standard error of the difference of means; df, degrees of freedom.*

5.7 Biological efficiency of cropping systems

5.7.1 Partial land equivalent ratios (PLER) for bi-crops

The $PLER_w$ and $PLER_b$ were not affected by the drilling patterns and bean cultivars (Table 5.16). The $PLER_w$ and $PLER_b$ were compared against 0.5 because each crop species in bi-cropping systems was sown at half of the sole crops densities (Bedoussac and Justes, 2010). The PLER value above 0.5 indicates the advantage of crop mixtures. If the PLER is equal to or below 0.5 indicates the disadvantage of bi-cropping systems.

5.7.2 Land equivalent ratio (LER) of bi-crops

The LER values for bi-cropping system in Table 5.16 were not significantly different from each other (Table 5.16). Across the drilling patterns and bean cultivars, the LER of 1.079 from bi-cropping treatment combinations showed no advantage of bi-cropping systems because it was equal to the unitary value of 1.0. The land saving advantage indicative values in bi-cropping systems were below the minimum productivity coefficient value of 25% which indicated no advantage of bi-cropping systems possibly due to bean disease effects. The drilling patterns x bean cultivar interaction (P<0.01) affected LER (Figure 5.3).

Table 5.16: Biological efficiency of bi-cropping on nitrogen use efficiency influenced cropping systems, drilling patterns and bean cultivars, in 2016 cropping season

		Partial Land Equivalent Ratio ($PLER_N$)		Total Land Equivalent Ratio (LER_N)	Land savings (%)
Treatments	Mix-proportion (%)	Wheat ($PLER_{wheat}$	Bean ($PLER_{bean}$)	($PLER_{wheat}$+$PLER_{bean}$)	
Drilling patterns					
Sole crop	100	0.500	0.500	1.00	-
1x1	50:50	0.557	0.537	1.09	8.5
2x2	50:50	0.570	0.472	1.04	4.0
3x3	50:50	0.582	0.512	1.09	8.6
Broadcast	50:50	0.540	0.559	1.09	9.0
SED (3 df)	-	0.380ns	0.079ns	0.087ns	7.5
P-value	-	0.723	0.723	0.902	-
Bean cultivars					
Fuego	50:50	0.561	0.548	1.109	-
Maris Bead	50:50	0.563	0.492	1.055	-
SED (1 df)	-	0.027ns	0.056ns	0.0879ns	-
P-value	-	0.938	0.329	0.395	

Values with the same letter under the same parameter are not significantly different at P<0.05; ns=not significant at P<0.05; SED, standard error of the difference; df, degrees of freedom; $PLER_N$, partial land equivalent ratio for nitrogen; LER_N, land equivalent ratio for nitrogen; $PLER_{wheat}$ and $PLER_{beans}$ partial land equivalent ratio for wheat and beans.

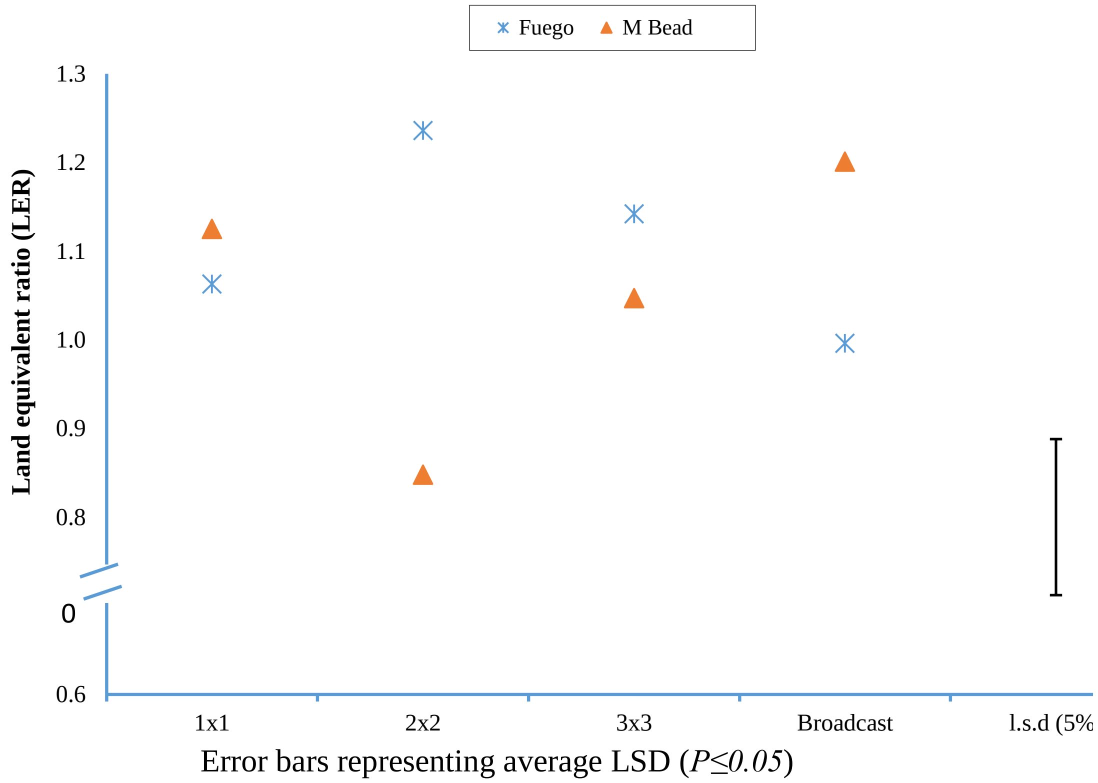


Figure 5.3: The effects of drilling pattern x bean cultivar interaction between on LER in 2016 spring cropping season

5.8. Competition indices

5.8.1 Aggressivity (A)

The results showed positive signs for the wheat bi-crops and a negative signs for the bean bi-crops which ecologically meant that the wheat bi-crops dominated the bean bi-crops in bi-cropping system on resource acquisition (Table 5.17). Among the alternate row bi-cropping treatments, the highest (0.059) and lowest (0.018) aggressivity values in the wheat/Fuego bi-cropping system was recorded from the 3x3 and the 2x2 bi-crop treatments respectively. The highest (0.167) and lowest (0.127) aggressivity values in wheat/Maris Bead bi-cropping system was recorded from the 2x2 and 1x1 alternate row bi-cropping treatments respectively. The wheat/Maris Bead had the higher aggressivity values than wheat/Fuego bi-cropping systems. The aggressivity values across the bean cultivars showed highest and lowest mean values from the 2x2 and the 3x3 alternate row bi-cropping treatments respectively. However, the 3x3 and the 1x1 alternate row bi-cropping treatments had almost similar aggressivity values.

Table 5.17: Aggressivity (A) as influenced by drilling patterns and faba bean cultivars in a wheat/bean based bi-cropping systems in 2016

Treatments	Aggressivity (A)				System Aggressivity (A)	
	Wheat (A_{w1})	Fuego (A_{FG})	Wheat (A_{w2})	Maris Bead (A_{MB})	Wheat ($(A_{w1+}A_{w2})/2$)	Legume ($(A_{fg+}A_{mb})/2$)
Drilling patterns						
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

Broadcast: Direct sowing of bean seeds randomly over precisely drilled wheat rows. A_{FG} and A_{MB} are Aggressivity indices for Fuego and Maris Bead bean cultivars in mixture with wheat (A_w)

5.8.2 Relative Crowding Coefficient (RCC or K)

The results in Table 5.18 showed that the partial *K* coefficient values for wheat were consistently higher than the partial *K* coefficient values for the beans. If the product *K* coefficient derived from the product of the bi-crop components (wheat*beans) is greater or lower than 1.0 it demonstrates yield advantage and disadvantage respectively. The product *K* coefficient values for the 1x1 and 2x2 alternate row treatments in wheat/Fuego bi-cropping system were equal to 1.0 which indicated no yield advantage. The product *K* coefficient values for the 3x3 and broadcast bi-cropping treatments were below 1.0 an indication of yield disadvantage. Similarly, the product *K* coefficients values for alternate row bi-cropping treatments were above 1.0 than broadcast bi-cropping treatments in wheat/Maris Bead bi-cropping system. This imply that in alternate rows bi-cropping treatments higher yield advantage was expected while yield disadvantages was expected in broadcast treatments.

Table 5.18: Relative Crowding Coefficient (K) of wheat/bean bi-cropping systems as influenced by drilling patterns and faba bean cultivars in 2016

Treatment	Relative Crowding Coefficient (K)					
Drilling patterns	Wheat (K_{w1})	Fuego (K_{FG})	System ($K_{w1}*K_{FG}$)	Wheat (K_{w2})	Maris Bead (K_{MB})	System ($K_{w2}*K_{MB}$)
1x1	1.108	0.989	1.095	1.049	1.769	1.856
2x2	1.057	0.984	1.040	1.682	0.852	1.432
3x3	1.081	0.876	0.947	1.687	0.947	1.563
Broadcast	1.073	0.523	0.562	1.228	0.456	0.559

Broadcast: Direct sowing of bean seeds over precisely drilled wheat rows. K_{FG} and K_{MB} are relative crowding coefficients of crop Fuego and Maris Bead bean cultivars bi-cropped with wheat (K_w).

5.9 Forage quality

5.9.1 Wheat performance on crude protein content

5.9.1.1 Crude protein content

The crude protein in the wheat straw and grain was (P<0.001) affected by cropping systems (Table 5.19). The highest and lowest mean wheat grain crude protein content of 134.5 g kg^{-1} DM and 106.0 g kg^{-1} DM was recorded from bi-cropping and sole cropping systems respectively. Similarly, the highest and lowest wheat straw crude protein content of 39.26 g kg^{-1} DM and 29.25 g kg^{-1} DM was recorded from bi-cropping and sole cropping systems respectively.

The drilling patterns did not influence the crude protein content in the wheat straw and grain (Table 5.19).

The wheat crude protein content was (P<0.05) affected by the bean cultivars only in the wheat straw, and Fuego (40.99 g kg^{-1} DM) increased wheat straw crude protein content than Maris Bead (37.53 g kg^{-1} DM) (Table 5.19).

5. 9.1.2 Protein yield

Cropping systems had a greater (P<0.001) effect on protein yield in the wheat grain, straw and total wheat biomass (Table 5.19). The sole cropping system increased protein yield than the bi-cropping system in the wheat grain, straw and total biomass.

The protein yield harvest index was (P<0.05) affected by cropping systems (Table 5.19). The sole cropping system (72%) had higher protein yield harvest index than the bi-cropping system (68%).

The drilling patterns did not affect the protein yield for wheat straw, grain and total wheat biomass (Table 5.19). However, the wheat protein harvest index was (P<0.05) was affected by the drilling patterns. The 2x2 and broadcast bi-cropping treatments had higher wheat protein harvest index than the 1x1 and the 3x3 bi-cropping treatments.

The bean cultivars did not affect protein yield for wheat straw, grain, total biomass and harvest index.

Table 5.19: Wheat crude protein content (g kg^{-1} DM) and protein yield (kg ha^{-1})adjusted at 15% moisture content, for fodder production influenced by cropping systems, drilling patterns and bean cultivars, in 2016 cropping season.

Treatments	Mix-proportion	Crude protein content (g kg^{-1} DM)		Wheat protein yield (kg ha^{-1})			
Drilling patterns		Straw	grain	Straw	Grain	total biomass	HI (%)
1x1	50:50	40.72	134.0	115.5	225.3	340.8	65[b]
2x2	50:50	37.15	132.8	95.4	225.1	320.5	70[a]
3x3	50:50	41.02	140.3	111.2	235.0	346.2	67 [b]
Broadcast	50:50	38.15	145.1	101.9	271.9	373.8	71[a]
SED (3 df)	-	2.119ns	10.150ns	7.03ns	31.56ns	33.70ns	2.41*
P-value	-	0.172	0.303	0.184	0.251	0.312	0.032
Cropping systems							
Bi-crop mean	50:50	39.26[a]	134.5[a]	106.0[b]	238.2[b]	344.2[b]	68[b]
Sole crop	100	29.25[b]	106.0[b]	164.2[a]	431.7[a]	595.9[a]	72[a]
SED (1 df)	-	2.119***	11.710**	6.08***	27.33***	29.19***	2.09*
P-value	-	<0.001	0.003	<0.001	<0.001	<0.001	0.015
Bean cultivars							
Fuego	50:50	40.99[a]	133.4	108.8	236.9	345.7	68
Maris Bead	50:50	37.53[b]	142.7	103.2	241.8	345.0	69
SED (1 df)	-	2.234*	10.690ns	6.41ns	28.81ns	30.76ns	2.20ns
P-value	-	0.023	0.105	0.115	0.181	0.790	0.535

*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; df, degrees of freedom; DM, dry matter; HI, harvest index.*

5.9.2 Beans performance on crude protein

5.9.2.1 Crude protein content

The results in Table 5.20 showed that the cropping systems, drilling patterns, bean cultivars and their interactions had no effect on bean crude protein content (g kg^{-1}DM).

5.9.2.2 Protein yield

Cropping systems had a greater (P<0.001) effect on the bean protein yield for bean straw, seed, total biomass and harvest index (Table 5.20). The highest bean protein yield values for bean straw (139.6 kg ha^{-1}), bean seed (356.0 kg ha^{-1}) and total bean biomass (496.0 kg ha^{-1}) were obtained from sole cropping systems. The lowest bean protein yield values for bean straw (51.0 kg ha^{-1}), bean seed (306.0 kg ha^{-1}) and total bean biomass (357.0 kg ha^{-1}) were obtained from bi-cropping systems.

However, cropping systems had a highly (P<0.001) effect on bean protein yield harvest index (Table 5.20). The bi-cropping system (85%) had higher bean protein yield harvest index than the sole bean cropping system (71%) by 19.7%.

Table 5.20: Bean crude protein content (g kg^{-1} DM) and protein yield (kg ha^{-1})adjusted at 15% moisture content, for fodder production influenced by cropping systems, drilling patterns and bean cultivars, in 2016.

Treatments	Mix-proportion	Bean crude protein content (g kg^{-1} DM)		Bean protein yield (kg ha^{-1})			
Drilling patterns		Bean Straw	Bean seed	Bean Straw	Bean seed	Total biomass	HI (%)
1x1	50:50	32.19	280.8	56.3	308.0	365.0^{b}	84
2x2	50:50	30.38	271.6	55.0	351.0	406.0^{a}	86
3x3	50:50	30.45	279.6	58.5	320.0	378.0^{ba}	84
Broadcast	50:50	34.97	277.7	35.7	245.0	281.0^{c}	87
SED (3 df)	-	2.623ns	7.470ns	13.86ns	38.60ns	38.33*	3.03ns
P-value	-	0.280	0.620	0.347	0.075	0.022	0.769
Cropping systems							
Bi-crop mean	50:50	32.2	277.4	51.4^{b}	306.0^{b}	357.0^{b}	85^{a}
Sole crop	100	32.3	273.7	139.6^{a}	356.0^{a}	496.0^{a}	71^{b}
SED (1 df)	-	2.073ns	5.910ns	10.96***	30.50***	30.30***	2.39***
P-value	-	0.851	0.528	<0.001	<0.001	<0.001	<0.001
Bean cultivars							
Fuego	50:50	31.27	276.0	47.6	280.0	328.0	85
M Bead	50:50	32.73	278.9	55.1	332.0	378.0	85
SED (1df)	-	2.932ns	8.350ns	15.49ns	43.20ns	42.9ns	3.39ns
P-value	-	0.484	0.856	0.750	0.186	0.113	0.964

Values with the same letter under the same parameter are not significantly different at P<0.05; ns=not significant at P>0.05; SED, standard error of the difference of means; df, degrees of freedom; DM, dry matter; HI, harvest index.

5.10 N uptake

5.10.1 Wheat N uptake

The N uptake in the wheat straw, grain and total wheat biomass was (P<0.001) affected by cropping systems (Table 5.21a). The bi-cropping system outperformed the sole cropping system on wheat grain N uptake. However, the wheat N uptake harvest index was (P<0.05) affected by cropping systems, and the bi-cropping system outperformed the sole cropping system on wheat N harvest index by 16% (Table 5.21a).

The drilling patterns and bean cultivars did not affect N uptake in wheat plant tissues.

Table 5.21a: The effects of cropping systems, drilling patterns and bean cultivars on wheat nitrogen yield (kgN ha^{-1}) in 2016 spring cropping seasons

Treatments	Mix-proportion	Wheat Straw N yield (kgN ha^{-1})	Wheat Grain N yield (kgN ha^{-1})	Wheat Total N Yield (kgN ha^{-1})	Wheat N harvest index (%)
Drilling patterns					
1x1	50:50	27.2	35.3	62.5	56
2x2	50:50	23.1	36.4	59.6	61
3x3	50:50	26.2	37.9	64.1	59
Broadcast	50:50	27.7	38.8	66.1	58
SED (3 df)	-	3.81^{ns}	3.00^{ns}	5.33^{ns}	3.0^{ns}
P-value	-	0.477	0.367	0.305	0.280
Cropping systems					
Bi-crop mean	50:50	26.0^{b}	37.1^{a}	63.1^{b}	58^{a}
Sole crop	100	69.6^{a}	31.4^{b}	101.0^{a}	31^{b}
SED (1 df)	-	3.30***	2.19**	3.84***	2.5***
P-value	-	<0.001	0.008	<0.001	<0.001
Bean cultivars					
Fuego	50:50	26.1	37.7	63.8	59
Maris Bead	50:50	26.0	36.6	62.6	58
SED (1 df)	-	3.48ns	2.70ns	4.80ns	2.4ns
P-value	-	0.980	0.460	0.656	0.716

*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; df, degrees of freedom.*

5.10.2 Bean N uptake

The effects of cropping systems

Bean seed

N uptake in the bean seed was ($P<0.05$) affected by cropping systems (Table 5.21b). The sole cropping system (56.60 kgN ha^{-1}) had higher N uptake in the bean seed than the bi-cropping systems (49.40 kgN ha^{-1}).

Bean straw

N uptake in the bean straw was ($P<0.001$) affected by cropping systems (Table 5.21b). The sole cropping system accumulated higher N (24.30 kgN ha^{-1}) in the bean straw than the bi-cropping system (8.40 kgN ha^{-1}).

Total bean N uptake

N accumulation in total bean biomass was ($P<0.001$) affected by cropping systems (Table 5.21b). The sole cropping system (80.0 kgN ha^{-1}) accumulated higher N than the bi-cropping system (57.8 kgN ha^{-1}).

Bean N harvest index

The cropping systems had a greater ($P<0.001$) effect on the bean N harvest index (Table5.21b). The bi-cropping system (85%) had higher N harvest index than the sole cropping system (68%).

The effects of drilling patterns on N uptake

Bean seed

The drilling patterns had a greater ($P<0.001$) effect on N accumulation in the bean seed (Table 5.21b). The alternate row treatments (53.3 kgN ha^{-1}) accumulated more N in the bean seed than broadcast bi-cropping treatment (37.6 kgN ha^{-1}). The 2x2 alternate row bi-cropping treatments had the highest bean N uptake compared to other drilling pattern treatments. Among the alternate rows, the 1x1 and 3x3 alternate row treatments had the lowest bean N uptake compared to the 2x2 alternate row bi-cropping treatments.

Bean straw

The bean straw N uptake was ($P<0.001$) affected by the drilling patterns (Table 5.21b). The alternate row bi-cropping treatments (9.5 kgN ha^{-1}) accumulated more N in the bean straw N than broadcast bi-cropping treatments (4.9 kgN ha^{-1}).

Total bean biomass

N uptake in the total bean biomass was (P<0.01) affected by the drilling patterns (Table 5.21b). The alternate rows bi-cropping treatments (62.8 kgN ha^{-1}) outperformed broadcast bi-cropping treatments (42 kgN ha^{-1}) on N uptake in the total bean biomass. The 2x2 alternate row treatment (69.0 kgN ha^{-1}) had the highest N accumulation than other drilling patterns treatments (53.8 kgN ha^{-1}). Among the alternate rows, the 1x1 treatment (58.4 kgN ha^{-1}) had the accumulated the lowest amount on N in the bean biomass compared to other alternate rows bi-cropping treatment (65.1 kgN ha-1)

The effects of bean cultivars on N uptake

N uptake in the bean seed and total bean biomass was (P<0.05) effected by the bean cultivars (Table 5.21b). Maris Bead (44.3 kgN ha^{-1}) accumulated more N in the bean seed than Fuego bean (54.5 kgN ha^{-1}). Similarly, Maris Bead (63.5 kgN ha^{-1}) accumulated more N in the total bean biomass than Fuego (52.1 kgN ha^{-1}).

Table 6.21b. The effects of cropping systems, drilling patterns and bean cultivars on bean nitrogen yield (kgN ha^{-1}) in 2016 spring cropping seasons.

Treatments	Mix-proportion	Bean straw N uptake (kg N ha^{-1})	Bean grain N uptake (kg N ha^{-1})	Total bean N uptake (kg N ha^{-1})	Bean N harvest index (%)
Drilling patterns					
1x1	50:50	8.7^{a}	49.7^{b}	58.4^{c}	84
2x2	50:50	9.9^{a}	59.0^{a}	69.0^{a}	85
3x3	50:50	9.9^{a}	51.2^{b}	61.2^{b}	83
Broadcast	50:50	4.9^{b}	37.6^{c}	42.0^{d}	87
SED (3 df)	-	1.773**	6.780*	6.790**	2.8ns
P-value	-	0.030	0.039	0.006	0.614
Cropping systems					
Bi-crop mean		50:50	8.4^{b}	49.4^{b}	57.8^{b}
Sole crop	100	24.3^{a}	56.6^{a}	80.0^{a}	68^{b}
SED (1 df)	-	1.402***	5.430*	5.370***	2.2***
P-value	-	<0.001	0.019	<0.001	<0.001
Bean cultivars					
Fuego	50:50	7.8	44.3^{b}	52.1^{b}	84
Maris Bead	50:50	8.9	54.5^{a}	63.5^{a}	85
SED (1 df)	-	1.982ns	7.680*	7.600*	3.0ns
P-value	-	0.155	0.012	0.050	0.621

*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; df, degrees of freedom; N, nitrogen*

Chapter 6

THE YEARS X TREATMENTS INTERACTIONS FOR CORE EXPERIMENTS (2015 AND 2016)

6.1 Chlorophyll Concentration Index (CCI)

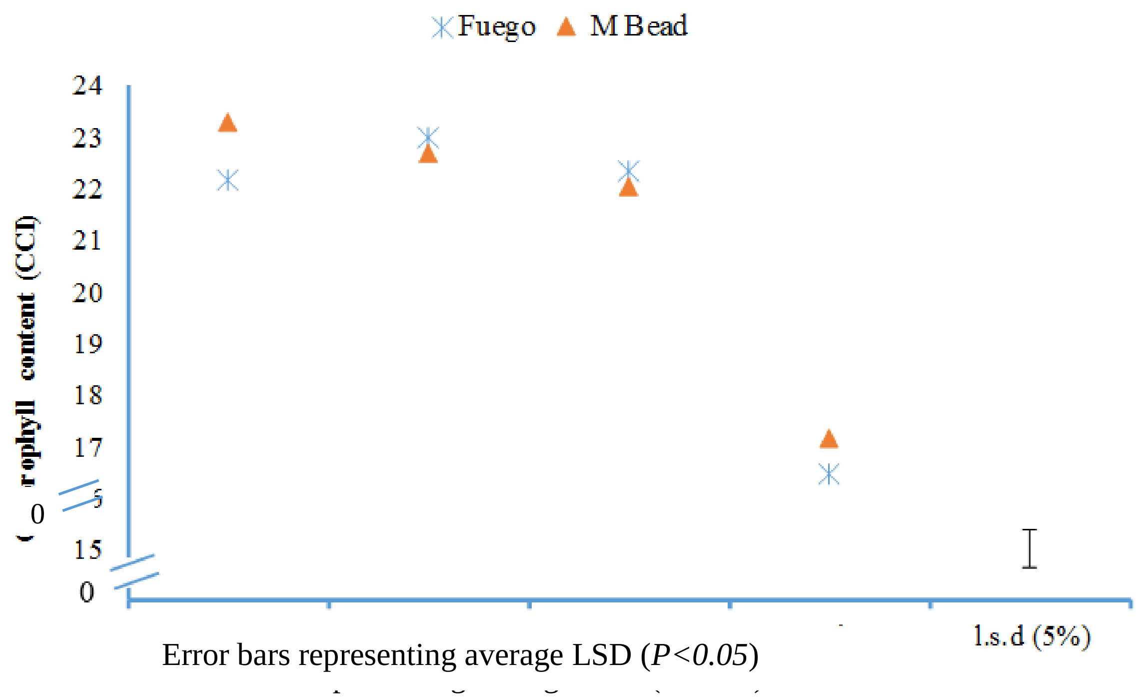
The combined analysis of variance revealed that CCI was (P<0.001) affected by cropping seasons (Appendix 6.1; Table 6.1). The 2016 cropping season had increased CCI values than in the 2015 cropping season. The cropping system x year interactions had a greater (P<0.001) effects on CCI in wheat plants within and between cropping seasons. The bi-cropping system increased CCI than the sole cropping system in both seasons. The 2016 cropping season increased CCI than the 2015 cropping season by was 36.7%.

The drilling patterns x year interactions had a greater (P<0.001) effect on CCI (Table 6.1: Figure 6.1). The drilling patterns in the 2016 cropping season increased CCI than in the 2015 cropping season by 21.5%. In both seasons, the alternate rows increased CCI than broadcast bi-cropping treatment. In 2016 cropping season, the 1x1 and the 2x2 alternate rows increased CCI than the 3x3 alternate row treatments.

Table 6.1: The effects of cropping systems, drilling patterns and bean cultivars on mean chlorophyll content (CCI) in wheat leaf in 2015 and 2016 cropping seasons

Treatments	Mix-proportion	CCI		
Drilling patterns		2015	2016	Mean
1x1	50:50	20.6[a]	24.7[a]	22.7
2x2	50:50	20.7[a]	25.0[a]	22.8
3x3	50:50	20.6[a]	23.7[b]	22.1
Broadcast	50:50	14.3[b]	19.2[c]	16.7
SED (3 df)	-	0.467***	0.422***	
P-value	-	<0.001	<0.001	
Cropping systems				
Bi-crop mean	50:50	19.0[a]	23.1[a]	21.1
Sole crop	100	6.6[b]	11.9[b]	9.3
SED (1 df)	-	0.399***	0.365***	0.276
P-value	-	<0.001	<0.001	
Bean cultivars				
Fuego	50:50	19.0	22.9	20.9
Maris Bead	50:50	19.1	23.4	21.2
SED (1 df)	-	0.421ns	0.385ns	0.411
P-value	-	0.886	0.056	

*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; df, degrees of freedom; CCI, Chlorophyll concentration index.*



Error bars representing average LSD ($P<0.05$)

Figure 6.1: The effects of drilling patterns x bean cultivars interactions on chlorophyll content across two cropping seasons (2015 and 2016)

6.2 Leaf Area Index (LAI)

LAI was (P<0.001) affected by cropping seasons (Appendix 5.1; Table 6.2). There was increased LAI in the 2016 cropping season than in the 2015 cropping season by 71.4%. The cropping system x year interaction had a greater (P<0.001) effect on LAI (Table 6.2). The bi-cropping system increased LAI than the sole cropping system in both cropping seasons.

LAI was (P<0.001) affected by the drilling pattern x year interaction (Table 6.2). The drilling patterns in the 2016 cropping season increased LAI than in the 2015 by 77.6%. The alternate rows increased LAI than broadcast in the 2016 season than in the 2015 season. The 2x2 alternate row bi-cropping treatments had the highest LAI than other drilling patterns treatments in both cropping seasons. Among alternate rows, the LAI was reduced in the 1x1 alternate row treatments only in the 2015 cropping season. LAI was reduced in the 3x3 alternate row treatments in both cropping seasons.

LAI was (P<0.001) affected the bean cultivar x year interaction (Table 6.2). The bean cultivars increased LAI in the 2016 than in the 2015 cropping seasons. Fuego increased LAI than Maris Bead in both seasons, irrespective of the seasonal variations.

Table 6.2: The effects of cropping systems, drilling patterns and bean cultivars on mean Leaf Area Index (LAI) in 2015 and 2016 spring seasons

Treatments	Mix-proportion	LAI		
Drilling patterns		2015	2016	Mean
1x1	50:50	1.95^{b}	3.62^{a}	2.78
2x2	50:50	2.03^{a}	3.60^{a}	2.83
3x3	50:50	1.97^{b}	3.37^{b}	2.67
Broadcast	50:50	1.62^{c}	2.86^{c}	2.23
SED (3 df)	-	0.047***	0.069***	
P-value	-	<0.001	<0.001	
Cropping systems				
Bi-crop mean	50:50	1.89^{b}	3.36^{b}	2.63
Sole crop (wheat)	100	1.38^{c}	2.30^{c}	1.84
Sole crop (beans)	100	2.11^{a}	3.56^{a}	2.50
SED (1 df)	-	0.035***	0.051***	
P-value	-	<0.001	<0.001	
Bean cultivars				
Fuego	50:50	1.92^{a}	3.66^{a}	2.79
Maris Bead	50:50	1.83^{b}	3.47^{b}	2.66
SED (1 df)	-	0.058***	0.0848***	
P-value	-	<0.001	<0.001	

*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; SED, standard error of difference of means; df, degrees of freedom; LAI, Leaf area Index.*

6.3 Intercepted photosynthetic active radiation (IPAR)

The combined analysis of variance revealed that IPAR was (P<0.001) affected by the cropping seasons (Appendix 5.1). The increased IPAR was recorded in the 2016 cropping seasons than in the 2015 cropping season. IPAR was (P<0.001) affected by the cropping system x year interaction (Table 6.3). In both seasons, bi-cropping systems outperformed sole cropping systems with a higher IPAR recorded in 2016 over 2015 cropping season.

The drilling patterns x year interaction had a greater (P<0.001) effect on IPAR (Table 6.3). During the 2016 cropping season the drilling patterns increased IPAR than in the 2015 cropping season by 17.9%. In both seasons, the 2x2 alternate rows bi-cropping treatments had the highest IPAR with the lowest recorded from broadcast bi-cropping treatment.

IPAR was (P<0.001) affected by the bean cultivar x year interaction (Table 6.3). Fuego increased IPAR than Maris Bead in the 2015 cropping season. Maris Bead increased IPAR than Fuego in the 2016 cropping season.

Table 6.3: The effects of cropping systems, drilling patterns and bean cultivars on mean Intercepted photosynthetic active radiation (IPAR) in 2015 and 2016 spring seasons

Treatments	Mix-proportion	IPAR (%)		
Drilling patterns		2015	2016	Mean
1x1	50:50	70.30[c]	85.00[b]	77.23
2x2	50:50	74.51[a]	86.80[a]	80.29
3x3	50:50	72.30[b]	84.90[b]	78.79
Broadcast	50:50	64.60[d]	75.50[c]	68.08
SED (3 df)	-	0.956***	0.628***	-
P-value	-	<0.001	<0.001	-
Cropping systems				
Bi-crop mean	50:50	70.42[a]	82.30[a]	76.20
Sole crop (wheat)	100	58.90 [c]	73.20[c]	66.32
Sole crop (beans)	100	68.00[b]	77.50[b]	74.13
SED (1 df)	-	0.861***	0.395***	-
P-value	-	<0.001	<0.001	-
Bean cultivars				
Fuego	50:50	72.1`0[a]	81.5[b]	76.80
Maris Bead	50:50	68.70[b]	83.1[a]	75.91
SED (1 df)	-	1.170***	0.769***	-
P-value	-	<0.001	<0.001	-

*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; SED, standard error of the difference; df, degrees of freedom; IPAR, Intercepted Photosynthetic Active Radiation.*

6.4 Plant heights

6.4.1 Wheat plant height

The combined analysis of variance in Appendix 5.1 showed that cropping seasons had a greater (P<0.001) effect on wheat plant height. During the 2016 cropping season, wheat plant heights were taller than in the 2015 cropping season by 41.6% (Table 6.4). The cropping system x year interaction had a greater (P<0.001) effect on wheat plant height (Table 6.4). Bi-cropping systems increased wheat plant heights than sole cropping systems in both cropping seasons.

The drilling patterns x year interactions had a greater (P<0.001) effect on the wheat plant height (Table 6.4). The drilling patterns increased wheat plant heights in the 2016 season than in the 2015 cropping seasons by 28.2%. In both cropping seasons, the alternate row bi-cropping treatments increased wheat plant heights than broadcast bi-cropping treatments. The 1x1 and the 3x3 alternate row bi-cropping treatments had shorter wheat plant height in the

2015 than the 2x2 alternate row treatments. During the 2016 season, the 3x3 alternate row treatments had taller wheat plant height than the 1x1 and 2x2 alternate row treatments. In both season, the 2x2 alternate rows bi-cropping treatments had an optimum wheat plant height due to better use of limited resources in the bi-cropping system.

Table 6.4: The effects of cropping systems, drilling patterns and bean cultivars on mean wheat plant height (cm) in 2015 and 2016 spring cropping seasons

Treatments	Mix-proportion	Wheat plant heights (cm)		Mean
		2015	2016	
Drilling patterns				
1x1	50:50	73.89b	90.46a	84.26
2x2	50:50	75.53a	91.62a	85.97
3x3	50:50	74.36b	100.00b	88.97
Broadcast	50:50	66.91c	90.68a	81.10
SED (3 df)	-	0.841***	2.237***	-
P-value	-	<0.001	<0.001	-
Cropping systems				
Bi-crop mean	50:50	72.65a	93.29a	85.08
Sole crop	100	56.15b	89.21b	76.83
SED (1 df)	-	0.693***	1.937*	-
P-value	-	<0.001	0.037	-
Bean cultivars				
Fuego	50:50	72.98	92.56	85.04
Maris Bead	50:50	72.37	94.01	85.11
SED (1 df)	-	0.746ns	2.042ns	-
P-value	-	0.611	0.267	-

*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; df, degrees of freedom; IPAR, Intercepted Photosynthetic Active Radiation.*

6.4.2 Bean plant height

A combined analysis of variance showed that cropping seasons had a greater (P<0.001) effect on bean plant heights (Appendix 5.1). The bean plant heights in the 2016 cropping season were 64.3% taller than in 2015 cropping seasons. The bean plant heights was (P<0.001) affected the cropping system x year interaction (Table 6.5). In both seasons, the sole cropping system increased the bean plant heights than the bi-cropping system.

The drilling patterns x year interactions had greater (P<0.001) effect on the bean plant height. During the 2016 cropping season the drilling patterns increased bean plant height than in the

2015 cropping season by 57.6% (Table 6.5). During the 2015 cropping season, the 1x1 and the 3x3 alternate row bi-cropping treatments had shorter bean plant heights compared to other alternate rows treatments. During the 2016 cropping season, the 1x1alternate row treatment had the shortest bean plant height while the 3x3 alternate row treatment had the tallest bean plant heights compared to the 2x2 alternate rows bi-cropping treatment. The 2x2 alternate row bi-cropping treatment did not affect the bean plant height due to spatial interspecific complementarity effects on better use of environmental resources.

The bean cultivar x year interactions had no effect on bean plant heights (Table 6.5).

Table 6.5: The effects of cropping systems, drilling patterns and bean cultivars on mean bean plant height (cm) in 2015 and 2016 cropping seasons

Treatments	Mix-proportion	Bean plant height (cm)		Mean
		2015	2016	
Drilling patterns				
1x1	50:50	76.08^{b}	107.27^{d}	92.48
2x2	50:50	77.04^{a}	120.53^{b}	98.93
3x3	50:50	75.66^{b}	126.09^{a}	100.23
Broadcast	50:50	73.30^{c}	122.23^{c}	98.09
SED (3 df)	-	0.648***	2.638***	-
P-value	-	<0.001	<0.001	-
Cropping systems				
Bi-crop mean	50:50	75.52^{b}	119.03^{b}	97.43
Sole crop	100	77.81^{a}	133.02^{a}	104.79
SED (1 df)	-	0.480*	2.086***	-
P-value	-	0.024	<0.001	-
Bean cultivars				
Fuego	50:50	74.93^{b}	115.69^{b}	95.27
Maris Bead	50:50	77.04^{a}	122.37^{a}	99.59
SED (1 df)	-	0.697***	2.949 *	-
P-value	-	<0.001	0.002	-

*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; SED, standard error of the difference of mean; df, degrees of freedom.*

6.5*a* Weed dry weights

The combined analysis of variance showed that cropping seasons had no effect on the transformed weed dry weight indicating that seasonal effects were consistent between cropping seasons (Appendix 5.1). Across the cropping seasons, cropping system had a greater (P<0.001) effect on weed dry weight (Table 6.6a). The sole cropping system (4.02 g m^{-2}) accumulated 58.8% higher transformed weed dry weights than the bi-cropping system (2.53 g m^{-2}). Across the cropping seasons, drilling patterns had a greater (P<0.001) effect on transformed weed dry weights (Table 6.6a). The broadcast bi-cropping treatment (3.61 g m^{-2}) accumulated 61.4% higher transformed weed dry weight than the alternate rows bi-cropping treatments (2.23 g m^{-2}). However, the transformed weed dry weights was (P<0.001) affected by the drilling patterns x year interaction (Appendix 5.1; Table 6.6a). In the 2015 cropping season, the effect of drilling patterns on transformed weed dry weights only occurred at 87 DAS while in the 2016 cropping season, the effects of drilling patterns on transformed weed dry weights occurred both at 51 DAS and 73 DAS (Appendix 5.1; Table 6.6a).

Table 6.6a: The effects of drilling patterns and bean cultivars on transformed weed dry weight (g m^{-2}) at different times of the cropping season in 2015 and 2016

		Weed dry weight (g m^{-2})				
Treatments	Mix-proportion	56 DAS 2015	51 DAS 2016	87 DAS 2015	73DAS 2016	Across seasons mean
Drilling pattern						
1x1	50:50	1.55[2.54]	2.04^{b} [4.36]	2.59^{b}[6.91]	2.11^{b}[5.00]	2.07^{b}[4.70]
2x2	50:50	2.20[5.22]	2.09^{b} [4.52]	2.35^{b}[5.61]	2.22^{b}[5.07]	2.22^{b}[5.10]
3x3	50:50	1.96[3.96]	2.27^{b} [5.28]	2.78^{b}[7.88]	2.67^{b}[7.30]	2.42^{b}[6.10]
Broadcast	50:50	1.89[4.48]	2.95^{a} [9.24]	3.84^{a}[15.13]	5.03^{a}[27.13]	3.61^{a}[13.99]
SED (3 df)	-	0.328ns	0.224*	0.248**	0.489***	0.255*
P-value	-	0.609	0.041	0.002	<0.001	0.036
Cropping systems						
Bi-crop mean	50:50	1.90^{c}[4.05]	2.34^{c} [5.85]	2.88^{c}[8.88]	3.01^{c}[11.12]	2.53^{c}[7.48]
Sole crop (wheat)	100	2.55^{b}[8.00]	2.65^{b}[7.07]	4.24^{b}[18.42]	3.42^{b}[12.22]	3.33^{b}[9.88]
Sole crop (beans)	100	3.12^{a}[11.10]	5.18^{a} [27.24]	5.54^{a}[30.88]	4.36^{a}[20.75]	4.71^{a}[22.47]
SED (1 df)	-	0.243**	0.164***	0.184***	0.362**	0.279***
P-value		0.007	<0.001	<0.001	0.005	<0.001
Bean cultivars						
Fuego	50:50	1.83[3.83]	2.46[6.35]	2.99[9.58]	3.07[11.68]	2.59[7.86]
Maris Bead	50:50	1.97[4.27]	2.22[5.35]	2.78[8.18]	2.94[10.57]	2.48[7.09]
SED (1 df)	-	0.402ns	0.272ns	0.304ns	0.598ns	0.312ns
P-value	-	0.310	0.993	0.089	0.375	0.188

*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; df, degrees of freedom; DAS, days after sowing. [ ] Data was subjected to square root √(x+0.5) transformation and figures in parenthesis are the means of original values.*

6.5*b* Weed smothering efficiency (WSE)

WSE was (P<0.001) affected by cropping seasons (Appendix 5.1; Table 6.6b). The effect of the cropping seasons on WSE occurred only at 87 DAS in the 2015 season. During the 2016 season, the effect of the seasons on WSE occurred at 51 DAS (Table 6.6b). WSE was (P<0.05) affected by drilling patterns x year (Table 6.6b). During the 2015 cropping season, the alternate rows had higher WSE effect than broadcast bi-cropping treatment. During the same season the 3x3 alternate row bi-cropping treatments had reduced effect on WSE compared to 1x1 and 2x2 alternate rows bi-cropping treatments. During the 2016 cropping season, the alternate rows outperformed broadcast treatment on WSE (Table 6.6b). The bean cultivar x year interaction had no effect on WSE (Appendix 5.1).

Table 6.6b: The effects of drilling patterns and bean cultivars on weed smothering efficiency (%) at different times of the season (DAS) in 2015 and 2016 spring seasons

		Weed smothering efficiency (%)				
Treatments	Mix-proportion	56 DAS	51 DAS	87 DAS	73 DAS	Mean
Drilling patterns		2015	2016	2015	2016	
1x1	50:50	76.6	84.1[a]	73.9[a]	78.1	76.0
2x2	50:50	68.2	83.1[a]	79.1[a]	78.1	78.6
3x3	50:50	61.9	80.5[a]	70.0[b]	81.9	76.0
Broadcast	50:50	77.0	66.9[b]	42.8[c]	76.5	59.6
Bi-crop mean	50:50	70.9	78.7	66.5	78.6	72.6
SED (3 df)	-	8.120ns	4.600**	6.740***	5.650ns	-
P-value	-	0.218	0.004	<0.001	0.798	
Bean cultivars						
Fuego	50:50	73.9[a]	76.8[b]	64.1	82.0[a]	73.1
Maris Bead	50:50	68.0[b]	80.6[a]	68.8	75.3[b]	72.0
SED (1 df)	-	5.740*	3.250*	4.770ns	4.000*	-
P-value	-	0.042	0.027	0.400	0.048	-

*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; df, degrees of freedom; DAS, days after sowing*

6.5c Weed N uptake

The combined analysis of variance showed that the cropping seasons had no effect on transformed weed N uptake (Appendix 5.1). Across the cropping seasons, cropping systems had a greater (P<0.001) effect on transformed weed N uptake (Table 6.7). Across the seasons, the sole cropping system had the highest (1.98 kgN ha^{-1}) transformed weed N accumulation compared to the bi-cropping system (1.36 kgN ha^{-1}). Across the cropping seasons, the sole wheat cropping system (1.53 kgN ha^{-1}) outperformed the sole bean cropping system (2.44 kgN ha^{-1}) on reducing weed N uptake from the production system.

Across the cropping seasons, the transformed weed N uptake was ($P<0.05$) affected by the drilling patterns (Table 6.7). The alternate rows bi-cropping treatments (1.2 kgN ha^{-1}) outperformed broadcast bi-cropping treatment (1.8 kgN ha^{-1}) by minimising N loss from the production system through weeds by 49.1%. However, the effect of the alternate rows bi-cropping treatments on transformed weed N uptake was similar. Across the cropping seasons the bean cultivars had no effects on transformed mean weed N uptake.

The transformed weed N uptake was ($P<0.05$) affected by the drilling patterns x year interactions (Table 6.7). During the 2015 season, the effect of drilling patterns on transformed weed N uptake was observed only at 87 DAS while in 2016 season it was observed at both 51 and 73 DAS. During the same season, the 2x2 alternate rows treatments (1.17 kgN ha^{-1}) had the lowest transformed weed N uptake compared to the 1x1 (1.26 kgN ha^{-1}) and the 3x3 (1.45 kgN ha^{-1}) alternate row bi-cropping treatments. During the 2016 cropping season, the alternate rows bi-cropping treatments had higher transformed weed N uptake than broadcast bi-cropping treatment both at 51 and 73 DAS.

Table 6.7: Effects of cropping systems, drilling patterns and bean cultivars on transformed aboveground shoot weed N uptake (kgN ha^{-1}) at 51 and 73 DAS; in 2015 and 2016 spring seasons

		Shoot weed N uptake (kgN ha^{-1})				
Treatment	Mix-proportion	56 DAS 2015	51 DAS 2016	87 DAS 2015	73 DAS 2016	Across seasons mean
Drilling patterns						
1x1	50:50	1.02 [1.09]	1.08^{b}[1.25]	1.26^{c}[1.65]	1.05^{b}[1.24]	1.11^{b}[1.30]
2x2	50:50	1.44 [2.22]	1.02^{b}[1.26]	1.17^{d}[1.39]	1.11^{b}[1.30]	1.20^{b} [1.54]
3x3	50:50	1.28 [1.71]	1.20^{b}[1.49]	1.45^{b}[2.18]	1.34^{b}[1.86]	1.32^{b} [1.81]
Broadcast	50:50	1.23 [1.89]	1.56^{a}[2.66]	1.92^{a}[3.80]	2.51^{a}[6.83]	1.81^{a} [3.80]
SED (3 df)	-	0.214ns	0.126***	0.143***	0.249	0.151*
P-value	-	0.620	<0.001	<0.001	<0.001	0.050
Cropping systems						
Bi-crop mean	50:50	1.24^{c}[1.87]	1.23^{c}[1.56]	1.45^{c}[2.18]	1.50^{c}[3.16]	1.36^{c}[3.16]
Sole crop (wheat)	100	0.86^{b}[0.78]	1.39^{b}[1.97]	2.17^{b}[4.76]	1.70^{b}[3.00]	1.53^{b}[2.63]
Sole crop (beans)	100	2.08^{a}[4.78]	2.73^{a}[7.69]	2.74^{a}[7.63]	2.19^{a}[5.37]	2.44^{a}[6.37]
SED (1 df)	-	0.158**	0.093***	0.106***	0.185	0.079***
P-value	-	0.007	<0.001	<0.001	0.016	<0.001
Bean cultivars						
Fuego	50:50	1.20[1.63]	1.30[1.81]	1.49[2.39]	1.54[3.25]	1.38[2.20]
Maris Bead	50:50	1.29[1.83]	1.17[1.52]	1.41[2.13]	1.47[3.39]	1.34[2.02]
SED (1 df)	-	0.262ns	0.155ns	0.175ns	0.306ns	0.1847ns
P-value	-	0.332	0.098	0.819	0.323	0.708

*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; df, degrees of freedom; [ ] DAS, days after sowing. Data was subjected to square root √(x+0.5) transformation and figures in parenthesis are the means of original values.*

6.7 Grain yield and components

6.7.1 Wheat performance

Cropping systems

The combined analysis of variance showed that cropping seasons had a greater (P<0.001) effect on wheat yield (Appendix 5.2). The wheat grain yield was 29.5% higher in the 2016 than in the 2015 copping season. The straw yield was 53.7% higher in the 2016 than in the 2015 season.

The wheat yield and harvest index was (P<0.001) affected by the cropping system x year interactions (Table 6.8; Appendix 5.2). In both years, the sole cropping system outperformed the bi-cropping system on wheat yield and components. In 2015 cropping season, the bi-cropping system had higher harvest index than the sole cropping system. In the 2016 cropping season, the sole cropping system had higher harvest index than the bi-cropping system.

Drilling patterns

The combined analysis of variance showed that cropping seasons had a greater ($P<0.001$) effect of drilling patterns on wheat growth and development (Appendix 5.2). However, the drilling patterns x year interactions had no effect wheat grain yield and its components (Table 6.8).

Table 6.8: The effects of cropping systems, drilling patterns and bean cultivars on wheat yield and components (t ha^{-1}) for forage production in 2015 and 2016 spring seasons

Treatments	Mix-proportion	Total wheat ear yield (t ha^{-1})			Total wheat straw yield (t ha^{-1})			Total wheat grain yield (t ha^{-1})			1000 seed weight (g)			Total wheat biomass yield (t ha^{-1})			Wheat harvest index (%)		
Drilling patterns		2015	2016	Mean	2015	2016	Mean	2015	2016	Mean	2015	2016	mean	2015	2016	mean	2015	2016	Mean
1x1	50:50	3.0	2.2	2.6	2.6	2.8	2.7	2.4	1.6	2.0	40.4	34.8^{a}	37.6	5.6	5.0	5.3	43	32	37
2x2	50:50	3.1	2.3	2.6	2.5	2.5	2.5	2.4	1.7	2.0	41.5	34.1^{a}	37.9	5.6	4.8	5.2	43	35	39
3x3	50:50	2.8	2.2	2.5	2.3	2.7	2.5	2.2	1.6	1.9	42.6	32.5^{b}	37.5	5.1	4.9	5.0	43	33	38
Broadcast	50:50	2.8	2.1	2.5	2.6	2.9	2.7	2.2	1.7	1.9	41.7	35.4^{a}	38.5	5.4	5.0	5.2	41	34	37
SED (3 df)	-	0.197ns	0.116ns	-	0.210ns	0.191ns	-	0.167ns	0.151ns	-	1.455ns	0.922**	-	0.332ns	0.266ns	-	2.2ns	2.0ns	-
P-value	-	0.230	0.729	-	0.100	0.074	-	0.138	0.891	-	0.483	0.002	-	0.422	0.091	-	0.841	0.175	-
Cropping systems																			
Bi-crop mean	50:50	2.9	2.1	2.5	2.5^{b}	2.7^{b}	2.6^{b}	2.3	1.7^{b}	2.0	41.5	34.2^{b}	37.9	5.4	4.8^{b}	5.1^{b}	43^{a}	35^{b}	39
Sole crop	100	2.7	2.0	2.4	2.9^{a}	5.6^{a}	4.2^{a}	2.1	4.0^{a}	3.1	40.3	35.9^{a}	38.1	5.6	7.6^{a}	6.6^{a}	38^{b}	53^{a}	45
SED (1 df)	-	0.171ns	0.141ns	-	0.182*	0.166***	-	0.144ns	0.131***	-	1.675ns	0.799*	-	0.287ns	0.230***	-	1.9**	1.8*	-
P-value	-	0.306	0.241	-	0.022	<0.001	-	0.203	<0.001	-	0.377	0.037	-	0.382	<0.001	-	0.008	0.047	-
Bean cultivars																			
Fuego	50:50	2.9	2.2	2.6	2.5	2.78	2.6	2.3	1.68	2.0	42.4	34.4	38.5	5.4	4.9	5.1	43	34	38
Maris Bead	50:50	2.9	2.1	2.5	2.4	2.75	2.6	2.3	1.59	1.9	40.7	34.0	37.5	5.3	4.8	5.0	43	33	38
SED (1 df)	-	0.179ns	0.148ns	-	0.192ns	0.175ns	-	0.152ns	0.138ns	-	1.529ns	0.842ns	-	0.303ns	0.243ns	-	2.0ns	1.9ns	-
P-value		0.880	0.135	-	0.262	0.825	-	0.713	0.075	-	0.084	0.494	-	0.111	0.094	-	0.244	0.075	-

*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; df, degrees of freedom. Total biomass yield was calculated as the sum of total straw and total ear yields (t ha^{-1}).*

6.7.2 Bean performance

Cropping systems effect

The combined analysis of variance showed that the cropping seasons had a greater (P<0.001) effect on the performance of the bean crop yield and its components (Appendix 5.2). The 2016 cropping season had higher bean straw and total bean biomass yield over the 2015 cropping season. The 2015 cropping season had higher bean seed yield over the 2016 cropping season (Table 6.9). The cropping system x year interactions had a greater (P<0.001) effect on the bean straw, seed and total bean biomass yield (Table 6.9). In both cropping seasons, the sole cropping system out yielded the bi-cropping system by 165%, 107% and 106% for bean straw, seed and total biomass yield respectively.

Drilling patterns effect

The combined analysis of variance showed that the cropping seasons had a greater (P<0.001) effect on the performance of the drilling patterns (Appendix 5.2). The drilling patterns in the 2016 season resulted in improved bean growth and development than in the 2015 cropping season. The alternate row treatments outperformed the broadcast bi-cropping treatments on bean seed and straw yields in both seasons.

Bean cultivars effect

The bean cultivar x year interactions had significant effect only on harvest index, 100 bean seed weight and total bean biomass. Fuego had higher harvest index than Maris Bead in the 2015 cropping season. In both cropping seasons, Fuego had higher 100 seed weight than Maris Bead. Maris Bead had higher total biomass than Fuego in the 2016 cropping season.

Table 6.9: The effects of cropping systems, drilling patterns and bean cultivars on bean seed yield and its components (t ha^{-1}) in 2015 and 2016 spring seasons

Treatments	Mix-proportion	Total bean Pod yield (t ha^{-1})			Total bean straw yield (t ha^{-1})			Total bean seed yield (t ha^{-1})			100 bean seed weight (g)			Total bean biomass yield (t ha^{-1})			Bean harvest index (%)		
Drilling patterns		2015	2016	Mean	2015	2016	Mean	2015	2016	Mean	2015	2016	Mean	2015	2016	mean	2015	2016	mean
1x1	50:50	1.3^{a}	-		0.491	1.76^{a}	1.12	0.970^{a}	1.09^{a}	1.030	59.1	32.2	45.7	1.8^{a}	2.86^{a}	2.3	53	43	47
2x2	50:50	1.2^{a}	-		0.587	1.80^{a}	1.20	0.977^{a}	1.28^{a}	1.129	54.5	32.2	43.4	1.8^{a}	3.08^{a}	2.4	52	46	47
3x3	50:50	1.1^{a}	-		0.522	1.90^{a}	1.20	0.863^{a}	1.13^{a}	0.997	59.3	32.9	45.0	1.6^{a}	3.04^{a}	2.3	51	40	46
Broadcast	50:50	0.6^{b}	-		0.377	0.96^{b}	0.70	0.447^{b}	0.86^{b}	0.654	54.5	32.7	44.0	0.9^{b}	1.83^{b}	2.3	50	44	47
SED (3 df)	-	0.165***	-		0.084ns	0.269**	-	0.119***	0.102**	-	3.490ns	0.785ns	-	0.218***	0.270***	-	2.4ns	4.3ns	-
P-value	-	<0.001	-		0.102	0.003	-	<0.001	0.002	-	0.313	0.772	-	<0.001	<0.001	-	0.586	0.337	-
Cropping systems																			
Bi-crop mean	50:50	1.1^{a}	-		0.494^{b}	1.61^{b}	1.05	0.814^{b}	1.01^{b}	0.985	56.8^{a}	32.5	44.5	1.5^{b}	2.60^{b}	2.0	52	42^{a}	47
Sole crop	100	3.4^{b}	-		1.3^{a}	4.30^{a}	2.79	2.7^{a}	1.30^{a}	2.044	48.6^{b}	32.8	42.6	4.8^{a}	5.60^{a}	5.2	55	24^{b}	40
SED (1 df)	-	0.131***	-		0.067***	0.212***	-	0.094***	0.080*	-	2.760**	0.620ns	-	0.172***	0.213***	-	3.9ns	3.4***	-
P-value	-	<0.001	-		<0.001	<0.001	-	<0.001	0.014	-	0.004	0.655	-	<0.001	<0.001	-	0.085	<0.001	-
Bean cultivars																			
Fuego	50:50	1.1	-		0.490	1.51	1.00	0.826	1.01	0.984	67.1^{a}	35.1^{a}	50.8	1.5	2.50^{b}	2.0	53^{a}	42	49
Maris Bead	50:50	1.0	-		0.498	1.71	1.11	0.802	1.19	0.986	46.5^{b}	29.9^{b}	38.3	1.5	2.89^{a}	2.2	50^{b}	43	46
SED (1 df)	-	0.185ns	-		0.094ns	0.300ns	-	0.133ns	0.114ns	-	3.900***	0.877***	-	0.244ns	0.302*	-	2.7**	4.8ns	-
P-value	-	0.678	-		0.051	0.181	-	0.892	0.051	-	<0.001	<0.001	-	0.234	0.044	-	0.002	0.494	-

*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; df, degrees of freedom. In 2015, total bean biomass was calculated as the sum of total pod and straw yields (t/ha); In 2016, total bean biomass was calculated as the sum of total bean straw and total grain yields (t/ha).*

6.8 Biological efficiency of bi-cropping systems

6.8.1 Land Equivalent Ratio (LER)

The combined analysis of variance showed that the LER was (P<0.001) affected by cropping seasons (Appendix 5.2). The LER of 1.50 in the 2015 cropping season was higher than the LER of 1.08 in the 2016 cropping season (Table 6.10). The LER in the 2015 showed the advantage of the bi-cropping system over the sole cropping system because it was above the unitary value of 1.0. The LER in the 2016 cropping season showed no advantage of bi-cropping systems was because it was below the unitary value of 1.0.

The drilling patterns x bean cultivar interaction had a greater (P<0.001) effect on the LER (Figure 6.2). Fuego had higher LER above the unitary value of 1.0 than Maris Bead under the same 2x2 alternate row bi-cropping treatment. The faba bean rust disease outbreak in the 2016 cropping might have contributed to the outcome of LER differences between the bean cultivars.

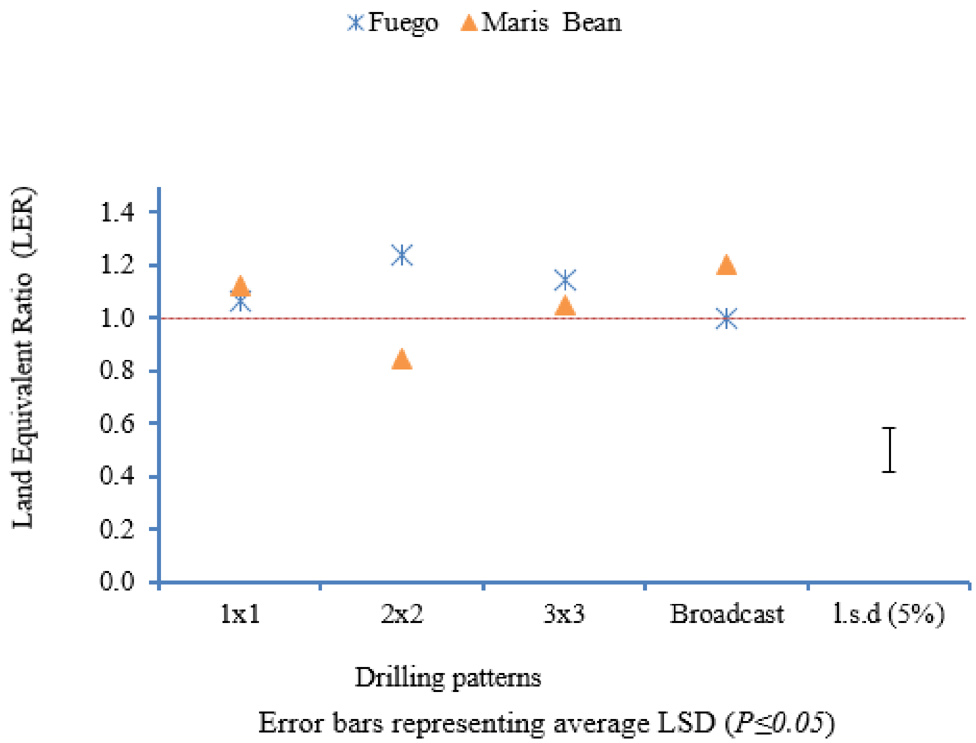


Figure 6.2: The Drilling patterns x bean cultivar interactions on mean LER across two spring experimental cropping seasons (2015 and 2016)

Table 6.10: Land equivalent ratio (LER) of bi-cropping compared to sole cropping for 2015 and 2016 cropping seasons influenced by cropping systems, drilling patterns and bean cultivars in 2015 and 2016 cropping seasons

		Partial Land Equivalent Ratio ($PLER_N$)				Total Land Equivalent Ratio (LER_N)			Land saving (%)	
Treatments	Mix-proportion	Wheat ($PLER_{wheat}$)	Bean ($PLER_{bean}$)	Wheat ($PLER_{wheat}$)	Bean ($PLER_{bean}$)	($PLER_{bean}$+ $PLER_{wheat}$)			-	
Drilling patterns		2015	2015	2016	2016	2015	2016	mean	2015	2016
Sole crop	100	0.500	0.500 [c]	0.500	0.500	1.000 [d]	1.000	1.000	-	-
1x1	50:50	1.205	0.404 [a]	0.557	0.537	1.609 [a]	1.094	1.351	37.8	8.5
2x2	50:50	1.248	0.387 [a]	0.570	0.472	1.635 [a]	1.042	1.333	38.8	4.0
3x3	50:50	1.136	0.359 [a]	0.582	0.512	1.495 [b]	1.095	1.290	33.1	8.6
Broadcast	50:50	1.102	0.189 [b]	0.540	0.559	1.291 [c]	1.099	1.215	22.5	9.0
Bi-crop mean	50:50	1.173	0.335	0.562	0.520	1.507	1.082	1.297	33.6	7.5
SED (3 df)	-	0.055 ns	0.071 **	0.038ns	0.168ns	0.085 **	0.087ns	-	-	-
P-value	-	0.061	0.023	0.723	0.723	0.002	0.902	-	-	-
Bean cultivars										
Fuego	50:50	1.190	0.341	0.561	0.548	1.109	1.109	1.328	-	-
Maris Bead	50:50	1.155	0.328	0.563	0.492	1.055	1.055	1.267	-	-
SED (1 df)	-	0.081ns	0.0498ns	0.027ns	0.056ns	0.062ns	0.062ns	-	-	-
P-value	-	0.382	0.795	0.938	0.329	0.433	0.395	-		

*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; df, degrees of freedom; LER_N, land equivalent ratio for nitrogen; $PLER_N$, partial equivalent ratio for nitrogen.*

6.9 Competition indices

6.9.1 Aggressivity (A)

Across the cropping seasons the aggressivity values for the wheat bi-crops had positive signs while the bean bi-crops had negative signs (Table 6.11). The positive signs meant that the wheat bi-crops acquired more resources than the faba bean bi-crops from the same production system. In both cropping seasons, aggressivity values were greater from the 2x2 alternate row bi-cropping treatments than other alternate rows in both cropping systems. The greater the aggressivity numerical value, the bigger the differences between actual and expected yields as a result of efficient utilisation of ecological resources (Wahla *et al.*, 2009).

The lower aggressivity values in both cropping seasons for both cropping systems were obtained from the 1x1 and 3x3 alternate rows bi-cropping treatments. The lower aggressivity values indicated the likelihood of interspecific competition for available resources (Mariotti *et al.*, 2009).

In general, the results have shown higher aggressivity values in the 2015 than in the 2016 cropping season (Table 6.11). This demonstrated the advantage of bi-cropping systems under dry conditions (Semere and Froud-Williams, 2001).

Table 6.11: 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 (A_{w1})	Fuego (A_{FG})	Wheat (A_{w2})	Maris Bead (A_{MB})	Wheat ($(A_{w1+}A_{w2})/2$)	Legume ($(A_{fg+}A_{mb})/2$)
			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

A_{FG} and A_{MB} are Aggressivity indices for Fuego and Maris Bead bean cultivars in mixture with wheat (A_w).

6.9.2 Relative Crowding Coefficient (K)

In both cropping seasons, the product *K* coefficient values for the wheat was greater than the beans which is an indication of the cereals' competitive ability over the legumes crops (Table 6.12). In 2015, product *K* coefficient values for both cropping systems were above the unitary value of 1.0 indicating the advantage of bi-cropping systems over sole cropping systems (Table 6.12).

During the 2016 season, the 1x1 and 2x2 alternate rows in wheat/Fuego bean showed no advantage of crop mixture because the product *K* coefficient values were equal to unitary value of 1.0. Under the same cropping system, the 3x3 and broadcast showed disadvantage of crop mixture because the product *K* coefficient values were below the unitary value of 1.0 (Table 6.12). During the 2016 season, under wheat/Maris Bead bi-cropping systems, all alternate row treatments had their product *K* coefficient values above the unitary value of 1.0 showing advantage of crop mixtures. Under the same cropping system, the broadcast bi-cropping treatments had the product *K* coefficient values below the unitary value of 1.0 indicating the disadvantage of crop mixtures. The relative crowding coefficient values above and below unitary value of 1.0 indicates the advantage and disadvantage of bi-cropping systems respectively over sole cropping systems.

Table 6 .12: Relative Crowding Coefficient (K) of wheat/bean bi-cropping systems as influenced by drilling patterns and bean cultivars in 2015 and 2016 cropping seasons

	Relative Crowding Coefficient (K)					
Drilling patterns	Wheat (K_{w1})	Fuego (K_{FG})	Fuego ($K_{w1}*K_{FG}$)	Wheat (K_{w2})	Maris Bead (K_{MB})	Maris Bead ($K_{w2}*K_{MB}$)
			Spring 2015			
1x1	7.189	0.761	5.472	9.955	0.556	5.537
2x2	8.535	0.597	5.094	7.807	0.489	3.819
3x3	16.719	0.700	11.710	7.077	0.473	3.347
Broadcast	6.694	0.204	1.366	6.910	0.222	1.534
			Spring 2016			
1x1	1.108	0.989	1.095	1.049	1.769	1.856
2x2	1.057	0.984	1.040	1.682	0.852	1.432
3x3	1.081	0.876	0.947	1.687	0.947	1.563
Broadcast	1.073	0.523	0.562	1.228	0.456	0.559

K_{FG} and K_{MB} are relative crowding coefficients of crop Fuego and Maris Bead bean cultivars bi-cropped with wheat (K_w).

6.10 Forage quality

6.10.1 Wheat crude protein content

Wheat straw

The combined analysis of variance showed that wheat crude protein content in the straw was ($P<0.001$) affected by cropping seasons (Appendix 5.3). The crude protein content in wheat straw in the 2016 cropping season was 44.9% higher than in the 2015 cropping season. In both cropping seasons, bi-cropping systems had higher wheat straw crude protein content than sole cropping systems (Table 6.13).

The bean cultivars x year interaction ($P>0.05$) did not affect wheat straw crude protein content. However, in the 2016 season, Fuego outperformed ($P<0.05$) Maris Bead by 9% on crude protein content in wheat straw (Table 6.13).

Wheat grain

The combined analysis of variance showed that cropping seasons had a greater ($P<0.001$) effect on the wheat grain crude protein content (Appendix 5.3). The 2016 cropping season had 32.1% higher wheat grain crude protein content than in the 2015 cropping season. In both cropping seasons, bi-cropping systems had significantly higher wheat grain crude protein content than sole cropping systems (Table 6.13).

Both the year x drilling patterns and year x bean cultivar interactions had no effect on crude protein content in the wheat grain (Table 6.13).

6.10.2 Wheat protein yield

The wheat protein yield was ($P<0.001$) affected by cropping seasons (Appendix 5.3). The seasonal effect in the 2016 cropping season resulted in higher protein yield in the straw, grain and total biomass than in the 2015 cropping season. The cropping system x year interactions had a greater ($P<0.001$) effect on wheat straw, grain and total biomass protein yield (Table 6.13). In the 2015 cropping season, the sole cropping systems had higher protein yield than in the 2016 cropping season. During the 2016 season bi-cropping systems had higher protein yield than sole cropping systems for all the yield components. The drilling patterns x year interaction had no effect on wheat straw protein yield. However, the seasonal effect for the drilling patterns was higher in the 2016 than in the 2015 cropping season except for grain protein yield.

Table 6.13: The effects of drilling patterns and bean cultivars on mean wheat crude protein content (g kg^{-1} DM) and protein yield (kg ha^{-1}) adjusted at 15% moisture content for fodder production, in 2015 and 2016 spring seasons.

		Wheat grain crude protein content (g kg^{-1} DM)				Protein yield (kg ha^{-1})							
		Straw	Straw	Grain	Grain	Wheat straw		Wheat grain		Total biomass		HI (%)	
Drilling patterns		2015	2016	2015	2016	2015	2016	2015	2016	2015	2016	2015	2016
1x1	50:50	25.4	40.7	94.0	134.0	65.8	115.5	232.5	225.3	298.3	340.8	78	65^{b}
2x2	50:50	25.1	37.2	96.6	132.8	64.4	95.4	240.2	225.1	304.6	320.5	79	70^{a}
3x3	50:50	25.5	41.0	96.2	140.3	55.4	111.2	216.5	235.0	271.6	346.2	80	67^{b}
Broadcast	50:50	25.4	38.2	97.1	145.1	64.6	101.9	219.1	271.9	283.7	373.8	77	71^{a}
SED (3 df)	-	1.891ns	2.119ns	3.142ns	10.150ns	7.93ns	7.03ns	14.39ns	31.56ns	19.02ns	33.70ns	1.90ns	2.41*
P-value	-	0.920	0.172	0.644	0.303	0.369	0.184	0.170	0.251	0.176	0.312	0.456	0.032
Cropping systems													
Bi-crop mean	50:50	24.8^{a}	39.3^{a}	96.0^{a}	134.5^{a}	62.6^{a}	106.0^{b}	227.0^{a}	238.2^{b}	289.3^{a}	344.2^{b}	78	68^{b}
Sole crop	100	18.8^{b}	23.9^{b}	86.1^{b}	106.0^{b}	55.1^{b}	164.2^{a}	188.0^{b}	431.7^{a}	243.1^{b}	595.9^{a}	77	72^{a}
SED (1 df)	-	1.638***	2.119***	2.74***	11.710**	6.86***	6.08***	12.46**	27.33***	16.47**	29.19***	1.65ns	2.09*
P-value	-	<0.001	<0.001	<0.001	0.003	<0.001	<0.001	0.005	<0.001	0.009	<0.001	0.511	0.015
Bean cultivars													
Fuego	50:50	24.2	40.9^{a}	95.9	133.4	62.7	108.8	228.9	236.9	291.6	345.7	78	68
Maris Bead	50:50	25.6	37.5^{b}	96.10	142.70	62.4	103.2	225.2	241.8	287.7	345.0	78	69
SED (1 df)	-	1.726ns	2.234*	2.860ns	10.690ns	7.23ns	6.41ns	13.14ns	28.81ns	17.36ns	30.76ns	1.74ns	2.20ns
P-value	-	0.212	0.023	0.919	0.105	0.954	0.115	0.664	0.181	0.724	0.790	0.751	0.535

*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; df, degrees of freedom; DM, dry matter; HI, harvest index.*

6.10.3 Bean crude protein content

The combined analysis of variance showed that the cropping seasons did not affect (P>0.05) the bean crude protein content (Appendix 5.4).

Both the drilling pattern x year interactions; and the cropping systems x year interactions had no effect on bean crude protein content in the bean straw and grain (Table 6.14).

The bean seed crude protein content was (P<0.05) affected the bean cultivar x year interaction. Maris Bead had 8.1% higher bean seed crude protein content than Fuego in the 2015 cropping season.

6.10.4 Bean protein yield

Bean straw protein yield

The combined analysis of variance showed that the cropping seasons had a greater (P<0.001) effect on the bean straw protein yield (Appendix 5.4). In the 2016 cropping season the bean straw protein yield was 53.1% higher than in 2015 cropping season (Table 6.14). However, the bean straw protein yield was (P<0.001) affected by the cropping system x year interaction. The sole cropping system had higher bean straw protein yield than the bi-cropping system in the 2016 season (Table 6.14). Both the drilling patterns x year interactions; and the bean cultivars x year interactions had no effect (P>0.05) on bean straw protein yield. However, the drilling patterns in 2016 cropping season had 301.1% higher seasonal effects than in 2015 cropping season on bean straw protein yield (Table 6.14). The bean cultivars x year interactions had no effects on bean straw protein yield.

Bean seed protein yield

The bean seed protein yield was (P<0.001) affected by cropping seasons (Appendix 5.4). The bean seed protein yield was 46.2% higher in the 2015 than 2016 cropping season despite having good weather conditions in the 2016 cropping season. The bean seed protein yield was (P<0.001) affected by the cropping systems x year interactions (Table 6.14). The bean seed protein yield was higher in sole cropping systems than bi-cropping systems in both cropping seasons. The bean seed protein yield was (P<0.001) affected by the drilling patterns x year interactions (Table 6.14). The seasonal effect for drilling patterns was 26.9% higher in the 2016 than 2015 cropping season on bean seed protein yield. The alternate rows had

59.6% higher bean seed protein yield in the 2015 than 2016 cropping season. The bean cultivar x year interactions had no effect bean seed protein yield.

Bean protein yield harvest index

The combined analysis of variance revealed that cropping seasons had a greater ($P<0.001$) effect on the protein yield harvest index (Appendix 5.4). Bi-cropping systems outperformed sole cropping systems on protein harvest index in the 2016 cropping season. The 2015 cropping season had no effect on protein yield harvest index.

Table 6.14: The effects of cropping systems drilling, patterns and bean cultivars on mean bean crude protein content (g kg^{-1} DM) and protein yield (kg ha^{-1}) adjusted at 15% moisture content for fodder production in 2015 and 2016 spring seasons.

		Bean crude protein content (g kg^{-1} DM)				Protein yield (kg ha^{-1})							
Treatments	Mix- proportion	Bean straw		Bean seed		Bean straw		Bean seed		Total biomass		HI (%)	
Drilling patterns		2015	2016	2015	2016	2015	2016	2015	2016	2015	2016	2015	2016
1x1	50:50	65.7	32.19	266.0^{b}	280.8	32.1	56.3	291.0^{a}	308.0	324.0^{a}	365.0^{b}	88	84
2x2	50:50	76.8	30.38	279.2^{a}	271.6	44.6	55.0	271.0^{a}	351.0	315.0^{a}	406.0^{a}	85	86
3x3	50:50	73.1	30.45	268.2^{b}	279.6	38.6	58.5	269.0^{a}	320.0	307.0^{a}	378.0^{ba}	85	84
Broadcast	50:50	68.2	34.97	275.3^{a}	277.7	42.6	35.7	133.0^{b}	245.0	175.6^{b}	281.0^{c}	84	87
SED (3 df)	-	5.33ns	2.62ns	5.82*	7.47ns	8.31ns	13.86ns	43.30**	38.60ns	43.11**	38.33*	3.10ns	3.03ns
P-value	-	0.184	0.280	0.046	0.620	0.121	0.347	0.008	0.075	0.007	0.022	0.624	0.769
Cropping systems													
Bi-crop mean	50:50	70.9	32.00	272.2	277.4	35.0^{b}	51.4^{b}	241.0^{b}	306.0^{b}	276.0^{b}	357.0^{b}	86	85^{a}
Sole crop	100	68.1	32.39	271.5	273.7	89.7^{a}	139.6^{a}	727.0^{a}	356.0^{a}	817.0^{a}	496.0^{a}	88	71^{b}
SED (1 df)	-	4.21ns	2.00ns	4.60ns	5.90ns	6.57***	10.96***	34.30***	30.50***	37.30***	30.30***	2.45ns	2.39***
P-value	-	0.512	0.851	0.884	0.528	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	0.248	<0.001
Bean cultivars													
Fuego	50:50	74.0	31.27	261.5^{b}	276.0	36.7	47.6	216.0	280.0	252.7	328.0	85	85
Maris Bead	50:50	67.9	32.73	282.9^{a}	278.9	33.2	55.1	225.0	332.0	258.2	378.0	86	85
SED (1 df)	-	7.53ns	2.93ns	6.50***	8.35ns	9.29ns	15.49ns	48.5ns	43.20ns	52.7ns	42.9ns	3.47ns	3.39ns
P-value	-	0.130	0.484	<0.001	0.856	0.201	0.750	0.422	0.186	0.332	0.113	0.969	0.964

*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; df, degrees of freedom; HI, harvest index.*

6.11 N uptake

6.11.1 Wheat N uptake

The combined analysis of variance showed that the cropping seasons had a greater ($P<0.001$) effect on the wheat N uptake (Appendix 5.5). Higher N uptake in the wheat straw was recorded in the 2016 than 2015 cropping season. However, higher N uptake in the wheat grain was recorded in the 2015 than 2016 cropping season (Table 6.15). The cropping system x year interactions had a greater ($P<0.001$) effect on N uptake in the wheat straw and grain (Table 6.15). Bi-cropping systems outperformed the sole cropping systems on N uptake in the wheat grain in both cropping seasons. The N uptake in sole wheat cropping systems was higher than in bi-cropping systems only in the 2016 cropping season in the wheat straw and total wheat biomass.

The drilling pattern x year interaction did not affect ($P>0.05$) N uptake in the wheat plant.

The bean cultivar x year interactions did not affect ($P>0.05$) N uptake in the wheat plant.

Table 6.15: The effects of cropping systems, drilling patterns and bean cultivars on wheat nitrogen yield (kgN ha^{-1}) in 2015 and 2016 spring seasons

Treatments	Mix-proportion	Wheat Straw N yield (kgN ha^{-1})			Wheat Grain N yield (kgN ha^{-1})			Wheat Total N Yield (kgN ha^{-1})			Wheat N harvest index (%)		
Drilling patterns		2015	2016	Mean	2015	2016	Mean	2015	2016	Mean	2015	2016	mean
1x1	50:50	13.2	27.2	20.1	41.5	35.3	38.4	54.8	62.5	58.6	75	56	66
2x2	50:50	13.4	23.1	18.2	43.0	36.4	39.5	56.4	59.6	57.7	76	61	69
3x3	50:50	11.4	26.2	18.8	39.0	37.9	38.4	50.5	64.1	57.2	77	59	68
Broadcast	50:50	12.8	27.7	20.5	38.1	38.8	38.4	50.9	66.1	59.5	74	58	67
SED (3 df)	-	1.73ns	3.81ns	-	2.39ns	3.00ns	-	3.48ns	5.33ns	-	4.4ns	3.0ns	-
P-value	-	0.531	0.477	-	0.068	0.367	-	0.126	0.305	-	0.522	0.280	-
Cropping systems													
Bi-crop mean	50:50	12.7	26.0^{b}	19.4	40.4^{a}	37.1^{a}	38.7	53.1^{a}	63.1^{b}	58.3	76	58^{a}	67^{a}
Sole crop	100	12.5	69.6^{a}	41.0	34.7^{b}	31.4^{b}	33.1	47.2^{b}	101.0^{a}	93.1	74	31^{b}	52^{b}
SED (1 df)	-	1.50ns	3.30***	-	2.07**	2.19**	-	3.01*	4.61***	-	3.8ns	2.3***	-
P-value	-	0.878	<0.001	-	0.011	0.008	-	0.050	<0.001	-	0.280	<0.001	-
Bean cultivars													
Fuego	50:50	12.3	26.1	19.2	41.0	37.7	39.4	53.4	63.8	58.7	76	59	67
Maris Bead	50:50	13.1	26.0	19.6	39.8	36.6	38.2	52.9	62.6	57.8	75	58	66
SED (1 df)	-	1.58ns	3.48ns	-	2.10ns	2.18ns	-	3.18ns	4.80ns	-	4.0ns	2.4ns	-
P-value	-	0.432	0.980	-	0.378	0.460	-	0.828	0.656	-	0.194	0.716	-

*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; df, degrees of freedom; N, nitrogen.*

6.11.2 Bean N uptake

The bean N uptake was (P<0.001) affected by cropping seasons (Appendix 5.5). The seasonal effect was 46.7% higher in 2016 than 2015 cropping season on N uptake in the bean straw. In contrary, the seasonal effect was 35.0% higher in 2015 than 2016 cropping season on N uptake in the bean seed. In the 2015 cropping season bean N harvest index was 12.9% higher than in 2016 cropping season (Table 6.16). There was a highly (P<0.001) effect of cropping system x year interaction on N uptake in the bean plant (Table 6.16). In both cropping seasons, the sole cropping system outperformed the bi-cropping system on N uptake in the bean straw and grain by 174% and 104% respectively. Bi-cropping system had higher bean N harvest index over the sole cropping system by 23.5% in 2016 season cropping which revealed the higher performance of bi-cropping systems for bean seed N uptake than dry matter N accumulation.

The drilling patterns x year interaction had a greater (P<0.01) effect on N uptake in the bean straw and seed (Table 6.16). The effect of drilling patterns was higher in the 2016 than 2015 cropping season by 35.7% and 24.0% on bean straw and grain N uptake respectively. In both cropping seasons, the alternate row bi-cropping treatments outperformed broadcast bi-cropping treatments on bean straw and seed N uptake. The 2x2 alternate row bi-cropping treatments had the highest N uptake in the bean seed compared to other drilling patterns.

The bean cultivar x year interactions did not affect bean N harvest index.

Table 6.16: The effects of cropping systems, drilling patterns and bean cultivars on bean nitrogen yield (kgN ha^{-1}) in 2015 and 2016 spring seasons

Treatments	Mix-proportion	Bean straw N yield (kgN ha^{-1})			Bean Seed N yield (kgN ha^{-1})			Bean total N yield (kgN ha^{-1})			N harvest index (%)		
Drilling patterns		2015	2016	Mean	2015	2016	Mean	2015	2016	Mean	2015	2016	Mean
1x1	50:50	5.7	8.7^{a}	7.2	48.9^{a}	49.7^{b}	49.3	54.6^{a}	58.4^{c}	56.5	88	85	86.2
2x2	50:50	7.6	9.9^{a}	8.8	44.0^{a}	59.0^{a}	52.1	51.7^{a}	69.0^{a}	60.9	85	86	85.1
3x3	50:50	6.9	9.9^{a}	8.4	43.9^{a}	51.2^{b}	47.6	50.8^{a}	61.2^{b}	56.0	86	84	84.7
Broadcast	50:50	4.4	4.9^{b}	4.7	22.4^{b}	37.6^{c}	27.4	26.8^{b}	42.0^{d}	34.4	84	87	85.5
SED (3 df)	-	1.60ns	1.77*	-	8.49*	6.78*	-	9.14*	6.79**	-	3.1ns	2.8ns	-
P-value	-	0.221	0.030	-	0.020	0.039	-	0.018	0.006	-	0.511	0.614	-
Cropping systems													
Bi-crop mean	50:50	6.2^{b}	8.42^{b}	7.3	39.9^{b}	49.4^{b}	44.1	46.0^{b}	57.8^{b}	51.4	87	85^{a}	85.5
Sole crop	100	16.1^{a}	24.3^{a}	20.2	123.4^{a}	56.6^{a}	90.0	139.5^{a}	81.0^{a}	110.3	88	70^{b}	78.4
SED (1 df)	-	1.26***	1.40***	-	6.72***	5.43*	-	7.23***	5.37***	-	2.4ns	2.2***	-
P-value	-	<0.001	<0.001	-	<0.001	0.019	-	<0.001	<0.001	-	0.380	<0.001	-
Bean cultivars													
Fuego	50:50	6.5	7.8	7.2	42.2	44.3^{b}	42.6	48.8	52.1^{b}	49.8	86	85	85.3
Maris Bead	50:50	5.8	8.9	7.4	37.4	54.5^{a}	45.6	43.2	63.5^{a}	53.0	87	86	85.3
SED (1 df)	-	1.78ns	1.98ns	-	9.50ns	7.68*	-	10.22ns	7.60*	-	3.4ns	3.0ns	-
P-value	-	0.445	0.155	-	0.576	0.012	-	0.623	0.050	-	0.883	0.621	-

*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; df, degrees of freedom; N, nitrogen.*

CHAPTER 7

Nodulation and morphological root characteristics of faba bean *(Vicia faba)* varieties under sole bean and wheat/bean cropping systems

7.1 Introduction

Soil, climatic, crop, biotic and agronomic factors can impair nodulation and limit Biological Nitrogen Fixation (BNF) in legume-*Rhizobium* symbiotic relationships (Ahlam *et al.,* 2014).

7.1.1 Soil factors

Physical, chemical and biological soil properties can influence nodulation and BNF in leguminous crops (Ferguson *et al.,* 2013). Soil texture can influence water holding capacity which can affect the survival of nitrogen fixing microbes, nodulation and BNF (Mohammadi *et al.,* 2012). Loam and clay soils can improve BNF through effective nodulation than sandy soils. Low water holding capacity plays a bigger role in reducing nodule function and BNF in sandy soils (Singh and Shivakuma, 2010). Soil temperatures of 20-30 ^{o}C can determine the optimum nodule formation and BNF in legume-*Rhizobium* symbiotic associations (Reddel *et al.,* 1985). Higher concentrations of mineral soil nitrogen can inhibit *Rhizobium* infection, nodulation and BNF (Uddin *et al.,* 2008). However different leguminous crops species can respond differently to different concentrations of mineral soil nitrogen and its subsequent effect on nodulation (Daoui *et al.,* 2010; Anne-Sophie *et al.,* 2002). Waterlogged soil conditions can limit aerations in the rhizosphere which can further affect the survival of nitrogen-fixing microbes and BNF (Hungria and Vargas, 2000). Water stress conditions can inhibit nodule formation and it can result in nodule decay and inhibited BNF under prolonged conditions (Benjamin and Nielsen, 2006). Saline soil condition with Electrical conductivity (EC) of > 4 and Exchangeable Sodium Percentage (ESP) of < 15 can negatively affect legume establishment, growth and nodule formation (Kenenil *et al.,* 2010). The effective legume plant growth and BNF via the rhizobia bacterial species takes place at optimal soil pH range of 6.0-7.0. Soil pH below 6.0 is often associated with increased Aluminium and Magnesium concentrations which limit the availability of phosphorus and calcium which are key nutrient elements for legume growth, nodulation and effective BNF (Waluyo *et al.,* 2004).

7.1.2 Climatic factors

According to Brockwell *et al.* (1991), air temperature and light are the two important climatic determinants of nodulation and BNF in legumes-*Rhizobium* symbiotic associations. Extremely high and low air temperatures of >35°C and <25°C respectively can negatively affect nodulation and BNF under tropical conditions though other symbiotic systems can tolerate such extreme air temperature thresholds (Brockwell *et al.,* 1991). The ideal air temperature of 15-25 °C favours the optimum growth and nodulation of temperate legume crops (Sprent *et al*., 1983). Light plays an important role in regulating photosynthesis which directly influences nodulation and BNF (Hungria and Vargas, 2000).

7.1.3 Crop factors

Genetic variations among grain legumes can influence differences in nodulation and BNF capacities (Abaidoo *et al.*, 2007). Reports indicate that the variability among legume varieties can differ in influencing nodulation and BNF through their compatibility with the nitrogen-fixing microbes (Farnia *et al.*, 2005). The phenological and morphological traits of legumes can influence the amount of nitrogen biologically fixed. For instance nodulation and N_2 fixation in some grain legume crops starts as early as four weeks until leaf senescence while in other legumes, nodulation and N_2 fixation stops at pod filling (Griffiths and Lawes, 1977). Contrasting root architecture can influence nodulation and BNF (Li *et al.*, 2006). Finally, it has been reported that high-yielding legume varieties require rapid translocation of translocates and long period which can affect that rate of nodulation and BNF (Pandey, 1996).

7.1.4 Biotic factors

Biotic factors such as weeds, pests and diseases; and crop competitions can induce stress in legume cops which can adversely affect the formation of nodules (Niblack *et al.,* 2006). Weeds compete with the crop for light, moisture and nutrients which in turn cause stress on the bean plants and impair nodule formation and BNF. Weeds competition can reduce leaf area index and photosynthetic efficiency of the legume plants which may result in reduced energy for nodule formation and subsequent BNF (Singh *et al.,* 1999). Feeding and sucking insects' pests on the legume forage can deform the leaf size and reduce light interception which may reduce the required amount of energy for optimum production of nodules. Migratory or sedentary soil pests feeding on the roots of legume such as nematodes in soybean can induce stress on the root which can adversely affect nodule formation and BNF (Vincent, 1990).

7.1.5 Agronomic factors

Agronomic factors such as sowing date, cropping systems (bi-cropping and sole cropping), spatial arrangements, sowing density, irrigation, seed inoculation, pests and disease control; and tillage practices can influence the rate of nodulation and BNF in the rhizosphere (Siyeni, 2016).

Bi-cropping, as an agronomic factor, can influence the legume-*Rhizobium* symbiotic relationship and its subsequent effect on nodule characteristics and BNF. In cereal/legume mixtures, interspecific complementarity due to efficient use of nitrogen (N) sources improves nodulation and BNF (Gunes *et al.,* 2007). Even though interspecific complementarity on N use in low input cereal/legume crop mixtures improve nodulation and BNF, factors such as plant morphology, spatial arrangements, the density of component bi-crops and competition for light can determine nodulation and BNF (Konlan *et al.,* 2015; Achakzai, 2007; Nambiar *et al.,* 1983).

The two bean cultivars understudy differ in morphology and growth rates traits. It can be claimed that these bean varietal differences can determine nodulation and BNF activities in cereal/legume mixtures. Interspecific competition for environmental resources between bi-crop components can negatively affects nodulation and BNF (Niblack *et al.,* 2006). The drilling patterns which are being evaluated in this study can influence either competition or complementarity on resource-use which in turn can directly affect roots performance, nodulation and BNF. Based on the background information, the study was designed to achieve the following objectives:

1. To investigate the influence of cropping systems, drilling patterns and bean cultivars on the number of root nodules, their relative colour and contribution to BNF.
2. To investigate the influence of cropping systems, drilling patterns and bean cultivars on bean root growth characteristics such as root length and diameter.

7.2 Materials and methods

This study was conducted within the core experiment in the 2016 cropping season. The details of experimental design and treatments are stated in Chapter 3.0 under material and methods.

7.2.1 Study site

The site location, physiochemical edaphic and meteorological characteristics for 2016 cropping season are described in Chapter 3 of this thesis.

7.2.2 Experimental design and treatment description

The experimental design, study factors, treatments combinations and randomisation were exactly similar to the main experiment for 2016 cropping season as explained in Chapter 3 of this thesis.

7.2.3 Root assessments

According to Lesley *et al.* (2015) there are three major categories of methods for assessing roots in crops which include: Field methods (*photographs/drawings, trench, pinboard, auger/core, mesorhizotron, and above-ground rhizotron*); Container methods (*root washing, root rating, , horhizotron, minihorhizotron, rhizometer, hydraulic conductance flow meters*); and Digital imaging methods (*image analysing computer, winrhizo, root reader, NMR and X-ray CT*).

In this study the field method using the trench approach as also described by Schuurman and Goedewaagen, (1971) was used in combination with root washing method (Oliveira *et al.,* 2000). The trench approach in the field was used to initially extract the bean plants from the soil depth of 30 cm using the spades without disturbing the entire roots system. The primary and lateral roots were targeted for assessments because nodule distribution is mostly found within these roots (Plate 4.3). The bean roots and soil were separated with gentle washing using tap water with a water gun. The roots were covered in a plastic mesh during washing to minimise loss of the root nodules and bean roots (Plate 4.3) before root and nodule assessments in the laboratory (Plates 4.4).

The destructive bean plant sampling was randomly done in the central part of each experimental plot using a 1 m^2 quadrant area replicated twice.

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Plate 4.1. 1x1 alternate row treatment

Plate 4.2. 3x3 alternate row

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Plate 4.3. Extracted bean root nodules

Plate 4.4. Root nodule assessments

Plate 4.5. Digital calliper

Plate 4. Bean roots assessments

7.2.4 Data collection

Since two different the bean cultivars were used in the study as bi-crops, assessments were conducted at bean flowering growth stage to provide a fair comparison between bean cultivars. The method for assessing beans N_2 fixation was adopted from Uaboi-Egbenni (2010), Woomer *et al.* (2011) and Ndukwu *et al.* (2016).

7.2.4.1 Total mean number of nodules per bean plant

The total number of nodules per plant was counted from four randomly selected bean plants using a 1 m^2 quadrant. The total numbers of nodules were averaged to get a mean total number of nodules per plant for each plot.

7.2.4.2 Mean number of pink coloured root nodules

Root nodules were dissected using a razor blade to detect the nodule colour. Nodules with leghaemoglobin or pink to red colour indicated effective symbiotic relationship between the bean and the micro symbiont which indicated the ability of the bean to fix nitrogen (Ben *et al.,* 2002). The root nodules with white colour indicated ineffective symbiotic relationship with poor BNF (Ben *et al.* 2002). Leghaemoblobin can be defined as a plant protein that is responsible for the supply of oxygen to the nitrogen fixing bacteria especially in nitrogen fixing leguminous plants.

7.2.4.3 Bean root characteristic - root length and diameter (cm)

The bean root length was assessed from four randomly selected bean plants from 1 m^2 quadrant area using a ruler in centimetres. The root length measurements were taken from the bean primary roots. The root diameter was measured from the lateral or secondary roots using a digital calliper in millimetres (Plate 4.5).

7.3 Results

7.3.1 Total number of root nodules

The analysis of variance (ANOVA) showed that cropping systems had a greater ($P<0.05$) effect on the total number of root nodules (Table 7.1). The sole cropping system had a higher (39.0) total number of bean nodules per plant over the bi-cropping system (31.8) by 14.8%. The drilling patterns and bean cultivars did not have an effect ($P>0.05$) on the total number of nodules per plant.

7.3.2 Mean number of effective pink root nodules

Cropping systems, drilling patterns, bean cultivars and their interactions did not affect ($P>0.05$) the number of effective pink root nodules per plant (Table 7.1).

7.3.3 Mean proportion (%) of pink root nodules

The results showed that the mean numbers of white or ineffective nodules were higher than pink nodules or effective nodules in bi-cropping systems than sole cropping systems (Table 7.1).

Table 7.1: Total number of nodules, number of pink nodules and the relative proportion of pink nodules, influenced by cropping systems, drilling patterns and bean cultivars in 2016 cropping season.

Treatments	Mix-proportion	Total nodule number (Nodules plants^{-1})	No. of pink nodule (Pink nodules plant $^{-1}$)	Relative proportion of pink nodules (%)
Drilling patterns				
1x1	50:50	34.0	14.4	57.4
2x2	50:50	33.5	14.2	54.6
3x3	50:50	30.3	10.3	65.1
Broadcast	50:50	29.4	10.2	60.1
SED (3 df)	-	5.180ns	2.626ns	6.68ns
P-value	-	0.763	0.717	0.446
Cropping systems				
Bi-crop mean	50:50	31.8^{b}	11.5	59.3^{b}
Sole crop	100	39.0^{a}	12.2	70.2^{a}
SED (1 df)	-	4.090*	2.076ns	5.28*
P-value	-	0.050	0.207	0.044
Bean cultivars				
Fuego	50:50	35.5	12.7	58.6
Maris Bead	50:50	33.2	11.5	64.4
SED (1 df)	-	5.790ns	2.936ns	7.46ns
P-value	-	0.273	0.765	0.358

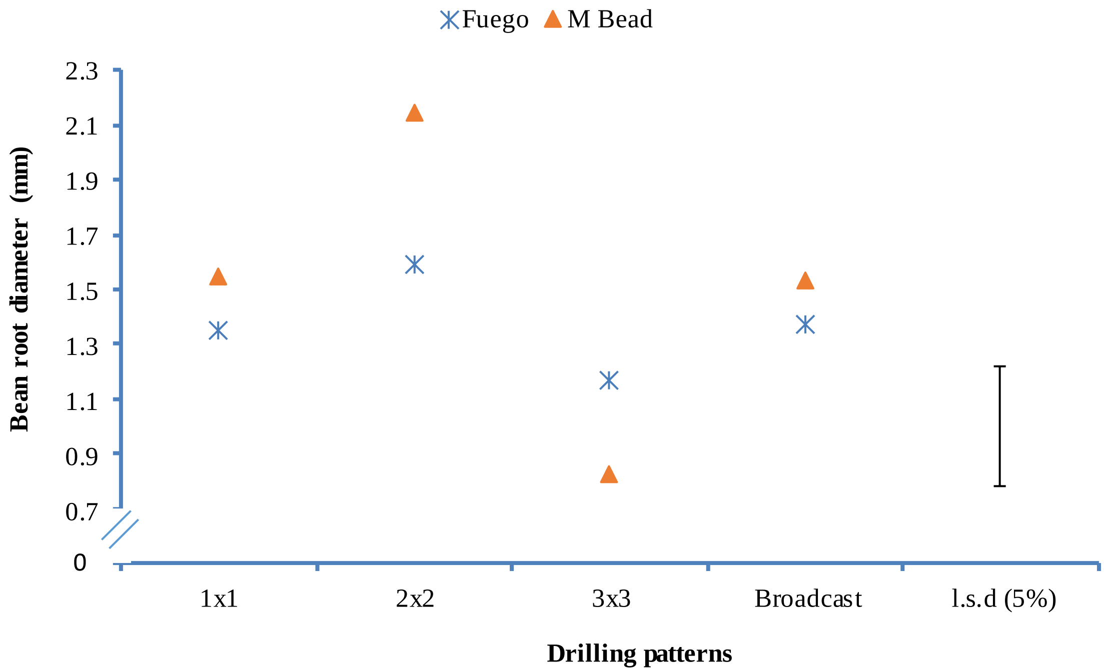
*Values with the same letter under the same parameter are not significantly different at P<0.05; *=P< 0.05; **=P< 0.01; ***=P< 0.001; ns = not significant at P<0.05; SED, standard error of difference of means; df, degrees of freedom.*

7.3.4 Mean bean root diameter

The bean root diameter was (P<0.001) affected by cropping systems. The sole bean cropping system had 55.5% thicker root diameter (2.24 mm) than the bi-cropping systems (1.44 mm), an indication that beans root spatial configuration changed with copping systems (Table 7.2).

The bean root diameter was (P<0.001) affected by the drilling patterns (Table 7.2). Drilling the bi-crops in alternate rows as 2x2 (1.87 mm) and 3x3 (0.99 mm) spatial arrangements had the highest and lowest mean diameter respectively. The 1x1 (1.44 mm) alternate row and broadcast (1.45 mm) bi-cropping treatments had similar effect on mean bean root diameter.

The bean root diameter was (P<0.05) affected by the drilling pattern x bean cultivar interaction (Figure 7.1). The bean root diameters were only affected at the 2x2 alternate row bi-cropping treatments than other drilling patterns treatments. Maris Bead had a higher mean root diameter than Fuego under the 2x2 alternate row bi-cropping treatments.



Error bars representing average LSD (*P≤0.05*)

Figure 7.1: The drilling pattern x bean cultivar interaction on the mean bean root diameter (mm), during 2016 spring cropping season.

<u>7.3.5 Mean bean length</u>

Cropping systems had no effect on the root length. The drilling patterns had a greater (P<0.01) effect on the bean root length (Table 7.2). Irrespective of the bean cultivars, the 1x1 (17.7 cm) alternate row bi-cropping treatments had and 3x3 (15.3 cm) longer bean roots lengths than the sole bean root length (16.4 cm). The 1x1 alternate row bi-cropping treatments had 7.9% longer roots than the sole bean cropping systems. The 3x3 alternate row bi-cropping treatments had 7.2% shorter root length than sole bean cropping systems. The 2x2 alternate rows bi-cropping treatments (16.2 cm) and the sole bean cropping systems has similar root lengths an indication of complementarity on resource-use efficiency.

The bean cultivars had a greater (P<0.001) effect on the bean root length. Maris Bead (18.3 cm) had 24.4% longer root length than Fuego (14.7 cm).

Table 7.2: The effects of cropping systems, drilling patterns and bean cultivars on the mean bean root diameter, and tap root length and root biomass in 2016 cropping season.

Treatments	Mix-proportion	Root diameter (mm)	Root length (cm)
Drilling patterns			
1x1	50:50	1.44[b]	17.70[a]
2x2	50:50	1.87[a]	16.20[b]
3x3	50:50	0.99[c]	15.30[d]
Broadcast	50:50	1.45[b]	16.90[b]
SED (3 df)	-	0.153***	0.625**
P-value	-	<0.001	0.003
Cropping systems			
Bi-crop mean	50:50	1.44[b]	16.50
Sole crop	100	2.24[a]	16.40
SED (1 df)	-	0.121***	0.494ns
P-value	-	<0.001	0.889
Bean cultivars			
Fuego	50:50	1.57	14.70[b]
Maris Bead	50:50	1.63	18.30[a]
SED (1 df)	-	0.171ns	0.699***
P-value	-	0.184	<0.001

*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 difference of means; df, degrees of freedom.*

7.4 Discussion

Total number of root nodules

The increased total number of nodules in sole cropping system than bean bi-crops from this study was probably influenced by significant reduction in interspecific interactions and early root establishment (Massawe *et al.*, 2016). The reduced number of nodules in bi-cropping systems may have been a competitive response of the beans to the competitive effect caused by the wheat bi-crop due to over dominance on resource acquisition (Mosses *et al.*, 2010). The findings concurred with Muhammad *et al*. (2012) who reported higher number of nodules per plant from mung bean *(Vigna radiata* L.) in the sole cropping system (9.87) than the bi-cropping system (4.98). Studies by Ghosh (2004) demonstrated higher total number of groundnuts root nodules in the sole cropping system than the bi-cropping system. Zoumana *et al.* (2012) reported increased number of cowpea nodule numbers in the sole cropping system over the bi-cropping system. The stress conditions experienced by the legumes bi-crops due to changes in ecology may contribute to reduction in the number of nodules which may consequently impaired BNF (Ghosh, 2004). Bi-cropping systems with taller cereal than legume bi-crops have been reported to reduce the number of nodules in bi-cropping systems due to shading effect (Kombiok *et al.,* 2005). One specific example is the study by Wahua and Miller (1978) where nodule number in bi-cropping system was reduced by 99% in a sorghum/soybeans bi-cropping system.

Contrary results by Bargaz *et al.* (2015) reported improved nodulation, nodule number and nodule dry weight in the wheat/faba bean bi-cropping systems over the sole bean cropping systems signifying the advantage of wheat/faba bean bi-cropping systems. According to Agbage *et al.* (2002), higher nodule number or dry weight in bi-cropping systems over sole cropping systems may be a sign of improved nitrogen fixation. Studies by Li *et al.* (2003) reported that such an ecological occurrence indicates facilitative interaction of bi-cropping systems.

Non-significant differences among the drilling patterns on nodules per plant may be attributed to interspecific complementarity on resource-use efficiency as a result of the replacement design where the population of bi-crops were reduced by half of their population in sole cropping (Fradgley *et al.,* 2013). This meant that there was non-limited flow of photo-assimilates to nodules due to non-limited light interception (Akundu, 2001). The nodule formation and numbers in legumes crop is usually influenced by improved light interception (Fan *et al.,* 2006). This is because any factors which influence photosynthesis will directly influence nitrogen fixing attributes such as nodulation (Akundu, 2001).

Pink nodules

The success of grain legumes in cropping system depends on their capacity to form effective nitrogen-fixing symbiosis with root-nodule bacteria (Jensen, 1996; Stagnari *et al.*, 2017). In situations where the natural N_2 fixation is not optimal, inoculation becomes essential to ensure that high and effective rhizobial population is available in the rhizosphere of the bean plants (Tena *et al.,* 2016). However, the causes for ineffective nodulation and BNF can vary ranging from inadequate amounts of native rhizobia in the soil (Denton *et al.*, 2013) to agronomic cultural practices. Therefore the remedial intervention to address ineffective nodulation and BNF in legumes can vary from inoculation (use of inoculants) to improved agronomic cultural practices (Sameh *et al.*, 2013).

This study suggested that cropping systems may have an equal influence on BNF particularly, in the study location. Similarly, faba bean cultivars can be sown at any of the tested drilling patterns without negatively affecting their nodulation capacity. These finding agrees with

Murinda and Saxena (1985); Patriquin (1986) who indicated that faba bean does not require inoculation because most cultivated soils contain large populations of indigenous rhizobia and mycorrhizae particularly of the land which was previously cultivated to faba bean. When faba beans are inoculated on soils containing large population of indigenous rhizobia and mycorrhizae populations, the inoculant strain may be responsible for a large proportion of the nodules (Carter *et al.,* 1994). Therefore, non-significant differences on the number of effective nodules may suggest that the study site had large populations of indigenous rhizobia and mycorrhizae. This means that any failure for the beans to biologically fix nitrogen at the study site may be accounted for agronomic cultural practices such as different drilling patterns which are likely to cause stress on the bean plant resulting in reduced nodulation capacity. The cereal/legume bi-crop mixtures have shown potential to increase soil fertility through a symbiosis of legumes with nodule bacteria (Song, 2007; Mariola *et al.,* 2016).

Root diameter

The different responses of faba bean root diameters to different bi-cropping treatment combinations demonstrated that belowground spatial interspecific competition and complementarity occurred (Mosses *et al.,* 2010). Thinner and longer bean root characteristics in the 1x1 alternate rows bi-cropping treatment was due to the belowground interspecific competition for soil water (Bargaz *et al.,* 2015). This implies that the bean plants invested more energy in the roots system than dry matter production in order to withstand the soil water competition by modifying the roots and extend the area of water exploration (Mariotti *et al.,* 2009). This finding is in agreement with the shorter bean plant heights results in Tables 6.4 and 6.5 which also directly responded to soil water stress under the same drilling patterns. These findings also concur with Semere and Froud-William (2001) where root competition for water stress in cereal/legume bi-cropping system, reduced plant height, leaf area and dry matter yield. Furthermore, Jones *et al.* (1989) indicated that thinner roots with reduced diameter size is an indication of stress and at the same time, it is a coping mechanism to improve water use efficient under water stress environments. According to Kotwica *et al.* (1999) the competitive potential of a single legume root is larger than a single cereal plant root but because of the larger number of cereals in mixture, their total root pressure on legumes is stronger than the pressure of legumes on cereals. Ecologically, this showed that the strength of interspecific competition depends on the severity of intraspecific competition, which is mostly linked to the participation of the individual components. The narrower and shorter bean root characteristic under the 3x3 alternate row bi-cropping treatments was a sign of aboveground resource competition for solar radiation (Tilman, 1988). More energy may have been invested in the taller plant height to withstand the completion (Mariotti *et al.*, 2009) as also shown in Tables 6.4 and 6.5. Thicker root diameter sizes under the 2x2 alternate row bi-cropping treatments, have shown the likelihood of interspecific complementary on efficient use of environmental resources due to lack of spatial antagonistic interactions between bi-crop roots (Vandermeer, 1989). This might have contributed to active root nodule formation, higher BNF and at a larger scale increases ecosystem nitrogen supplies (Fan *et al.*, 2006). This further suggest that the 2x2 treatment may potentially contribute to reduce use of non-renewable nitrogen sources, as shown by the larger nodule sizes, an indication of effective nitrogen fixation by the legume bi-crops (Mubarik and Sunatmo, 2014; Zhang *et al*., 2002). The 2x2 treatment showed to be the bi-crop treatment.

Bean root length

Root system is the basis for crop production because it provides access to sufficient nutrients and moisture which are conducive for higher crop yield (Liu *et al.,* 2017a). The spatial distribution of roots in a production system can be affected by biotic, abiotic factors and agronomic practices factors (Bao *et al.,* 2014; Guan *et al.,* 2014). This study discovered that modifications of the root distribution in the 1x1 and 3x3 alternate row drilling patterns was a response to interspecific competition for water resource and solar radiation respectively (Ascehoug *et al.,* 2016), which showed they are less suitability drilling patterns for wheat/faba bean bi-cropping system. Their respective longer root length of 7.9% (in 1x1) and shorter root length of 6.7% (in 3x3) than the sole bean cropping system provided an evidence of root exploration for water and sunlight in the environment. These findings concur with Neykova *et al.* (2011). According to Jones *et al.* (1989) root modifications in mixed cropping systems is an adaptive mechanism to improve water use efficiency, particularly in the 1x1 treatments where tightly interwoven root system in the rhizosphere occurred due to closer proximity of bi-crops. The modification of the root plasticity in plants occurs to adapt and respond to environmental soil moisture stress (Forde, 2009). Beans roots are reported poor competitors for water extraction against the wheat roots than they do for above ground solar radiation (Yahuza, 2011a). The longer bean root lengths under the 1x1 treatment demonstrated the root struggle to cope up with the water stress conditions. The shorter bean roots under the 3x3 treatment signified competitive response to solar radiation because more

plant energy was invested in plant height than the root to outcompete the wheat bi-crop for light interception (Ascehoug *et al.,* 2016). This is could be true because soil water was not limiting than solar radiation in the 2016 cropping season hence shorter bean roots under the 3x3 treatments (Tilman, 1988; Cahill, 1999).
The comparable bean roots lengths between the 2x2 alternate row bi-cropping treatments and the sole cropping system showed interspecific complementarity on resource-use efficiency (Mariotti *et al.,* 2009). Despite the alternate rows are reported suitable for bi-cropping small grains with legumes (Tofinga and Snaydon, 1992), not all bi-cropping combinations can offer similar benefits (Brooker *et al.,* 2015). According to Anil *et al.* (1998), the sowing ratios of bi-crops in addition to specific growing conditions and; cereal/legume crop species can be influenced by belowground spatial root interactions.

Maris Bead had a longer primary root than Fuego, which may made it suitable for spring bi-cropping under water stress environmental conditions. Most spring sown faba beans have shallower primary root compared to autumn-sown faba beans which make them more sensitive to water stress. Spring faba bean responds strongly to water deficits during flowering and early pod filling via many physiological effects (Green *et al.,* 1986). Studies by Saxena *et al.* (1986) showed that alleviating moisture stress in faba bean had a greater effect than alleviating nutrient supply constraints. Therefore, identification of relatively deep rooted spring faba bean cultivars such as Maris Bead can provide an opportunity for successful spring bi-cropping systems for fodder production.

7.5 Conclusion

Root characteristics should be considered among other selection criterion for spring bean cultivars for wheat/bean low input bi-cropping systems. Maris Bead had longer primary root than Fuego which led to specialised their adaption and performance under different environmental conditions. Non-differences between cropping systems on active nodulation of legumes bi-crops suggested that the study area had sufficient indigenous rhizobia mycorrhizae population in the soils. Drilling wheat and beans in alternate rows as 1x1 and 3x3 spatial arrangement can negatively modified bean root, nodule size and can impair BNF due interspecific competition. Drilling wheat and beans crop mixtures in 2x2 alternate row spatial arrangements can promote spatial root interspecific complementarity on efficient resource-use resulting in optimised root sizes, nodulation and possibly BNF activities.

CHAPTER 8

GREENHOUSE GAS EMISSION (GHG) MITIGATION STUDIES IN BI-CROPPING SYSTEMS

8.1 Introduction

The use of nitrogen (N) fertilizers in cereal monoculture production systems (Figure 8.1) has contributed to undesirable nitrogen related pollution in the environment (Mueller *et al.,* 2014; Kim and Dale, 2008; Hawkesford, 2014; FAO, 2013). Imbalances between N applied and N uptake by cereal crops contribute to excess N in the environment, with adverse consequences for water quality, air quality and climate change (Mueller *et al.,* 2014). Nitrogenous gases such as nitrous oxide (NO_2), ammonia and nitric oxide (NO) directly contribute to climate change except for nitrate which contaminates ground waters (Pinder *et al.,* 2012; Keeler *et al.,* 2012). NO_2 has a greater contribution to greenhouse gas (GHG) emission in agriculture and it has a global warming potential of 298 times greater than carbon dioxide (CO_2). It is involved in the destruction of the stratospheric ozone layer (Reay, 2012; Skiba and Rees, 2014). The simulation models have predicted that by the year 2100, CO_2 concentrations will be as high as 500-1000 ppm (IPCC, 2014). Projected increase in CO_2 concentrations threaten the sustainability of future food and feed production systems through climate change impacts (Anselm and Taofeeq, 2010).

Shifting the current cereal monoculture production systems to low input cereal/legume bi-cropping systems, which may reduce the need for non-renewable external N sources, could be a sustainable crop production strategy to counteract negative impacts of climate change (Stagnari *et al*., 2017). Cereal/legume bi-cropping systems aim to be self-sustaining low-input and energy-efficient, which has demonstrated their capacity to achieve the sustainability in agricultural systems (Jackson *et al.,* 2007). Bi-cropping can potentially address major challenges associated with modern intensive agricultural practices (Lithourgidis *et al.,* 2011).

Biological Nitrogen Fixation (BNF) can benefit cereal/legume bi-cropping systems as they reduce the need for inorganic nitrogen fertilizer use, leading to significant reduction in GHG emissions (Legumes Future, 2014; Stagnari *et al.,* 2017). BNF has been reported as the second most important biochemical process on earth after photosynthesis by considering its positive contribution towards achieving sustainability of production systems (Vance *et al.,* 1988).

The idea to assess GHG emissions in wheat/faba bean bi-cropping system was influenced by higher BNF capacity of faba bean (*Vicia faba* L.) as reported in chapter two which is in the context of promoting sustainable production of home grown protein crops as endorsed by the EU parliament (Häusling, 2011).

The grain legumes in European agroecosystems has been reported to fix total N amounting to 225 Gg dominated by pea, faba bean and soya bean as shown in Figure 8.2. (Baddeley *et al.*, 2013).

Source: Hawkesford (2014).

Figure 8.1: Wheat yields (continuous line) and N application rates (bar chart) in Great Britain (1942- 2010).

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Figure 8.2: Calculated quantities of total N fixed (Gg) by grain legume crops in European production systems as reported by Baddeley *et al.* (2013).

This section attempts to estimate the reduction in GHG emission by relying on faba bean BNF instead of using nitrogen fertiliser

There are various methods used for calculating GHG emissions in cropping systems such as life cycle assessments (LCA). However, for this study, the methodology by Kopke and Thomas (2010) was adopted because it specifically focused on faba bean grain legumes. Faba bean yield per hectare was used as one of the factors for calculating and simulating the GHG emissions from bi-cropping systems. A yield of 4 t/ha of faba bean grain was reported to correspond to 180 kg/ha of symbiotically fixed N or 480 kg CO_2e ha^{-1} yr^{-1}. Based on this relationship, the yield data from field experimental plot was converted to hectare basis, which further used to calculate and simulate annual GHG emissions in bi-cropping systems. The simulated GHG emission value of 175 kg CO_2e ha^{-1} yr^{-1} generated by Legume Future (2014) for Europe was adopted for comparison against our experimentally simulated results because it was validated accurate. Most published GHG emission estimates had simply multiplied crop area by BNF per unit area. The estimates reported by Legumes Future (2014) re-analysed existing literature by taking into account variation in crop yields across Europe, a factor which was ignored by previous authors. The carbon dioxide equivalent or CO_2e units of measure was used for comparisons because it is the standard term for describing different GHG emissions in a common unit (IPCC, 2007).

8.2 Results from field experiments

8.2.1 Effects of copping systems

The combined analysis in Appendix 5.5 showed that the cropping seasons had no effect on mean GHG emission mitigation. Therefore, the effects of cropping systems were similar across the seasons on influencing the mitigation of GHG emissions. Across the cropping seasons, cropping systems had a greater ($P<0.001$) effect on the mitigation of GHG emissions (Table 8.1). The sole cropping system had higher influence over the bi-cropping system.

8.2.2 The effects of drilling patterns

The cropping seasons had no effects on the performance of drilling patterns with regard to GHG emission mitigation (Appendix 5.5). Across the cropping seasons, the drilling patterns had a greater ($P<0.001$) effect on mitigating GHG emissions (Table 8.1). Across the bean cultivars, the alternate row bi-cropping treatments (165.9 kg CO_2e ha^{-1} yr^{-1}) resulted in higher GHG emission mitigation values than broadcast bi-cropping treatments (86.6 kg CO_2e ha^{-1} y^{-1}).

8.2.3 The effects of bean cultivars

Across the cropping seasons, the bean cultivars had no effect on mitigation GHG emissions (Table 8.1, Appendix 5.5).

Table 8.1: Mean carbon dioxide emissions (CO_2 equivalent ha^{-1} yr^{-1}) savings in wheat/bean bi-cropping systems influenced by cropping systems, drilling patterns and bean in 2015 and 2016 spring seasons

Treatments	Mix-proportion	Emissions savings (kg CO_2e ha^{-1} yr^{-1})		Mean
		2015	2016	
Drilling patterns				
1x1	50:50	116.4[a]	212.0[a]	164.2[a]
2x2	50:50	117.2[a]	216.0[a]	166.6[a]
3x3	50:50	103.6[a]	229.0[a]	166.3[a]
Broadcast	50:50	53.6[b]	116.0[b]	84.8[b]
SED (3 df)	-	14.28***	32.30***	24.24***
P-value	-	<0.001	<0.001	<0.001
Cropping systems				
Bi-crop mean	50:50	97.7[b]	193.0[b]	145.3[b]
Sole crop	100	321.1[a]	516.0[a]	418.5[a]
SED (1 df)	-	11.29***	25.50***	34.28***
P-value	-	<0.001	<0.001	<0.001
Bean cultivars				
Fuego	50:50	99.2	181.0	140.1
Maris Bead	50:50	96.2	205.0	150.6
SED (1 df)	-	15.97ns	36.10[ns]	27.10[ns]
P-value	-	0.892	0.188	0.051

*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 difference of means; df, degrees of freedom; CO_2e, carbon dioxide equivalent.*

8.3 Discussion

Effects of cropping systems

Recent studies have focused on the role of the legumes' contribution towards reducing GHG emissions in agroecosystems and transform agroecosystems into sustainable production units (Yadav *et al.,* 2015; Stagnari *et al.*, 2017). Jeuffroy *et al.* (2013) found that legume crops can emit 5-7 times less GHG emissions per unit area compared to other crops. This demonstrated that dependence on synthetic N fertilizer sources for cereal production can potentially reduce with the inclusion of grain legumes in cereal based production systems (Beaudette *et al.,* 2010).

This study demonstrated that the sole bean cropping system had greater effect than the bi-cropping system on the GHG emission mitigation potential. The higher effects of the sole bean cropping system than the bi-cropping system may be accounted for higher sowing density because nitrogen uptake and density are directly related (Sadeghpour *et al.,* 2013). However, across the cropping seasons, the sole bean cropping system showed higher effect than the simulated mean value of 175 kg CO_2e ha^{-1} yr^{-1} for faba bean reported for EU countries sown under crop rotation systems which was reported by Legumes Future (2014), Reckling *et al.* (2014). The higher mean effect from this study may suggest the higher nitrogen fixation potential of the beans cultivars (Fuego and Maris Bead) than the bean cultivars used across EU countries. The smaller mean difference of 28.9 kg CO_2e ha^{-1} y^{-1} between this study under bi-cropping systems and the EU reported simulated mean value of 175 kg CO_2e ha^{-1} y^{-1} under crop rotation systems may suggested the potential advantage of bi-cropping to mitigate GHG emissions comparable to crop rotation systems (Kope and Nemceek, 2010; Jensen *et al*., 2010; Rose *et al.,* 2016; Patriquin, 1986). The interspecific competition effects for soil N and complementarity on resource-use, particularly N in bi-cropping systems may have improved biological nitrogen fixation than in crop rotation systems (Akter *et al.,* 2004; Bedoussac and Justes, 2010). This agrees with findings by Pappa *et al.* (2011) study in Eastern Scotland which reported reduced cumulative NO_2 emission from barley/pea bi-cropping systems. According to Legume Future (2014), an inclusion of grain legumes in European cropping systems may provide a small climate benefit compared to importing soybeans to Europe. There are higher chances for the bean to fix more N in bi-cropping systems than in crop rotation systems. It has been reported that sole bean cropping systems in rotation are vulnerable to biotic interferences such as weed, pests and diseases which may adversely affect their productivity than in bi-cropping systems (Bedoussac *et al.,* 2017).

The drilling patterns

The alternate row bi-cropping treatments had a greater effect on the mitigation of GHG emissions than bi- broadcast bi-cropping treatments which can be attributed to higher light interception capacity and its efficient use (Olsen and Weigner, 2007). The regular spatial arrangement compared to random distribution of bean bi-crops determined light interception capacity and subsequent mitigating effects on GHG emission (Sedghi *et al.,* 2008). The nodulation and subsequent biological nitrogen fixation processes in legumes is highly dependent on the energy from solar radiation (Akundu, 2001; Fan *et al.*, 2006). The regular arrangement of bean bi-crops resulted in improved light interception and BNF, hence higher GHG mitigation potential. Irregular spatial distribution of bean bi-crops possibly contributed to poor light interception, low BNF hence low GHG mitigation potential (Chapagain, 2014). The annual simulated GHG emission mean value per hectare for EU countries differed from alternate rows and broadcast bi-cropping treatments by 5.5% and 102.1% respectively (Legumes Future, 2014). The smaller difference for alternate rows showed higher effect than broadcast on GHG emission mitigation potential due to their differences in utilising solar radiation. Similarly, Chapagain (2014) reported higher GHG emissions mitigation potential for the alternate rows (1:1) than broadcast bi-cropping treatments. Findings of this study are in agreement with Senbayram *et al.* (2016) where faba bean showed potential in reducing GHG emissions in cereals/bean bi-cropping systems. Alternate row bi-cropping treatments displayed great potential to enhance BNF and GHG emission mitigation capacity which may lead to significant reduction in the use of external inorganic nitrogen fertiliser sources.

8.4 Conclusion

The findings from the study showed that low input wheat/faba bean bi-cropping system has demonstrated potential to contribute to mitigate the risks associated with climate change such as non-renewable nitrogen fertiliser use, leading to improved environmental sustainability. The alternate row spatial arrangement bi-cropping systems provided an opportunity to mitigate potentially greater GHG emissions than broadcast bi-cropping production system. The bean cultivars, due to complementarity on N use, demonstrated higher BNF abilities which contributed to greater mitigation of GHG emission which was also demonstrated by Stagnari *et al*. (2017).

CHAPTER 9

GENERAL DISCUSSION

9.1 Seasonal variability and its effects

Precipitation and air temperature are the most important meteorological weather elements which determine the productivity of rain-fed crop production (Ceglar *et al.,* 2016). Their combined effects under extreme weather events can have serious negative effects on crop growth and development (Vining, 1990). Seasonal variability is an important aspect of field experiments because it can determine the response of treatments to contrasting growing conditions (Achouri and Gifford, 1984). The 2015 and 2016 spring cropping seasons had contrasting meteorological weather conditions which directly resulted in contrasting responses of experimental variables. The 2016 cropping season was warmer and wetter compared to 2015 and the 10-year average. Warm and wet conditions in 2016 growing season might have influenced the outbreak of Faba bean rust disease (*Uromyces viciae-fabae).* According to Maalouf *et al.* (2016), warm and wet environmental conditions favour the outbreak of fungal diseases such as Faba bean rust. Similarly, the outbreaks of black bean aphid (*Aphis fabae*) and Ascochyta blight *(Ascochyta fabae)* in the 2015 cropping season were possibly influenced by the specific seasonal weather conditions.

The contrasting seasonal weather conditions determined the sowing dates for each cropping season. The total amount of rainfall received at the end of March of each cropping season determined the sowing date for the succeeding spring cropping season due to differences in the time taken for the clay soils to dry before achieving suitable moisture content for sowing the seeds. During the month of March, higher total rainfall amounting to 111.3 mm in the 2016 season resulted in delayed sowing (02/05/16) while lower total rainfall amounts of 34.2 mm in 2015 season resulted timely sowing (09/04/15). Bi-crops were more competitive in the 2015 than 2016 cropping seasons as indicated by the competition indices results (Relative Crowding Coefficient and Aggressivity). Similar findings were reported in other studies for instance Semere and Froud-Williams (1998) and Tsubo *et al.,* (2005).

9.2 Chlorophyll Concentration Index (CCI)

Effects of cropping systems

This study demonstrated that bi-cropping can potentially lead to higher CCI in the wheat bi-crop plants than sole cropping. This may be due to morphological and physiological complementarity between the bi-crops on efficient use of resources particularly N (Bedoussac *et al.*, 2014). This finding agrees with Koohi *et al.* (2014); SU *et al.* (2014) and Ghosh *et al*. (2006). The positive seasonal effects on CCI were higher in the 2016 than 2015 season, due to improved weather conditions such as soil water availability and warmer temperature, which might have favoured the positive microbial interaction with the beans (Vining, 1990).

Since inorganic N fertilizer was not applied to the wheat bi-crop plants in bi-cropping systems, higher CCI benefits demonstrated the benefit of the cereal/legume bi-cropping systems on efficient use of different sources of N between the bi-crops (Bedoussac *et al.*, 2014; Hauggaard-Nielsen *et al.*, 2009). According to Griffiths and Lawes (1977), BNF in faba beans starts between 3 to 4 weeks after emergence. Studies by Vinther and Dahlmann-Hansen (2005), reported that BNF in faba beans begins as early as 2 weeks after emergence with the highest N_2 fixation at flowering. This therefore suggested that direct N transfer from the legume bi-crop to the non-legume bi-crop (cereal) through common mycorrhizal networks (CMN), could be one of the biological mechanisms responsible for increased CCI in the wheat bi-crop plants as reported by Aminifar and Ghanbari (2014), Johansen and Jensen (1996). Similar innovation has been developed in the UK by PlantWorks in Sittingbourne, which produce bio fertiliser containing living Arbuscular Mycorrhizae (MA) whose hyphae networks may promote root growth and extend its absorptive circumference, which can enhance nutrient transfer and availability in bi-cropping systems.

He *et al.* (2009) confirmed direct N transfer in bi-cropping systems using ^{15}N isotopic method. According to Chapagain (2014), N fixed by the legume bi-crop component can be available for the cereal bi-crop within the same cropping season as also confirmed by higher CCI (Table 6.1) in bi-cropping systems over the sole cropping system. Also, higher BNF capacity of faba bean might have contributed to higher CCI in bi-cropping systems throughout wheat growth stages (Walley *et al.*, 1996).

The higher CCI in bi-cropping systems may predict subsequent improved cereal fodder quality better than sole cropping systems because chlorophyll is an important pigment required for photosynthesis and amino acids synthesis (Ghosh *et al*., 2006). Soil N availability has been reported to determine the cereal forage quality in low input production systems (Bilsborrow *et al.,* 2013; López-Bellido *et al.,* 2004). The low CCI in the sole cropping system was possibly attributed to low soil N availability, which enhanced intraspecific competition for N among the wheat plants sown at two times higher sowing density than in the bi-cropping system (Hauggaard-Nielsen and Jensen, 2005). Similar findings were reported by Ghosh *at al.,* (2006) in sorghum (*Sorghum bicolor*)/cowpea (*Glycine max L.*) bi-cropping systems. The CCI may also play a significant role in detecting if the legume bi-crops are fixing atmospheric N_2 in the bi-cropping system (Musa *et al.* (2010). According to Midmore (1993) the failure of the legume bi-crop to fix N_2 in crop mixtures, can convert interspecific complementarity on N use into interspecific competition for mineral soil N.

Effects of drilling patterns

This study showed higher CCI in alternate rows than in broadcast bi-cropping treatments, due to weaker interspecific competition than intra-specific competition as reported by Vandermeer (1989). The regular arrangement of the bi-crops might have improved the use of environmental resources particularly solar radiation as a result of total ground canopy cover. Physical root intermingling between the bi-crops in the rhizosphere may have contributed to increased CCI in the wheat bi-crops through direct N transfer as reported by Musa *et al.* (2010), Johansen and Jensen (1996). The random spatial distribution of the bean bi-crops in the broadcast treatment contributed to low CCI, due to poor total canopy ground canopy, which may have resulted in poor light interception as reported in other studies by Bastiaans *et al.* (2008), Olsen and Weigner (2007). The beans are vulnerable to weed infestation (Hauggaard-Nielsen *et al.,* 2007). Therefore, the broadcast may have stimulated more weed growths which might have negatively impaired the beans plants growth and subsequent N fixation capacities hence low CCI.

The higher CCI in the 1x1 and the 2x2 alternate row treatments than in other drilling patterns in the 2016 season may have been influenced by complementarity effects on efficient use of different N sources between the bi-crops as reported by Bedoussac *et al.* (2014), Corre-Hellou *et al.* (2006) and Jensen (1996). Therefore, improved fodder quality can be expected under the 1x1 and 2x2 alternate row treatments than 3x3 alternate treatments during the 2016 season. According to Musa *et al.,* (2010), physical root intermingling could be the reason for higher CCI shown in the 1x1 and 2x2 alternate row treatments. This agrees with Chapagain,

(2014) who reported highest rate of N transfer from legume to barley bi-crop in a 1x1 system than a mixed treatment. Zhang *et al.* (2017) reported that in crop mixtures, close proximity between bi-crop plays a significant role in enhancing direct N transfer. This study showed low CCI in the 3x3 alternate row treatments due to interspecific competition for aerial environmental resources (solar radiation) (Geno and Geno, 2001; Sadeghpour *et al.,* 2014). This may have altered the leaf size which reduced light interception capacity hence resulted in low CCI. Polthanee and Trelo-ges (2003) also reported the effects of interspecific competition on reduced leaf size and its subsequent effect on environmental resource-use such as solar radiation.

The drilling pattern x bean interaction showed greater performance of Maris Bead than Fuego on influencing CCI in the 1x1 alternate row treatments. This was due to tap root advantage (Table 7.2) which may have helped to tolerate season soil water fluctuation in the upper soil profile than Fuego with superficial root system. This agrees with Streeter (2003) who indicated that soil water availability determines plant growth, nodulation and symbiotic biological N_2 fixation in leguminous crop. The findings suggest that Maris Bead can influence increased CCI under different environmental conditions.

Effects of bean cultivars

This study showed that despite the bean cultivar bi-crops differing in morphology and growth rate, their influence on CCI was similar in both cropping seasons, due to spatial interspecific complementarity on better use of environmental resources between bi-crops particularly N (Hauggaard-Nielsen *et al.,* 2008). This suggests that both the bean cultivars can potentially improve the quality of cereal based forage because chlorophyll and N are directly related (Tucker, 2004).

9.3 Leaf Area Index (LAI)

Effects of cropping systems

LAI is a canopy index which determines the productivity of bi-cropping systems through increased photosynthetic area and greater PAR interception than sole cropping systems (Yin, 2016; Mansab *et al.,* 2003; Xinyou *et al.,* 2003). This study showed greater LAI in bi-cropping systems than the sole cropping systems in both cropping seasons. This may have been attributed to lack of niche overlap on environmental resource-use, which resulted in greater light interception, photosynthetic processes and dry matter yield (Vandermeer, 2011).

However, too high LAI may increase leaf fall of the lower leaves due to limited access to light and carbon dioxide resulting in impaired photosynthetic processes (Frank and Cleon, 1992). The advantages of cereal/legume bi-cropping systems over sole cropping systems on greater LAI has been attributed to efficient use of solar radiation (Bilalis *et al.,* 2010). Therefore, bi-cropping systems may potentially influence higher forage quality through increased LAI and greater light interception than sole cropping systems. Wheat/faba bi-cropping systems are reported to be restricted to areas with low temperatures and ample water (Haymes and Lee, 1999). Therefore, improving LAI through planned biodiversity in space can improve light interception and sustain forage productivity in such areas. Generally, most legumes have low LAI during the early part of the growing season, which result in more light wastage (see Figure 5.1), due to poor vegetative ground canopy cover (Parsa and Bagheri, 2008). Therefore, bi-cropping systems may improve LAI during the early stages of crop growth and minimise light wastage than sole cropping systems as similarly reported by Harris (1990).

Effects of drilling patterns

This study showed greater LAI values in alternate row bi-cropping treatments than in broadcast treatment in both cropping seasons due to efficient use of available growth resources, which was influenced by the uniform arrangement of rows and bi-crops (Vandermeer, 1989). The random spatial distribution of the bean bi-crops in broadcast treatment produced inconsistent total ground canopy cover, which resulted in low LAI (Olsen and Weigner, 2007). Soil water was more limiting than solar radiation in the 2015 season. This led to belowground interspecific competition in the 1x1 and the 3x3 alternate row treatments and resulted in reduced LAI. The effect of belowground competition for soil water may have altered the aboveground plant morphology such as LAI, which may affect efficient use of environmental resources (Tilman, 1988 and Mariotti *et al.,* 2009). Similar findings by Semere and Froud-Williams (2001) reported a reduction in leaf size and subsequent LAI due to water stress environmental conditions.

Solar radiation was more limiting than edaphic based resources in the 2016 cropping season and may have influenced interspecific competition for solar radiation in the 3x3 alternate row treatments, hence reduced LAI as reported by Tilman, (1998) and Mariotti *et al.* (2009). LAI can determine plant growth and development (Lucas *et al.*, 2015) by affecting carbon dioxide (CO_2) input, solar radiation interception, photosynthesis and biomass accumulation (Kandiannan *et al.,* 2009). Improved conditions, such as soil water in the 2016 than 2015 cropping season as shown in Figure 3.2 and Appendix 1.1 may have stimulated vigorous and competitive growth of crop canopies possibly due to greater use of environmental resources hence resulted in higher LAI.

Effects of bean cultivars

This study showed that Fuego had greater LAI compared to Maris Bead in both cropping seasons to due lack of mutual leaf shading and premature loss of the lower bean leaves (Frank and Cleon, 1992; wolf, 1972). Mutual leaf shading is a condition in plant canopies where the lower leaves drop down to the ground due to restricted access to light and CO_2 by the upper leaves (Brintha and Seran, 2009). Even though Maris Bead had planophile leaf types with the capacity to influence greater LAI than Fuego, its LAI declined with increased crop canopy growth due to mutual leaf shading.

9.4 Intercepted Photosynthetic Active Radiation (IPAR)

Effects of cropping systems

This study showed higher IPAR in bi-cropping systems than sole cropping systems in both cropping seasons due to spatial interspecific complementarity effects, which improved efficient use of resources (such as water and non N nutrients) than when bi-crops were grown separately (Willey, 1990). Increased performance of bi-cropping systems over sole cropping systems occurred possibly because the wheat and the bean bi-crops differed in their vertical arrangement of foliage and canopy architecture (Khashayar *et al.,* 2014; Tsubo *et al.,* 2001; Willey, 1990; Keating and Carberry, 1993). For example; the combination of the wheat and beans bi-crops with mono-foliate and tri-foliate leaf types respectively contributed to improve IPAR in bi-cropping systems than sole cropping systems (Baumann *et al.,* 2001). Ghambari-Bonjar (2000) also reported higher portion of the incident ray of the solar radiation intercepted in bi-cropping systems than sole cropping systems. Studies by Jahansooz et *al.* (2007) in wheat/chickpea mixtures reported higher IPAR in bi-cropping systems than sole cropping systems. Bilalis *et al.* (2010) reported IPAR in maize/legume bi-cropping systems than sole cropping systems. According to Fan *et al.* (2006), higher IPAR improved the productivity of bi-cropping systems through enhanced nodulation and biological N_2 fixation. Studies by Malezieux *et al.* (2009) reported increased total biomass yield in bi-cropping systems than sole cropping systems due to improved IPAR. The benefits of bi-cropping systems on improved IPAR over sole cropping systems have also been reported by Liu *et al.,* (2017b) in maize/soybean mixtures and Bedoussac and Justes (2011) in durum wheat/winter pea mixtures.

The greater benefits from bi-cropping systems occur because the photosynthetic active solar radiation (PAR) which could have been lost during the early and end of the growing season in sole cropping systems can be used efficiently by bi-cropping systems. According to Hay and Walker (1989), crop yield is a function of total incoming light (Q) x fraction of crop canopy intercepted light (I) x photosynthetic efficiency (E) x harvest index (H). A similar finding was reported by Eskandari and Ghanbari-Bonjar (2010) in wheat/faba bean bi-cropping systems. In contrast, Keating and Carberry (1993) concluded that selective breeding enables plants to absorb maximum IPAR in pure stands or sole cropping systems rather than in crop mixtures. However this research has shown higher IPAR in bi-cropping systems than sole cropping systems contradicting Keating and Carberry (1993). However, improved weather conditions such as soil water and air temperature in the 2016 over 2015 cropping season improved LAI (Table 6.2) which resulted in greater IPAR in Table 6.3.

Effects of drilling patterns

The drilling patterns improved IPAR in the 2016 than in 2015 cropping season as a result of better improved growing conditions, such as soil water and warm temperatures (Figures 3.1 and 3.2), which might have improved canopy development, due to better use of other resources such light and non-nitrogen nutrients (Ceglar *et al.,* 2016; Hook and Gascho, 1988).

This study showed greatest IPAR from the 2x2 alternate row treatments in both cropping seasons which could result in maximum yields and economical advantage for commercial farmers. This was due to weaker interspecific competition than intraspecific competition between the bi-crop components (Willey, 1990; Vandermeer, 1989), which resulted in efficient partitioning of available resources in space (Willey, 1990; Hinsinger *et al.,* 2011; Liu *et al.,* 2017b). This further improved the total canopy ground cover, promoted more IPAR and enhanced the performance of other associated ecological services such as weeds, insects' pests and disease control (Evers and Bastiaans, 2016; Koocheki *et al.*, 2016). The higher performance of the 2x2 alternate row treatments demonstrated the positive relationship between plant diversity and ecosystem productivity (Li *et al.*, 2011), which fulfilled the competitive exclusive principle that allows indefinite co-existence of the bi-crops in mixture as long as their intensity of interaction does not promote niche overlap (Vandermeer, 1970). Matusso *et al*. (2014) also reported highest IPAR and yield benefits from the 2x2 alternate rows treatment in maize/soybean bi-cropping system in Kenya which prompted farmers to nickname the treatment '*mbiri*' meaning two in appreciation of the treatment performance over their traditional sole cropping system. Mucheru-Muna *et al.* (2010) reported 40 percent higher economic net benefits in the 2x2 alternate row bi-cropping treatments compared to traditional crop mixture of beans and maize. Studies by Jalilian *et al.* (2013), Sadeghpour *et al.* (2014), Langati *et al.* (2006) and Long *et al.* (1999) also reported higher performance of the 2x2 alternate row spatial arrangements on yield and LER.

The production of faba bean in mixtures with wheat in organic production systems, is restricted to areas where water is not a limiting environmental factor of production than solar radiation (Haymes and Lee, 1999). Therefore, the 2x2 alternate row spatial arrangements could be a suitable cultural practice to optimise light management and productivity of spring wheat/faba bean bi-cropping systems in such areas. The findings are in agreement with Haymes and Lee (1999) and Bulson *et al.* (1997) who indicated that in wheat/faba bean bi-cropping systems, spatial rather than temporal complementarity determines the productivity mostly due to efficient use of resources including IPAR.

This study showed low IPAR in the 1x1 and 3x3 alternate row treatments in the 2015 season due to the reduction in plant height and leaf sizes (Tables 6.2 and 6.3), which negatively affected light interception as a result of belowground competition for soil water. Studies by Sobkowicz (2001) confirmed the effect of belowground competition on reduced plant height and resource-use efficiency. The lowest IPAR in broadcast was attributed to poor ground canopy cover as a results of random spatial distribution of bi-crops, which was also reported by Bastiaans *et al*. (2008).

Effects of bean cultivars

This study showed that Fuego intercepted more light than Maris Bead bi-crops in the 2015 season probably due to the absence of mutual leaf shading, which is a common characteristic of most erectophile leaves (Wolf, 1972; Yunasa *et al.*, 1993 Wang *et al.*, 2007)). The erectophile leaves do not drop prematurely before reaching senescence due to their geometrical leaf arrangement. The light interception per leaf in erectophile leaves increases because more light is intercepted at large solar angles (early in the morning, at noon and late in the evening) than planophiles (Yunasa *et al.*, 1993). Kanton and Dennett (2008) also reported higher photosynthetic rates, IPAR and RUE in the erectophile than planophile leaves.

Maris Bead had lower IPAR than Fuego in the 2015 season due to increased loss of the lower leaves (Wolf, 1972), which was caused by mutual leaf shading and the higher transpiration rate in broader leaves under water stress conditions (Smith and Geller, 2013; Hikosaka and Hirose, 1997). When soil water was not limiting in the 2016 season, Maris Bead had higher IPAR than Fuego. However, their smaller difference of 1.9% in the 2016 season compared to 4.9% in the 2015 season suggested that mutual leaf shading and premature leaf fall was taking place in Maris Bead, which reduced the LAI and IPAR capacity. Solar radiation determines dry matter yield in crops when biotic and abiotic factors are not limiting in a production system (Bedoussac and Jutes, 2010). Therefore, the bean cultivar bi-crops with higher light interception traits are essentially ideal for low input bi-cropping system (Campbell, 1990; Bedoussac *et al.*, 2014).

The study showed that Fuego had the potential to improve light interception in bi-cropping systems irrespective of seasonal variations. Maris Bead with planophile leaves characteristics can effectively intercept more light only in the early stages of the crop cycle. Falster and Westoby (2003) confirmed that IPAR in plants can be affected both leaf shape and size, which are key attributes of the leaf morphology that affect mutual shading of leaves and light absorption of the canopy. Similarly, Hoad *et al.* (2006) reported that wheat plants with planophiles leaves were more effective at light interception and weed suppression, but only during the early canopy development rather than at maximum canopy development. Similarly, Coll *et al*. (2012) and Niinemets (2007) reported that plant architecture and canopy structure can affect light interception in bi-cropping.

This drilling pattern x bean cultivar interaction of this study showed higher performance of Fuego than Maris Bead on IPAR in the 1x1 alternate row spatial arrangements. This was possibly due to its similar plant height to the wheat bi-crop component as also reported by

Haymes and Lee (1999) and Wahua and Miller (1978). This study further infer that in addition to plant height advantage between the bi-crop components, the erectophile leaf traits for Fuego contributed to enhanced higher IPAR as confirmed by Falster and Westoby (2003).

9.5 Radiation Use Efficiency (RUE)

Effects of cropping systems

This study showed higher total RUE in bi-cropping systems than sole cropping systems in both cropping seasons due to improved LAI as shown in Table 6.2 and canopy ground cover. Research findings by Tsubo *et al.* (2001) and Liu *et al.* (2017b attributed higher RUE in bi-cropping systems than sole cropping systems to complete canopy ground cover, which led to maximised light interception. According to Willey (1979) better use of radiation in bi-cropping systems can be achieved by efficient use rather than greater amounts of intercepted solar radiation. Therefore, higher RUE in the wheat/bean bi-cropping system than the sole cropping system demonstrated the capacity of the system to improve forage productivity in temperate conditions where light is the main determinant environmental resource of crop production (Bulson *et al.*, 1997). The differences in morphology, physiology and phenology between the bi-crop component crops may have contributed to improved resource-use efficiency in bi-cropping systems than the sole cropping systems (Eskandari and Ghanbari-Bonjar, 2010). For example, the wheat bi-crop may have ensured good early light interception while the bean bi-crops ensured later interception hence higher dry matter yield (Wikiti *et al.*, 1993).

Effects of drilling patterns

This study showed no effect of drilling patterns on RUE in the 2015 season possibly due to water stress conditions, which might have reduced plant growth such as LAI in Table 6.2 and plant heights in Table 6.5, hence reduced RUE. Soil water stress conditions can negatively affect foliage expansion and light interception hence, a reduction in RUE (Adeboye *et al.*, 2016) reported. During the 2016 season, the reduction in RUE was only observed in the 3x3 alternate row treatments as a result of interspecific competition for solar radiation (Geno and Geno, 2001). Similar findings in maize/soybean crop mixtures were reported by Liu *et al.* (2017b).

Effects of bean cultivars

Fuego had higher capacity to efficiently convert intercepted solar energy into dry matter production than Maris Bead in the 2015 season due to their differences in leaf morphology and growth rates (Sinoquet and Caldwell, 1995). Fuego had erectophile leaf type, which may have promoted more light penetration into the canopy than Maris Bead. Maris bead with planophile leaf type, may have restricted more light penetration into the canopy hence low RUE (Wolf, 1972). Fast growing plants such as Fuego have the capacity to start intercepting light earlier and efficiently convert into dry matter production than slow growing plants (Richards, 2016). Borger *et al.* (2010) confirmed increased mutual leaf shading in planophiles, which resulted in increased premature leaf fall and reduced RUE. Fuego is proven a suitable candidate for low input bi-cropping systems because it's efficient in the utilisation of intercepted solar radiation capacity can contribute to improve biological nitrogen fixation, crude protein in wheat and mitigate greenhouse emissions (Stagnari *et al.,* 2017).

9.6 Dry matter accumulation

Effects of cropping systems

This study showed higher dry matter accumulation for both wheat and bean in sole cropping systems than their corresponding bi-cropping systems in both cropping seasons due to differences in their respective sowing densities (Joliffe *et al.,* 1984). The sowing density for sole cropping systems was two times higher than for bi-cropping systems. Reducing the sowing density in bi-cropping systems is a strategy to achieve spatial interspecific complementarity on resource-use efficiency in replacement designed bi-cropping experiments (Snaydon, 1994; Joliffe *et al.,* 1984; Fradgley *et al.,* 2013).

Although bi-cropping systems had lower wheat and bean dry matter accumulation than sole cropping systems, the total dry matter yield from bi-cropping systems was higher than sole cropping systems, which demonstrated the advantage of bi-cropping over sole cropping as shown in Table 6.10. Similar findings were reported by Dusa and Stan (2013) for oat/pea, Sadeghpour *et al.* (2013) for barley/annual medic, Pappa *et al.* (2012) for burley/pea and Dhima *et al.* (2013) for oat/faba bean mixtures. In contrary, Berkenkamp and Meeres, (1987) reported higher dry matter accumulation 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.

Effects of drilling patterns

Wheat DM yield

This study showed no effects of the drilling patterns on wheat dry matter yield possibly due to spatial interspecific complementarity on resource-use efficiency between the bi-crops (Vandermeer, 1989). This was achieved by reducing the sowing density of bi-crops by 50% of their sole cropping systems to promote access to more nutrients for each plant than in a denser sole cropping system (Joliffe *et al.,* 1984). Also the competition for light may have been lowered because the two bi-crops used light in different parts of the canopy at different times of the season (Tsubo and Walker, 2002; Fradgley *et al.,* 2013).

Bean DM yield

This study demonstrated higher bean dry matter yield in the alternate rows than in broadcast treatment due the weaker interspecific competition than intraspecific competition might have led to efficient use of environmental resources (Vandermeer, 1989). This was achieved as a result of improved light interception (Table 6.3) and improved biological weed control (Table 6.6), which was influenced by total canopy ground cover than in broadcast treatment (Olsen *et al.*, 2012). Studies by Sherwan and Kazhala (2014) in wheat/faba bean bi-cropping system reported similar findings.

The higher bean dry matter accumulation in the 2x2 than in the 3x3 and 1x1 alternate rows treatments in the 2015 season was attributed to spatial complementarity due to niche differentiation between the bi-crops, which may have resulted in better use of available resources (Fargione and Tilman, 2005). The lower bean dry matter yield in the 1x1 and 3x3 alternate rows during the 2015 season may have been caused by spatial interspecific competition for soil water resources (Ascehoug *et al.*, 2016) which was also evidenced by reduced bean plant heights in Table 6.5. In bean production systems, water is reported a major yield determinant factor than either solar radiation or plant competition (Siddigue *et al.*, 2015; Loss *et al.*, 1997). Therefore, drilling beans and wheat as 1x1 and 3x3 spatial arrangements under water stress environmental conditions can contribute to reduce the bean dry matter accumulation. This finding suggests that farmers who are interested in investing in low input wheat/faba bean bi-crop mixture for fodder production are better off sowing wheat/bean crop mixtures as 2x2 alternate row arrangements than broadcast bi-cropping for higher returns. Similarly, Chen *et al.* (2004) reported higher yield when the components bi-crops of barley and pea were spatially separated in alternate twin rows of each than their respective sole crops.

The bean cultivars had equal effect on both wheat and bean dry matter accumulation which showed that irrespective of drilling patterns and seasons they both used environmental resources in space more efficiently.

9.7 Weed suppression

Effects of cropping systems

Weed control poses as a serious problem in spring drilled wheat and beans in organic based production systems (Liebman and Dyck, 1993; Haymes and Lee, 1999; Baker and Mohler, 2014). However, bi-cropping systems have been widely reported to perform extra ecological services such as weed control besides food production than sole cropping systems (Altieri, 1999). This study averaged over two years showed higher weed suppression effects in bi-cropping systems than in sole cropping systems due to complementarity on efficient use of environmental resources in space such as solar radiation and N, which are the two major environmental resources involved in controlling weeds in bi-cropping systems (Bedoussac *et al.,* 2014; Corre-Hellou *et al.*, 2011). Bi-cropping systems out-competed weed species on the acquisition of these resources and left inadequate supply to support weed growth and development (Bedoussac *et al.,* 2014). The two ecological mechanisms responsible for effective biological weed control in bi-cropping systems over sole cropping systems include: (i) effective capturing of growth resources from weeds species; and (ii) efficient conversion of unexploited growth resources by weeds into harvestable materials (Khashayar *et al.,* 2014). The improvement in weed suppression in bi-cropping systems demonstrate their capacity to reduce weed seed bank and the return of weed seeds than sole cropping systems (Bastiaan *et al.,* 2008). The denser crop canopy ground cover in bi-cropping systems provided the shading environmental condition, which reduced weeds germination and growth (Corre-Hellou *et al.,* 2011). The capacity of low input bi-cropping systems on the improvement of weed control than sole cropping systems through associated ecological services has been described as a risk-free and low cost intervention by Röös *et al.,* (2018).

Between the sole cropping systems, the sole bean cropping system had poorer weed control compared to the sole wheat cropping system during the early growth stage as shown in Figure 4.2b and Figure 5.1. During this period, the sole bean plants grew slowly with poor vegetative canopy ground cover which was unable to filter the solar radiation sufficiently to effectively suppress weeds species (Hauggaard-Nielsen *et al.,* 2007). Grain legumes are generally reported as weak competitors against weeds species, a trait which makes them outcompeted by weed species particularly in early stages of the crop cycle (Smitchger *et al.,* 2012; Sadeghpour *et al.,* 2014). Caballero and Goicoechea (1995) suggested that growing beans in sole cropping systems is not ideal for forage production because of its higher vulnerability to weed infestations (Corre-Hellou *et al.,* 2011). This may lower the nutritional quality of forage compared to bi-cropping systems. Higher weed suppression in sole wheat cropping system was due to faster growth rate and exploitative root systems of wheat plants which may have over dominated the weed species on the acquisition of edaphic based environmental resources particularly in early stages of the crop cycle (Li *et al.,* 2011; Sadeghpour *et al.,* 2014). Studies by Banik *et al.* (2006), Hauggaard-Nielsen *et al.* (2008) and Choudhary *et al.* (2013) had reported similar findings. Findings of this study suggest that low input spring wheat/faba bean bi-cropping systems, is a low cost intervention, which can serve as an alternate biological weed control practice to herbicides-use towards improving sustainable forage production and environmental quality.

Effects of drilling patterns

This study showed more effective weed suppression in alternate row bi-cropping treatments than in broadcast bi-cropping treatments as a results of morphological and physiological complementarity, which might have led to better use of ecological resources, particularly solar radiation and N (Bedoussac *et al.,* 2014). Uniform arrangement of bi-crops and early canopy ground cover in alternate rows led to improved light interception and subsequent weed smothering efficiency (Olsen *et al.,* 2005; Evers and Bastiaans, 2016). Poor weed suppression in broadcast treatment was attributed to inefficient light interception as a result of poor total canopy ground cover (Bastiaans *et al.,* 2008). Similar findings were reported by Choudhary *et al.* (2014). Based on this finding, it can be further inferred that the broadcast treatment is unsuitable for adoption by organic farmers because it is vulnerable to increase weed seed bank and weed seed returns (Bastiaans *et al.,* 2008). The alternate rows bi-cropping treatments improves competitiveness of bi-crops which in turn contribute to improve weed suppression in (Evers and Bastiaans, 2016).

Effects of bean cultivars

This study showed similar effects of the bean cultivar bi-crops on weed suppression across the seasons due to greater influence of interspecific complementarity than interspecific competition in the production systems, which improved the use of environmental resources and subsequently deprived the weed species of light and N availability (Bedoussac *et al.,* 2014).

However, the seasonal effect showed higher weed smothering for Fuego than Maris Bead during the early stages of the crop cycle (53 DAS) in the 2015 season; and at advanced stages of the crop cycle (73 DAS) in the 2016 season. Higher performance of Fuego than Maris Bead may be attributed to (i) lack of mutual leaf shading, and (ii) fast growth rate. This might have promoted earlier vegetative canopy development resulting in early weed smothering.

It was also noted that Maris Bead smothered more weeds than Fuego only in the early stages of the crop cycle (51 DAS) in the 2016 season. This meant that Maris Bead, influenced by broad and horizontal leaf traits, was able to smother more weeds in the early stages of the crop cycle when the mutual leaf shading was possibly lower than at advanced stages of the crop cycle. Other studies such as Hoad *et al.,* (2006) have also reported better performance of planophile leaves only in the early stages of the crop cycle.

9.8 Weed N uptake

Effects of cropping systems

This study showed high weed N uptake in sole cropping systems than in bi-cropping systems as a result of increased weed dry matter (Sadeghpour *et al.,* 2013; Corre-Hellou *et al.,* 2005). The lowest weed N uptake in bi-cropping systems than in sole cropping systems was due to interspecific complementarity in space which led to better use of N sources (Bedoussac *et al.,* 2014). However between the sole cropping systems, the sole bean cropping system had higher weed N uptake than the sole wheat cropping system due to lack of competition for mineral soil N resource between the bean plants and weed species (Corre-Hellou *et al.,* 2005). The bean plants survived on using biologically fixed N_2 while weeds species survived on the soil mineral N to meet respective demands for N (Bedoussac and Justes, 2010). The sole wheat cropping system had the lower weed N uptake compared to the sole bean cropping system because of its fast growth rate and the ability to acquire disproportionately greater share of available resources in early stages of growth over the weed species (Hauggaard-Nielsen *et al.,* 2001; Li *et al.,* 2011). This demonstrated an advantage of relative growth rate, as one of the key plant traits which can help crops to out compete weed species in a production system (Aschehoug *et al.,* 2016).

Effects of drilling patterns systems

The alternate row bi-cropping treatments influenced lower weed N uptake compared to broadcast because of their ability to capture a greater share of available environmental resources particularly light and N, which directly affected the growth and survival of weeds (Bedoussac *et al.,* 2014). This was enhanced by the uniform arrangement of bi-crops, which promoted early total canopy ground cover, maximised light interception, weed suppression and reduced weed N uptake than broadcast. These findings are also in conformity with Orcluchukwu and Edensi (2013), Dwivedi *et al.* (2011), Olsen and Weigner (2007).

9.9 Plant heights

Effects of cropping systems

Wheat plant heights

This study revealed taller wheat plants in the bi-cropping system than in the sole cropping system in both cropping seasons. Taller wheat plants in the bi-cropping system was attributed to the shading effect from the bean bi-crop plants, which influenced the wheat bi-crop plants to grow taller for light resource capture, regulated by the accumulation of auxins growth hormones (Badran, 2011). Similar findings have been reported by Eskandari and Ghanbari (2010).

Bean plant heights

This study showed taller bean plants in the sole cropping system than in the bi-cropping system in both cropping seasons. The shorter bean plants in bi-cropping systems was influenced by the strong competitive effect of the wheat bi-crops over the bean bi-crops plants as also reported by Dordas and Lithourgidis (2011) in oat/faba bean and Ghanbari-Bonjar, 2000 in wheat/faba bean crop mixtures.

Effects of drilling patterns

Wheat plant heights

This study showed taller wheat plants in alternate rows than in broadcast treatment in both cropping seasons, which was probably attributed to efficient use of environmental resources such as solar radiation and better facilitation of other associated ecological services such as biological weed control (Vandermeer, 1989). Shorter wheat plants in broadcast bi-cropping treatments in the 2015 cropping season was caused by weeds interference. This is because the randomly distributed bean bi-crops in space did not developed a uniform ground canopy cover, which is necessary for higher light interception and weed control (Choudhary *et al.,* 2014). The beans are weak competitors against weeds due to their slow growth rate during the early part of their growth cycle (Hauggaard-Nielsen *et al.,* 2007; Mcdonald, 2003; Mohler and Liebman, 1987). Therefore, sowing the beans and wheat in mixtures as broadcast was proved less suitable bi-cropping system because of poor use of environmental resources such as light and its vulnerability to weed infestation, which may lead to the reduction of quantity and quality of forage.

This study showed that shorter wheat plant heights in the 1x1 and the 3x3 alternate row bi-cropping treatments in the 2015 season was a direct response to interspecific competition for soil water resources, which was more limiting than solar radiation (Tilman, 1988). The taller wheat plant height influenced by the 3x3 treatment in the 2016 season, was a direct response to the interspecific competition for solar radiation because soil water resource was not limiting than solar radiation (Aschehoug *et al.,* 2016; Tilman, 1988). The plant height response to soil water stress in crop mixtures agrees with findings by Semere and Froud-Williams (2001). Similarly, Sobkowicz (2001) reported a reduction in plant height due to competition for soil resources and increased plant height for oats and barley bi-crops due competition for light. The 2x2 alternate row bi-cropping treatments influenced optimum wheat plant height due to efficient partitioning of below and aboveground growth resources as a result spatial niche differentiation between bi-crop components (Vandermeer, 1989). The response of plants to limited growth resources via plant height has been clearly elaborated by Mariotti *et al.* (2009) and Aschehoug *et al.* (2016). The 1x1 is potential option for bi-cropping under optimum environmental conditions, particularly where soil water is not limited because it promotes physical root intermingling advantage, which may facilitate symbiotic N_2 fixation and direct N transfer between the bi-crops to satisfy their N requirements (Voisin *et al*., 2014). Similarly, Hongchun *et al.* (2013) also reported the advantage of root connections on nutrient uptake under the 1x1 alternate row treatments in cereal/legume mixtures.

Bean plant heights

The shorter bean plant heights in the (1x1 and 3x3) alternate rows in the 2015 season and taller bean plants in the (3x3) alternate rows in the 2016 season were influenced by interspecific competition for limited soil water and solar radiation respectively. The taller and shorter bean plant height implied that more plant energy was invested in the plant shoot and roots to effectively compete for solar radiation and soil water respectively (Tilman, 1988). When water is not limiting, solar radiation becomes the main growth limiting factor for bi-crop plants, resulting in taller bean plants (Lunagaria and Shekh, 2006; Aschehoug *et al.,* 2016). The competition between bi-crops in crop mixtures is distant dependent (Sobkowicz and Tendziagolska, 2015). Therefore, the bi-crop species root proximity and their relative intermingling in the rhizosphere aggravated negative effect particularly on the beans which are weak competitors against the wheat on edaphic based resources especially water (Li *et al.,* 2011). The beans are reported as stronger competitors for light as also confirmed by the 3x3 treatments while the wheat is reported stronger competitor for soil water resources. When solar radiation is not a growth limiting factor in the environment, soil water becomes the main limiting growth factor resulting shorter plant heights (Mariotti *et al.*, 2009).

The 2x2 alternate row bi-cropping treatments showed optimum bean height due to lack of antagonistic interactions on resource-use between bi-crops, influenced by interspecific complementarity in space (Vandermeer, 1989). The 3x3 alternate row treatments have been proved unsuitable for forage production because it induces negative interactions in bi-cropping habitats. Similarly, the 1x1 alternate row bi-cropping treatments can significantly reduce the forage productivity under water stress environmental conditions.

Effects of bean cultivars

This study showed shorter bean plant heights in the 2015 than 2016 season due to soil water stress conditions as shown in Figure 3.2. This highlights the importance of water in bean production. Sobkowicz (2001) reported similar findings in barley and oats in mixture under water stress conditions. This meant that in the 2015 season, the bean plants invested more energy in the roots to compete for water at the expense of aboveground dry matter production (Ascehoug *et al.,* 2016).

Maris Bead plants were taller than Fuego in bi-cropping system due to their genetic differences (PGRO, 2017). When Maris Bead was drilled as 3x3 alternate rows spatial arrangement in 2016 under ample water availability, its plant height was taller than its corresponding sole cropping system. This was attributed to competition for light as competitive response to competitive effect induced by the fast growing wheat bi-crop component plants (Ascehoug *et al.,* 2016).

The findings suggest that Maris Bead is not suitable for bi-cropping under the 3x3 alternate row spatial arrangement. This agrees with Lateef and Farrg (2014) who indicated that the beans with slow growth rate traits like Maris Bead do not respond to intensification than fast growing the beans because they are affected by population just as the crowded plants under the 3x3 alternate row treatments. This is the reason why Sinoquet and Caldwell (1995) suggested that the slow growing or shorter planophile legume bi-crop need to be mixed with the eretophile cereal bi-crop component to achieve a productive bi-cropping systems. On other hand Kanton and Dennet (2008) suggested that for a productive bi-cropping, the slow growing or shorter erectophile legume bi-crop can be combined with the tall cereal bi-crop component with erectophile traits.

9.10 Final yield and components

Effects of cropping systems

Wheat yield

This study showed higher grain and total biomass wheat yield in sole cropping systems than in bi-cropping systems in the 2016 cropping season due to higher relative sowing density (Joliffe *et al.,* 1984). The sowing density for the sole cropping system was two times higher than that for the bi-cropping system. However, the reduction in the sowing density for the bi-crops by 50% of their sole cropping systems in replacement designed bi-cropping experiments helps to achieve complementarity to improved resource-use (Snaydon, 1994; Fradgley *et al.,* 2013). Similar findings in 50:50 replacement designed bi-cropping studies were reported by Jamshidi (2011), Jahanzad *et al.* (2011), Sadeghpour and Jahanzad (2012). The study showed higher harvest index of 58% in the bi-cropping system than the sole cropping system, which demonstrated the advantage of bi-cropping on wheat grain rather than wheat dry matter. This was due to lack of niche overlap for growth resources which resulted in maximised resource consumption (Vandermeer, 2011). Similar findings were reported by Ghanbari-Bonjar (2000) and Megawer *et al.* (2010). Low harvest index in the sole cropping system was probably attributed to soil N deficiency as evidenced by CCI values in Table 6.1 due to increased intraspecific competition for soil N at 100% sowing density (Majumdar *et al.*, 2016).

Bean yield

This study showed higher bean straw, seed and total biomass yield in the sole cropping system than in the bi-cropping system in both seasons because the sowing density for the sole cropping was two times higher than the bi-cropping system as reported by Joliffe *et al.* (1984) and Snaydon (1994). The lower bean seed yield in bi-cropping systems was affected by the reduction in the sowing density, beans vulnerability to weed infestation and weak competitive ability against the wheat bi-crops on resource acquisition in crop mixtures (Oskoii *et al.*, 2015). Similar findings were reported by Herbert *et al.* (1984), Sadeghpour *et al.* (2014) and Legesse *et al.* (2015) in corn/soybean, barley/annual medic and barley/faba crop mixtures respectively. The bean yield benefits in bi-cropping systems over sole cropping systems can be achieved by the total yield of bi-crops (Willey, 1979). Higher harvest index of 42% in the bi-cropping system than in the sole cropping system showed the advantage of bi-cropping on the bean seed than bean dry matter yield. This was due to spatial interspecific complementarity, which may have contributed to greater utilisation of growth resources (Fargione and Tilman, 2005). Bi-cropping systems have been reported to show greater efficiencies in converting available resources to harvestable yield, either through greater physiological efficiency or changes in dry matter partitioning (Trenbath, 1986).

Effects of drilling patterns

Wheat yield

This study showed no effect of the drilling patterns on wheat final yield due to spatial interspecific complementarity by better use of environmental resources caused by the reduction in sowing density of bi-crops by half of sole cropping systems (Sadeghpour *et al.*, 2013; Fradgley *et al.*, 2013). According to Hauggaard-Nielsen *et al.* (2008), the reduction in sowing density reduced the competition for major resources such as mineral soil N, water and solar radiation per plant. However, findings showed lowest 1000 wheat seed weight in the

3x3 alternate row treatments due interspecific competition for light as a result of crowdedness and vigorous growth of bi-crop plants in the 2016 season under ample soil water availability.

Bean yield

This study showed higher bean seed and total biomass yield in alternate rows than in broadcast treatment in both seasons attributed to weaker interspecific competition than intraspecific competition between the bi-crops (Vandermeer, 1989; Vandermeer, 2011). This led to efficient utilisation of available growth resources such as: light, soil water and non N resources (Agegnehu *et al.,* 2008). This also promoted effective performance of associated ecological services such as: biological N_2 fixation and weed control hence higher bean yield (Eskandari, 2012). The superior performance of alternate rows than broadcast bi-cropping systems was also reported by Olsen and Weigner (2007).

Effects of bean cultivars

This study showed similar influence of the bean cultivars on both the wheat and bean yield components possibly due to over-dominance of the interspecific complementarity interactions over the interspecific competition interactions on resource-use (Geno and Geno, 2001). This occurs when the bi-crops differ physiologically and morphologically and it influences resource-use (Jensen *et al.,* 2015).

Across the seasons, Fuego had the larger bean seed sizes than Maris Bead as a result of their genetic differences (PGRO, 2016). Even though soil water was not limiting in the 2016 cropping season, the bean seed size for both bean cultivars were reduced compared to the 2015 cropping season possibly due to the effect of the bean rust disease which occurred at pod filling growth stage as shown in Appendix 7.1.

Even though Maris Bead had the higher total bean biomass yield than Fuego in the 2016 season, Fuego had the higher harvest index than Maris Bead demonstrating better performance of Fuego on seed rather than dry matter yield. This finding was consistent with higher LAI in Table 6.2, IPAR in Table 6.3 and erectophile leaf type. The leaf angle distribution of a plant can determine biomass production (Mooney *et al.,* 1977). This suggests that Fuego has potential to biologically fix N_2 and use it more efficiently in low input bi-cropping systems than Maris Bead.

9.11 Crude protein

Wheat crude protein

Effects of cropping systems

Crude protein content of forage is one of the most important parameters for assessing the quality of forage. This study showed improved wheat crude protein content in bi-cropping systems than in sole cropping systems in both seasons. Averaged over two seasons the crude protein content in the beans was 2.4 times greater than that in wheat. Ghambari-Bonjar (2000) reported 1.9 times greater crude protein content in the beans than in wheat. Mariotti *et al.,* (2006) reported 2.4 times higher crude protein content in the legumes than in cereals and Chapagain (2014) reported 1.9 times higher crude protein in the legume than in cereal. The higher wheat crude protein content in bi-cropping systems than in sole cropping systems demonstrated the advantage of bi-cropping systems compared to growing sole cropping systems for forage production. These findings have demonstrated that wheat/bean bi-cropping systems can potentially reduce the need for outsourcing protein-rich supplements when compared to sole cropping systems. Also, enriched wheat forage quality from bi-cropping systems can help to achieving a balanced feed for ruminants than sole wheat cropping systems (Lithourgidis *et al.,* 2011). Above all, bi-cropping can serve as low cost intervention for generating both high quantity and quality forage (Flores *et al.*, 2012).

Improved wheat crude protein content in bi-cropping systems was influenced by spatial interspecific complementarity, which resulted in efficient use of N sources between the bi-crop species due to reduced sowing density of each bi-crop species by 50% (Bedoussac and Jutes, 2010). According to Jensen (1996), Chalk *et al.* (2014) and Bedoussac *et al.* (2014), the direct N transfer from the legume bi-crop to the cereal bi-crop might be one of the reasons for crude protein improvement in low input bi-cropping systems. Increased wheat crude protein in wheat/faba bean bi-cropping studies was also reported by Ghanbari-Bonjar and Lee (2003), Lithourgidis and Dordas (2010) and Chapagain (2014). Haq *et al*. (2018) reported higher crude protein in cereal/legume cropping systems compared to sole cereal cropping systems. According to Samaan *et al.* (2006) and Gooding *et al*. (2007), limited soil N availability in low input production systems, such as organic farms, can limit the capacity of wheat crops to attain the expected crude protein thresholds in the wheat grain. Improved crude protein content in the wheat bi-crops through bi-cropping systems can help to influence the adoption of bi-cropping systems among organic farmers because it can significantly reduce the costs of purchasing expensive non-forage feed supplements (Bedoussac *et al.,* 2014; Gebrehiwot *et al.,* 1996).

Even though the 2016 cropping season had better weather conditions, such as soil water, it influenced lower wheat protein concentration in bi-cropping systems than in the 2015 cropping season. Reduced wheat protein yield and quality under wet environmental conditions was also reported by Wang *et al.* (2004) and Zeleke *et al.* (2016).

Effects of drilling patterns

This study showed similar effects of drilling patterns treatments on wheat crude protein content and N yield, possibly due to spatial interspecific complementarity which promoted greater efficiency in the utilisation of growth resources (Jensen, 1996; Sadeghpour *et al.,* 2013). However, the high (2x2 drilling pattern) and low (1x1 and 3x3 drilling patterns) harvest index for wheat N yields demonstrated the positive and negative ecological interspecific interactions on efficiency of resource-use.

Effects of bean cultivars

The bean cultivars had similar influence on wheat grain crude protein content in both seasons. This was due to their morphological and physiological complementarities with the wheat bi-crops, which led to efficient utilisation of environmental resources particularly N (Jensen *et al.,* 2015). This finding is in agreement with results in Table 6.3 on CCI and Table 6.15 on wheat N uptake which further suggested that in a 50:50 replacement design, both bean cultivars are capable of improving wheat grain crude protein content.

However, Fuego influenced higher wheat straw crude protein content than Maris Bead under ample soil water conditions in the 2016 cropping season. This was possibly because of two reasons: firstly, spatial interspecific complementarity on efficient use of N resources and; secondly, the superficial root system of Fuego is reportedly capable of promoting strong fungi arbuscular mycorrhizae symbiotic networking, which is responsible for enhancing direct N transfer (Jensen *et al.,* 2010).

<u>Bean crude protein</u>

Effects of cropping systems

This study showed no differences between sole cropping systems and bi-cropping systems on bean crude protein content in the bean straw, seed and total bean biomass. Similarly, Bedousaac *et al.* (2014) found no differences between cropping systems on crude protein content in spring wheat/faba bean bi-cropping systems. This demonstrated the suitability of spring wheat/faba bean bi-cropping systems on improving bean crude protein in low input environments.

This study showed higher N yield in the sole cropping system than the bi-cropping system because sowing density for the sole cropping system was two times higher than the bi-cropping system. The higher sowing density might have influenced higher protein yield, which resulted in more N removed from the field during harvest than the bi-cropping system (Dordas and Lithourgidis, 2011). However, the higher N yield harvest index for the bi-cropping system than the sole cropping system, showed the advantage of bi-cropping systems over sole cropping systems, due to efficient utilisation of environmental resources, such as N, caused by spatial niche differentiation (Corre-Hellou *et al.,* 2006).

Effects of drilling patterns

This study showed a similar influence of the drilling patterns on bean crude protein content. Morphological and physiological differences between the bi-crops possibly led to spatial complementarity on efficient use of different N sources (Hauggaard-Nielsen *et al.,* 2008; Corre-Hellou *et al.,* 2006).

This study showed higher N yield from the alternate row bi-cropping treatments than broadcast treatment due to spatial interspecific complementarity effects, which led to improved use of growth resources, especially solar radiation (Hauggaard-Niesen *et al.,* 2009). Differences in the spatial arrangements of the bi-crops between alternate rows and broadcast treatments determined their respective canopy density, light interception capacity and subsequent N yield. Higher light interceptions has been reported as a key plant factor responsible for enhancing legumes nodule formation and biological N fixation, which may have led to greater protein content (Fan *et al.,* 2006; Oluwasemire and Odugbenro, 2014). Therefore higher N yield could have been attributed to higher light interception. The broadcast treatment proved less suitable for protein production in low input system because of poor canopy cover, light interception and weed control, which may limit biological N fixation and produce a lower protein content (Hauggaard-Niesen *et al.,* 2001a). Weed infestation has been reported to severely limit the nutrition of grain legumes in organic farms (Corre-Hellou and Crozat, 2005).

Effects of bean cultivars

This study showed higher bean seed crude protein content in Maris Bead than Fuego in the 2015 season under water limiting environmental conditions due to the advantage of a taproot system (Table 7.2). Moreover, since solar radiation was not limiting in the 2015 season, most of the solar radiation intercepted by Maris Bead may have contributed to enhanced biological N fixation, hence; higher crude protein content because N_2 fixation is directly related to crude protein (Carr *et al.,* 2004). As soil water was not limiting in the 2016 season the bean cultivars had similar influence on bean seed crude protein possibly due to lack of competition for mineral soil N between the bean and wheat bi-crops, which was influenced by reduced sowing density of bi-crops (Corre-Hellou *et al.,* 2006).

9.12 N uptake

<u>Wheat N uptake</u>

Effects of cropping systems

This study showed greater influence of bi-cropping systems on the wheat grain N uptake than sole cropping systems in both seasons due to spatial interspecific complementarity, which possibly improved the efficient use of N between the bi-crops species (Corre-Hellou *et al.,* 2006). This meant that low input wheat/faba bean bi-cropping systems can increase N uptake in the cereal bi-crops, improve protein quality and making it highly suitable for livestock feed and bread making (Gooding *et al.,* 2007).

Wheat grain N uptake was lower in the 2016 than 2015 season, which may have been caused by wet weather conditions (Figure 3.2 and Appendix 1.1). This might have affected N availability as similarly reported by Wang *et al.* (2004).

This higher N harvest index for the bi-cropping system than the sole cropping system showed the advantage of bi-cropping on efficient utilisation of different N pools, due to spatial complementarity between the bi-crops (Bedoussac *et al.,* 2015). This finding agreed with the CCI results (Table 6.1) which predicted higher wheat N uptake and improved wheat crude protein content (Table 6.13) in bi-cropping systems than sole cropping systems. Similar findings were reported by Dordas and Lithourgidis (2011) in wheat/faba bean bi-cropping systems. The interspecific competition for mineral soil N in bi-cropping systems may have forced the bean bi-crop to actively fix more atmospheric N_2 and reduced competition for available mineral soil N with the wheat bi-crops (Hauggaard-Nielsen *et al.,* 2008; Latati *et al.,* 2016).

Effects of drilling patterns

This study showed no effect of drilling patterns on N uptake in the wheat bi-crop plants (e.g. straw, grain and total biomass), due to efficient utilisation of different N pools by each plant than in sole crops, as a results morphological and physiological complementarity (Naudin *et al.,* 2010).

Effects of bean cultivars

This study showed similar effects of the bean cultivars on wheat N uptake because of the greater influence of spatial interspecific complementarity than interspecific competition on efficient use of environmental resources particularly N between the bi-crops (Jensen, 1996).

<u>Bean N uptake</u>

Effects of cropping systems

The sole cropping system had higher N uptake in the bean straw, seed and total biomass than the bi-cropping system due to higher sowing density. The sowing density for the sole cropping system was two times higher than for the bi-cropping system. This influenced higher bean biomass yield which directly resulted in increased N uptake as also reported by Stern (1993) and Meng *et al.* (2013). Higher N uptake in sole cropping systems was similarly reported in other 50:50 replacement designed bi-cropping studies by Sadeghpour *et al.* (2013) and Zhang *et al.* (2015).

This study showed higher N harvest index for the bi-cropping system than the sole cropping system due to improved nitrogen use efficiency as a result of lower interspecific competition than intraspecific competition between bi-crops (Naudin *et al.,* 2010). This agrees with various studies (e.g. Bedoussac and Justes, 2010) which have shown higher productivity of bi-cropping systems under low input systems.

Effects of drilling patterns

This study showed higher bean N uptake in alternate rows than in broadcast treatments under dry weather conditions in the 2015 season. Improved total ground canopy cover, due to uniform arrangement of bi-crop spatially, might have improved light interception, weed suppression, reduced inter-row evaporation and N fixation, which possibly resulted in higher N uptake (Devi *et al.,* 2014; Bastiaans *et al.,* 2008; Fan *et al.,* 2006). A patchy and less dense total ground canopy cover in broadcast treatment, may have contributed to poor light interception, weed control, water conservation and possibly impaired N fixation, which resulted in reduced bean N uptake. Similarly, the over performance of the alternate rows than broadcast treatments have been confirmed by Evers and Bastiaans (2016), Musa *et al.* (2010) and Chapagain (2014). The over performance of the 2x2 alternate row treatments in the 2016 season, was due to a higher degree of complimentary use of N between the bi-crops (Bedoussac *et al.,* 2015;Corre-Hellou *et al.,* 2006). This was probably influenced by their niche differentiation (Fargione and Tilman, 2005). Highest IPAR results in Table 6.3 under the 2x2 alternate row treatment, could be main environmental factor responsible for higher bean N uptake, because biological N_2 fixation in legumes depends on solar radiation (Dreccer *et al.,* 2000; Fan *et al.,* 2006; Eskandari *et al.,* 2009; Lucas and Hungrian 2014). Better growing conditions in the 2016 season, may have contributed to improved use of available ecological resources particularly solar radiation because the beans plants are good competitors for solar radiation than the wheat plants hence improved N uptake (Hook and Gascho, 1988).

Effects of bean cultivars

Maris Bead influenced higher N uptake than Fuego in the bean seed and total biomass in the 2016 season. This was possibly influence by planophile leaf characteristic, which is reportedly effective in light interception earlier in the season before reaching maximum canopy development (Hoad *et al.*, 2006). Light interception and nitrogen uptake are directly related (Dreccer *et al*. 2000). The higher cumulative light interception might have contributed to lower soil temperatures, reduced evaporation, improve nodulation and biological N fixation hence improved N uptake in the bean seed and total biomass (Harris and Natarajani, 1987; Akunda, 2001; Fan *et al*., 2006).

9.13 Biological efficiency of bi-cropping system

The LER in the 2015 cropping season was above the unitary value of 1.0, which revealed the advantage of bi-cropping systems over sole cropping systems, due to efficient acquisition of growth resources between the bi-crops (Rao and Willey, 1980). The LER value of 1.50 obtained in the 2015 cropping season meant that bi-cropping was 1.5 times advantageous over sole cropping. It also meant that 50% of the land in sole cropping system would be required to achieve the same yield as in the wheat/faba bean bi-cropping system (Rao and Willey, 1980).

The LER value in the 2016 cropping season was equal to the unitary value of 1.0, which showed that the bi-cropping system had no advantage over the sole cropping system (Rao and Willey, 1980). The lack of bi-cropping advantage during the 2016 season, was possibly caused by the faba bean rust disease *Uromyces viciae-fabae* outbreak, which infected the beans plants at pod filling bean growth stage due to the prevailed warm and wet growing conditions, which favour fungal disease outbreak in a disease triangle (Putasso *et al.*, 2012). This finding can further infer that biotic stress such as fungal bean diseases can negatively affect the biological efficiency of bi-cropping systems.

The bi-cropping system during the 2015 cropping season showed land saving advantage because the mean value of 33.6% was above the minimum threshold value of 25% (Adetiloye *et al.*, 1983). During the 2016 season there was no land saving advantage because the mean value of 7.5% was lower than the minimum threshold value of 25% (Adetiloye *et al.*, 1983).

The higher LER for alternate rows than broadcast treatments was driven by morphological, physiological and phenological complementarity in space which led to efficient use of growth resources such as water, light and non N nutrients (Mead and Willey, 1980). The 2x2 alternate row treatments influenced relatively higher land use efficiency than other alternate rows in the 2015 season, as a result of improved environmental resource-use between the bi-crops (Abu-Bakar *et al.*, 2014). However, the biological efficiency of the bi-cropping system in the 2015 season was reduced as the number of rows increased beyond the 2x2 alternate row spatial arrangements, due to negative interspecific interaction, which may have gradually converted interspecific complementarity to interspecific competition (Geno and Geno, 2001). These findings agreed with Sadeghpour *et al.* (2014) who reported reduced productivity of barley/annual medic crop mixtures as a result increasing the number of rows. Similar findings with LER above 1.0 in wheat/faba bean bi-cropping studies were reported by Haymes and Lee (1999), Ghambari-Bonjar (2000), Agegnehu *et al.* (2008), Legesse *et al.,* (2015) and Fikadu *et al.* (2016). The benefits of bi-cropping with LER >1.0 in other cereal/legume crop mixtures were also reported in lentil/mustard bi-crop mixtures (Konthoujam *et. al.,* 2014), pea/barley bi-crop mixtures (Koohi *et al.,* 2014) and sorghum/mung bean bi-crop mixture (Megawe *et al.,* 2010).

Despite the beans were affected by the disease in 2016 cropping season, the bean cultivar x drilling patterns interaction effect revealed the higher LER for Fuego than Maris Bead when sown as 2x2 alternate row arrangements. This probably meant that Fuego might have escape heavy infestation of the disease due to its fast growth rate. Slow growth rate trait for Maris Bead might have coincided with the peak faba bean rust disease infestation while the pods were at early filling stage. This demonstrated the advantage of short and earliness to maturity bean cultivars (Fuego) for successful bi-cropping in low input environments compared to tall and medium to late maturity bean cultivars (Maris Bead) as reported by Taylor and Cormack (2002).

9.14 Competition indices

Aggressivity (A)

This study showed the positive and negative aggressivity values for the wheat and bean bi-crops respectively in both cropping seasons. This meant that the bean bi-crops were dominated by the wheat bi-crops on environmental resource acquisition. In bi-cropping systems, this is a common competitive behaviour of the cereal bi-crops over the legumes bi-crops for soil based resources due to their massive and exploitive root systems (Dhima *et al.,* 2007). Similar findings in cereal/legume bi-cropping systems in replacement designs were reported by Abu-Bakar *et al.* (2014), Konthoujam *et al.* (2014), and Oseni (2010).

The drilling pattern treatment with the lower aggressivity value is a sign of interspecific competition for environmental resources. The drilling pattern treatment with the higher aggressivity value is a sign of interspecific complementarity as a result of equitable and judicious use of environmental resources (Abu-Bakar *et al.,* 2014; Choudhary, 2014; Ghosh *et al.,* 2006). The findings of this study showed the lower aggressivity values from the 1x1 and 3x3 alternate row bi-cropping treatments, which revealed the occurrence of interspecific competition for available resources. These treatments showed their vulnerability to reduce the forage quality. This finding was in agreement with reduced plant heights due to competition in Tables 6.4 and 6.5. The 2x2 alternate row bi-cropping treatments had the higher aggressivity value, which demonstrated the dominance of interspecific complementarity by better use of environmental resources. This treatment showed the potential to improve the forage quality (Zhang and Li 2003).

However, Fuego bean cultivar had relatively the lower aggressivity value compared to Maris Bead suggesting that under water stress conditions, Fuego with fast growth rate trait faced strong competition for soil water resource due to closer proximity of the bi-crops and physical root intermingling. These findings conform to the results in Table 6.5 and as reported by Ascehoug *et al.* (2016).

Relative Crowding Coefficient (K)

The Relative Crowding Coefficient measures the relative dominance of one crop species over the other in a crop mixture (Ghosh, 2004). The findings of this study showed higher partial *K* coefficient values for the wheat than the beans bi-crop in the bi-cropping habitat. The higher partial *K* coefficient values for the wheat bi-crops than the beans bi-crops revealed the stronger competitive ability of the wheat bi-crop on the exploitation of resources in wheat/legume bi-cropping mixture. The similar findings were reported by Dhima *et al.* (2007) and Ghosh (2004).

The product *K* coefficient value was greater than the unitary value of 1.0 for all the bi-cropping treatment combinations in 2015 season, which meant that the bi-cropping system was advantageous over the sole cropping system on land saving with regard to efficient utilisation of resources.

However, in the 2016 season, the 1x1 and 2x2 alternate rows in wheat/Fuego bean bi-cropping system showed no advantage of crop mixtures because the product *K* coefficient values were equal to the unitary value of 1.0. Under the same cropping system (wheat/Fuego bean), the 3x3 and broadcast treatments showed disadvantage of the crop mixture because the product *K* coefficients values were less than the unitary value of 1.0, which could be attributed to interspecific competition for growth resources (Megawer *et al.*, 2010).

The aggressivity and relative crowding coefficient values were higher in the 2015 than 2016 cropping season, which demonstrated the advantage of the bi-cropping system under relatively drier weather conditions as in 2015 season. This finding concurs with Semere (1998) in maize/pea bi-cropping where bi-crops were more competitive in the drier than wet growing conditions. Tsubo *et al.* (2005) reported best performance of soybean/maize bi-crops during water scarcity periods. Tesfamichael and Reddy (1996) reported greater bi-crop yield advantage from a low than medium rainfall areas. Agegnehu *et al*. (2006) reported more efficient use of resources and greater yield stability under water stress in bi-cropping system than sole cropping system. Bi-cropping can improve water use efficiency leading to increased use of other environmental resources (Devi *et al.,* 2014; Hook and Gascho, 1988). This can partly explain for the better performance of the 2x2 alternate row treatments under water stress conditions in the 2015 cropping season. Cereal/legume bi-cropping systems use water more efficiently than mono-cropping systems (Willey, 1979).

9.15 Pests and disease control

Effects of cropping systems

The advantage of bi-cropping systems over sole cropping systems on reducing the incidences of pests and diseases below economic threshold was demonstrated by a wide range of reports including Enikuomehin *et al.* (2010). This study also showed that bi-cropping systems were less affected than sole cropping systems by the Faba bean rust *(Uromyces viciae-fabae),* Ascochyta blight *(Ascochyta fabae)* and Black bean aphids (*Aphis fabae*), due to spatial interspecific complementarity effects (Dempster and Coaker, 1974). The effective performance of the mechanisms which help to reduce pests and diseases in crop mixtures were influenced by spatial interspecific complementarity on resource-use efficiency (Vandermeer, 1989).

Effects of drilling patterns

The 1x1 alternate row treatments was highly affected by Faba bean rust *(Uromyces viciae-fabae)* and Ascochyta blight *(Ascochyta fabae)*, due to closer proximity of bi-crop plants, which influenced ease transmission of the disease causing inoculum by wind (ICARDA, 1986; Khan *et al.,* 2010).

Effects of bean cultivars

This study showed that morphological leaf differences between the bean cultivars might have influenced the increased infestation and distribution of Faba bean rust *(Uromyces viciae-*

fabae), Ascochyta blight *(Ascochyta fabae)* and Black bean aphids (*Aphis fabae*) on the bean plants. According to Ogenga-Latigo *et al.* (1993), the electrophile leaf type for Fuego (narrow and vertical) influenced higher incidences of pests and disease attacks, due to its capacity to intercept more light for long hours throughout the canopy, which probably provided warm environmental conditions conducive for pest and disease survival hence higher infections. In contrast, planophile leaf types for Maris Bead (broad and horizontal) was associated with mutual leaf shading conditions within the canopy, which probably did not favour pests and disease survival hence lower infections.

CHAPTER 10

CONCLUSION

This study was developed with the aim of improving the sustainable production of home-grown forage for livestock production through evaluation of the potential field bean (*Vicia faba* L.*)* and wheat (*Triticum aestivum* L.) variety mixture as a bi-cropping opportunity.

The results have revealed that bi-cropping systems can improve the yield and crude protein of wheat forage over sole cropping systems through improved resource use efficiency. The greater improvement in resource use efficiency in bi-cropping systems over sole cropping systems was demonstrated by the LER in Table 6.10 which led to the improvement of wheat crude protein in Table 6.13 and reduction in biotic stresses in Tables 4.13 & Table 6.6a.

Generally, drilling wheat and faba beans bi-crops in the alternate row spatial arrangement demonstrated the capacity to improve forage dry matter yield production and land productivity over broadcast spatial arrangement. Broadcast is a less suitable bi-cropping practice for forage production in low input environments because of vulnerability to increased weed seed bank and weed seed returns due to poor weed control.

Drilling wheat and faba beans in mixture as 2x2 alternate row spatial arrangements proved an attractive option because this had the highest influence on the productivity of forage irrespective of contrasting seasonal characteristics.

When soil water was limiting during the 2015 cropping season, the 1x1 alternate row spatial arrangement influenced reduced plant heights and light interception due to interspecific competition for edaphic resources. The closer spatial proximity between bi-crops and their physical root intermingling contributed to an increase in competition for limited soil water resources.

During the 2016 cropping season, when soil water was not limiting, the 1x1 alternate row spatial arrangements improved leaf area index, light interception and biological weed control which directly influenced improved forage productivity.

In a spring season with severe outbreaks of fungal diseases, the 1x1 alternate row spatial arrangement option can facilitate spreading of fungal diseases such as faba bean rust (*Uromyces viciae-fabae*) and Ascochyta blight (*Ascochyta fabae***)** which can affect forage quality due to the closer proximity of bean bi-crop plants.

The 3x3 alternate row spatial arrangements is an unattractive bi-cropping option for forage production because it is always associated with both below and aboveground interspecific competition, irrespective of seasonal characteristics.

Fuego proved a suitable faba bean candidate over Maris Bead for forage production in low input bi-cropping systems because its superior performance does not change with seasonal variation. It also used available resources more efficiently than Maris Bead as demonstrated by the harvest index in Table 6.9 and Figure 6.2. However, in a year with high rates of pest and disease outbreaks, it is susceptible to higher infestation than Maris Bead. Maris Bead is less suitable for bi-cropping except under the 2x2 alternate row arrangement.

However, even if Maris Bead had high protein content suitable for livestock feed and its tap root system suitable to tolerate water stress conditions, its taller plant height limits its suitability for modern large scale mechanised bi-cropping for forage production, which favours short bean cultivars due to their compatibility to combined harvesting.

To conclude, the successful production of forage yield and improved crude protein in spring low input wheat/field bean bi-cropping systems depends on appropriate drilling patterns and selection of suitable crop varieties among others agronomic management practices as schematically described in Figure 10.1. The performance of study factors (beans and drilling patterns) on influencing the productivity of forage based bi-cropping systems are summarised in Appendix 6.1 & 6.2.

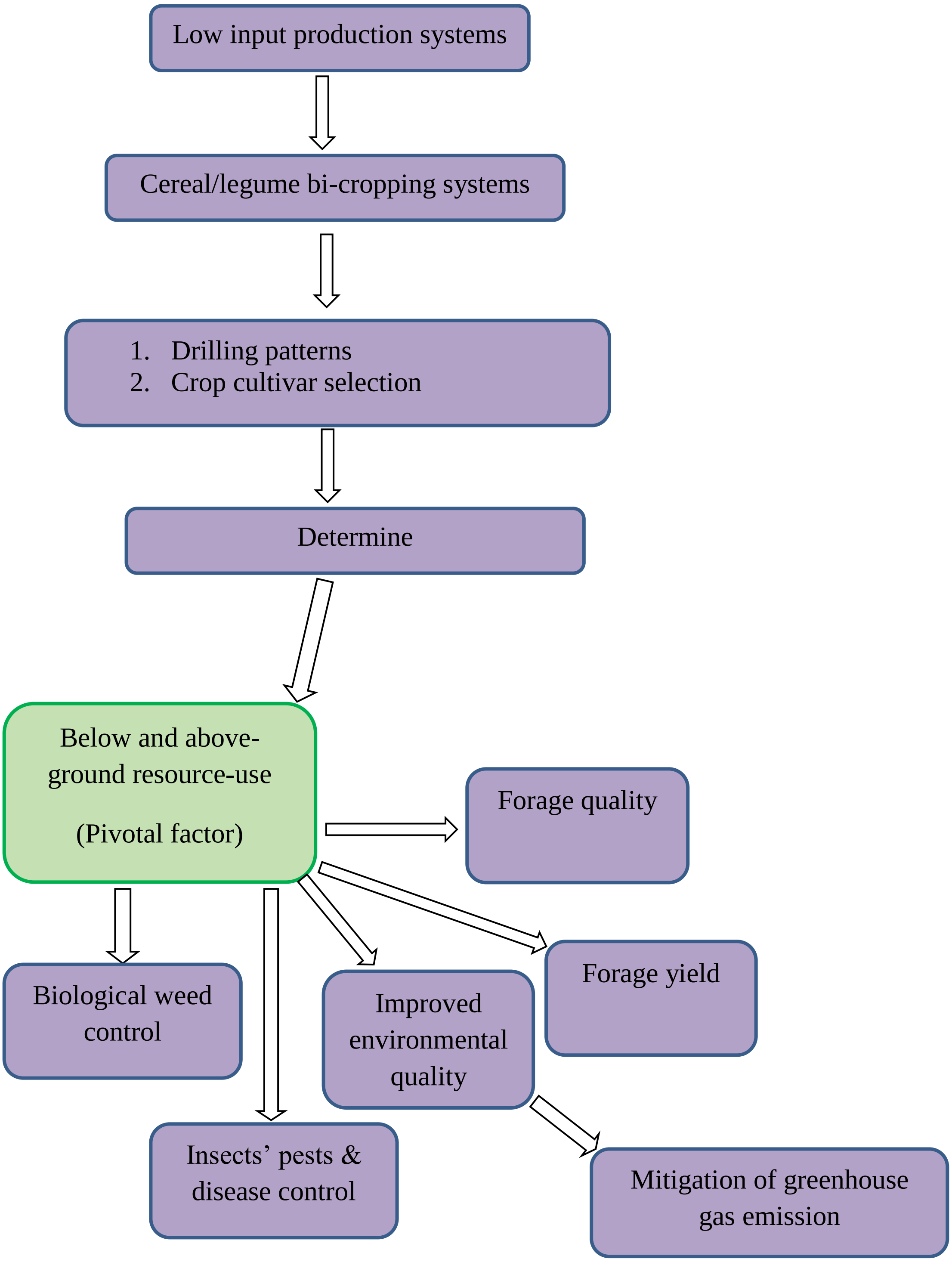

Fig. 10.1: A schematic model of a sustainable low input wheat/bean bi-cropping system for forage production

Limitations of the study

Economic benefit is one of the primary factors which drive the wider adoption of any agricultural technology by farmers. In this study, the economic aspect of bi-cropping system for forage production was not assessed due to time limitations. In future, it would be useful to involve a student of agricultural economics to generate this useful information to support agronomic findings and enhance the wider adoption of bi-cropping systems.

The study was conducted at one site with similar weather conditions and soil type. In future, depending on the project budget, it would be better to replicate a similar study at two contrasting sites within the Cotswold District to determine the site x treatments interaction effects.

To verify crop responses to underground based interspecific competition for growth resources through reduced plant heights in Table 6.4 and long and narrow bean root characteristics in Table 7.2 under the 1x1 alternate row arrangement, soil water was not assessed due to the absence of the Time Domain Reflectrometry (TDR) equipment which directly measures soil moisture content. Alternatively, to rectify the problems of mid-season water stress conditions, perhaps supplementary irrigation may prove an appropriate remedial intervention.

Recommendations

There is a need for the continued assessment of newly released faba bean cultivars for their suitability for forage production in low input bi-cropping systems using the 2x2 alternate row bi-cropping treatments as a standard yard stick.

There is a need to engage stakeholders in popularising wheat/faba bean bi-cropping systems. As young farmers are inheriting the management of farms within the UK, they may not have the know-how on bi-cropping system and there is a need to sensitise them regarding the importance of the systems in relation to its relevance to the modern and future sustainability of livestock/crop farming systems. The research institutions may help to extend further research from where the university lacks continuity due to limited resources such as time, finances and relevant facilities. Policy makers may help to recommend subsidises that may help to promote wide spread of bi-cropping systems among organic farms.

While Fuego has demonstrated its suitability for spring low input bi-cropping systems, future attention needs to examine agronomic practices that can help to reduced biotic stresses in collaboration with plant breeders and plant pathologists.

With the prevailing seasonal weather variability, soil water studies in bi-cropping systems need to be assessed to better understand impacts on the bean performance and the ultimate productivity of bi-cropping systems.

REFERENCE

Abaidoo, R.C., Keyser, H.H., Singleton, P.W., Dashiell, K.E. and Sanginga, N. (2007) Population size, distribution, and symbiotic characteristics of indigenous *Bradyrhizobium* spp. that nodulate TGx soybean genotypes in Africa. *Applied Soil Ecology* 35: 57-67.

Abdel-Wahab, T.I. and Elmanzalawy, A.M. (2016) Yield and quality of intercropped wheat with faba bean under different wheat plant densities and slow - Release nitrogen fertilizer rates in sandy soil. *American Journal of Experimental Agriculture.* 11(6): 1-22.

Abu-Bakar, M., Ahmad, R., Jabbar, A., Muhammad Abid, M., and Husain, I. (2014) Competitive ability of different barley based intercropping systems. *International Journal of Agronomy and Agricultural Research*. 5 (3): 17-22.

Achakzai, A.K. (2007) Effect of nitrogen fertilizer on nodulation of pea cultivars. *Pakistan Journal of Botany*. 39(5): 1673-1680.

Achouri, M. and Gifford, G.F. (1984) Spatial and seasonal variability of field measured infiltration rates on a rangeland site in Utah. *Journal of Range Management*. 37(5):451-455.

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

Adeboye, O.B., Schultz, B., Adekalu, K.O. et al. (2016) Impact of water stress on radiation interception and radiation use efficiency of soybeans (*Glycine max* L. Merr.) in Nigeria. *Brazilian Journal of Science and Technology*. 3(15): 1-21.

Adetiloye, P.O., Ezedinma, F.O.C. and Okigho, B.N. (1983) A land equivalent coefficient concept for the evaluation of competitive and productive interactions on simple complex crop mixtures. *Ecological Modelling*. 19: 27-39.

Agbaje, G.O., Ogunbodede, B.A. and Makinde, J.O. (2002).Biological and economical efficiency of maize + soybean intercrop pattern in rainforest and savanna areas of Nigeria. *Moor Journal of Agricultural Research*. 3: 37-40.

Agboola, A.A. and Fayemi, A.A. (1971) Preliminary trials on the intercropping of maize with different tropical legumes in western Nigeria. *The Journal of Agricultural Science*. 77: 219-225.

Agegnehu, G., Ghizaw, A., and Sinebo, W. (2008) Yield potential and land-use efficiency of wheat and faba bean mixed intercropping. *Agronomy for Sustainable Development*. 28: 257-263.

Agegnehu, G., Ghizaw, A., and Sinebo, W., (2006) Yield performance and land use efficiency of barley and faba bean mixed cropping in Ethiopian highlands. *European Journal of Agronomy*. 25: 202-207.

AHDB (2015). Wheat growth guide. AHDB Cereals and Oilseeds. Agriculture and Horticulture Development Board. Warwickshire, UK. [Online] Available from: https://cereals.ahdb.org.uk/media/185687/g66-wheat-growth-guide.pdf. [Date accessed 18/05/2015].

AHDB (2016). Recommended Lists for cereals and oilseeds 2016/17. Summer 2016 edition. [Online] Available from: https://cereals.ahdb.org.uk/media/800462/recl1617-recommended-lists-2016-2017-summer-edition.pdf [date accessed 11/11/2016]

Ahlam, E., Mukhtar, N.O., Babiker, H.M. and Adam, A.I. (2014) Effect of nitrogen fertilization and *Bradyrhizobium* inoculation on the growth, symbiotic properties and yield of pigeon pea *(Cajanus cajan*). *Journal of Natural Resources and Environment.* 2 (1): 27-31.

Akinnifesi, F.K., Ajayi, O.C., Sileshi, G., Chirwa, P.W. and Chianu, J. (2010) Fertiliser trees for sustainable food security in the maize-based production systems of East and Southern Africa. A review. *Agronomy for Sustainable Development.* 30(3): 615-629.

Akter, M.D.N., Alim, A., Islam, M.M., Naher, Z., Rahman, M. and Hossain, A. (2004) Evaluation of mixed and intercropping of lentil and wheat. *European Journal of Agronomy*. 3: 48-51.

Akundu, E.M.W. (2001) Improving Food production by understanding the effects of Intercropping and plant population on soybean nitrogen fixing attributes. *Journal of Food Technology in Africa.* 6(4): 110-115.

Alexandratos, N. and Bruinsma, J. (2012) World Agriculture towards 2030/2050: The 2012 Revision. ESA Working Paper No. 12-03. Food and Agriculture Organization of the United Nations, Rome.

Altieri, M. (1999) The ecological role of biodiversity in agroecosystems. *Agriculture, Ecosystems and Environment*. 74: 19–31.

Altieri, M. A. and Toledo, V. M. (2011) The agroecological revolution in Latin America: rescuing nature, ensuring food sovereignty and empowering peasants. *Journal of Peasant Studies*. 38: 587-612.

Altieri, M.A., Nicholls, C.I. and Rene Montalb, R. (2017) Technological approaches to sustainable agriculture at a crossroads: An agroecological perspective. *Sustainability*. 9(3): (349).

Altieri, M.A., Nicholls, C.I., Henao, A. and Lana, M.A. (2015) Agroecology and the design of climate change-resilient farming systems. *Agronomy for Sustainable Development.* 35 (3): 869–890.

Aminifar, J. and Ghanbari, A. (2014). Biological facilitative interactions and their roles on maximize growth and productivity of crops in intercropping systems. *Scientia Agriculturae*. 6 (2): 90-95

Ananthi, T., Mohamed. A.M. and Al-Tawaha, A.R.M. (2017) A Review on maize- legume intercropping for enhancing the productivity and soil fertility for sustainable agriculture in India. *Advances in Environmental Biology*. 11(5): 49-6.

Anderson, W.K. (2010) Closing the gap between actual and potential yield of rainfed wheat. The impacts of environment, management and cultivar. *Field Crops Research*. 116: 14–22

Andrew, D.J. and Kassam, A.H. (1976) The importance of multiple cropping in increasing world food supplies. In, Papendick, R.I., Sanchez, P.A. and Triplett, G.B. (eds.) *Multiple cropping*. American Society of Agronomy. *Special Publications*. 27: 171- 200.

Andrew, M., James, E.K., Cummings, S.P., Zavalin, A.A., Vinogradova, L.V. and McKenzie, A. (2003) Use of nitrogen fixing bacteria inoculants as a substitute for nitrogen fertilizer for drylands graminaceous crops. Progress made mechanisms of action and future potential. *Symbiosis*. 35: 549-560.

Anil, L., Mazaheri, D., Phipps, R.H. and Harris, P.M. (1996) Intercropping maize with kale: scope, results and preliminary conclusions. *Aspects of Applied Biology*. 47: 399-403.

Anil, L., Park, J., Phipps, R.H. and Miller, F.A. (1998) Temperate intercropping of cereals for forage: a review of the potential for growth and utilization with particular reference to the UK, *Grass Forage Science*. 53: 301–317.

Anne-Sophie, V., Christophe, S., Nathalie, G., Munier-Jolain and Ney, B. (2002) Effect of mineral nitrogen on nitrogen nutrition and biomass partitioning between the shoot and roots of pea (*Pisum sativum* L.). *Plant and Soil*. 242: 251–262.

Anonymous (2017) Short Term Outlook for arable crops, meat and dairy markets. Directorate-General for Agriculture and Rural Development - Short Term Outlook – No. 18. [Online]. Available from: https://ec.europa.eu/agriculture/sites/agriculture/files/markets-and-prices/short-term-outlook/current_en.pdf [Date accessed: 12/08/2017]

Anselm A. E., and Taofeeq, A. A. (2010) Challenges of Agricultural Adaptation to Climate Change in Nigeria: a Synthesis from the Literature. *Field Actions Science Reports*. 4. [Online]. Available from: http://www.factsreports.revues.org/678.

Armstrong, K.L., Albrecht, K.A., Lauer, J.G. and Riday, H. (2008) Intercropping corn with lablab bean, velvet bean, and scarlet runner bean for forage. *Crop Science*. 48 (1):371-379.

Aschehoug, E.T., Brooker, R., Atwater, D.Z., Maron, J.L. and Callaway, R.M. (2016) The mechanisms and consequences of interspecific competition among plants. *Annual Review of Ecology, Evolution, and Systematics*. 47: 263-281.

Askew, M. (2016) MI Prospects. 19(6): 5-6. [Online]. Available from: https://cereals.ahdb.org.uk/media/1128601/mi-prospects-vol-19-6.pdf [Date accessed: 25/09/ 2016].

Asten, P.J.A.V., Wairegi, L.W.I., Mukasa, D. and Uringi, N.O. (2011) Agronomic and economic benefits of coffee-banana intercropping in Uganda's small holder farming systems. *Agricultural Systems*. 104: 326-334.

Awal, M.A. and Ikeda, T. (2003) Controlling canopy formation, flowering, and yield in field-grown stands of peanut (*Arachis hypogaea* L.) with ambient and regulated soil temperature. *Field Crops Res*earch. 81: 131-132.

Aynehband, Y.A., Behrooz, M. and Afshar, A.H. (2010) Study of intercropping agroecosystem productivity influenced by different crops and planting ratio. *American-Eurasian Journal of Agricultural and Environmental Sciences*. 7: 163–169

Azam-Ali, S.N. and Squire, G.R. (2002) Principles of tropical agronomy. CABI Publishing, Oxon, UK.

Aziz, M., Mahmood, A., Asif, M. and Ali, A. (2015) Wheat-based intercropping: A Review. *The Journal of Animal and Plant Sciences*. 25(4): 896-907.

Azo, W. M., Lane, G. P. F., Davies, W. P. and Cannon, N. D. (2012) Bi-cropping white lupins (*Lupinus albus* L.) with cereals for wholecrop forage in organic farming: the effect of seed rate and harvest dates on crop yield and quality. *Biological Agriculture and Horticulture*. 28: 86-100.

Baddeley, J.A., Jones, S., Topp, C.F.E., Watson, C.A., Helming, J. and Stoddard, F.L. (2013) Biological nitrogen fixation (BNF) by legume crops in Europe. *Legume Futures Report* 1.5. [Online]. Available from: http:// www.legumefutures.de/images/Legume_Futures_Report_1.5.pdf. [Date accessed: 12/08/2016].

Badran, M.S.S. (2011) Effect of intercropping wheat with faba bean on wheat productivity under Sandy Soil Conditions. *Alexandria Science Exchange Journal*. 31 (2): 103-112.

Baghdadi, A., Halim, R. A., Ghasemzadeh, A., Ebrahimi, M., Othman, R., and Yusof, M.M. (2016) Effect of intercropping of corn and soybean on dry matter yield and nutritive value of forage corn. *Legume Research*. 39 (6): 976-981.

Baidoo, P. K., Mochiah, M. B. and Apusiga, K. (2012) Onion as a pest control intercrop in organic cabbage (Brassica Oleracea) production system in Ghana. *Sustainable Agriculture Research*. 1: 36-41.

Baker, B.P., and Mohler, C.L. (2014) Weed management by upstate New York organic farmers: Strategies, techniques and research priorities. *Renewable Agriculture Food Systems*. 30: 418-427.

Balsdon, S.L., Martin, T.M., Clements, R.O. and George, S. (1997) The potential of a clover: cereal bi-cropping system to produce high quality whole-crop silage. Fifth Research

Conference British Grassland Society, 8-10 September 1997. Seale Hayne Faculty of Agriculture, Food and Land Use, University of Plymouth, I-IK. pp. 85-86.

Banik, P., Midya, A., Sarkar, B.K., and Ghosh, S.S. (2006) Wheat and chickpea intercropping systems in an additive series experiment: Advantages and weed smothering. *European Journal of Agronomy*. 24:325-33.

Bantie, Y.B. (2015) Determination of effective spatial arrangement for intercropping of maize (*Zea mays* L.) and potato (*Solanum tuberosum* L.) using competition indices *Journal of Horticulture and Forestry.* 2 (2): 137-143.

Bao, Y., Aggarwal, P., Robbins, N.E., Sturrock, C.J., Thompson, M.C. *et al.* (2014) Plant roots use a patterning mechanism to position lateral root branches toward available water. *Proceedings of the National Academy of Sciences*.111: 9319-9324.

Bargaz, A., Isaac, M.E., Jensen, E.S. and Carlssona, G. (2015) Intercropping of faba bean with wheat under low water availability promotes faba bean nodulation and root growth in deeper soil layers. *Procedia Environmental Sciences*. 29:111-112.

Bastiaans, L., Paolini, R., and Baumann, D. T. (2008) Focus on ecological weed management: What is hindering adoption? *Weed Research.* 48(6): 481-491.

Baumann, D.T., Bastiaans, L. and Kropff, M.J. (2001). Effects of intercropping on growth and reproductive capacity of late-emerging *Senecio vulgaris* L., with special reference to competition for light. *Annals of Botany*. 87, 209-217.

Bayu, W., Addisu, M., Tadesse, B. and Admassu, L. (2007) Intercropping tef and sunflower in semi-arid areas of Welo, Ethiopia. *Tropical Science*. 47: 16-24.

Beaudette, C., Bradley, R.L., Whalen, J, K., McVetty, P.B.E., Vessey, K. and Smith, D.L. (2010) Tree-based intercropping does not compromise canola (*Brassica napus* L.) seed oil yield and reduces soil nitrous oxide emissions. *Agriculture, Ecosystems and Environment*. 139: 33–39.

Bedoussac, L. and Justes, E. (2010) The efficiency of a durum wheat-winter pea intercrop to improve yield and wheat grain protein concentration depends on N availability during early growth. *Plant Soil*. 330:19–35

Bedoussac, L. and Justes, E. (2011) A comparison of commonly used indices for evaluating species interactions and intercrop efficiency: Application of durum wheat-winter pea bi-crops. *Field Crops Research.* 124: 25-36.

Bedoussac, L., Journet, E.P., Hauggaard-Nielsen, H., Naudin, C., Corre-Hellou, G., Jensen, E. S. and Justes, E. (2015) Ecological principles underlying the increase of productivity achieved by cereal-grain legumes in organic farming. A review. *Agronomy for Sustainable Development.* 35: 911–935.

Bedoussac, L., Journet, E-P., Hauggaard-Nielsen, H., Naudin, C., Corre-Hellou, G., Jensen, E. S. and Justes, E. (2017) Ensuring sustainable grain legume-cereal cropping systems. In, Sivasankar, S. (eds.) *Achieving sustainable cultivation of grain legumes*. Burleigh Dodds Series in Agricultural Science: 36.

Bedoussac, L., Justes, E., Journet, E.P., Hauggaard-Nielsen, H., Naudin, C., *et al.* (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. and Penvern, S. (eds.) *Organic farming, prototype for sustainable agricultures: Prototype for sustainable agricultures*. Berlin: Springer: 47-63.

Beets, W.C. (1982) Multiple cropping and tropical farming systems. Westview Press, Boulder, Colorado.

Belel, M.D., Halim, R.A., Rafii, M.Y. and Saud, H.M. (2014) Intercropping of corn with some selected legumes for improved forage production: A Review. *Journal of Agricultural Science*. 6 (3): 42-68.

Ben, R.F., Pre´vost, D. and Tyagi, R.D. (2002) Growth of alfalfa in sludge-amended soils and inoculated with rhizobia produced in sludge. *Journal of Environmental Quality*. 31: 1339-1348.

Benjamin, J.G. and Nielsen, D.C. (2006) Water deficit effects on root distribution of soybean, field pea and chickpea. *Field Crops Research*. 97: 248-253.

Berkenkamp, B. and Meeres J. (1987) Mixtures of annual crops for forage in central Alberta. *Canadian Journal of Plant Science.* 67: 175–183.

Bilalis, D., Papastylianou, P., Konstantas, A., Patsiali, S., Karkanis, A. and Efthimiadou, A. (2010) Weed-suppressive effects of maize/legume intercropping in organic farming. *International Journal of Pest Management*. 56(2): 173-181.

Bilsborrow, P., Cooper, J., Tétard-Jones, C., Srednicka-Tober, D., Baranski, M., Eyre, M., *et al*. (2013) The effect of organic and conventional management on the yield and quality of wheat grown in a long-term field trial. *European Journal of Agronomy*. 51: 71-80.

Bouyoucos, G.J. (1962) Hydrometer method for measuring particle size analysis of soil. *Agronomy Journal*. 54: 464-465.

Borger, C.P.D., Hashem, A., and Pathan, S. (2010). Manipulating crop row orientation to suppress weeds and increase crop yield. *Weed Science*. 58, 174–178.

Briggs, S.R., Cuttle, S., Goodlass, G., Hatch, D., King, J., Roderick, S. and Shepherd, M. (2005). Soil nitrogen building crops in organic farming – Defra research project OF0316 project publication. [Online]. Available from: http://orgprints.org/5582/1/Res_review_7_wright.doc [Date accessed: 23rd January, 2017].

Brintha, I., and Seran, T.H. (2009) Effect of paired row planting of radish (*Raphanus sativus* L.) intercropped with vegetable Amaranthus (*Amaranthus tricolor* L.) on yield components of radish in sandy regosol. *Journal of Agriculture Science.* 4: 19-28.

Brockwell, J., Pilka, A., and Holliday, R. A. (1991) Soil pH is a major determinant of the numbers of naturally occurring *Rhizobium meliloti* in non-cultivated soils in central New South Wales. Australian. *Journal Experimental Agriculture*.31: 211-219.

Brooker, W., Bennett, A.E., Daniell, T.J., Cong, W.F., George, T.S., Hallett, P.D., Hawes, C. *et al* (2015) Improving intercropping: a synthesis of research in agronomy, plant physiology and ecology. *New Phytologist.* 206: 107-117.

Bue, A, Preibel, S., Reckling, M., Kuhlman, T., Topp, K., Wats, C. *et al.* (2013) The environmental role of protein crops in the new common agricultural policy. Policy Department B: Structural and Cohesion Policies. European Parliament Brussels. [Online].Available from: http://www.europarl.europa.eu/RegData/etudes/etudes/join/2013/495856/IPOL-AGRI_ET(2013)495856_EN.pdf. [Date accessed: 22/05/2016]

Bulson, H.A.J., Snaydon, R, N. and Stopes, C.E. (1997) Effects of plant density on intercropped wheat and field beans in an organic farming system. *Journal of Agricultural Sciences*. 128: 59-71.

Caballero, R., Goicoechea, E.L. and Hernaiz, P.J. (1995) Forage yields and quality of common vetch and oat sown at varying seeding ratios and seeding rates of common vetch. *Field Crops Research*. 41:135-140.

Cahill, J.F. (1999) Fertilization effects on interactions between above-and belowground competition in an old field. *Ecology*. 80: 466–480

Cahill, J.F. (2002) What evidence is necessary in studies which separate root and shoot competition along productivity gradients? *Journal of Ecology*. 90: 201–205.

Calvino, P.A. and Sandras, V.O., (1999) Inter annual variation in soybean yield: Interaction among rainfall, soil depth and crop management. *Field Crops Research*. 63: 237–246.

Campbell, G. (1990). Derivation of an angle density function for canopies with ellipsoidal leaf angle distributions. *Agricultural and Forest Meteorology*. 49: 173-176.

Campiglia, E., Mancinelli, R., Di Felice, V. and Radicetti, E. (2014) Long-term residual effects of the management of cover crop biomass on soil nitrogen and yield of endive (*Cichoriumendivia* L.) and savoy cabbage (*Brassica oleracea* var. sabauda). *Soil and Tillage Research*. 139: 1-7.

CAP Reform 2014-2020. Agricultural Policy Perspectives Brief no. 5. December 2013. [Online]. Available from: https://ec.europa.eu/agriculture/sites/agriculture/files/policy-perspectives/policy-briefs/05_en.pdf [Date accessed: 13th January, 2017].

Carr, P.M., Horsley, R.D., and Poland, W.W. (2004) Barley, oat, and cereal–pea mixture as dryland forages in the northern Great Plains. *Agronomy Journal*. 96: 677–684.

Ceglar, A., Toreti, A., Lecerf, R., Van der Velde, M. and Dentener, F. (2016) Impact of meteorological drivers on regional inter-annual crop yield variability in France. *Agricultural and Forest Meteorology*. 216: 58-67.

Chalk, P.M., Peoples, M.B., McNeill, A.M., Boddey, R.M., Unkovich, M.J., Gardener, M.J., Silva, C.F., Chen, D. (2014) Methodologies for estimating nitrogen transfer between legume and companion species in agro-systems: A review of 15N enriched techniques. *Soil Biology and Biochemistry.* 73:10-21.

Chapagain, T. (2014) Intercropping wheat and barley with nitrogen fixing legume species in low input organic systems. PhD Thesis. The University of British Columbia. Vancouver. Canada.

Chapagain, T. and Riseman, A. (2014) Barley-pea intercropping: effects on land productivity, carbon and nitrogen transformations. *Field Crop Research.* 166: 18-25

Charles, H., Godfray, C.J., Beddington, J.R., Crute, I.R., Haddad, L., Lawrence, D. *et al*. (2010) Food Security: The challenge of feeding 9 billion people. *Science*. 327: 812-818.

Carter, M.R., Angers, D.A., and Kunelius, H.T. (1994). Soil structural form and stability, and organic matter under cool-season perennial grasses. *Soil Science Society of America Journal*. 58, 1194–1199.

Chen, C., Westcott, M., Neill, K., Wichmann, D., and Knox, M., (2004) Row configuration and nitrogen application for barley-pea intercropping in Montana. *Agronomy Journal*. 96: 1730-1738.

Chimonyo, V.G.P., Modi, A.T., Mabhaudhi, T. (2016) Water use and productivity of a sorghum/ cowpea/bottle gourd intercropping system. *Agricultural Water Management*. 165: 82-96.

Confalonieri, R., Foi, M., Casa, R., Aquaro, S., Tona, E., Peterle, M. *et al.* (2013). Development of an app for estimating leaf area index using a smartphone. Trueness and precision determination and comparison with other indirect methods. *Field Crops Research*. 96: 67-74.

Chongo, G. and Bernier, C.C. (1999) Field and growth chamber evaluation of components of partial resistance to *Colletotrichum truncatum* in lentil. *Canadian journal of plant pathology.* 21: 58–63.

Choudhary, V.K., Dixit, A., Kumar, P.S. and Chauhan, B.S. (2014) Productivity, weed dynamics, nutrient mining, and monetary advantage of maize-legume intercropping in the eastern Himalayan region of India. *Plant Production Science*. 17: 342-352.

Choudhary, V.K., Suresh-Kumar, P. and Bhagawati, R. (2013) Response of tillage and in situ moisture conservation on alteration of soil and morpho-physiological differences in maize under Eastern Himalayan region of India. *Soil Tillage Research*. 134: 41-48.

Ciampitti, I.A. (2012) A comprehensive study of plant density consequences on nitrogen uptake, partitioning, and use efficiencies relative to biomass accumulation over time in maize. Ph.D. Thesis. Purdue University, West Lafayette, Indiana.

Clement, A., Chalifour, F. P., Bharati, M. P. and Gendron, G. (1992) Effects of nitrogen supply and spatial arrangement on the grain yield of a maize/soybean intercrop in a humid subtropical climate. *Canadian Journal of Plant Science*. 72: 57–67.

Coll, L., Cerrudo, A., Rizzalli, R., Monzon, J.P. and Andrade, F.H. (2012) Capture and use of water and radiation in summer intercrops in the South-east Pampas of Argentina. *Field Crops Research*. 134: 105-113.

Corre-Hellou, G. and Crozat, Y. (2005) N_2 fixation and N supply in organic pea *(Pisum sativum L.)* cropping systems as affected by weeds and peaweevil *(Sitona lineatus L.). European Journal of Agronomy*. 22: 449-458.

Corre-Hellou, G., Dibet, A., Hauggaard-Nielsen, H., Crozat, Y., Gooding, M. *et al*. (2011) The competitive ability of pea–barley intercrops against weeds and the interactions with crop productivity and soil N availability. *Field Crop Research.* 122(3): 264-272.

Corre-Hellou, G., Fustec, J. and Crozat, Y. (2006) interspecific competition for soil N and its interaction with N_2 fixation, leaf expansion and crop growth in pea-barley intercrops. *Plant Soil*. 282:195-208.

Crepon, K., Marget, P., Peyronnet, C., Carrouée, B., Arese, P. and Duc, G. (2010) Nutritional value of faba bean (*Vicia faba* L.) seeds for feed and food. *Field Crops Research*. 115 (3): 329-339.

Crew, T.E. and Peoples, M.B. (2004) Legume versus fertilizer sources of nitrogen: ecological trade-offs and human needs. *Agriculture, Ecosystems & Environment.* 102: 279-297.

Dakora, F.D. (2003) Defining new roles for plant and rhizobial molecules in sole and mixed plant cultures involving symbiotic legumes. *New Phytologist*. 158: 39- 49.

Daoui, K., Fatemi, Z.E., Kallida, R., El Hezmir, A., Mrabet, R. and Ouhnider, M. (2010) Effects of nitrogen on nodulation and productivity of different faba bean (*Vicia faba* L.) genotypes. The IXth ESA Congres. Montpellier, 29th August – 3rd September.

Das, A.K., Khaliq, Q.A. and Haider, M.L. (2011). Effect of intercropping on growth and yield in wheat lentil and wheat chickpea intercropping system at different planting configurations. *International Journal of Innovation Science.* 5, 125-137.

David, C., Jeuffroy, M.H., Laurent, F., Mangin, M. and Meynard, J.M. (2005) The assessment of a decision making tool for managing the nitrogen fertilization of organic winter wheat. *European Journal of Agronomy*. 23: 225-242.

Davis, J.H.C. and Woolley, J.N. (1993) Genotypic requirement for intercropping. *Field Crops Research*. 34: 407–30.

De Haan, C., Gerber, P. and Opio, C. (2010) Structural changes in the Livestock sector. In, Mooney, H., Neville, L., Steinfeld, H. and Schneider, F. (eds.) *Livestock in a changing landscape* Vol. 1. Drivers, Consequences, and Responses. Island Press: 35-50.

De Stefanis, E., Sgrulletta, D., Pucciarmati, S., Ciccoritti, R. and Quaranta, F. (2017) Influence of durum wheat-faba bean intercrop on specific quality traits of organic durum wheat. *Biological Agriculture and Horticulture*. 33(1):28-39.

De Visser, (2013) Protein Crops. EIP-Agri. Agriculture and innovation. European Union. [Online]. Available from: https://ec.europa.eu/eip/agriculture/sites/agri-eip/files/fg2_protein_crops_starting_paper_2013_en.pdf [Date accessed: 20th May, 2017].

De Visser1, C.L.M., Schreuder, R. and Stoddard, F. (2014) The EU's dependency on soya bean import for the animal feed industry and potential for EU produced alternatives. *Oilseeds and fats, Crops and Lipids.* 21(4): (D407).

De Wit, C. T. (1960) On competition. *Versl. landbouwk. Onderzoek*. 66: 1-82.

De Wit, C. T. and Van Den Bergh, J.P. (1965) Competition between herbage plants. *Netherlands Journal of Agricultural Science.* 13: 212-21.

Dehidashti, S.M. and Riahinia, S. (2008) Effects of plant density on some growth indixes, radiation interception and grain yield in maize (*Zea mays* L.). *Journal of Biological Sciences*. 8(5): 908-913.

Dempster, J.P. and Coaker, T.H. (1974) Diversification of Crop Ecosystems as a Mean of Controlling Pests. In Jones, D. P. and Solomon, M. E. (eds.) *Biology in pest and disease control.* Oxford, Blackwell: 106-114.

Denton, M.D., Pearce, D.J. and Peoples, M.B. (2013) Nitrogen contributions from faba bean (*Vicia faba* L.) reliant on soil rhizobia or inoculation. *Plant Soil*. 365: 363–374.

Devi, K.N., Shamurailatpam, D., Singh, T.B., Singh, H., Singh, N.G., Singh, N.B. *et al.* (2014) Performance of lentil (*Lens culinaris* M.) and mustard (*Brassica juncea* L.) intercropping under rainfed conditions. *Australian Journal of Crop Science.* 8(2):284-289.

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

Dhima, K.V., Vasilakoglou, I.B., Keco, R.Xh., Dima, A.K., Paschalidis, K.A. and Gatsis, T.D. (2013) Forage yield and competition indices of faba bean intercropped with oat. *Grass and Forage Science*. 69:376-383.

Dhima, K.V., Vasilakoglou, I.B., Keco, R.X., Dima, A.K., Paschalidis, K.A. and Gatsis, T.D. (2014) Forage yield and competition indices of faba bean intercropped with oat. *Grass and Forage Science.* 69:376-383.

Dobermann, A. and Nelson, R. (2013) Opportunities and solutions for sustainable food production. Background paper for the high-level panel of eminent persons on the Post-2015 Development Agenda; 15 January 2013; United Nations. [Online]. Available from: http://www.post2015hlp.org/wp-content/uploads/2013/05/Doberman-Nelson_Solutions-for-Sustainable-Food-Production.pdf [Date accessed: 22/01/2017].

Dolijanović, Ž., Oljača, S., Kovačević, D., Simić, M., Momirović, N. and Jovanović, Ž. (2013) Dependence of the productivity of maize and soybean intercropping systems on hybrid type and plant arrangement pattern. *Genetika*. 45 (1): 135-144.

Dong, N., Tang, M., Zhang, W., Bao, X., Wang, Y., Christie, P. *et al.* (2018) Temporal differentiation of crop growth as one of the drivers of intercropping yield advantage. *Scientific Reports.* 8(3110): 1-11.

Dordas, C.A. and Lithourgidis, A.S. (2011) Growth, yield and nitrogen performance of faba bean intercrops with oat and triticale at varying seeding ratios. *Grass and Forage Science*. 66: 569–577.

Dreccer, M.F., van Oijen M., Schapendonk, A.H.C.M., Pot, C.S. and Rabbinge, R. (2000). Dynamics of vertical leaf nitrogen distribution in a vegetative wheat canopy. Impact on canopy photosynthesis. Annuals of Botany. 86: 821-831.

Dubey, D.N., Kulmi, D.S. and Jha, G. (1995) Relative productivity and economics of sole, mixed and intercropping systems of sorghum (*Sorghum bicolor)* and grain legumes under dry land condition. *Indian Journal of Agricultural Sciences*. 65: 469–473.

Duc, G. (1997). Faba bean (*Vicia faba* L.). *Field Crops Research*. 53(1):99-109.

Dusa, E. M. (2009) Researches regarding the productivity of oat-lentil intercropping in the organic agriculture system. *Research Journal of Agricultural Science* 41 (1): 22-26.

Dusa, E. M. and 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* L.) cultivated in pure stand and mixtures, in the organic agriculture system. *European Scientific Journal*. 9 (21): 69-78.

Dwivedi, A., Dev, I., Kumar, V., Singh, R. Y., *et al.* (2015) Potential role of maize-legume intercropping systems to improve soil fertility status under smallholder farming systems for sustainable agriculture in India. *International Journal of Life Sciences Biotechnology and Pharma Research.* 4(3): 145-157.

Enikuomehin, O. A., Aduwo, A. M., Olowe, V. I.O., Popoola, A. R. and Oduwaye, A. (2010) Incidence and severity of foliar diseases of sesame (*Sesamum indicum* L.*)* intercropped with maize (*Zea mays* L.). *Archives of phytopathology and plant protection*. 43(10): 972-986.

Ennin, S.A., Clegg, M.D. and Francis, C.A. (2002) Resource utilization in soybean/maize intercrops. *African Crop Science Journal.* 10: 251-261.

Eskandari, H. (2012) Yield and quality of forage produced in intercropping of maize (*Zea mays* L.) with cowpea (*Vignasinensis* L.) and Mungbean (*Vigna radiate* L.) as double cropped. *Journal of Basic and Applied Scientific Research*. 2: 93-97.

Eskandari, H. and Ghanbari-Bonjar, A. (2010) Effect of different planting pattern of wheat (*Triticum aestivum* L.) and bean (*vicia faba* L.) on grain yield, dry matter production and weed biomass. *Notulae Scientia Biologica*e. 2: 111-115.

Eskandari, H. and Ghanbari-Bonjar, A. (2009) Intercropping of maize (*Zea mays*) and cowpea (*Vigna sinensis*) as whole-crop forage: effect of different planting pattern on total dry matter production and maize forage quality. *Notulae Botanicae Horti Agrobotanici Cluj-Napoca*. 37:152-155.

Eskandari, H., Ghanbari, A., and Javanmard, A. (2009) Intercropping of cereals and legumes for forage production. *Notulae Scientia Biologicae*. 1(1): 7-13.

Esmaeili, A., Sadeghpour, A., Hosseini, S.M.B., Jahanzad, E., Chaichi, M.R. and Hashemi, M. (2011) Evolution of seed yield and competition indices for intercropped barley (*Hordeum vulgare*) and annual medic (*Medicago scutellata*). *International Journal of Plant Production*. 5: 395-404.

European Parliament (2011) The EU protein deficit: what solution for a long-standing problem. Brussels, Belgium: European Parliament.

Eurostat (2012) Agriculture, fishery and forestry statistics. Main results: 2010-11. European Commission. [Online]. Available from: http://epp.eurostat.ec.europa.eu/portal/page/portal/agriculture/introduction. [Date accessed on 17th December, 2016].

Evers, J.B. and Bastiaans, L. (2016) Quantifying the effect of crop spatial arrangement on weed suppression using functional-structural plant modelling. *Journal of Plant Research*.129: 339–351.

Falster, D.S. and Westoby, M. (2003) Leaf size and angle vary widely across species: what consequences for light absorption? *New Phytologist*.158: 509-525.

Fargione, J. and Tilman, D. (2005) Niche differences in phenology and rooting depth promote coexistence with a dominant C_4 bunchgrass. *Oecologia*. 143(4): 598-606.

Faithfull, N. T. (2002) Methods in agricultural chemical analysis: a practical handbook. CABI Publishing, Wallingford, Oxon, UK

Fan, F., Zhang, F., Song, Y., Sun, J., Bao, X., Guo, T. and Li, L. (2006) Nitrogen fixation of faba bean (*Vicia faba* L.) Interacting with a non-legume in two contrasting intercropping systems. *Plant Soil*. 283: 275-286.

FAOSTAT (2008) [Online]. Available from: http://www.faostat.fao.org/default.aspx [Date accessed: 12/09/2017].

Food and Agriculture Organisation of the United Nations of the United Ntions (2013). Food Outlook. Food and Agriculture Organisation of the United Nations, Rome Italy.

Farnia, A., Noormohammadi, G. and Cyadat, A. (2005) Evaluation of soybean cultivars growth analysis effected from *Rhizobium japonicum* strains. *Journal of New Agricultural Science* 1: 26–34.

Ferguson, B.J., Lin, M.H. and Gresshoff, P.M. (2013) Regulation of legume nodulation by acidic growth conditions. *Plant Signal and Behaviour*. 8 (3): (e23426).

Fikadu, K., Lakew, and W., Tadesse, D. (2016) Yield Potential of Wheat (*Triticum aestivum*) and faba bean (*Vicia faba*) mixed intercropping in Western Shoa. *International Journal of Research Studies in Agricultural Sciences*. 2(7): 27-31.

Flesch, R.D. (1994) Wheat-soybean relay intercropping: Temporal and spatial effects. Ph.D. Thesis. Iowa State University. USA.

Flores, F., Nadal, S., Solis, I., Winkler, J., Saa, O. and Stoddard, F.L. (2012) Faba bean adaptation to autumn sowing under European climates. *Agronomy for Sustainable Development.* 32:727-734.

Food and Agriculture Organization (2013) *Food Outlook*. FAO, Rome, Italy.

Food and Agriculture Organization **(**2014) *Building a Common Vision for Sustainable Food and Agriculture*. FAO-UN, Rome, Italy.

Forde, B.G. (2009) The role of developmental instability in the shaping of a root system. *Journal of Experimental Botany*. 60: 3989–4002

Foster, A. and Malhi, S. S. (2013) Influence of Seeding date on growing season's conditions on forage yield and quality of four annual crops in Northeastern Saskatchewan. *Communication in Soil Science and Plants Analysis*. 44: 884 -891.

Fradgley, N., Winkler, L. and Doring, T. (2013) Beans and wheat intercropping: a new look at an overlooked benefit. ORC Bulletin No. 112-spring/summer 2013. [Online]. Available from: http://www.organicresearchcentre.com/manage/authincludes/article_uploads/Fradgley112.pdf [Date accessed: 22/03/2017].

Francis, C.A. (1989) Biological efficiencies in multiple-cropping systems. *Advances in Agronomy*. 42: 1-42.

Frank, B. S. and Cleon, W. R. (1992) Plant physiology. Wadsworth Publishing Company, California.

Fritz, T. (2014) The illusory promise of the livestock revolution. Meatification of diets, industrial animal farms and global food security. [Online].Available from: http://fdcl-berlin.de/fileadmin/fdcl/Publikationen/Fleisch_macht_Hunger/The_illusory_promise_of_the_livestock_revolution_web_kl.pdf [Date accessed: 23/08/2017]

Fujita, K., Ofosu-Budu, K. G. and Ogata, S. (1992) Biological nitrogen fixation in mixed legume-cereal cropping systems. *Plant Soil*. 141: 155-176.

Fukai, S. and Trenbath, B.R. (1993) Processes determining intercrop productivity and yields of component crops. *Field Crop Research*. 34: 247-271.

Gallandt, E. (2014) Weed management in organic farming. In, Chauhan, B. and Mahajan G. (eds.) *Recent advances in weed management*. New York: Springer: 63-85.

Gao, Y. and Wu, P. (2014) Growth, yield, and nitrogen use in the wheat/maize intercropping system in an arid region of north-western China. *Field Crops Research*. 167: 19-30.

Garrity, D., Akinnifesi, F., Ajayi, O., Weldesemayat, S., Mowo, J., Kalinganire, A., Larwanou, M. and Bayala, J. (2010) Evergreen Agriculture: a robust approach to sustainable food security in Africa. *Food Security*. 2:197-214.

Gebrehiwot, L., McGrow, R. L., and Assefu, G. (1996) Forage yield and quality profile of three annual legumes in the tropical highlands of Ethiopia. *Journal of Agriculture*. 73: 83-98.

Gebru, H. (2015) A review on the comparative advantage of intercropping systems. *Journal of Biology, Agriculture and Healthcare*. 5(9): 28-38.

Geno, L. and Geno, B. (2001) Polyculture production: Principle, benefits and risk of multiple cropping. A report for the Rural Industry Research and Development Corporation (RIRDC), Publication, No. 01134. Fixation in legumes. *Pakistan Journal of Biological Sciences.* 18: 1631–1640.

Ghaley, B.B., Hauggaard-Nielsen, H., Høgh-Jensen, H. and Jensen, E.S. (2005) Intercropping of wheat and pea as influenced by nitrogen fertilization. *Nutrient Cycling in Agroecosystems*. 73:201–212.

Ghanbari-Bonjar, A. (2000) Intercropping wheat (*Triticum aestivum* L.) and bean (*Vicia faba*) as a low input forage. PhD Thesis. University of London, Wye College. United Kingdom.

Ghanbari-Bonjar, A. and Lee, H.C. (2003) Intercropped wheat and bean as whole crop forage: effect of harvest time on forage yield and quality. *Grass Forage Science*. 58: 28-36.

Ghanbari-Bonjar, A. and Lee, H.C. (2002) Intercropped field beans (*Vicia faba*) and wheat (*Triticum aestivum*) for whole crop forage: effect of nitrogen on forage yield and quality. *Journal of Agricultural Science,* 138: 311-315.

Ghanbari-Bonjar, A., Dahmardeh, M., Siahsar, B.A. and Ramroudi, M. (2010) Effect of maize (*Zea mays* L.) - cowpea (*Vigna unguiculata* L.) intercropping on light distribution, soil temperature and soil moisture in arid environment. *Journal of Food, Agriculture and Environment*. 8 (1): 102-108.

Gharineh, M.H. and Moosavi, S.A. (2010) Effect of intercropping (Canola/faba bean) on density and diversity of weeds. *Notulae Scientia Biologicae*. 2:109-112.

Ghosh, P.K., (2004) Growth, yield, competition and economics of groundnut/ cereal fodder intercropping systems in the semi-arid tropics of India. *Field Crops Research*. 88: 227-237.

Ghosh, P.K., Manna, M.C., Bandyopadhyay, K.K., Ajay, T.A.K., Wanjari, R.H., *et al.* (2006) Inter-specific interaction and nutrient use in soybean-sorghum intercropping system. *Agronomy Journal*. 98: 1097-1108.

Giller, K.E., Ormesher, J., and Awah, F.M. (1991) Nitrogen transfer from Phaseolus bean to intercropped maize measured using ^{15}N-enrichment and ^{15}N-isotope dilution methods. *Soil Biology and Biochemistry*. 23: 339–346.

Giordano, A., Liu, Z., Panter, S.N., Dimech, A.M., Shang, Y., *et al.* (2014) Reduced lignin content and altered lignin composition in the warm season forage grass *Paspalum dilatatum* by down-regulation of a Cinnamoyl CoA Reductase Gene. *Transgenic Research*. 23(3): 503-517.

Gnanavel, I. (2015) Eco-Friendly weed control options for sustainable agriculture. Science International. 3: 37- 47.

Gomez, K.A. and Gomez, A.A. (1984) *Statistical Proceedings for Agricultural Research*. Second Edition. John Wiley, New York.

Gomiero, T., Pimentel, D. and Paoletti, M.G. (2011) Environmental impact of different agricultural management practices: Conventional vs. organic agriculture. *Critical Reviews in Plant Sciences*. 30: 95-124.

Gooding, M.J. and Davies, W.P. (1997) Wheat production and utilization, CAB International, Wallingford.

Gooding, M.J., Kasyanova, E., Ruske, R., Hauggaard- Nielsen, H., Jensen, E.S., *et al.* (2007) Intercropping with pulses to concentrate nitrogen and sulphur in wheat. *Journal of Agricultural Science*. 145: 469-479.

Goudriaan, J. (1988) The bare bones of leaf-angle distribution in radiation models for canopy photosynthesis and energy exchange. *Agricultural and Forest Meteorology*. 43: 155-169.

Green, C.F., Hebblethwaite, P.D. and Ricketts, H.E. (1986) Irrigating faba bean crops. *Vortr. Pflanzenzücht.* 11: 7-24.

Grethe, H., Dembélé, A. and Duman, N. (2011) How to feed the world's growing billions: understanding FAO world food projections and their implications. Heinrich Böll Stiftung and WWF Deutschland. [Online]. Available from: http://www.boell.de/publications [Date accessed: 24/02/2016].

Griffiths, D.W. and Lawes, D.A. (1977) Genetic variation in the protein content and composition of field beans (*Vicia faba* L.) in relation to improvement by plant breeding. In, Protein Quality of Leguminous Crops, pp. 361-368. EEC, Luxembourg. [Online]. Available from: https://www.publications.europa.eu/en/publication-detail/-/publication/3c4c5a08-c3ef-4116-9b4f-1fb5c8953237 [Date accessed: 13/07/2017].

Guan, D.H., Mahdi, M., Kaisi, A.L., Duan, L.S., Tan, W.M., Zhang, M.C. and Li, Z.H. (2014) Tillage practices affect biomass and grain yield through regulating root growth: root-bleeding sap and nutrients uptake in summer maize. *Field Crops Research*, 157: 89-97.

Gunes, A., Inal A., Adak, M.S., Alpaslan, M., Bagci, E.G., Erol, T., and Pilbeam, D.J. (2007) Mineral nutrition of wheat, chickpea and lentil as affected by mixed cropping and soil moisture. *Nutrient Cycling in Agroecosystems*. 78: 83-96.

Haq, S.A., Korieng,K.J., Shiekh, T.A., Bahar, F.A., Dar,K.A., Raja, W., Wani, R.A. and Khuroo, N.S. (2018) Yield and quality of winter cereal-legume fodder mixtures and their pure stand under temperate conditions of Kashmir Valley, India. *International Journal of Current Microbiology and Applied Sciences.* 7(2): 3626-3631.

Hailu, E., Getaneh, G., Sefera, T., Tadesse, N. and Bitew, B. (2014) Faba bean Gall; a new threat for faba bean (*Vicia faba*) production in Ethiopia. *Advanced Crop Science Technology.* 2(44): (1000144).

Hall, R.L. (1974) Analysis of the nature of interference between plants of different species 1.Concepts and extension of the de wit analysis to examine effects. *Australian Journal Agriculture Research*. 25: 739-747.

Hamzei, J. and Seyedi, M. (2015) Evaluation of the effects of intercropping systems on yield performance, land equivalent ratio, and weed control efficiency. *Agricultural Research.* 4(2): 202–207.

Harper, J.L. (1977). Population Biology of Plants. Academic Press, London.

Harris, P.M. (1990) Potato crop radiation use: A justification for intercropping. *Field Crops Research*. 25: 25-39.

Harris, D. and Natarajan, M. (1987) Physiological basis for yield advantage in a sorghum-groundnut intercrop exposed to drought. II. Plant temperature, water status and components of yield. *Field Crops Research*. 17:273-288.

Hauggaard-Nielsen H., Gooding M., Ambus P., Corre-Hellou G., Crozat Y. and Dahlmann C., (2009) Pea-barley intercropping for efficient symbiotic N_2-fixation, soil N acquisition and use of other nutrients in European organic cropping systems. *Field Crop Research.* 113: 64-71.

Hauggaard-Nielsen, H. and E. S. Jensen (2001b) Evaluating pea and barley cultivars for complementarity in intercropping at different levels of soil N availability. *Field Crops Research.* 72: 185–196.

Hauggaard-Nielsen, H. and Jensen, E.S. (2005) Facilitative root interactions in intercrops. *Plant Soil*. 274:237–250.

Hauggaard-Nielsen, H., Ambus, P. and Jensen, E.S. (2001a) interspecific competition, N use and interference with weeds in pea-barley bi-cropping. *Field Crops Research* 70: 101-109.

Hauggaard-Nielsen, H.N., Jornsgaard, B., Kinane, J. and Jensen, E. S. (2007) Grain legume-cereal intercropping: The practical application of diversity competition and facilitation in arable and cropping system. Renewable Agriculture and food systems. 23 (1): 3-12.

Hauggaard-Nielsen, H., Andersen, M.K., Jornsgaard, B. and Jensen, E.S. (2006) Density and relative frequency effects on competitive interactions and resource use in pea–barley intercrops. *Field Crops Research*. 95: 256–267.

Hauggaard-Nielsen, H., Jornsgaard, B., Kinane, J. and Jensen, E.S. (2008) Grain legume-cereal intercropping: The practical application of diversity, competition and facilitation in arable and organic cropping systems. *Renewable Agriculture and Food Systems*. 23 (1): 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. [Online]. Available from: http://www.europarl.europa.eu/sides/getDoc.do?type=REPORT&reference=A7-2011-0026&language=EN [Date accessed: 23/11/2017].

Hawkesford, M. (2014). Reducing the reliance on nitrogen fertilizer for wheat production. *Journal of Cereal Science*. 59(3): 276–283.

Hay, R. K. M. and Walker, A. J. (1989) *An introduction to the physiology of crop yield.* Essex, United Kingdom: Longman Scientific & Technical.

Haymes, R. and Lee, H.C. (1999) Competition between autumn and spring planted grain intercrops of wheat (*Triticum aestivum*) and field bean (*Vicia faba*). *Field Crop Research*. 62:167-176.

Hayward, C.F. (1990) The effects of sowing date on grain quality of winter wheat. *Aspects of Applied Biology*. 25: 163-170.

He, X., Critchley, C. and Bledsoe, C. (2003) Nitrogen transfer within and between plants through common mycorrhizal networks (CMNs). *Critical Reviews in Plant Sciences.* 22: 531-567.

He, X., Xu, M., Qiu, G.Y. and Zhou, J. (2009). Use of ^{15}N stable isotope to quantify nitrogen transfer between mycorrhizal plants. *Journal of Plant Ecology*. 2(3): 107-118.

Herbert, S.J., Putnam, D.H., Poos-Floyd, M.L., Vargas, A., Creighton, J.F. (184) Forage yield of intercropped corn and soybean in various planting patterns. *Agronomy Journal.* 76: 507-510.

Hiebsch, C.K. and McCollum, R.E. (1987) Area-x-time equivalency ratio; a method for evaluating the productivity of intercrops. *Agronomy Journal*. 79: 15-22.

Hikosaka, K. and Hirose, T. (1997). Leaf angle as a strategy for light competition: optimal and evolutionarily stable light-extinction coefficient within a leaf canopy. *Ecoscience*. 4: 501-507.

Hinsinger, P., Betencourt, E., Bernard, L., Brauman, A., Plassard, C., and Shen, J. (2011) P for two, sharing a scarce resource: Soil Phosphorus acquisition in the rhizosphere of intercropped species. *Plant Physiology.* 156: 1078-1086.

Hirpa, T. (2014) Effect of intercrop row arrangement on maize and haricot bean productivity and the residual soil. *World Journal of Agricultural Sciences.* 2(4): 069-077.

Hoad, S.P., Davies, D. H. K., and Topp, C. F. E. (2006) How to select for organic farming: science and practice. What will organic farming deliver? COR 2006, *Aspects of applied Biology*. 79: 117-120.

Høgh-Jensen, H. and Schjoerring, J.K. (2000) Below-ground nitrogen transfer between different grassland species: Direct quantification by ^{15}N. *Plant and Soil*. 227: 171-183.

Hongchun, X., Shen, H., Zhang, L., Zhang, Y., Guo, X., Wang, P. *et al.* (2013) Comparative proteomic analysis for assessment of the ecological significance of maize and peanut intercropping. *Journal of Proteomics*. 78: 447-460.

Hongo, H. (1995) Light and water use in intercropping. PhD Thesis, University of Reading, United Kingdom.

Hook, J.E. and Gascho, G.J. (1988) Multiple cropping for efficient use water and nitrogen. In, Hargrove, W.L. (ed.). *Cropping strategies for efficient use of water and nitrogen*, American Society of Agronomy, Crop Science Society of America and Soil Science Society of America, Madison: 7-20.

Horrigan, L., Lawrence, R. S. and Walker, P. (2002) How sustainable agriculture can address the environmental and human health harms of industrial agriculture. *Environmental Health Perspectives*. 110 (5): 445–56.

Htet, M.N.S., Soomro, R.N. and Bo, H. (2017) Effects of different planting pattern of maize (*Zea mays* L.) and soybean (*Glycine max* (L.) Merrill) Intercropping in resource consumption on fodder yield, and silage quality. *American Journal of Plant Sciences*. 8: 666-679.

Hungria, M. and Vargas, M.A.T. (2000) Environmental factors affecting N_2 fixation in grain legumes in the tropics, with an emphasis on Brazil. F*ield Crop Research*. 65: 151-164.

ICARDA, (1986) Screening techniques for disease resistance in faba bean. Center for Agricultural Research in the Dry Areas, Aleppo, Syria. 59 pp.

Iderawumi, A.M. (2014) Effects of cowpea on growth and yield parameter in a maize-cowpea intercrop. *Journal of Management and Science*. 4 (1): 37-42.

Inal, A., Gunes, A., Zhang, F. and Cakmak, I. (2007). Peanut/maize intercropping induced changes in rhizosphere and nutrient concentrations in shoots. *Plant Physiology and Biochemistry*. 45: 350–356.

Intergovernmental Panel on Climate Change (IPCC, 2007) The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK.

Intergovernmental Panel on Climate Change (IPCC, 2014) Summary for Policymakers. In, Edenhofer, O., Pichs-Madruga, R., Sokona, Y., Farahani, E., Kadner, S., Seyboth, K. *et al.* (eds.) *Climate Change 2014*: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Jackson, L.E., Pascual, U. and Hodgkin, T. (2007) Utilizing and conserving agrobiodiversity in agricultural landscapes. *Agriculture, ecosystems and environment.* 121(3): 196-210.

Jacobs, J. L. and Ward, G. N. (2013) Effect of cereal and pea monocultures and combinations and silage additives on whole-crop cereal silage nutritive and fermentation characteristics. *Animal Production Science.* 53(5): 427-436.

Jahansooz, M.R., Yunusa, I.A.M., Coventry, D.R., Palmer, A.R., Eamus, D. (2007) Radiation-and water use associated with growth and yields of wheat and chickpea in sole and mixed crops. *European Journal of Agronomy*. 26: 275-282.

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

Jamshidi, K.H. (2011) Evaluation of quantity and quality of the yield of two wheat cultivars in intercropping system. *Desert*, 16: 153-158.

Javanmard, A., Nasab, A.D.M., Javanshir, A., Moghaddam, M. and Janmohammadi, H. (2009) Forage yield and quality in intercropping of maize with different legumes as double-cropped. *Journal of Food, Agriculture and Environment*. 7(1): 163-166.

Jedel, P.E. and Helm, J.H. (1993) Forage potential of pulse–cereal mixtures in Central Alberta. *Canadian Journal of Plant Science*. 73:437- 444.

Jensen, E.S. (1996) Grain yield, symbiotic N_2 fixation and interspecific competition for inorganic N in pea-barley intercrops. *Plant Soil*. 182: 25-38.

Jensen, E.S., Ambus, N., Bellostas, N., Boisen, S., Brisson, N., Corre-Holou, G., *et al.* (2006) Intercropping of cereals and grain legumes for increased production, weed control, improved product quality and prevention of N-losses in European organic farming systems, Proceedings of the European Joint Organic Congress, May 30-31, Odense, Denmark: 180-181

Jensen, E.S., Hauggaard-Nielsen, H., Kinane, J., Andersen, M.K. and Jørnsgaard, B. (2005) Intercropping- the practical application of diversity, competition and facilitation in arable and organic cropping systems; In, *Researching Sustainable Systems 2005*. Proceedings of the First Scientific Conference of the International Society of Organic Agricultural Research *(ISOFAR):* 22-25.

Jensen, E.S., Peoples, M.B. and Hauggaard-Nielsen, H. (2010) Faba bean in cropping systems. *Field Crops Research*. 115: 203-216.

Jensen, E.S., Bedoussac, L., Carlsson, G., Journet, E., Jutes, E. and Hauggaard-Nielsen, H. (2015) Enhancing yields in organic crop production by Eco-function intensification. *Sustainable Agriculture Research*. 4(3): 42-50.

Jeuffroy, M.H., Baranger, E., Carrouée, B., Chezelles, E.D., Gosme, M. and Hénault, C. (2013) Nitrous oxide emissions from crop rotations including wheat, oilseed rape and dry peas. *Biogeosciences*. 10: 1787–1797.

Johansen, A. and Jensen, E.S. (1996) Transfer of N and P from intact or decomposing roots of pea to barley interconnected by an arbuscular mycorrhizal fungus. *Soil Biology and Biochemistry*. 28: 73-81.

Jolliffe, P.A., Minjas, A.N. and Ruenkles, V.C. (1984) A reinterpretation of yield relationships in replacement series experiments. *Journal of Applied Ecology*. 24: 227-243.

Jones, G. P. D., Blair, G. J. and Jessop, R. S. (1989) Phosphorus efficiency in wheat a useful selection criterion. *Field Crops Research*. 21: 257-264.

Jones, P.J., Thomas, D., Hazzledine, M. and Rymer, C. (2014) *Replacing soya in livestock feeds with UK-grown protein crops: prospects and implications (CAS Report 19)*, Centre for

Agricultural Strategy, University of Reading, July 2014. [Online]. Available from: http://www.reading.ac.uk/news-andevents/releases/PR595090.aspx [Date accessed: 23/05/2017].

Kandiannan, K., Parthasarathy, U., Krishnamurthy, K.S., Thankamani, C.K. and Srinivasan, V. (2009) Modelling individual leaf area of ginger (*Zingiber officinale* Roscoe) using leaf length and width. *Scientia Horticulturae Journal*. 120: 532–537.

Kankanen, H., Eriksson, E., Rakkolainen, M. and Vuorinen, M. (2001) Effect of annually repeated undersowing on cereal grain yields. *Journal of Agriculture and Food Sciences*. 10: 197-208.

Kanton, R.A.L and Dennett, M.D. (2008) Radiation capture and use as affected by morphologically contrasting maize/pea in sole and intercropping. *West African Journal of Applied Ecology*. 13 (1): 1-13.

Karanja, S.M., Kibe, A.M., Karogo, P. N. and Mwangi, M. (2014) Effects of intercrop population density and row orientation on growth and yields of sorghum-cowpea cropping systems in semi-arid Rongai, Kenya. *Journal of Agricultural Science,* 6 (5): 34 -43.

Keady, T.W.J., Kilpatrick, C.M., Cushnahan, A. and Murphy, J.A. (2002) The cost of producing and feeding forage. Proceedings of the XIII international Silage Conference, Auchincruive, Scotland: 322-323.

Keating, B. and P. Carberry (1993) Resource capture and use in intercropping: Solar radiation. *Field Crops Research*. 34: 273-301.

Keeler, B. L., Polasky, S., Brauman, K. A., Polasky, S., Johnson, K. A., Finlay, J. C., O'Neill, A., Kovacs, K. and Dalzell, B. (2012) Linking water quality and well-being for improved assessment and valuation of ecosystem services. *Proceedings of the National Academy of Sciences*. 109: 18619–24.

Kenenil, A., Assefa, F. and Prabu, P.C. (2010) Characterization of acid and salt tolerant rhizobial strains isolated from faba bean fields of Wollo, Northern Ethiopia. *Journal of Agricultural Science and Technology*. 12: 365-376.

Khan, H.R., Paull, G.J., Siddique, K.H.M., and Stoddard, F.L. (2010) Faba bean breeding for drought-affected environments: A physiological and agronomic perspective. *Field Crops Research*. 115: 279-286.

Khare, M., Bayaa, B. and Beniwal, S. (1993) Selection methods for disease resistance in lentil. In, K. Singh and M. Saxena, (ed.) *Breeding for stress tolerance in cool-season food legumes*. Chichester: John Wiley & Sons, pp.107-121.

Khashayar, R. (2014). Hamid, R.M., Mohammad, R.V. (2014) Effect of intercropping on resources use, weed management and forage. A review. *International Journal of Plant, Animal and Environmental Sciences*. 4(2):706-713.

Kim, S. and Dale, B. E. (2008) Effects of nitrogen fertilizer application on greenhouse gas emissions and economics of corn production. *Environmental Science and Technology*. 42: 6028–6033.

Klimeck-Kopyra, A., Kulig, B., Oleksy, A. and Zajac, T. (2015) Agronomic performance of naked oat (*Avena nuda* L.) and faba bean intercropping. *Chilean Journal of Agricultural Research*. 75(2): 168-173.

Knudsen, M.T., Hauggaard-Nielsen, H., Jornsgard, B., Jensen, E.S. (2004) Comparison of interspecific competition and N use in pea-barley, faba bean-barley and lupin-barley intercrops grown at two temperate locations. *Journal of Agricultural Science*. 142: 617–627.

Kombiok, J.M., Safo, E.Y., and Quansah, C. (2005) Yield and nitrogen fixation of cowpea as affected by tillage and cropping system in Northern Savanna zone of Ghana. *West African Journal of Applied Ecology*. 7: 95-108.

Koning, R.E. (1994) Light. *Plant Physiology Information.* [Online] Available from: http://www.plantphys.info/plant_physiology/light.shtml (Date accessed: 16/04/2017).

Konlan, S., Sarkodie-Addo, J., Kombiok, M. J., Asare, E. and Bawah, I. (2013) Yield response of three groundnut (Arachis hypogaea L.) varieties intercropped with maize (Zea mays) in the guinea savannah zone of Ghana. *Journal of Cereals and Oilseeds*. 6(32): 76-84.

Konlan, S., Sarkodie-Addo, J., Kombiok, M.J. Asare, E. and Bawah, I. (2005) Effect of intercropping on nitrogen fixation of three groundnut (*Arachis hypogaea* L) genotypes in the Guinea savanna zone of Ghana. *International Journal of Plant & Soil Science.* 5: 1-9

Konthoujam, N.D., Shamurailatpam, D., Singh, T.B., Singh, A., N.B., *et al.* (2014) Performance of lentil (*Lens culinaris* M.) and mustard (*Brassica juncea* L.) intercropping under rainfed conditions. *Australian Journal of Crop Science*. 8(2): 284-289

Koocheki, A., Mahallati, M.N., Solouki, H., and Karbor, S. (2016) Evaluation of radiation absorption and use efficiency in substitution intercropping of sesame (*Sesamum indicum* L.) and mung bean (*Vigna Radiata* L.). *Advances in Plants and Agriculture Research*.3 (5): (00109)

Koohi, S.S., Nasrollahzadeh, S., and Raei, Y. (2014) Evaluation of chlorophyll value, protein content and yield of sorghum (*Sorghum bicolor* L.)/ mung bean (*Vigna radiate* L.) intercropping. *International Journal of Biosciences*. 4 (8): 136-143.

Kopke, U. (1987) Symbiotische Stickstoff Fixierung und Vorfuchtirkung von Ackerbohnen (*Vicia faba*). Habilitation. Thesis University of Gottingen. Germany.

Kopke, U. and Nemecek, T. (2010) Ecological services of faba bean. *Field Crops Research*. 115: 217-233.

Kotwica, K. and Rudnicki, F., (1999) Competition between spring triticale and yellow lupine in mixture. In, *Przyrodnicze I produkcyjne aspekty uprawy roślin w mieszankach: Proceedings of the Scientific Conference*, 2-3 December 1999, Poland.

Kremen, C. and Miles, A. (2012) Ecosystem services in biologically diversified versus conventional farming systems: Benefits, externalities, and trade-offs. *Ecology and Society*. 17 (4): 1-40.

Lampkin, N., Measures, M. and Padel, S. (2011). 2011/12 Organic Farm Management Handbook. (9th ed). Organic Research Centre, Newbury.

Langat, M.C., Okiror, M.A., Ouma, J.P. and Gesimba, R.M (2006) The effect of intercropping groundnut (*Arachis hypogeal* L.) with sorghum (*Sorghum bicolor* L.) on yield and cash income. *Agriculture Tropica et Subtropica*. 39: 87-91.

Latati, M., Bargaz, A., Belarbi, B., Lazali, M., Benlahrech, S., Tellaha, S., *et al.* (2016) The intercropping common bean with maize improves the rhizobial efficiency, resource use and grain yield under low phosphorus availability. *European Journal of Agronomy*. 72: 80-90.

Lateef, E. and Farrag, M. (2014). Effects of spatial arrangements, growth habits and cropping pattern on growth and yield of faba bean. [*Online*] Available from: http://www.esa2014.hu/proceedings (Date accessed: 16/3/2016].

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

Legesse, H., Gobeze, L. and Tenaw, W. (2015) Effect of barley (*Hordeum vulgare* L) / faba bean (*Vicia fabae* L) intercropping on productivity and land use efficiency in highlands of Southern Ethiopia. *Journal of Biology, Agriculture and Healthcare*. 5(14): 103-107.

Legume Future (2014) Legume-supported cropping systems for Europe. General project report. [Online] Available from http://ww.legumefutures.de [Date accessed: 22/04/2017]

Lemaire, G. and Gastal, F. (1997) N uptake and distribution in plant canopies. In, Lemaire G, (ed.) *Diagnosis of the nitrogen status in crops*. Springer, Heidelberg, pp 3-43.

Lemke, R.L., Zhong, Z., Campbell C.A. and Zentner, R.P. (2007) Can pulse crops play a role in mitigating greenhouse gases from North American agriculture? *Agronomy Journal.* 99: 1719-1725.

Lesley, A. J., Brian E. J. and William, C. F. (2015) Advancements in root growth measurement technologies and observation capabilities for container-grown plants. *Plants*. 4: 369-392.

Lesschen, J. P., van den Berg, M., Westhoek, H. J., Witzke, H. P. and Oenema, O. (2011) Greenhouse gas emission profiles of European livestock sectors. *Animal Feed Science and Technology*. 166-167: 16-28.

Li, Q.Z., J.H. Sun, X.J. Wei, P. Christie, F.S. Zhang, and L. Li. (2011) Over yielding and interspecific interactions mediated by nitrogen fertilization in strip intercropping of maize with faba bean, wheat and barley. *Plant and Soil.* 339:147-161.

Liebman, M. (1995) Polyculture cropping systems in agro ecology. In, Altieri, M. A. (ed.) *The science of sustainable agriculture.* London: Intermediate Technology Publications, pp. 205-218

Liebman, M. and Dyck, E. (1993) Crop rotation and intercropping strategies for weed management. *Ecological Applications.* (3) 1: 92-122.

Link, W., C. Balko, and F.L. Stoddard. (2010) Winter hardiness in faba bean: Physiology and breeding. *Field Crops Research*. 115:287-29.

Lithourgidis, A.S. and Dordas, C.A. (2010) Forage yield, growth rate, and nitrogen uptake of faba bean intercrops with wheat, barley, and rye in three seeding ratios. *Crop Science.* 50: 2148-2158.

Lithourgidis, A.S., Dhima, K.V., Vasilakoglou, I.B., Dordas, C.A. and Yiakoulaki, M.D. (2007) Sustainable production of barley and wheat by intercropping common vetch. *Agronomy for Sustainable Development*. 27: 95-99.

Lithourgidis, A.S., Vasilakoglou, .I.B., Dhima, K.V., Dordas, C.A. and Yiakoulaki, M.D. (2006) Forage yield and quality of common vetch mixtures with oat and triticale in two seeding ratios. *Field Crops Research*. 99:106-113.

Lithourgidis, A.S., Dordas, C.A., Damalas, C.A. and Vlachostergios, D.N. (2011) Annual intercrops: an alternative pathway for sustainable agriculture. *Australian Journal of Crop Science.* 5: 396-410.

Liu, X, Rahman, T., Yang, F., Song, C., Yong, T., Liu, J. *et al*. (2017b) PAR Interception and utilization in different maize and soybean Intercropping Patterns. *PLoS ONE*. 12(1): e0169218.

Liu, Z., Zhu, K., Dong, S., Liu, P., Zhao, B. and Zhang J. (2017a) Effects of integrated agronomic practices management on root growth and development of summer maize. *European Journal of Agronomy*. 84: 140-151.

Long, Li, L., Yang, S., Li, X., Zhang, F., and Christie, P. (1999) Interspecific complementary and competitive interactions between intercropped maize and faba bean. *Plant and Soil*. 212:105-114.

Long, J., Lin., Hou, X., Duan, X. and Duan, H. (1989). Food Legume Crops. Science Publishing House

López-Bellido, R.J., Caroline, S. and Barraclough, P.B. (2004) Predicting post-anthesis N requirements of bread wheat with a Minolta SPAD meter. *European Journal of Agronomy.* 20(3): 313-320.

Loss, S.P. and Siddique, K.H.M. (1997). Adaptation of faba bean (*Vicia faba*, L.) to dry land Mediterranean-type environment. I. Seed yield components. *Field Crops Research*. 54, 17-28

Lunagaria, M.M. and Shekh, A.M. (2006) Radiation interception, light extinction coefficient and leaf area index of wheat (*Triticum aestivum* L.) crop as influenced by row orientation and row spacing. *The Journal of Agricultural Sciences*. 2: 43-54.

Lucas, M.J. and Hungría, M. (2014). Plant densities and modulation of symbiotic nitrogen fixation in soybean. *Scientia Agricola*. 71(3): 181-187.

Lucas, D. D., Heldwein, A.B., Hinnah, F.D., Maldaner, I.C. and Loose, L.A. (2015) Estimation of leaf area index in the sunflower as a function of thermal time. *Revista Ciência Agronômica*. 46(2): 404-411.

Lüscher, A., Mueller-Harvey, I., Soussana, J.F., Rees, R.M. and Peyrau, J.L. (2014) Potential of legume-based grassland–livestock systems in Europe: a review. *Grass Forage Science*. 69(2): 206-228.

Maalouf, F., Ahmed, S., Shaaban, K., Bassam, B., *et al.* (2016) New faba bean germplasm with multiple resistances to Ascochyta blight, chocolate spot and rust diseases. *Euphytica*. 211(2):157-167.

Machado, S. (2009) Does intercropping have a role in modern agriculture? *Journal of Soil Water Conservation.* 64 (2): 55A-57A

MAFF, (1988) Agricultural Land Classification of England and Wales. Ministry of Agriculture, Fisheries and Food, pp52.

Magomya, A.M., Kubmarawa, D., Ndahi, J.A. and Yebpella, G.G. (2014) Determination of Plant Proteins via the Kjeldahl Method and Amino Acid Analysis: A Comparative study. *International journal of scientific and technology research*. 3(4): 68-72.

Mahama, G.Y., Vara Prasad, P. V., Roozeboom, K.L. and Nippert, J.B., Rice, C.W. (2016) Cover crops, fertilizer nitrogen rates, and economic return of grain sorghum. Crop ecology and physiology. *Agronomy Journal.* 108: 1-16.

Majumdar, K., Sanyal, S.K., Dutta, S.K., Satyanarayana, T. and Singh, V.K. (2016) Nutrient Mining: Addressing the challenges to soil resources and food security. In, Singh, U., Praharaj, C., Singh, S.and Singh, N. (eds.) *Biofortification of Food Crops*. Springer: pp177-198.

Malezieux, E., Crozat, Y., Dupraz, C., Laurans, M., Makowski, D., Ozier-Lafontaine, H., *et al.* (2009) Mixing plant species in cropping systems: concepts, tools and models. A review. *Agronomy for Sustainable Development*. 29: 43-62.

Maliha, R., Samina, K., Najma, A., Sadia, A. and Farooq, L. (2004) Organic acids production and phosphate solubilisation by phosphate solubilizing microorganisms under in vitro conditions. *Pakistan Journal of Biological Science.* 7:187–196.

Mansab, A. L., Jeffers, D.L. and Henderlong, P.R. (2003) Interrelationship between leaf area, light interception and growth rate in a soybean-wheat system. *Asian Journal of Plant Sciences*. 2: 605-612.

Mariola, S., Księżak, J. and Bojarszczuk, J. (2016) maMixtures of legumes with cereals as a source of feed for animals. Organic Agriculture towards Sustainability [Online]. Available from:https://www.intechopen.com/books/organic-agriculture-towards-sustainability/mixtures-of-legumes-with-cereals-as-a-source-of-feed-for-animals[Date accessed: 24/11/2016].

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

Mariotti, M., Masoni, A., Ercoli, L. and Arduini, I. (2011) Optimizing forage yield of durum wheat/field bean intercropping through N fertilization and row ratio. *Grass and Forage Science*. 67:1-12.

Mariotti, M., Masoni, A., Ercoli, L. and Arduini, I. (2015). Nitrogen leaching and residual effect of barley/faba bean intercropping. *Plant Soil and Environment*. 61: 60-65.

Mariotti, M., Masoni, A., Ercoli, L. and Arduini, I. (2006) Forage potential of winter cereal/legume intercrops in organic farming. *Italian Journal of Agronomy*. 3: 403-412.

Martin, M.P.L.D. and Snaydon, R.W. (1982) Intercropping barley and beans I. Effects of planting pattern. *Experimental Agriculture*. 18: 139-148.

Martinez, S., Hand, M., Da Pra, M., Pollack, S., Ralston, K. and Smith, T. (2010) Local food systems concepts, impacts, and issues. USDA, Economic Research Service Economic, Research Report Number 97, 80 p.

Massawe, P.I. Mtei, K.M, Munishi, L.K and Ndakidemi, P.A. (2016) Effect of *Rhizobium* and intercropping systems on soil nutrients and Biological Nitrogen Fixation as influenced by legumes (*Phaseolus vulgaris* and *Dolichos lablab*). *International Journal of Current Microbiology and Applied Sciences*. 5(10): 135-149.

Matusso, M., Mateus, J., Mugwe, J., Mucheru-Mun, M. (2014) Effect of different maize (*Zea mays* L.) - soybean (*Glycine max* (L.) Merrill) intercropping patterns on yields light interception and leaf area index in Embu West and Tigania East sub counties Abstract Academy. *Agricultural Science Research Journal.* 2(2): 6-21.

McCree, K.J**. (**1972) The action spectrum, absorptance and quantum yield of photosynthesis in crop plants. *Agricultural and Forest Meteorology*. 9:191-216.

Mcdonald, G.K. (2003) Competitiveness against grass weeds in field pea genotypes. *Weed Research*. 43: 48-58.

McGilchrist, C.A. (1965) Analysis of competition experiments. *Biometrics*. 21: 975–985.

Mead, R. and Stern, R.D., (1979) Statistical considerations in experiments to investigate intercropping. Proc. of International Workshop on Intercropping. Hyderabad, India: ICRISAT. Hyderabad, pp 263-276.

Mead, R. and Willey, W.R. (1980) The concept of a land equivalent ratio and advantages in yields from intercropping. *Experimental Agriculture*. 16: 217-222.

Megawer, E.A., Sharaan, A.N. and EL-Sherif, A.M. (2010) Effect of intercropping patterns on yield and its components of barley, lupin or chickpea grown in newly reclaimed soil. *Egyptian Journal of Basic and Applied Sciences.* 25(9): 437-452.

Mei, P.P., Gui, L.G., Wang, P., Huang, J.C., Long, H.Y., Christie, P. and Li, L. (2012) Maize/faba bean intercropping with rhizobia inoculation enhances productivity and recovery of fertilizer P in a reclaimed desert soil. *Field Crops Research*. 130: 19-27.

Meng, Q., Yue, S., Chen, X., Cui, Z., Ye, Y., *et al.* (2013) Understanding dry matter and nitrogen accumulation with time-course for high-yielding wheat production in China. *PLoS ONE. 8*(7): e68783.

Midmore, D.J., (1993) Agronomic modification of resource use and intercrop productivity. Field Crops Res., 34: 357–380.

Mishra, R.K., Chaudhary, S.K. and Tripathi, A.K. (1997) Intercropping of cowpea (*Vigna ungisculata*) and horse gram (*Macrotyloma uniflorum*) with sorghum for fodder under rainfed condition. *Indian Journal of Agronomy.* 42 (3): 405-408.

Mohammadi, K., Sohrabi, Y., Heidari, G., Khalesro, S. and Majidi, M. (2012) Effective factors on biological nitrogen fixation. *African Journal of Biotechnology*. 7: 1782-1788.

Mohler, C.L. and Liebman, M. (1987) Weed productivity and composition in sole crops and intercrops of barley and field pea. *Journal of Applied Ecology.* 24: 685–699.

Mohsin, Z.M., Abbasi, K., Khaliq, A. and Zahidur-Rehman, Z. (2011) Effect of combining organic materials with inorganic phosphorus sources on growth, yield, energy content and phosphorus uptake in maize at Rawalakot Azad Jammu and Kashmir, *Pakistan Journal of Biological Sciences*.3(2):199-212.

Molaaldoila, Y.A.A., Al-Mosanif, E.M., Al-Aqil, M.M. and Al-Kumali, A.H.A. (2017) Effect of nitrogen levels on yield, competitive, economic indices and efficiency of sorghum cultivars and common bean intercropping. *Agricultural Research and Technology.* 3(3):1-17

Monteith, J.L. (1972) Solar radiation and productivity in tropical *Ecosystems.Journal of Applied Ecology*. 9:747-766.

Mooney, H.A., Ehleringer, J. and Bjorkman, O. (1977) The energy balance of leaves of the evergreen desert shrub atriplex hymenelytra.Oecologia. 29: 301-310.

Morgado, L.B. and Willey, R.W. (2003) Effect of plant population and nitrogen fertilizer on yield and efficiency of maize-bean intercropping. *Pesquisa Agropecuária Brasileira***.** 38: 1257-1264.

Motavalli, P., Nelson, K., Udawatta, R., Jose, S. and Bardhan, S. (2013) Global achievement in sustainable land management. *International Soil and Water Conservation Research*. 1(1): 1-110.

Mousavi, S.R. and Eskandari, H. (2011) A general overview on intercropping and its advantages in sustainable agriculture. *Journal of Applied Environmental and Biological Sciences*. 1(11): 482-486.

Mubarik, N.R. and Sunatmo, T. (2014) Symbiotic of nitrogen fixation between acid aluminium tolerant *Bradyrhizobium japonicum* and Soybean. Advances in biology and ecology of nitrogen fixation. [Online]. Available from http://www.dx.doi.org/10.5772/57491 [Date accessed: 12/01/2017].

Mucheru-Muna, M., Pypers, P., Mugendi, D., Kung'u, J., Mugwe, J., Merck, R. and Vanlauwe, B. (2010) A staggered maize–legume intercrop arrangement robustly increases crop yields and economic returns in the highlands of Central Kenya. *Field Crops Research*. 115:132-139.

Mueller, N.D., West, P.C. and Gerber, J.S. (2014) Trade-off frontier for global nitrogen use and cereal production. *Environmental Research Letters*. 9(5): (054002).

Muhammad, A.K., Khalid, N., Kawsar, A., Bashir, A. and Samin, J. (2012) Impact of mung bean/maize intercropping on growth and yield of mung bean. *Pakistan Journal of Weed Sciences Research.* 18(2): 191-200.

Muller-Schärer, H. (1996) Interplanting ryegrass in winter leek: effect on weed control, crop yield and allocation of N-fertiliser. *Crop Protection*. 15(7): 641-648.

Multari, S., Stewart, D. and Russell, W. R. (2015) Potential of fava bean as future protein supply to partially replace meat intake in the human diet. *Comprehensive Reviews in Food Science and Food Safety.*14: 511–522.

Munir, M., Saeed, M. and Imran, M. (2004) Crop productivity and net return in wheat- gram intercropping. *Pakistan Journal of Agricultural Research*. 18: 20-24.

Murinda, M.V. and Saxena, M.C. (1985) Agronomy of faba beans, lentils and chickpeas. In, *Proceedings of the International Workshop on Faba Beans, Kabuli Chickpeas and Lentils in the 1980s,* May 1985, ICARDA. Ed. by M.C. Saxena and S. Verma.

Murphy, W.M., Welch, J.G., Palmer, R.H., Gilman, B.H., Albers, C.W., Dugdale, T. (1984) Digestibilities of silages made from corn interplanted with soybean or fababean. *Journal of Dairy Science.* 67: 1532-1534.

Musa, M., Leitch, M.H., Iqbal, M. and Sahi, F.U.H. (2010) Spatial arrangement affects growth characteristics of barley-pea intercrops. *International Journal of Agriculture and Biology*.12: 685–690.

Mwengi, J.E. (2011) Faba bean growth response to soil temperature and nitrogen. Master's Thesis, Washington State University, Pullman, Washington.

NABIM, (2014) *Wheat Guide*. National Association of British and Irish Millers (NABIM). London. UK.

Nadeem, A., Kashani, S., Ahmed, N., Buriro, M., Saeed, Z., Mohammad, F. and Ahmed, S. (2015) Growth and yield of sesame (*Sesamum indicum* L.) under the influence of planting geometry and irrigation regimes. *American Journal of Plant Sciences*. 6: 980-986.

Nambiar, P.T.C., Rao, M.R., Reddy, M.S., Floyd, C.N., Dart, P.J. and Willey, R.W. (1983) Effects of intercropping on nodulation and N2 -fixation by groundnut. *Experimental Agriculture*. 19:79-86.

Naudin, C., Corre-Hellou, G., Pineau, S., Crozat, Y. and Jeuffroy, M.H. (2010) The effects of various dynamics on winter pea-wheat intercrops: crop growth, N partitioning and symbiotic N_2 fixation. *Field Crops Research*. 119: 2-11.

Ndukwu, B.N. , Asawalam, D.O. , Umeh, M.O. , Ahukaemere, C.M. (2016) Assessment of growth, nodulation and nitrogen fixation in different varieties of cowpea in a humid tropical environment using N-difference method. *Journal of Multidisciplinary Engineering Science Studies.* 2(7): 717-724.

Newman, E. I. (1988) Mycorrhizal links between plants: Their functioning and ecological significance. *Advances in Ecological Research.* 18: 243-270.

Neykova, N., Obando, J., Schneider, R., Shisanya, C., Thiele-Bruhn, S. and Thomas, F.M. (2011) Vertical root distribution in single-crop and intercropping agricultural systems in Central Kenya. *Journal of Plant Nutrition and Soil Science.* 174:742–749.

Ngwira, A.R., Aune, J.B. and Mkwinda, S. (2012) On-farm evaluation of yield and economic benefit of short term maize legume intercropping systems under conservation agriculture in Malawi. *Field crops research.* 132: 149-157.

Niblack, T. L., Lambert, K. N. and Tylka, G. L. (2006) A model plant pathogen from the Kingdom animala: Heteroderaglycines, the soybean cyst nematode. Annual Review of Phytopathology 44: 283-303.

Niinemets, Ü. (2007) Photosynthesis and resource distribution through plant canopies. *Plant, Cell and Environment*. 30: 1052-1071.

Norton, G., Bliss, F.A. and Bressani, R. (1985) Biochemical and nutritional attributes of grain legumes. In, Summerfield, R.J. and E.H. Roberts (eds.) *Grain Legume Crops*. Collins, London, UK.

Nsowah, G. F. (1986) Effect of surface covers and planting depth on seedling emergence and growth of soybeans (*Glycine max* L. Merr.). *Ghana Journal of Agricultural Science.* 19: 64-69.

Ofori, F. and Stern, W.R. (1987) Cereal–legume intercropping systems. *Advanced Agronomy*. 41: 41-90.

Ogenga-Latigo, M.W., Baliddawa, C.W. and Ampofo, J.K.O. (1993) Factors influencing the incidence of the black bean aphid (*Aphis fabae* Scop) on common beans intercropped with maize. *African Crop Science Journal.* 1: 49-58.

O'Leary, N. and Smith, M.E. (1999) Breeding corn for adaptation to two diverse intercropping companions. *American Journal of Alternative Agriculture*. 14: 158-164.

Oliveira, M.R.G., van Noordwijk, M., Gaze, S.R., *et al.* (2000) Auger sampling, in growth cores and pinboard methods. In, Smit, D.A.L, Bengough, D.A.G, Engels, P.D.C., van Noordwijk, D.M., Pellerin, D.S. and van de Geijn, D.S.C. (eds.) *Root methods*. Berlin, Springer: 175–210.

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

Olsen, J., Kristensen, L., Weiner, J. and Griepentrog, H.W. (2005). Increased density and spatial uniformity increase weed suppression by spring wheat. *Weed Research*. 45: 316–321.

Olsen, J.M., Griepentrog, H.W., Nielsen, J. and Weiner, J. (2012) How important are crop spatial pattern and density for weed suppression by spring wheat? *Weed Science*. 60: 501-509

Olsen, S.R., Cole, C.W., Watanabe, F.S. and Dean, L. A. (1954) Estimation of available phosphorus in soils by extraction with sodium bicarbonate. USDA Circular No. 939. pp, 19-23.

Oluwasemire, K. and Odugbenro, G. (2014) Solar radiation interception, dry matter production and yield among different plant densities of *Arachis spp*. in Ibadan, Nigeria. *Agricultural Sciences*. 5: 864-874.

Orluchukwu, J.A. and Udensi, U.E. (2013) The effect of intercropping pattern of okra, maize, and pepper on weeds infestations and okra yield. *African Journal of Agricultural Research*. 8(10): 896-902.

Osborne, T.B. (1907) The Proteins of the wheat kernel. Washington, D.C.: Carnegie Institute Washington Publication, Judd and Detweiler, 84 pp.

Oseni, T.O. and Aliyu, I.G. (2010) Effect of row arrangements on sorghum-cowpea intercrops in the semi-arid savannah of Nigeria. *International Journal of Agriculture and Biology*. 12: 137-140.

Oskoii, F.J., Nasrollahzadeh, S., Shakiba, M.R. and Nasab, A.D.M. (2015). Effect of different intercropping patterns on yield and yield components of maize (*Zea mays* L.) and faba bean (*Vicia faba* L.) Biological Forum – *An International Journal* 7(2): 854-858.

Osman, A.A.M., Yagoub, S.O. and Tut, O.A. (2010) Performance of faba beans (*Vicia faba* L.) cultivars grown in new agro-ecological regions of Sudan (South Sudan). *Australian Journal of Basic and Applied Sciences.* 4 (11): 5516–5521.

Pandey, M. (1996) Effect of photosynthate availability on N_2-fixation in soybean nodules. *Indian Journal of Plant Physiology*. 1: 18-20.

Pandey, R. K., Saxena, M. C., Agrawal, B. D. and Subramaniam, K. K. (1976). Photosynthetically active radiation in and out of maize canopy in subtropical conditions of Pantnagar. *Pantnagar Journal of Research*. 1: 45-47.

Pappa, V.A., Rees, R.M., Walker, R.L., Baddeley, J.A. and Watson, C.A. (2012) Legumes intercropped with spring barley contribute to increased biomass production and carry-over effects. *Journal of Agricultural Science*. 150:584-94.

Pappa, V.A., Rees, R.M., Walker, R.L., Baddeley, J.A. and Watson, C.A. (2011) Nitrous oxide emissions and nitrate leaching in an arable rotation resulting from the presence of an intercrop. *Agriculture, Ecosystems and Environment.* 141: 153-161.

Park, S.E., Benjamin, L.R. and Watkinson, A.R. (2003) The theory and application of plant competition models: an agronomic perspective. *Annals of Botany*, 92: 741-748.

Parkhurst, A. M. and Francis, C. A. (1986) Research methods for multiple cropping. In, Francis, C. A. (ed.) Multiple Cropping Systems. New York, Macmillian Publishing Company: 285-316.

Parsa, M. and Bagheri, A. (2008) Pulses. Ferdowsi University of Mashhad Press. 522 pp.

Patriquin, D. (1986) Biological husbandry and the “nitrogen” problem. *Biological Agriculture and Horticulture.* 3: 167-189.

Pautasso, M., During, T.F., Garbelotto, M., Pellis, L. and Jeger, M.J. (2012). Impacts of climate change on plant diseases – opinions and trends. *European Journal of Plant Pathology*. 133: 295-313.

Pecetti, L. and Piano, E. (2000) Future of Alfalfa as a grazing crop in Europe. In, Rochon *et al.* (2005). Grazing legumes in Europe: a review of their status, management, benefits, research needs and future prospects. *Grass and forage science*. 59: 197-214.

Peoples, M.B., Brockwell, J., Herridge, D.F., Rochester, I.J. *et al.* (2009) The contributions of Nitrogen-fixing crop legumes to the productivity of agricultural systems. *Symbiosis* 48: 1-17.

Pinder, R. W., Davidson, E. A., Goodale, C. L., Greaver, T. L., Herrick, J. D. and Liu, L. (2012) Climate change impacts of US reactive nitrogen. *Proceedings of the National Academy of Sciences*. 109: 7671-7675.

Polthanee, A. and Trelo-ges, V. (2003) Growth, yield and land use efficiency of corn and legumes grown under intercropping systems. *Plant Production Science*. 6(2): 139-146.

Ponisio, L., M'Gonigle, L., Mace, K., Palomino, J., de Valpine, P. and Kremen, C. (2015) Diversification practices reduce organic to conventional yield gap. *Proceedings of the Royal Society B: Biological Sciences.* 282 (1799): (20141396).

Poppi, D.P. and McLennant, S. (2014) Protein and energy utilization by ruminants on pasture. *Journal of Animal Science*. 73: 278-290.

Postma, J. and Lynch, J.P. (2012) Complementarity in root architecture for nutrient uptake in ancient maize/bean and maize/bean/squash polycultures. *Annals of Botany*. 110: 521–534.

Powell, D. (2008) The role and management of whole-crop forage for organic ruminants. Institute of Organic Training and Advice (IOTA), Craven Arms. [Online]. Available from: http://www.orgprints.org/13556/1/Res_review_11_powell.pdf [Date accessed: 08/09/2017].

Prew, R.D. and Dyke, G.V. (1979) Experiments comparing 'break crops' as a preparation for winter wheat followed by spring barley. *The Journal of Agricultural Science Cambridge*. 92; 189-201.

Pristeri, A., Dahlmann, C., Von Fragstein, P., Gooding, M. J., Hauggaard-Nielsen, H., Kasyanova, E. and Monti, M. (2006) Yield performance of faba bean-wheat intercropping on spring and winter sowing in European organic farming system. In, *Proceedings of European Joint Organic Congress 2006*: Organic Farming and European Rural Development: 294-295.

Processors and Growers Research Organisation (2015) PGRO Pulse Agronomy Guide. [Online] Available from: http://www.pgro.org/images/site/jan-2015/PGRO-AGRONOMY-GUIDE-2015.pdf [Date accessed 11/11/2016].

Processors and Growers Research Organisation (2016) PGRO Pulse Agronomy Guide. [Online] Available from: http://www.pgro.org [Date accessed 11/11/2016].

Processors and Growers Research Organisation (2017) PGRO Pulse Agronomy Guide. [Online] Available from: http://www.pgro.org/images/site/jan-2015/PGRO-AGRONOMY-GUIDE-2015.pdf [Date accessed 11/11/2016].

Rao, M. R. and Willy, R. W. (1980) Evaluation of yield stability in intercropping: studies on sorghum/pigonpea. *Experimental Agriculture.* 16: 105-116

Rao, M.R., Nair, P.K.R. and Ong, C.K. (1997) Biophysical interactions in tropical agroforestry systems. *Agroforestry Systems*. 38: 3-50.

Rao, M.R., Rego, T.J. and Willey, R.W. (1987) Response of cereals to nitrogen in sole cropping and intercropping with different legumes. *Plant and Soil.* 101(2): 167-177.

Raseduzzaman, M.D. and Jensen, E.S. (2017) Does intercropping enhance yield stability in arable crop production? A meta-analysis. *European Journal of Agronomy*. 91: 25-33.

Reay, D. S., Davidson, E. A., Smith, K. A., Smith, P., Melillo, J. M., Dentener F., Crutzen, P.J. (2012) Global agriculture and nitrous oxide emissions. Nature Climate Change. 2: 410-416.

Reckling, M., Schläfke, N., Hecker, J.M., Bachinger, J., Zander, P. and Bergkvist, G. (2014) Generation and evaluation of legume-supported crop rotations in five case study regions across Europe. [Online] Available from: http://ww.Legumefuture.de [Date accessed: 22/04/2017].

Reddell, P., Bowen, G.D., Robson, A.D., (1985) The effects of soil temperature on plant growth, nodulation and nitrogen fixation in *Casuarina cunninghamiana* Miq. *New Phytologist*. 101: 441–450.

Reddy, L.J. (1990) Pigeonpea: Morphology. In, Nene, Y.L; Hall S. D. and Sheila (ed.) *The pigeonpea.* Wallingford: CAB International, pp. 47-88.

Reddy, T.Y. and Reddi, G. H. S. (2007) Principles of agronomy, Kalyani Publishers, India. pp. 468-489.

Reta Sánchez, D.G., Espinosa Silva, J. T., Palomo Gil, A., Serrato Corona, J. S., Cueto Wong, J. A.and Gaytán Mascorro, A. (2010). *Spanish Journal of Agricultural Research*. 8(3): 713-721.

Reza, Z.O., Allahdadi, I., Mazaheri, D., Akbari, G.A., Jahanzad, E., and Mirshekari, M. (2011). Effect of different planting proportions and nitrogen fertilizer in intercropping forage sorghum and lima bean. *African Journal of Agricultural Research*. 8(49): 6488-6498.

Richards, J.E. and Soper, R.J. (1982) N fertilization of field-grown faba beans in Manitoba. *Canadian Journal of Soil Science*. 62: 21-30.

Richards, R.A. (2016). Selectable traits to increase crop photosynthesis and yield of grain crops. *Journal of Experimental Botany*.51 (1): 447-458.

Robertson, L.D., Singh, K.B., Erskine, W., Ali M. and Abd, E.L. (1996) Useful genetic diversity in germplasm collections of food and forage legumes from West Asia and North Africa. *Germplasm Resources and Crop Evolution* 43: 447-460.

Röös, E., Mie, A., Wivstad, M., Salomon, E., Johansson, B., Gunnarsson, S., Wallenbeck, A. *et al*. (2018) Risks and opportunities of increasing yields in organic farming. A review. *Agronomy for Sustainable Development.* 38 (14): 1-20.

Rose, T.J., Julia, C.C., Shepherd, M., Rose, M.T. and Van Zwieten, L. (2016) Faba bean is less susceptible to fertiliser N impacts on biological N2 fixation than chickpea in monoculture and intercropping systems. *Biology and Fertility of Soils*. 52: 271-276.

Rubiales, D. (2010) Faba beans in sustainable agriculture. *Field Crops Research*. 115: 201-202.

Rusinamhodzi, L., Corbeels, M., Nyamangara, J. and Giller, K.E. (2012) Maize–grain legume intercropping is an attractive option for ecological intensification that reduces climatic risk for smallholder farmers in central Mozambique. *Field Crops Research.* 136: 12-22

Sadeghpour, A. and Jahanzad, E. (2012) Seed yield and yield components of intercropped barley (*Hordeum vulgare* L.) and annual medic (*Medicago scutellata* L.). *Australian Journal of Agricultural Engineering*. 3 (2): 47-50.

Sadeghpour, A., Jahanzad, E., Hashemi, M. and Esmaeili, A. (2011) Forage yield and quality of annual medic intercropped with barley. American Society of Agronomy, Northeastern Branch Chesapeake, Maryland. June 26-29. Abstract.

Sadeghpour, A., Jahanzad, E., Lithourgidis, A.S., Hashemi, M., Esmaeili, A., and Hosseini, M.B. (2014) Forage yield and quality of barley-annual medic intercrops in semi-arid environments. *International Journal of Plant Production.* 8: 77-89.

Sadeghpour, A., Jahanzad, E., Hashemi, M., Esmaeili, A. and Herbert, S.J. (2013) Intercropping annual medic with barley may improve total forage and crude protein yield in semi-arid condition. *Australian Journal of Crop Science*. 7: 1822-1828.

Sadeghpour, A., Jahanzad, E., Lithourgidis, A.S., Hashemi, M., Esmaeili, A., Hossein, M.B. (2014). Forage yield and quality of barley-annual medic intercrops in semi-arid environments. *International Journal of Plant Production*. 8(1): 77-90.

Salter, M.A. (2017). Improving the sustainability of global meat and milk production. *Proceedings of the Nutrition Society*. 76: 22-27.

Samaan, J., El-Khayat, G.H., Manthey, F.A., Fuller, M.P., Brennan, C.S. (2006) Durum wheat quality: II The relationship of kernel physicochemical composition to semolina quality and end product utilization. *International Journal of Food Science and Technology*. 41 (2): 47-55.

Sameh, H.Y., Fayrouz, H. A. and Saleh, A. (2017) Improvement of faba bean yield using Rhizobium/Agrobacterium inoculant in low-fertility sandy soil. *Agronomy Journal*. 7(2).

San-nai, J. and Ming-pu, Z. (2000) Nitrogen transfer between N_2-fixing plant and non-N_2-fixing plant. *Journal of Forestry Research.* 11 (2): 75-80.

Sarr, P.S., Fujimoto, S. and Yamakawa, T. (2015) Nodulation, nitrogen fixation and growth of Rhizobia-inoculated cowpea (*Vignaunguiculata* L. Walp) in relation with external nitrogen and light intensity. *International Journal of Plant Biology and Research.* 3(1): 1025.

Saucke, H. and Ackermann, K. (2006) Weed suppression in mixed cropped grain peas and false flax (*Camelina sativa*). *Weed Research*. 46: 453-461.

Sauvant, D., and S. Giger-Reverdin. 2009. Modélisation des ineractions digestives et de la production de méthane chez les ruminants. *INRA Production Animales*. 22:375-384.

Sawyer, C.A. (2006) Forage Soybean-A potential new home grown potential new home-grown protein source for livestock feed in the UK. PhD Thesis. Coventry University. UK.

Saxena, M.C., Skim, S.N., and Murwda, M.V. (1986) Effect of moisture supply and fertilizer application on the yield build-up of some contrasting faba bean genotypes. *Lectures Plant cultivation*.11: 40-48.

Schreuder, R. and De Visser, C. (2014) EIP-AGRI Focus Group. Protein Crops: final report. Eip-Agri. Agriculture and innovation. European Union. [Online]. Available from: https://ec.europa.eu/eip/agriculture/sites/agri-eip/files/fg2_protein_crops_final_report_2014_en.pdf [Date accessed: 20th May, 2017].

Schuurman, J. J. and Goedewaagen, M.A.J. (1971) Methods for the examination of root systems and roots. Wageningen, Pudoc. 86 p.

Sedghi, M, Sharifi, R.S. and Gholipouri, A. (2008) Practical methods of increasing light interception efficiency and root growth in soybean. *Pakistan Journal of Biological Sciencies.* 11(4): 595-600.

Semere, T. (1998) Studies on ecophysiological approach of weed management in maize by intercropping with field pea. PhD Thesis. University of Reading, Reading, UK.

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

Senbayram, M., Wenthe, C., Lingner, A., Isselstein, J., Steinmann, H., Kaya, C. and Köbke, S. (2016) Legume-based mixed intercropping systems may lower agricultural born N_2O emissions. *Energy, Sustainability and Society*. 6(2):1-9.

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

Sherwan, I.T. and Kazhala, R.A. (2014) The Role of Intercropping Wheat with Legumes (Chickpea or Pea) in Improving the yield and Land Equivalent Ratio in Rain fed Regions. *Journal of Zankoy Sulaimani*-Part A, Special Issue. 16

Lutman, P.J.W., Moss, S., Cook, S.K. and Welham, S.J. (2013) A review of the effects of crop agronomy on the management of Alopecurus myosuroides. *Weed Research.* 53: 299-313.

Siddiqui, M.H., Al-Khaishany, M.Y., Al-Qutami, M.A., Al-Whaibi, M.H., Grover, A., Ali, H.M and Al-Wahibia, M.S. (2015) Morphological and physiological characterization of different genotypes of faba bean under heat stress. *Saudi Journal of Biological Sciences*. 22(5): 656-663.

Singh, A.K., Chandra, N., Bharati, R.C. and Dimree, S.K. (2010) Effect of seed size and seeding depth on faba bean (*Vicia faba* L.) productivity. *Journal of Environment and Ecology*. 28: 1522-1527.

Singh, G. and Shivakumar, B. G. (2010) The role of soybean in agriculture. In, Singh, E. (ed.) *The soybean: Botany, production and uses*. CAB International, Oxfordshire, UK, pp. 24–47.

Singh, S.P. (1983). Intercrop sorghum with legumes. *Indian Journal of Farming*. 33(6): 15-22.

Singh, V. P., Mishra, J. S. and Bhan, V. M. (1999). Integrated weed management in soybean. *Indian Journal Weed Science* 31: 267-268.

Sinoquet, H. and Caldwell, R. M. (1995). Estimation of light capture and partitioning in intercropping systems. In, Sinoquet, H. and Cruz, P. *Ecophysiology of tropical intercropping.* Paris: INRA:79-96.

Sinoquet, H. and Cruz, P. (1993) Analysis of light interception and use in pure and mixed stands of *Digitaria decumbens* and *Arachis pintoi*. *Acta Oecologica*.14: 327-39.

Siyeni, (2016) Effect of Rhizobia inoculation and phosphorus fertilizer on nodulation and yield of soybean [*Glycine max* (L.) Merril] In Dedza, Kasungu and Salima Districts of Malawi. Master of Science in Agronomy. University of Malawi. Bunda College of Agriculture, Lilongwe. Malawi.

Skiba, U.M.and Ree, R.M. (2014) Nitrous oxide, climate change and agriculture. *CAD Review*.9 (10): 1-7.

Smitchger, J.A., Burke, I.C. and Yenish, J.P. (2012) The critical period of weed control in lentil (*Lens culinaris*) in the Pacific Northwest. *Weed Science*. 60: 81-85.

Smith, W. K. and Geller, G. N. (2013) Leaf and Environmental Parameters Influencing Transpiration: Theory and Field Measurements. *Oecologia.* 46 (3): 308-313

Snaydon, R.W. (1991) Replacement or additive designs for competition studies? *Journal of Applied Ecology*. 28: 930-946.

Snaydon, R.W. (1994) Replacement and additive designs revisited: comments on the review paper by N. R. Sackville Hamilton. *Journal of Applied Ecology.* 31: 784–786.

Sobkowicz, P. (2001) Aboveground and belowground competition between barley and oats in mixture at the beginning of growth. *Fragmenta Agronomica*. 70 (2): 103-119.

Sobkowicz, P. (2005) Shoot and root competition between spring Triticale and field beans during early growth. *Acta Scientiarum Polonorum seria Agricultura.* 4(1): 117-126.

Sobkowicz, P., and Tendziagolska, E. (2015) Intercropping barley and pea at uniform and alternate row arrangement of the cereal component. *Electronic Journal of Polish Agricultural Universities*. 18(2):06

Soil Association, (2002) Soil association organic standards and certification. Soil Association, Bristol, UK.

Song, Y.N., Zhang, F.S., Marschner, P., Fan, F.L., Gao, H.M. *et al.* (2007) Effect of intercropping on crop yield and chemical and microbiological properties in rhizosphere of wheat (*Triticum aestivum* L.), maize (*Zea mays* L.) and faba bean (*Vicia faba* L.). *Biology and Fertility of Soils*. 43: 565-574.

Sprent, J.I., Minchin, F.R. and Thomas, R.J. (1983) In, Jones, D.G and Davies, D.R. (eds.) *Temperate Legumes*: Physiology, Genetics and Nodulation. London: Pitman, pp.115-114.

Stagnari, F., Maggio, A., Galieni, A. and Pisante, M. (2017) Multiple benefits of legumes for agriculture sustainability: an overview. *Chemical and Biological Technologies in Agriculture.* 4(2).

Stark, J. C. and Tindall, T. A. (1992) Timing split applications of nitrogen for irrigated hard red spring wheat. *Journal of Production Agriculture*. 5: 221-226.

Stern, W.R. (1993) Nitrogen fixation and transfer in an intercropping systems. *Field Crop Research*. 34: 335-356.

Stoltz, E. and 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 Research*. 169: 21-29.

Streeter, J.G. (1985) Nitrate inhibition of legume nodule growth and activity. *Plant Physiology*. 77: 321–324.

Strydhorst, S.M., King, J.R., Lopetinsky, K.J. and Harker, K.N. (2008) Forage potential of intercropping barley with faba bean, lupin, or field pea. *Agronomy Journal*. 100: 182–190.

Su, B.Y., Song, Y.X. and Song, C. (2014) Growth and photosynthetic response of soybean seedlings to maize shading in relay intercropping system in Southwest China. *Photosynthetica*. 52 (3): 332-340.

Subedi, K. D. (1997) Wheat intercropped with tori (*Brassica campestris* var. toria) and pea (*Pisum sativum*) in the subsistence farming system of Nepalese hills. *Journal of Agricultural Science*. 128: 283-289.

Sullivan, P. (2003) Intercropping principles and production practices. [Online]. Available from: http://attra.ncat.org/attra-pub/intercrop.html. [Date accessed: 17th May, 2017]

Sutharsa, S. and Srikrishnah, S. (2015) Effect of different spatial arrangements on the growth and yield of Maize (*Zea mays* L.) and Groundnut (*Arachis hypogaea* L.) intercrop in the Sandy Regosol of Eastern region of Sri Lanka. *Research Journal of Agriculture and Forestry Sciences.* 3(2): 16-19.

Swinton, S.M., Lupi, F., Robertson, G.P. and Hamilton, S.K. (2007) Ecosystem services and agriculture: Cultivating agricultural ecosystems for diverse benefits. *Ecological Economics.* 64: 245–252.

Szumigalski, A. and van Acker, R. (2008) Land equivalent ratios, light interception, and water use in annual intercrops in the presence or absence of in-crop herbicides. *Agronomy Journal.* 100: 1145-1154.

Taylor, B.R. and Cormack, W.F. (2002) Choice of cereal and pulse species and varieties. In, Younie, D., Taylor, B.R., Welch, J.P. and Wilkinson, J.M. (eds.) *Organic cereals and pulses*. Papers presented at conferences held at the Heriot-Watt University, Edinburgh, and at Cranfield University Silsoe Campus, Bedfordshire, 6 and 9 November 2001, Chalcombe Publications: 9-28.

Tena, W., Wolde-Meskel, E. and Walley, F. (2016) Symbiotic efficiency of native and exotic Rhizobium strains nodulating Lentil (*Lens culinaris* Medik.) in soils of southern Ethiopia. *Agronomy Journal*. 6 (1):11.

Tesfamichael, N. and Reddy, M.S. (1996) Maize/bean intercropping effects on component yield, land use efficiency and net-returns at Awassa and Melkassa. In, *Proceedings of the 1st*

Conference of the Agronomy and Crop Physiology Society of Ethiopia. Ed. by W. Sinebo, Z. Tadele, and N, Alemayehu. Addis Ababa, Ethiopia: 51–55.

Tharanathan, R.N. and Mahadevamma, S. (2003) Grain legumes-a boon to human nutrition. *Trends in Food Science and Technology*. 4: 507-18.

Thole, A. (2007) Adaptability of soybean (*Glycine max* L. Merr.) varieties to intercropping under leaf stripped and detasselled Maize (*Zea mays* L.). MSc. Thesis. University of Zimbabwe.

Tilman, D. (1988) Plant strategies and the dynamics and function of plant communities. Princeton University Press, Princeton, New Jersey.

Tilman, D., Balzer, C., Hill, J. and Beforta, B. (2011) Global food demand and the sustainable intensification of agriculture. *Proceedings of the National Academy of Sciences*. 108(50): 20260–20264.

Tisdall, J.M. and Adem, H.H. (1990) Mechanised relay-cropping in an irrigated red-brown earth in 613 south-eastern Australia. *Soil Use and Management.* 6: 21-28.

Tofinga, M.T. and Snaydon, R.W (1992) The root of cereals and peas when grown in pure stands and mixtures. *Plant and Soil*. 142: 281-285.

Tong, P.Y. (1994) Achievements and perspectives of tillage and cropping systems in China. *Cropping System and Cultivation Technology*. 77: 1–5.

Tosti, G., and Guiducci, M. (2010). Durum wheat-faba bean temporary inter-cropping: Effects on nitrogen supply and wheat quality. European Journal of Agronomy. 33:157-165.

Trenbath, B.R. (1986) Resource use by intercrops. In, Francis, C.A. (ed.) Multiple cropping systems, Macmillan, New York, pp. 57-81.

Trenbath, B.R. (1993) Intercropping for the management of pests and diseases. *Field Crop Research*. 34:381-405.

Trinder, C.J., Brooker. R.W. and Robinson, D. (2013) Plant ecology's guilty little secret: understanding the dynamics of plant competition. *Functional Ecology*. 27:918-29.

Tsubo, M., Ogindo, H.O., Walker, S. (2004) Yield evaluation of maize-bean intercropping in a semi-arid region of South Africa. *African Crop Science Journal*, 12 (4): 351-358.

Tsubo, M., Walker, S., and Mukhala, E. (2001) Comparison of radiation use efficiency of mono/intercropping system with different row orientation. *Field Crops Research*. 71: 17-29.

Tsubo, M., Walker, S., and Ogindo, H.O. (2005) A simulation model of cereal legume intercropping systems for semi-arid regions II. Model application. *Field Crops Research*. 93: 23-33.

Turker, M (2004) Primary nutrients and plant growth. In SCRIBD (ed.) *Essential plant nutrients.* North Carolina: North Carolina Department of Agriculture, Raleigh, pp. 1-9.

Uaboi-Egbenni, P. O., Okolie, P. N., Okafor, C. N., Akinyemi, O., *et al.* (2010) Effect of soil types and mixtures on nodulation of some beans and groundnut varieties. *African Journal of Food, Agriculture, Nutrition and Development*. 10(3): 2272-2290.

Uddin, M. B., Khan, M.A.S.A., Mukul, S.A. and Hossain, M.K. (2008) Effects of inorganic fertilizers on biological nitrogen fixation and seedling growth of some agroforestry trees in Bangladesh. *Journal of Forestry Research*. 19 (4): 303–306.

Vance, C.P., Egli, M.A. and Griffith, S.M. (1988) Plant regulated aspects of nodulation and N_2 fixation. *Plant Cell and Environment*.11:413-427.

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

Vandermeer, J.H. (1970) The community matrix and the number of species in a community. *The American Naturalist*. 104: 73-83.

Vandermeer, J.H. (1989) The ecology of intercropping. Cambridge, UK: Cambridge University Press.

Van Dorland, H.A., Wettstein, H.R.L., Euenberger, H. and Kreuzer M. (2007) Effect of supplementation of fresh and ensiled clovers to ryegrass on nitrogen loss and methane emissions in dairy cows. *Livestock Science*. 111: 57-69.

Viliana, V. (2016) Botanical composition improvement with subterranean clover (*Trifolium subterraneum* L.) in Grass Mixtures. *Journal of Applied Sciences.* 16: 68-76.

Vining, K.C. (1990) Effects of weather on agricultural crops and livestock: An overview. *International Journal of Environmental Studies*. 36(1-2): 27-39.

Vinther, F. P. and Dahlmann-Hansen, L. (2005). Effects of ridging on crop performance and symbiotic N_2 fixation of faba bean (*Vicia faba* L.). *Soil Use and Management.* 21(2):205-211.

Voisin, A.S., Guéguen, J., Huyghe, C., Jeuffroy, M.H., Magrini, M.B. and Meynard, .JM. (2014) Legumes for feed, food, biomaterials and bioenergy in Europe: a review. *Agronomy for Sustainable Development*. 34: 361-80.

Wahbi, S., Prin, Y., Thioulouse, J., Hervé, S., Baudoin, S., Maghraoui, T. *et al.* (2016) Impact of wheat/Faba bean mixed cropping or rotation systems on soil microbial functionalities. *Frontiers in Plant Science*.7: 1364.

Wahla, I.H., Ahmad, R., Ehsanullah, A., Ahmad, A. and Jabbar, A. (2009) Competitive functions of components crop in some barley based intercropping systems. *International Journal of Agriculture and Biology*. 11: 69–72.

Wahua, T. A. T., and Miller, D. A. (1978) Relative yield totals and yield components of intercropped sorghum and soybean. *Agronomy Journal*. 70 (2): 287-291.

Walker, S., Stigter, C.J., Ofori, E. and Kyei-Baffour, N. (2011) Intercropping and its implications for soil management. In, Hatfield, J.L. and Sauer, T.J. (eds.) *Soil management: Building a stable base for agriculture.* American Society of Agronomy and Soil Science Society of America.

Walley, F.L., Tomm, G.O., Matus, A., Slinkard, A.E. and van Kessel, C. (1996) Allocation and cycling of nitrogen in alfalfa-bromegrass sward. *Agronomy journal*.88: 834-843.

Waluyo, S.H., Lie, T.A. and Mannetje, L. (2004) Effect of phosphate on nodule primordia of soybean (Glycine max L. Merrill) in acid soils in rhizotron experiments. *Indonesian Journal of Agricultural Science* 5: 37–44.

Wang, C.Y., Guo, T.C., Peng, Y., Zhu, Y.J., Ma, D.Y. and Zhang, C.J. (2004) Effect of post-anthesis irrigation on grain Quality indices and yield in winter wheat (*Triticum aestivum* L.). *Acta Agronomica Sinica*. 30: 1031-1035.

Wang, Z.G, Jin, X., Bao, X.G., Li, X.F and Zhao, J.H (2014) Intercropping enhances productivity and maintains the most soil fertility properties relative to sole cropping. PLoS ONE 9(12): e113984.

Wang, Z., Zhao, X., Wu, P. and Chen, X. (2015) Effects of water limitation on yield advantage and water use in wheat (*Triticum aestivum* L.)/maize (*Zea mays* L.) strip intercropping. *European Journal of Agronomy*. 71: 149-159.

Watiki, J.M., Fukai, S., Banda, J.A. and Keating, B.A. (1993) Radiation interception and growth of maize/cowpea intercrop as affected by maize plant-density and cowpea cultivar. *Field Crops Research*. 35:123-133.

Weigner, J. and Thomas, S.C. (1986) Size variability and competition in plant monocultures. *Oikos*. 47: 21-222.

Willey, R.W. (1979) Intercropping its importance and research needs. I. Competition and yield advantages. *Field Crop Abstracts*. 32: 1-10.

Willey, R.W. and Rao, M.R. (1980) A competitive ratio for quantifying competition between intercrops. *Experimental Agriculture*. 16: 117-125.

Willey, R.W. (1990) Resource use in intercropping systems. *Journal of Agriculture and Water Management*. 17: 215-231

Wnuk, A., Górny, A. G., Bocianowski, J. and Kozak, M. (2013) Visualizing harvest index in crops. *Communications in Biometry and Crop Science.* 8: 48-59.

Wolf, D. D., Carson, E. W. and Brown, R. H. (1972) Leaf area index and specific leaf area determination. *Journal of Agronomic Education*. 1: 24-27.

Woomer, P.L., Karanja, N., Kasamuli. S.M. and Bala, A. (2011) A revised manual for *Rhizobium* methods and standard protocols. [Online]. Available from: http// www.N2Africa.org [Date accessed: 12/01/2018].

Xia, H.Y., Wang, Z.G., Zhao, J.H., Sun, J.H., Bao, X.G., Christie, P. *et al.* (2013) Contribution of interspecific interactions and phosphorus application to sustainable and productive intercropping systems. *Field Crops Research.* 154: 53-64.

Xinyou, Y., Lantinga, E.A., Schapendonk, A.C.M., and Zhong, X. (2003) Some quantitative relationships between leaf area index and canopy nitrogen content and distribution. *Annals of Botany*. 91(7): 893–903.

Yadav, S.S., Hunter, D., Redden, B., Nang, M., Yadava, D.K. and Habibi, A.B. (2015) Impact of climate change on agriculture production, food, and nutritional security. In, Redden, R., Yadav, S.S., Maxted, N., Dulloo, M.S., Guarino, L., Smith, P., (eds.) *Crop wild relatives and climate change.* New Jersey, USA: Wiley: 1–23.

Yahuza, I. (2011a) Review of radiation interception and radiation use efficiency in intercropping in relation to the analysis of wheat/faba bean intercropping system. *Journal of Biodiversity and Environmental Sciences.* 1 (5): 1-15.

Yahuza, I. (2011b) Review of some methods of cultivating intercrop efficiencies with particular reference to the estimates of intercrop benefits in wheat/faba bean system. *International Journal of Biosciences*. 1(50): 18-30.

Yahuza, I. (2012) Productivity of wheat/bean intercropping systems in response to sulphur fertilization and seed rate under contrasting management options *International Journal of Agricultural Agronomy and Agricultural Research*. 2(3): 41-58.

Yasar, K. and Buyukbure, U. (2003) Effect of seed rate on forage production, seed yield and hay quality of annual legumes-barley mixtures. *Turkish Journal of Agriculture and Forestry*. 27:169-174

Yoda, K., Kira, T., Ogawa, H. and Hozami, K. (1963) Self-thinning in overcrowded pure stands under cultivated and natural conditions. *The Journal of Biological Chemistry.*14: 107-129.

Yunasa, I.A.M., Siddique, K.H.M., Belford, R.K. and Karimi, M.M. (1993) Effect of canopy structure on efficiency of radiation interception and use in spring wheat cultivars during the pre-anthesis period in a Mediterranean-type environment. *Field Crops Research*. 35: 113-122.

Zadoks, J. C., Chang, T. T. and Konzak, C. F. (1974) A decimal code for the growth stages of cereals. *Weed Research.* 14: 415-421.

Zebarth, B. J., Botha, E. J. and Rees, H. (2007) Rate and time of fertilizer nitrogen application on yield, protein and apparent efficiency of fertilizer nitrogen use of spring wheat. *Canadian Journal of Plant Science*. 87: 709-718.

Zeleke, K.T. and Nendel, C. (2016) Analysis of options for increasing wheat (*Triticum aestivum* L.) yield in South-eastern Australia: The role of irrigation, cultivar choice and time of sowing. *Agricultural Wateranagement*. 166: 139-148.

Zhang, E., Li, L., Huang, G., Huang, P. and Chai, Q. (2002) Regulation of fertilizer application on yield and root growth of spring wheat/faba bean intercropping system. *Chinese Journal of Applied Ecology*. 13: 839–842.

Zhang, F.S. and Li, L. (2003) Using competitive and facilitative interactions in intercropping systems enhance crop productivity and nutrients-use efficiency. *Plant Soil*. 248: 305–312.

Zhang, H., Zeng, F., Zou, Z., Zhang, Z., and Li, Y. (2017) Nitrogen uptake and transfer in a soybean/maize intercropping system in the karst region of southwest China. *Ecology and Evolution*. 7: 8419-8426.

Zhang, Y., Liu, J., Zhang, J., Liu, H., Liu, S, Zhai, L, *et al.* (2015) Row ratios of intercropping maize and soybean can affect agronomic efficiency of the system and subsequent wheat. *PLoS ONE*. 10(6): e0129245.

Zomer, R.J., Trabucco, A., Coe, R. and Place, F. (2009) Trees on farm: analysis of global extent and geographical patterns of agroforestry. ICRAF Working Paper no. 89. Nairobi, Kenya: World Agroforestry Centre.

Zougmore, R., Kambou, F.N., Ouattara, K. and Guillobez, S. (2000) Sorghum-cowpea intercropping: An effective technique against runoff and soil erosion in the Sahel (Saria, Burkina Faso). *Arid Land Research and Management.* 14: 329-342.

Zoumana, K., Tatiana, K., Inamoud Ibny, Y., and Marc, N. (2012) Symbiotic potential and yields of cowpea (*Vigna unguiculata* L. Walp) and pearl millet (*Pennisetum glaucum* L.) in the Sudano-Sahelian zone of Mali. *International Journal of Agronomy*. [Online]. Available from: https://www.hindawi.com/journals/ija/2012/761391/cta/ [Date accessed: 16th November, 2017].

APPENDICES

Appendix 1. Long term meteorological weather conditions

Appendix 1.1: Long term monthly total precipitation (mm) 2005-2016 at the Royal Agricultural University

	Cropping seasons/years											
Months	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016
January	33.5	20.2	89.7	128.1	68.7	85.3	72.3	59.7	67.2	170.3	93.1	106.8
February	22.8	32.2	91.3	30.1	56.7	52.6	66.2	29.2	39.1	143.8	51.9	80.7
March	71.8	79.6	66.1	89.2	25.0	60.5	10.9	24.9	76.8	39.5	34.2	111.3
April	54.9	26.7	5.6	52.9	37.8	26.9	3.3	126.3	31.5	65.9	13.9	55.0
May	45.3	102.8	117.1	94.5	49.5	43.0	43.3	50.9	76.6	97.3	71.0	78.9
June	36.3	12.9	98.3	55.9	44.6	34.6	71.6	175.0	42.5	49.7	41.8	106.1
July	32.3	68.9	188.3	125.5	98.8	32.1	55.2	99.8	31.5	56.6	56.3	27.1
August	34.5	36.2	21.3	86.2	72.4	127.2	46.2	112.2	33.3	91.5	75.7	52.1
September	36.0	79.8	21.3	98.3	21.7	61.4	51.2	73.5	42.3	11.3	62.0	42.8
October	90.2	69.7	78.2	48.6	72.0	49.3	38.9	98.2	139.2	78.8	48.9	31.0
November	72.1	95.9	81.9	73.0	168.3	60.1	34.4	147.3	68.3	85.5	106.9	113.6
December	67.9	116.6	55.6	49.2	54.2	34.3	106.3	165.5	125.9	59.3	109.0	34.8

Appendix 1.2: Long term monthly mean air temperature (ºC) 2005-2016) at Royal Agricultural University

	Cropping seasons/years											
Months	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016
January	5.5	4.1	6.4	6.2	0.0	1.5	3.8	5.5	3.3	4.7	3.8	5.0
February	4.2	3.4	6.1	5.1	3.9	3.0	6.0	3.3	2.7	0.0	4.4	4.6
March	6.9	4.8	7.0	6.5	6.9	6.0	7.4	8.4	3.0	7.2	6.3	5.3
April	9.1	8.6	11.8	7.9	9.7	9.0	12.3	6.8	7.5	9.9	9.1	7.7
May	11.0	12.5	12.0	13.2	11.7	11.4	12.3	11.8	10.0	12.1	11.5	12.6
June	15.3	16.4	15.2	14.1	14.9	15.6	13.7	13.7	13.7	15.4	14.3	15.2
July	17.1	20.0	15.5	16.0	16.1	16.9	15.5	10.2	18.9	18.0	17.1	16.9
August	16.7	16.9	14.2	16.0	16.6	15.8	15.3	16.5	17.7	14.7	15.6	17.4
September	21.4	16.8	14.2	13.6	14.4	13.5	15.4	12.9	14.2	15.7	12.7	16.1
October	13.2	12.9	11.0	9.4	11.4	10.4	12.7	9.5	12.7	12.7	11.0	10.9
November	5.5	7.5	6.8	6.8	8.5	2.8	9.4	6.2	5.9	8.4	9.3	6.1
December	4.3	6.0	4.2	3.5	3.0	-0.2	5.4	4.6	5.4	4.8	9.5	5.6

Appendix 2: Spatial arrangements of wheat and beans in bi-cropping

Some materials have been removed due to 3rd party copyright. The unabridged version can be viewed in Lancester Library - Coventry University.

Every alternate *single row* meant for sowing beans was blocked with buckets. The wheat meant for those rows were harvested in the bucket.

1 row of wheat *against* 1 row of beans (1x1)

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Every alternate *two rows* meant for sowing beans was blocked with buckets. The wheat meant for those rows were harvested in the bucket.

2 rows of wheat *against* 2 rows of beans (2x2)

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Every alternate *three rows* meant for sowing beans was blocked with buckets. The wheat meant for those rows were harvested in the bucket.

3 rows of wheat *against* 3 rows of beans (3x3)

Some materials have been removed due to 3rd party copyright. The unabridged version can be viewed in Lancester Library - Coventry University.

Beans seeds were randomly hand sown in orderly drilled wheat rows.

Broadcast

Appendix 3: Crop growth stages

Appendix 3.1: Wheat growth stages description

Main stage	Description	Sub-stage
0	Germination	0.0-0.9
1	Main stem leaf production	1.0-1.9
2	Tiller production	2.0-2.9
3	Main stem production (stem elongation)	3.0-3.9
4	Booting	4.0-4.9
5	Heading	5.0-5.9
6	Anthesis	6.0-6.9
7	Grain milk stage	7.0-7.9
8	Grain dough stage	8.0-8.9
9	Ripening	9.0-9.9

Source: Zadoks *et al.* (1974)

Appendix 3.2: Faba bean growth stages

Growth stage	Code	Definition	Description
Germination and emergence	**000**	**Dry seed**	
	001	Imbibed seed	
	002	Radicle apparent	
	003	Plumule and radicle apparent	
	004	Emergence	
	005	First leaf unfolding	
	006	First leaf unfolded	
Vegetative stage	**Refer to main stem. Two small scale leaves appear first but the nodes where these occur are not recorded; only nodes where the leaf has unfolded are recorded**		
	101	First node	
	102	Second node	
	103	Third node	
	10x	X node	
	1n	N, last recorded node	
Reproductive stage	**Refer to main stem and first flower or first pod apparent at first fertile node (1). Stage for determinate cultivars there is an inflorescence at the terminal position as well as other racemes on the stem**		
Node	201(1)	Flower bud visible	(first buds visible and still green)
	203(1)	First open flowers	(first open flowers on first racemes)
	204(1)	First pod set	(first pods visible at first fertile node)
	205(1)	Pods fully formed, pods green	(pods fully formed but with small immature seed within)
	207(1)	Pod fill, pods green	
	209(1)	Seed rubbery, pods still pliable turning black	(seeds at maximum size fill the pod cavity)
	2010(1)	Seed dry and hard, pods dry and black	
Senescence	**Pod senescence and seed ripening refer to the whole plant**		
	301	10% pods dry and black	
	305	50% pods dry and black 80% pods dry and black, some upper pods green	
	308	80% pods dry and black, some upper pods green	
	309	90% pods dry and black, most seed dry	
	310	All pods dry and black and seeds hard	
Stem senescence	**refer to the whole plant**		
	401	10% pods dry and black	
	401	10% stem brown/black (or most stem green)	
	405	50% stem brown/black (or 50% stem green)	
	409	90% stem brown/black (or 10% stem green)	
	410	All stems brown/black; all pods dry and black; seed dry	

Source: PGRO (2015)

Appendix 4: Soil textural triangle

Some materials have been removed due to 3rd party copyright. The unabridged version can be viewed in Lancester Library - Coventry University.

Source: http://www.landis.org.uk/services/tools.cfm

Appendix 5: The combined analysis of variance

Appendix 5.1: The combined analysis of variance for growth and performance of wheat/bean bi-cropping system influenced by seasons, cropping systems, drilling patterns, bean cultivars and their interaction over two years (2015 and 2016)

		Mean squares							
Source of	Degrees of				Plant heights		Weeds		
variation	Freedom	CCI	LAI	IPAR	Wheat	Bean	WSE	DM	N uptake
CS	1	4937.5^{***}	2.7073^{***}	2501.08^{***}	532.73^{***}	851.86^{***}	-	43.1817^{***}	11.5389^{***}
DP	3	678.5^{***}	6.4482^{***}	2311.18^{***}	202.32^{***}	3234.27^{***}	502.6^{**}	7.383^{***}	1.8035^{***}
B	1	7.1^{ns}	8.6124^{***}	515.63^{***}	3.42^{ns}	153.17^{*}	17.9^{ns}	4.7007^{***}	1.4485^{***}
Y	1	820.7^{***}	95.6360^{***}	7183.79^{***}	4296.83^{***}	15113.32^{***}	1583.1^{***}	0.5299^{ns}	0.0042^{ns}
DP x B	2	10.6^{**}	0.1163^{ns}	46.66^{*}	9.13^{ns}	25.48^{ns}	28.1^{ns}	0.1766^{ns}	0.0628^{ns}
DP x Y	3	11.3^{*}	0.6480^{**}	163.58^{***}	99.60^{**}	457.41^{***}	77.2^{*}	1.1838^{*}	0.3396^{*}
B x Y	1	4.6^{ns}	1.7357^{***}	305.67^{***}	18.17^{ns}	55.47^{ns}	2.5^{ns}	0.1698^{ns}	0.447^{ns}
DP x B x Y	3	4.1^{ns}	0.2130^{ns}	144.50^{***}	27.72^{ns}	74.89^{ns}	90.6^{ns}	0.1770^{ns}	0.0721^{ns}

, **, and * show significant differences at $P< 0.05$, $P< 0.01$, and $P< 0.001$ respectively; ns=No significant differences at $P>0.05$); CS, cropping systems; DP, drilling patterns; B, bean cultivars; Y, years (cropping season); LAI, leaf area index; IPAR,. Intercepted Photosynthetic Active Radiation; WSE, weed smothering efficiency; DM, dry matter; N, nitrogen; CCI, chlorophyll concentration index; LER, land equivalent ratio*

Appendix 5.2: The combined analysis of variance for growth and performance of wheat/bean bi-cropping system influenced by seasons, cropping systems, drilling patterns, bean cultivars and their interaction over two years (2015 and 2016).

		Mean squares						
Source of variation	Degrees of Freedom	Wheat grain yield	Wheat straw yield	Wheat HI	Bean seed yield	Bean straw yield	Bean seed HI	LER
CS	1	27.49^{***}	38.11^{***}	7.86^{ns}	27.89^{***}	79.24^{***}	716.02^{**}	-
DP	3	0.319^{ns}	2.3^{ns}	42.94^{*}	1.77^{***}	1.94^{***}	70.73^{ns}	0.058^{ns}
B	1	0.747^{ns}	0.115^{ns}	8.18^{ns}	0.114^{ns}	0.257^{ns}	9.67^{ns}	0.061^{ns}
Y	1	13.09^{***}	30.39^{***}	895.76^{***}	8.65^{***}	55.63^{***}	2734.45^{***}	2.816^{***}
DP x B	2	0.106^{ns}	0.208^{ns}	7.03^{ns}	0.124^{ns}	0.088^{ns}	113.72^{ns}	0.050^{*}
DP x Y	3	0.229^{ns}	1.006^{ns}	7.21^{ns}	0.065^{ns}	0.906^{ns}	57.11^{ns}	0.152^{ns}
B x Y	1	0.007^{ns}	0.0193^{ns}	33.95^{ns}	0.196^{ns}	0.998^{*}	57.83^{ns}	0.003^{ns}
DP x B x Y	3	0.137^{ns}	0.142^{ns}	20.28^{ns}	0.201^{ns}	0.595^{ns}	114.76^{ns}	0.066^{ns}

, **, and * show significant differences at P< 0.05, P< 0.01, and P< 0.001 respectively; ns= No significant differences at P>0.05); CS, cropping systems; DP, drilling patterns; B, bean cultivars; Y, years (cropping season); HI, harvest index; LER, Land equivalent ratio.*

Appendix 5.3: The combined analysis of variance for growth and performance of wheat/bean bi-cropping system influenced by seasons, cropping systems, drilling patterns, bean cultivars and their interaction over two years (2015 and 2016).

		Mean squares				
Source of variation	Degrees of Freedom	Wheat grain CP	Wheat straw CP	Wheat grain N yield	Wheat straw N yield	Wheat N yield HI
CS	1	3135.5^{***}	460.7^{***}	42458.0^{***}	4515.1^{***}	7.97^{ns}
DP	3	174.7^{ns}	14.7^{ns}	924.0^{ns}	328.4^{ns}	24.22^{ns}
B	1	361.7^{ns}	16.2^{ns}	6.0^{ns}	114.6^{ns}	1.17^{ns}
Y	1	14562.1^{***}	1773.1^{***}	60378.0^{***}	27186.9^{***}	770.38^{***}
DP x B	2	30.8^{ns}	36.36^{ns}	2384.0^{ns}	11.1^{ns}	23.93^{ns}
DP x Y	3	103.5^{ns}	14.92^{ns}	3281.0^{ns}	500.6^{ns}	31.81^{ns}
B x Y	1	333.9^{ns}	92.6^{ns}	290.0^{ns}	120.1^{ns}	6.21^{ns}
DP x B x Y	3	121.0^{ns}	16.7^{ns}	1821.0^{ns}	695.0^{ns}	10.96^{ns}

, **, and * show significant differences at P< 0.05, P< 0.01, and P< 0.001 respectively; ns=No significant differences at P>0.05); CS, cropping systems; DP, drilling patterns; B, bean cultivars; Y, years (cropping season); CP, crude protein; HI, Harvest Index.*

Appendix 5.4: The combined analysis of variance for growth and performance of wheat/bean bi-cropping system influenced by seasons, cropping systems, drilling patterns, bean cultivars and their interaction over two years (2015 and 2016).

		Mean squares				
Source of variation	Degrees of Freedom	Bean Grain CP	Bean Straw CP	Bean seed N yield	Bean straw N yield	Bean N yield HI
CS	1	72.0^{ns}	19.38^{ns}	1016579.0^{***}	65669.6^{***}	416.2^{**}
DP	3	43.9^{ns}	58.74^{ns}	64335.0^{***}	1508.8^{*}	5.7^{ns}
B	1	1504.9^{**}	90.83^{ns}	10487.0^{ns}	240.8^{ns}	1.2^{ns}
Y	1	254.5^{ns}	14652.52^{***}	325680.0^{***}	7049.9^{***}	643.1^{***}
DP x B	2	386.3^{ns}	70.03^{ns}	5867^{ns}	89.5^{ns}	34.0^{ns}
DP x Y	3	395.4^{ns}	178.65^{ns}	1508^{ns}	209.7^{ns}	29.3^{ns}
B x Y	1	918.2^{*}	181.28^{ns}	8442^{ns}	486.9^{ns}	1.1^{ns}
DP x B x Y	3	53.9^{ns}	145.73^{ns}	8943^{ns}	629.0^{ns}	19.3^{ns}

, **, and * show significant differences at P< 0.05, P< 0.01, and P< 0.001 respectively; ns=No significant differences at P>0.05); CS, cropping systems; DP, drilling patterns; B, bean cultivars; Y, years (cropping season); CP, crude protein; HI, Harvest Index.*

Appendix 5.5: The combined analysis of variance for growth and performance of wheat/bean bi-cropping system influenced by seasons, cropping systems, drilling patterns, bean cultivars and their interaction over two years (2015 and 2016).

		Mean squares						
Source of variation	Degrees of Freedom	Wheat grain N uptake	Wheat straw N uptake	Wheat N HI	Bean seed N uptake	Bean straw N uptake	Bean N HI	Emissions savings (kg CO_2e ha^{-1})
CS	1	236.14***	3310.66***	1515.12***	27012.7***	2129.40***	603.11***	1539ns
DP	3	3.84ns	19.51ns	24.48ns	2031.4***	52.87**	10.95ns	6176ns
B	1	27.14ns	2.12ns	23.90ns	153.9ns	2.41ns	1.49ns	11132ns
Y	1	90.83**	4699.80***	4257.09***	9495.1***	178.62***	763.53***	1393ns
DP x B	2	9.85ns	18.85ns	33.37ns	75.5ns	3.46ns	34.17ns	4080ns
DP x Y	3	71.30ns	26.85ns	10.68ns	160.4ns	4.58ns	29.35ns	2899ns
B x Y	1	0.05ns	3.07**	3.27ns	497.5ns	32.09ns	18.8ns	19418ns
DP x B x Y	3	9.42ns	12.08ns	8.08ns	352.1ns	15.16ns	13.57ns	13052ns

, **, and * show significant differences at P< 0.05, P< 0.01, and P< 0.001 respectively; ns=No significant differences at P>0.05); CS, cropping systems; DP, drilling patterns; B, bean cultivars; Y, years (cropping season); N, nitrogen; N HI, Nitrogen uptake harvest Index.*

Appendix 6.1: The positive and negative contribution of drilling patterns on bi-cropping performance.

Drilling patterns	Positive/strength	Negative/weakness
1 x 1	Physical root intermingling advantage can help to enhance direct N transfer from the donor bi-crop (beans) to recipient bi-crop (wheat) under optimum soil water conditions as evidenced by increased CCI and wheat N uptake.	Prone to serious interspecific competition when edaphic based resources such as water is limited as in 2015 season resulting in reduced plant height & IPAR. It also influenced thinner and smaller nodule sizes.
	Close proximity of bi-crop roots can help to stimulate the bean to improve biological N fixation due to greater exploitation of soil mineral N by wheat than bean in mixture as evidenced by wheat N uptake.	It is vulnerable to wide-spread of fungal bean diseases such as Faba bean rust (*Uromyces viciae-fabae*) and Ascochyta blight (*Ascochyta fabae***)** due to closer proximity of bean bi-crop plants.
	Close proximity of bi-crops resulted in higher light interception and improved weed control. *All alternate rows treatments* provided uniform seed sowing depth, 100% seed germination, and uniform utilisation of resources by bi-crops, easier and faster harvesting with mechanisation.	Under soil water stress conditions crop growth and development was limited as in 2015 season while under optimum soil water conditions crop growth and development improved as in 2016 season. *All alternate rows spatial arrangements* are time consuming during drilling except if the right equipment such as a one pass seeder is used.
2 x 2	Promoted spatial interspecific complementarity on resource-use efficiency hence; improved spatial root distribution, root nodules sizes and land & forage productivity.	-
	Interspecific complementarity improved other associated ecological services such as weed, insects' pests and diseases control.	
3 x 3	It is a type of crop diversification in space for sustainable crop intensification.	It is associated with interspecific competition which reduced reduce leaf size, IPAR and weed control under soil water stress conditions as in 2015 season. It can also reduce root nodule sizes and affect plant performance.
	-	When soil water is not limiting as in 2016 season, overcrowded and vigorous growth of bi-crop plants competed for light which resulted in the alteration of leaf architecture hence; reduced light interception, weed control efficiency and bi-cropping system productivity.
Broadcast	It is a type of crop diversification in space for sustainable crop intensification. It is relatively less cost effective and time saving.	Germination up to 100% of the bean bi-crops is not attainable compared to the wheat bi-crops because the bean seeds are not placed at the desired soil depth; use of mechanisation for field operations such has combined harvesting is sometimes difficult; poor total ground canopy cover, poor light interception & high weed seed returns.

Appendix 6.2: The impact of the bean cultivars on assessed parameters

	Bean cultivars	
Outcome factor	**Maris Bead**	**Fuego**
Seed size	Small	Large
Seed establishment	Good seed establishment in all weather conditions.	Good seed establishment, except under water stress conditions.
Growth rate	Relatively slower.	Relatively faster.
Root type	Tap root system.	Superficial root system.
Leaf type	Planophile.	Erectophile.
Leaf Area Index	Relatively lower due to increased mutual shading (Table 6.2).	Relatively high due to reduced mutual shading (Table 6.2).
Plant height	Relatively taller. (Table 3.2 & 6.5).	Relatively shorter. (Table 3.2 & 6.5).
Weed smothering (Weed control)	Effective during early part of growth cycle (Table 6.6b).	Effective throughout the growth cycle (Table 6.6b).
Pest and disease control Black bean aphids *(Aphis fabae*) and Faba bean rust (*Uromyces viciae-fabae*) and Ascochyta blight (*Ascochyta fabae*)	Tolerant (Tables 4.13; 4.14 & 5.13).	Susceptible (Tables 4.13; 4.14 & 5.13).
Legume yield (t ha^{-1})	Low (Table 3.2).	High (Table 3.2).
Protein (%)	High (Table 3.2).	Low (Table 3.2).

Appendix 7.1: Faba bean rust (*Uromyces viciae-fabae)* disease situation in 2016 cropping season.

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Faba bean rust (*Uromyces viciae-fabae)*

Appendix 8: Seed germination test

Appendix 8.1. Seed germination counts and calculations (%) for wheat and beans at the Royal Agricultural University Laboratory.

Spring crop	Crop type	Total seed planted	First germination count				Second germination count				Mean total germination	Germination (%)
			Replicates				Replicates					
			1	2	3	4	1	2	3	4		
Paragon wheat	Cereal	25	24	24	25	24	25	25	24	24	24.5	98.0
Fuego	legume	20	19	18	20	16	20	18	19	19	19.0	95.0
Maris Bead	legume	20	19	19	19	19	20	20	19	19	19.5	97.5

Appendix 8.2: Seed germination results for Maris Bead

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Appendix 8.3: Seed germination results for Fuego

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Appendix 8.4: Seed germination results for Paragon wheat

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