OPTIMISING CANOPY SIZE AND STRUCTURE IN FIELD BEANS (*VICIA FABA*) GROWN IN A TEMPERATE CLIMATE

Leona Murphy, B.Sc.

Thesis submitted to the University of Nottingham in
partial fulfilment for the degree of Doctor of Philosophy

FEBRUARY 2021
Division of Plant and Crop Sciences
School of Biosciences, University of Nottingham

Abstract

Field beans are an up-and-coming crop in Irish agriculture, helping to reduce imports of feed protein and encouraging a home-grown source for cattle feed. Since the introduction of the protein grant in 2015 as part of the Common Agricultural Policy (CAP) greening scheme, the area of field beans sown in Ireland has increased rapidly. However, due to their unpredictable year on year variation in yield, field beans have not yet reached their full potential in Irish agriculture. A better understanding of their growth and development as well as management of the crop for full yield potential is essential to encourage growers to avail of the added benefits of having field beans in their crop rotations.

This thesis outlines research which aimed to develop a better understanding of the agronomy and physiology of field beans in the temperate Irish climate, to gather information and create advice for Irish growers on the best way to grow and manage field beans. This was achieved through three years of field experiments from 2017-2019, where different sowing dates, seed rates and varieties were used to vary the canopy size. Through this canopy manipulation, the variation in leaf green area, pods per unit area and seeds per unit area was evaluated in order to identify the key components of yield in field beans.

Throughout this research, several parameters were studied. This thesis outlines the results of this study on the effect of sowing date, seed rate and variety on the growth and development of the field bean crop in a temperate climate. The results of this study found that even though field beans show great variability in yield from year to year, with the correct sowing conditions and management, they have the potential to produce high yields in the Irish climate. Using a broad range of seed rates from 10 – 80 seeds per square metre over six sowing dates, the response of field bean yield to these factors could be thoroughly studied over three years. In 2017, yield in this study was found to be 6.2 t ha^{-1}, which was close to the national average yield for field beans of 6.7 t ha^{-1} (Teagasc, 2018). Yield was found to be the lowest in 2018 when it dropped to 2.5 t ha^{-1} due to lower-than-average rainfall from pre-flowering to harvest.

The October sowing date generally yielded highest for the winter sown treatments and February/March for the spring sown treatments, coinciding with the current recommendations for sowing field beans in Ireland by the Department of Agriculture, Food and Marine (DAFM). However, with the variation found in crop establishment over the three years of study, yield was examined and presented against plant populations instead of seed rate. The general trend showed that as plant populations increased, yield increased. This led to the study of the economic plant population in field beans for Ireland, which we believe to be the first to report. The economic plant population for the spring variety was between 24 – 38 plants per square metre and 13 plants per square metre for the winter variety. This study concluded that yield and profit will not improve by sowing at higher plant densities.

Further study into the components of yield in field beans found a strong relationship between pod number and final yield. It was generally found that pod number closely related to the Green Area Index (GAI) of the crop during the pod development phase of growth, which led to the hypothesis that light interception during the pod development phase determined pod number and thereby yield. A supplementary experiment was carried out to support this, where shades were erected over the plots, reducing the intercepted radiation by c.60%. This found that when light was reduced during the reproductive phase, there was a 27% yield reduction, resulting from a 38% reduction in pod number. With green area strongly relating to pod number per square metre, it can be concluded that radiation intercepted during the reproductive phase is crucial for the determination of pod number which in turn is a driving factor in final yield of field beans.

Crops like cereals and oilseeds have been studied to determine management strategies for fertilisers and spray treatments throughout the season. Field beans are a relatively new, up and coming crop in Irish agriculture and the knowledge behind field bean management in Ireland is being trialled. This study found that green area in field beans is strongly related to leaf fresh biomass. From this, we hypothesised that leaf fresh biomass can be used as a predictor of GAI and in turn be used by growers as a tool in canopy and overall crop management throughout the season. A model was created using the relationship between leaf green area and leaf fresh biomass, resulting in the equation $y = 0.0021x – 0.0734$. Using an independent field bean data set and the equation from the model, results showed a strong correlation between measured leaf green area and predicted leaf green area with an $R^2 = 0.92$ and RMSE of 0.38.

The greater understanding of yield components and the driver of final yield in field beans will lead to further studies in this area and a greater understanding of this potentially high yielding crop in temperate climates. Overall, the findings in this thesis

are a foundation for further research in field beans and other protein crops in Irish agriculture.

Acknowledgements

I would firstly like to acknowledge Teagasc, The Walsh Scholarship Programme and the Irish Farmers Association for providing the funding and facilities needed to complete this project.

I would like to sincerely thank Prof. Debbie Sparkes, for her dedication to this project and constant support. Without her encouragement and motivation, I never would have gotten this far. I would also like to thank my Teagasc supervisors, Dr. Sheila Alves and Mr. John Spink, for their continual support, help and advice throughout the entirety of the project.

To all the Teagasc Oak Park admin staff, research staff and farm staff, thank you for all your help throughout the years. A big thanks to all the bean technicians that have helped me do my field work and process endless samples. A special thanks must be given to Kevin Murphy and Frank Ryan for their constant support, helping whatever way they could in my field trials and throughout the sampling season. I would not have gotten any of the field work done without you!

Many thanks must be given to all the summer interns that have been a huge part of the Bean Team:

2016/2017: Margaux, Marion, Tiphaine, Benjamin, Henri, Remi

2017/2018: Guillaume, Lucie, Simon, Leáne, Thomas

2018/2019: Jean, Paul D, Paul P, Charlene, Amelie, Samantha, Margot

To all the friends I have made along the way, Niamh, Katie, Tomás, David, Tara, Muireann, Robyn, Aisling, Keith, and Conor. I would not have made it through some days without you all! Our morning meetings, game nights, Zoom quizzes and endless laughs got me through this PhD!

To my boyfriend, Cormac, thank you for keeping me sane throughout the last year, and motivating me to keep going. Your constant love and support is truly appreciated.

Finally, I would like to thank my parents, Martin and Bernadette and my sister, Rebecca for their continuous support and love for me. I would not have had the opportunities I’ve had in life or be where I am today without you.

Table of Contents

Chapter 1

Chapter 2

Chapter 3

Chapter 4

Chapter 5

List of Abbreviations

Abbreviation	**Full form**
°C	Degree Celsius
ANOVA	Analysis of Variance
c.	Circa
CAP	Common Agricultural Policy
cm	centimetre
CSO	Central Statistics Office
cv.	Cultivar
DAFM	Department of Agriculture, Food and Marine
DAS	Days after sowing
et al.	et alia
FAO	Food and Agriculture Organisation of the United Nations
Fig.	Figure
g	gram
GAI	Green area index
GS	Growth stage
ha	Hectare
LAI	Leaf area index
LSD	Least Significant Difference
m	metre
mJ	millijoules
mm	millimetre
N	Nitrogen

PAR	Photo-synthetically active radiation
PGRO	Processors and Growers Research Organisation
PPD	Plant Population Density
R^2	Coefficient of Determination
RMSE	Root Square Mean Error
SR	Seed rate
t	tonne
TGW	Thousand grain weight
TOS	Time of sowing

List of Tables

Chapter 1- General introduction and Literature review

Chapter 2 – Yield response of field beans (Vicia faba) to plant population and sowing date in a temperate climate.

Chapter 3 - Yield of field beans (Vicia faba) is determined by light interception during the pod development phase

List of Figures

Chapter 1 – General introduction and Literature review

Chapter 2 - Yield response of field beans (Vicia faba) to plant population and sowing date in a temperate climate.

Chapter 3 - Yield of field beans (Vicia faba) is determined by light interception during the pod development phase

Chapter 4 - Predicting Green Area Index (GAI) from leaf biomass in field beans (*Vicia faba*)

Chapter 1

General introduction & Literature review

1. General introduction

Field beans (*Vicia faba*) or more commonly known as faba beans or broad beans are part of the family of grain legumes, *Leguminosae*. They are cultivated and used as a major source of protein in both human and animal diets with an estimated protein content of 25-35% dry matter (Nachi and Le Guen, 1996). The field bean originated in western Asia and spread through to central Europe, where it constituted a great part of the European diet before the introduction of potatoes and were the only edible bean known in Europe before the voyages of Columbus to America in 1492. By the 16th century, field beans were introduced to America by the Spaniards and made it as far as Australia by the 20th century (Cubero, 2011). At present, beans and other dry pulses only constitute 1.2% of arable land in Europe (FAO, 2018), with France being the largest producer of dried pulses followed by the United Kingdom and Poland (FAO, 2018).

One of the notable characteristics of field beans is the unpredictable variation in seed yield from year to year, despite sufficient control of pests and diseases (McEwen et al., 1981, Reckling et al., 2018). European farmers consider these crops to be risky because their yields vary more compared to non-leguminous crops such as cereals (Cernay et al., 2015). Additionally, and despite a significant increase of published studies on field bean breeding over the last decade, evaluated by Scopus search engine (20 articles/year), the overall breeding effort with respect to field beans was still rather limited, compared to cereal crops breeding, such as wheat (749 articles/year), and barley (179 articles/year), and even to other legumes, such as soybean breeding (238 articles/year) over the same period.

Field beans are a relative newcomer in the Irish commercial market. With the introduction of the protein grant in 2015 as part of the Common Agricultural Policy (CAP) greening measures, to encourage the addition of protein crops in cereal crop rotations, the area of beans sown in Ireland has increased rapidly from c.3,500 ha in 2014 to its highest of c.12,000 ha in 2017 (Figure 1) (CSO, 2020). As a legume that is high in protein, field beans have the potential to reduce imports, encourage home grown protein for animal feed and add residual nitrogen into the soil which benefits the following crop (Mwanamwenge et al., 1998). However, a major concern with field beans in the Irish climate is yield stability. Field beans have the potential to produce high yields but low temporal yield stability is a major downside for this crop and a disincentive for growers (Sprent et al., 1977). The addition of field beans and other legumes such as the field pea (*Pisum sativum*) and lupin (*Lupinus sp.*) could have numerous agronomic advantages for growers, such as weed control, residual nitrogen in the soil for the following crop, as well as the benefits of a deep rooting break crop, if they were grown more widely in cereal crop rotations.

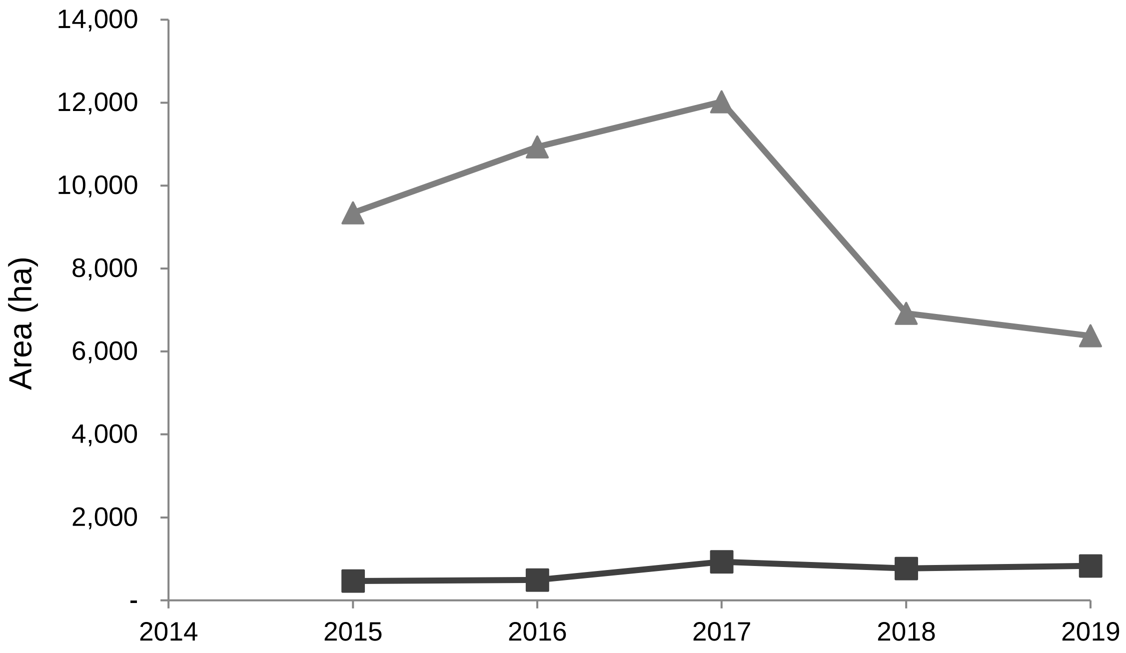


Figure 1. Spring (▲) and winter (■) bean area (ha) sown in Ireland from 2015 to 2019. Data sourced from the Central Statistics Office, Ireland.

2. Crop physiology

Egli (2010) defined crop physiology as the plant processes that are responsible for growth, development, and economic yield. All crops advance through a series of well-defined developmental stages, commonly known as growth stages (GS), and field beans are no exception. Growth stages have been well defined in most crops, from germination through to ripening, establishing a universal decimal code system to track the growth of the developing crops (Lancashire et al., 1991, Meier et al., 2009, Zadoks et al., 1974).

2.1 Emergence and establishment

Germination, initial growth, and development of the field bean crop is mainly driven by temperature, more importantly, daytime temperature (Dantuma and Thompson, 1983). This requirement depends on the cultivar. Low temperatures over the winter period from autumn sowings may prompt seedling mortality if the choice of cultivar is not winter hardy (López-Bellido et al., 2005).

Another factor that has an impact on emergence and establishment is seeding rate. Loss et al. (1998a) describe how, in the Mediterranean climate of South-western Australia, there is a slight trend that shows greater mortality rates at higher plant densities. Aguilera-Diaz and Recalde-Manrique (1995) state that seed proximity is the crucial factor for emergence and establishment. Close seed proximity, coinciding with other factors such sowing conditions, water availability and air temperature can lead to a decrease in germination rate. Once plants are emerged, higher planting densities, or reduction in row spacing can lead to increased competition between plant and a greater mortality rate (Pilbeam et al., 1990).

2.2 Vegetative growth

Growth depends on the crop’s ability to capture light and the efficiency of the crop to convert this energy into biomass. Early stages of vegetative growth have shown that there is a linear correlation between dry matter and the number of plants per square metre (López-Bellido et al., 2005). Depending on plant density, competition arises between plants for light and nutrients, affecting the growth, development, and production of each plant (Dantuma and Thompson, 1983, López-Bellido et al., 2005).

Studies have shown that field bean output is regulated by a number of compensatory factors, some of which are fixed in the vegetative stage such as number of plants per square metre and number of stems per plant (López-Bellido et al., 2005).

The length of the vegetative phase, that varies with weather conditions and day length, influence the compensatory capacity of field beans (López-Bellido et al., 2005). In longer growing seasons, with optimum conditions for growth, lower plant densities have been found to compensate effectively by developing a greater number of branches than higher plant densities. Sowing date can also affect the duration of the vegetative phase, and the growing season can be prolonged by earlier sowing, thereby providing more time for compensatory growth. Marcellos and Constable (1986) found that in Mediterranean conditions, early autumn sowings prolonged the growing season compared to later sowings which resulted in a larger crop and higher yields. They also showed that if sowing was delayed, grain yield, plant dry matter and the pod filling duration was reduced. Late sowing was found to also reduce the height of the first pod above ground, and increased the likelihood of yield loss through foliar disease (Marcellos and Constable, 1986).

2.3 Reproductive phase and pod development

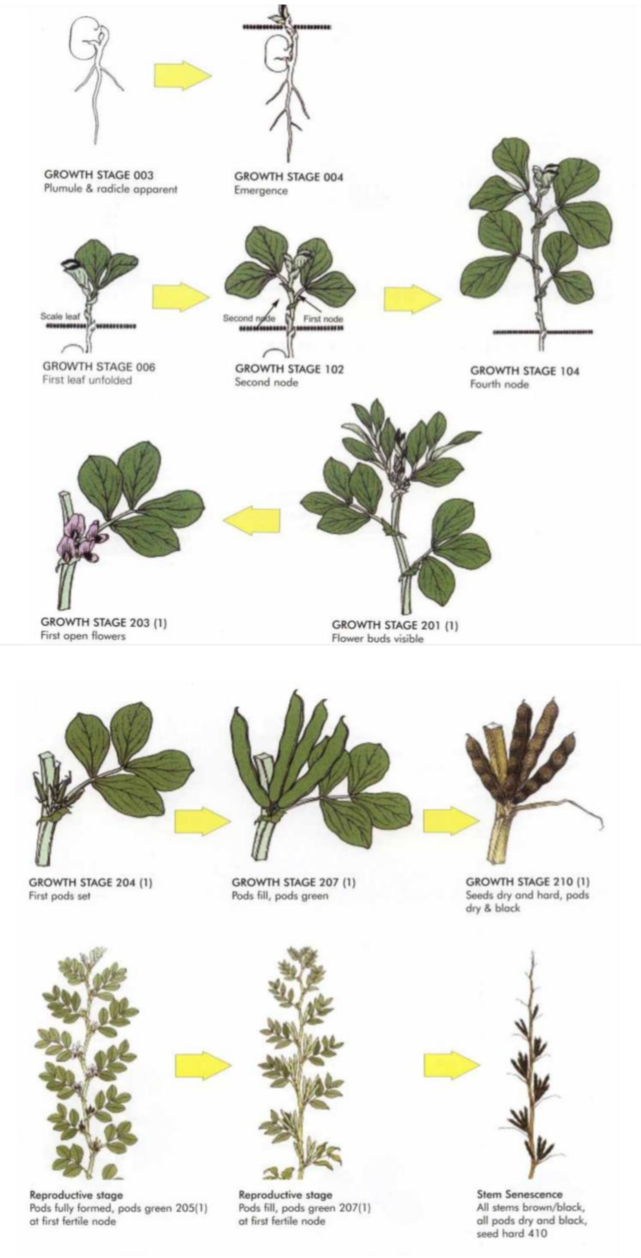


Figure 2. Stages of development for field beans (BBCH scale). Source: PGRO, UK

Aguilera Díaz (1987) as cited by López-Bellido et al. (2005) state that the reproductive phase in field beans involves the establishment of the number of podding nodes per stem, number of pods per podding node, number of seeds per pod and mean seed weight, which together with the fixed elements of the vegetative phase form crop yield. Crops sown in autumn have long flowering, pod development and pod filling phases (Adisarwanto and Knight, 1997). Field beans are considered to be either a day-neutral crop; that is they flower irrespective of the length of the period of light they are exposed to or a long-day crop meaning that they need 12 or more hours of light to produce flowers (Savonen, 2003). Losses in flowers and pods occur throughout the reproductive phase, due to inter-plant competition, especially at higher plant densities (Amato et al., 1992), the amount of insect pollination or self-pollination that occurs (Bishop et al., 2020), and extreme weather conditions such as excessive rainfall and drought (Kulig et al., 2011).

2.4 Pod set and pod filling

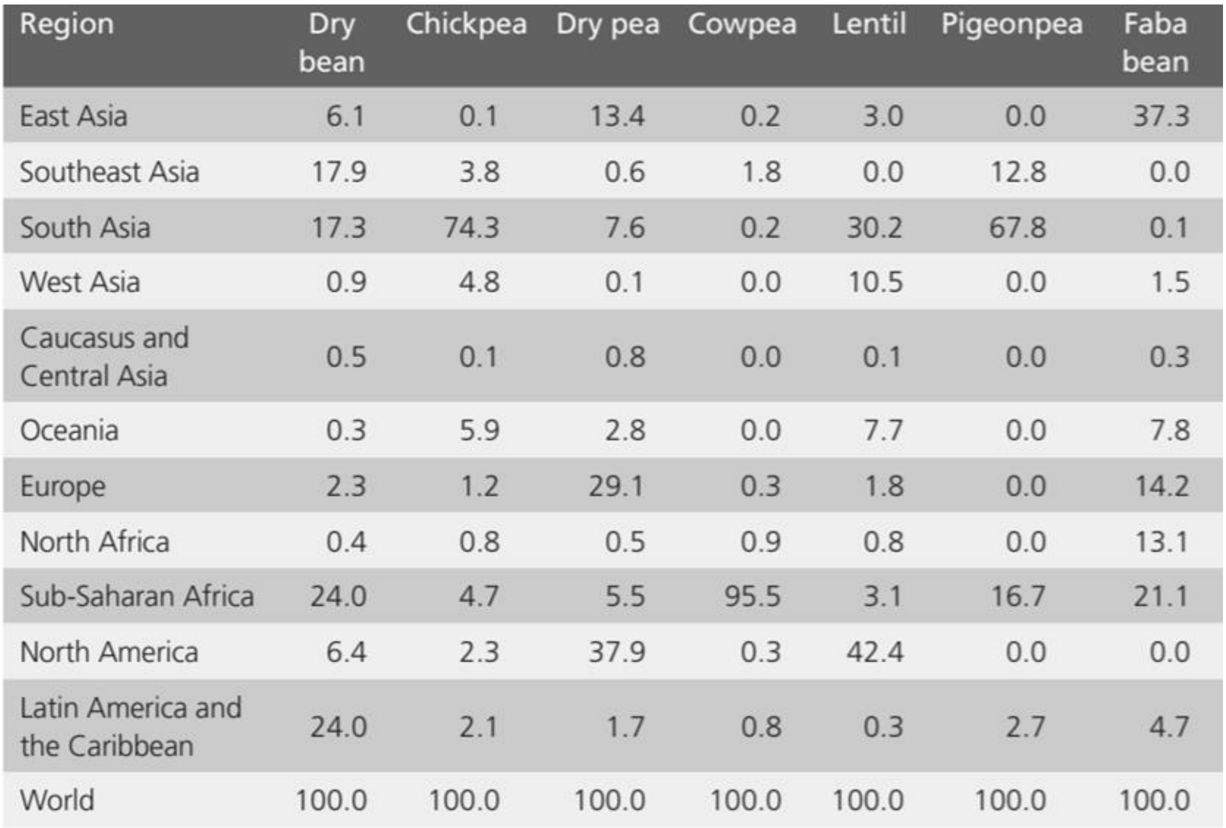
Crop density affects the number of pods per podding node and number of pods per plant. Plant density also modifies the source-sink ratio, altering intra-plant competition for assimilates (Pilbeam et al., 1991b). As plant density increases, a decrease was found in the number of active nodes per plant (Hodgson and Blackman, 1956), leading to a decrease in the number of flowers per plant and in turn the number of pods per plant. Loss of podding nodes has been found to take place uniformly over all reproductive stems, and therefore there will be a greater number of podding nodes per plant at lower plant densities (López-Bellido et al., 2005).

Pod set is possibly a function of the growth rate during flowering (Stützel and Aufhammer, 1992). Choice of cultivar is generally the determining factor in seed filling, seed size and final grain weight (López-Bellido et al., 2005). However, Dantuma and Thompson (1983) suggest that seeds per pod and seed size are relatively stable yield components and not visibly affected by competition between plants for light, water and other nutrients. They regard these components as the most stable in field bean crops, even though they also found that the number of seeds per pod varied considerably in the same plant. Water availability and environmental factors after flowering are the most influential factors for pod setting and filling.

Dantuma and Thompson (1983) propose that flower budding takes priority over assimilate supply in early pod development phase. However, this is contradicted by Baker et al. (1984) who suggest that vegetative growth does not affect the amount of assimilate available to reproductive sinks. Early competition for assimilates may account for the high level of flower and pod abortion in field bean crops, however, this has not been sufficiently studied.

López-Bellido et al. (2005) found that little is known about the growth and development of field beans. As the second most widely grown grain legume in the EU after peas (*Pisum sativum*), field beans are currently underrepresented in European agriculture, with grain legumes produced on only 1.5% of the arable land in Europe compared with 14.5% worldwide (Watson et al., 2017) (FAO, 2019; Table 1). Further studies and research in this area would be valuable for growers across Europe.

Table 1. Share of different regions of the world in production of major pulses (%), 2012–14, taken from FAO “The Global Economy of Pulses”, 2019.



Region	Dry bean	Chickpea	Dry pea	Cowpea	Lentil	Pigeonpea	Faba bean
East Asia	6.1	0.1	13.4	0.2	3.0	0.0	37.3
Southeast Asia	17.9	3.8	0.6	1.8	0.0	12.8	0.0
South Asia	17.3	74.3	7.6	0.2	30.2	67.8	0.1
West Asia	0.9	4.8	0.1	0.0	10.5	0.0	1.5
Caucasus and Central Asia	0.5	0.1	0.8	0.0	0.1	0.0	0.3
Oceania	0.3	5.9	2.8	0.0	7.7	0.0	7.8
Europe	2.3	1.2	29.1	0.3	1.8	0.0	14.2
North Africa	0.4	0.8	0.5	0.9	0.8	0.0	13.1
Sub-Saharan Africa	24.0	4.7	5.5	95.5	3.1	16.7	21.1
North America	6.4	2.3	37.9	0.3	42.4	0.0	0.0
Latin America and the Caribbean	24.0	2.1	1.7	0.8	0.3	2.7	4.7
World	100.0	100.0	100.0	100.0	100.0	100.0	100.0

3. Canopy structure

3.1 Canopy management

The size and structure of a crop’s canopy is important for maximising the amount of light intercepted to produce and utilise assimilates efficiently throughout its life cycle. Extensive research has been carried out on crops such as wheat and oilseed rape to examine yield potential through optimising canopy size (Scott et al., 1999, Sylvester-Bradley et al., 2000). By managing the canopy through adjusting N fertiliser, smaller, more efficient canopies can be grown that avoids the production of excess leaf area, which can lead to poor penetration of light to the lower parts of the plant, resulting in severe mutual shading, pod and seed abortion, and low, variable yields (Long et al., 2006, Scott et al., 1999). Reducing the size of the canopy and stunting growth of the plants also leads to reduced lodging of the crop.

In oilseed rape, an optimum canopy size during seed filling is estimated to be 3.5 units of green area (Berry and Spink, 2006, Roques and Berry, 2016). Scott et al. (1999) found that when the crop canopy was restricted to a GAI of 3 during early seed filling, yield improved by 0.4 t ha^{-1}. Canopy management in wheat has been found to be slightly different. This approach is based on the understanding that yield in wheat is formed later in the growth cycle than in oilseed rape. The optimum canopy size in wheat starts by managing the seeding rate and then managing shoot production through the adjustment of N fertiliser, giving an optimum canopy size of 6 units of green area (Sylvester-Bradley et al., 2000).

Nitrogen (N) application plays a huge role in canopy manipulation in non-leguminous crops; however, this is not the case for field beans. As a nitrogen fixing crop, further application of N to beans has been found to make no significant difference to final yield of the crop, in fact, it is known that application of N fertiliser to legumes decreases nodulation and the nitrogen fixing rate (Dean and Clark, 1980, McEwen, 1970). The easiest way to manipulate the size and structure of a bean crop’s canopy is through seeding rate. Low seed rates can produce a sparse canopy that could possibly compensate by branching to fill in the area around the plants. A higher crop density leads to quicker canopy closure and optimum interception of light by the canopy. Too high a seed rate can lead to a dense canopy causing shading of the lower leaves, high disease pressure, and a taller crop which can possibly lead to lodging (Loss et al., 1998b). Studies on field beans in southern Italy found that c.30% of plants lodged at a seeding rate of 30 plants per square metre compared to 90% of plants lodging at the higher seed rate of 100 plants per square metre (Stringi et al., 1986). Finding the optimum seeding rate when sowing field beans will lead to a more productive crop canopy, maximising the amount of radiation intercepted by the crop and reducing the risk of lodging.

3.2 Photosynthesis

Solar radiation has a range of wavelengths from infrared to ultraviolet. Light is essential for driving crop growth, biomass production and yield. Crops are very efficient at absorbing light energy. This energy is essential for fundamental physiological processes such as photosynthesis. Within the range of wavelengths in solar radiation is a designated spectral range that can be used by photosynthetic organisms. This is known as photo-synthetically active radiation (PAR) and is the light that is visible to the human eye, ranging from 400 – 700 nanometres (Lambers et al., 2008).

Solar radiation is responsible for the photochemical reduction of CO_2 to higher energy products. The process, better known as photosynthesis, can be described by the following expression:

$$Carbon\ dioxide\ (CO_2) + Water\ (H_2O)\ \frac{Sunlight}{Chlorophyll}\ Glucose\ (C_6H_{12}O_6) + Oxygen\ (O_2)$$

Taking place in the chloroplasts of plant cells, photosynthesis can be broken into two phases: the light dependent phase and the Calvin cycle or dark phase. Through these phases, energy in the form of NADPH and ATP are produced and used to create carbohydrates.

3.3 Interception of solar radiation

Most of the solar radiation absorbed by a crop's canopy is intercepted by its leaf blades. However, leaves can become saturated by light and energy is wasted (Hay and Walker, 1989). In more tropical environments such as Australia, it has been found that the leaves of crops like beans and cereals, can become saturated at a photosynthetic photon flux density (PPFD) of about one-quarter of maximum sunlight. This means that any PPFD captured by the leaves in the crop canopy above this level is wasted. This can be avoided by improving canopy structure to provide a better distribution of light through the crop. Studies by Long et al. (2006) found that leaves that are mainly in a horizontal orientation would intercept most of the sunlight at the uppermost layer; with about 10% penetrating to the next layer and about 1% to the layer below that (Plant A, Figure 2). About two-thirds of the energy intercepted by this uppermost layer is wasted. Instead, a better arrangement for the leaves in the crop's canopy would be for the upper leaves to be more vertical, intercepting smaller amounts of light and allowing more energy to reach the more horizontal lower leaves (Plant B, Figure 2). By distributing light energy in this way, plants with more vertical leaves at the uppermost layer of their canopy, would have over double the efficiency of light energy use than plants with an upper canopy of horizontal leaves (Long et al., 2006, Ort and Long, 2003). The ability of a plant to intercept radiation is linked to canopy structure, with crop density, leaf area index (LAI, leaf area/ground area), and leaf positioning all influencing how effectively radiation is intercepted by the canopy.

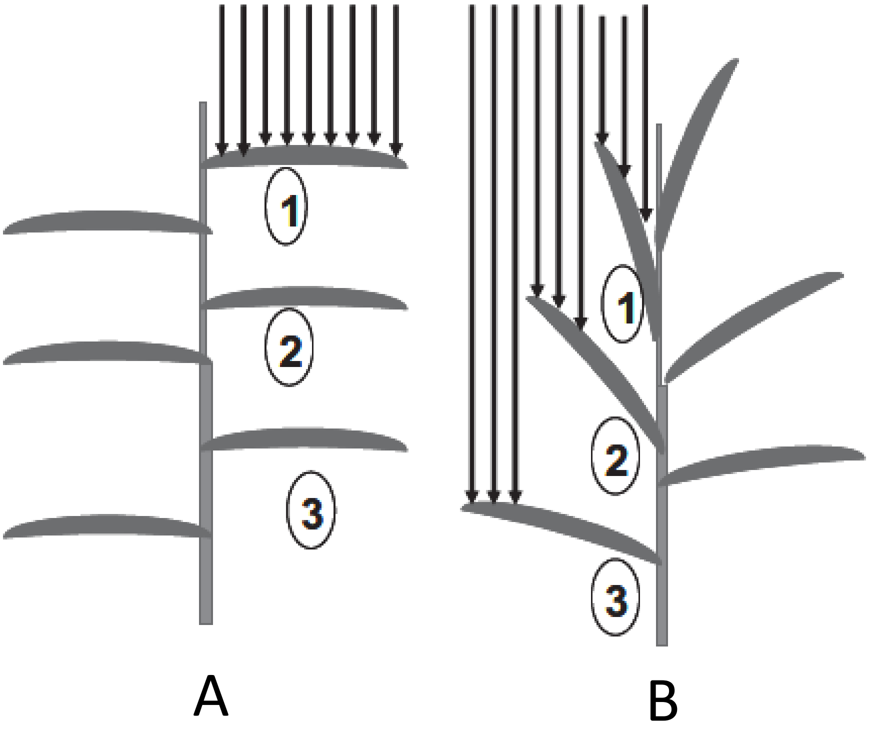


Figure 3. Differences between leaf orientation in the canopy. Plant A presents with horizontal leaves throughout the canopy, allowing the uppermost layer (1) to absorb the most solar energy, shading the lower layers (2)(3) and plant B with a more vertical leaf orientation at the uppermost layer (1) allowing the light to be spread more evenly and penetrate through to the bottom horizontal layers (2)(3) (Long et al., 2006).

Plants have developed three different chemo-anatomical systems: C3, C4 and CAM, which offer appropriate internal environments for the light and dark reactions (Loomis and Connor, 1992). C4 plants are adapted to hot, sunny environments and include crops such as maize, sugarcane and sorghum. CAM plants are adapted to much drier environments and include plants such as cacti and pineapples. Most of the crops cultivated in agriculture are C3 plants such as cereals, potatoes and beans and are particularly efficient at photosynthesis in cool, temperate climates. However, they are prone to light saturation on sunny days, and this highlights the importance of optimising canopy structure to allow maximum use of radiation from sunlight.

From the literature it is well known that light sources are necessary for plant growth and the structure of the crops canopy, ie. canopy size, leaf angle, plays an important role in the amount of light that is intercepted or transmitted by the plants canopy. This can typically be expressed using the extension coefficient (K). The extinction coefficient is the measure of how strongly a substance absorbs light at a particular wavelength which can be adapted to a plants canopy as the area of shadow cast on a horizontal surface by the canopy divided by the area of leaves in the canopy (Monteith, 1975).

The Beer-Lambert Law is used to calculate the extinction coefficient for a particular species using the formula:

$$A = \varepsilon Lc$$

Where A represents the amount of light absorbed by the species for a particular wavelength, ε is the molar extinction coefficient, L is the distance that the light travels through the species and c is the concentration of the absorbing species per unit volume. This has been adapted to many crop models, where light intercepted by a canopy is calculated from a variation on the Beer`s Law equation: IPAR = PAR x [1 - exp (-k x LAI)], where k is the extinction coefficient, PAR the photosynthetically active radiation and LAI the leaf area index.

For field beans, an average value for K of 0.78 was proposed by Ridao et al., (1996). Environmental impacts such as water deficits can have an effect on the canopy. In the same study by Radio et al. (1996), field beans under water stress changed their leaf angle becoming more erect in order to reduce radiation interception as water deficits developed, in comparison to a semi-leafless pea variety in the same study which had a more rigid canopy and did not change its orientation.

3.4 Effect of Plant Population Density (PPD) on plant development

Like most cultivated plants, field beans can modify their morphological structure according to the space that is available to each individual plant (Poulain, 1984b). As previously stated, most of the solar radiation absorbed by a crop's canopy is through the leaf blades. Because of this, it is possible to express the ability of a crop to intercept solar radiation by its leaf area index (LAI) (Hay and Walker, 1989). Leaf area index is the area of leaf per unit area of ground. High sowing densities will have a higher LAI and dry matter values during the vegetative growth stage (López-Bellido et al., 2005). Coelho and Pinto (1989) found that field beans display great plasticity in response to variations in plant density. Development of LAI mainly depends on the temperature, water availability and plant density (Poulain, 1984b). Maximum leaf area index is generally achieved with higher plant densities. Although, according to Loss et al. (1998b), highest LAI values have been recorded in favourable environmental conditions regardless of plant density. They found that higher plant densities resulted in significantly quicker canopy closure, leading to a higher leaf green area and greater interception of radiation with maximum LAI found from flowering and until the start of pod fill (Coelho and Pinto, 1989). This was also supported by Whaley et al. (2000) who found that virtually all plant densities of wheat managed to close their canopies, the lower plant densities just took longer than the higher densities. They found that if canopy closure was achieved by GS39, there was no yield penalty.

As previously stated, there are some advantages to sowing higher population densities. However, this does not necessarily mean that yield will increase as plant population is increased. As the number of plants increase, competition arises, and each plant captures less light. This limits plant growth and productivity. Increasing plant densities increase competition for water and other nutrients. Higher planting densities are known to produce taller crops (Loss et al., 1998b, Pilbeam et al., 1990). Hodgson and Blackman (1956) found that as the plant density increased, the extent of branching fell progressively, most commonly leading to single stemmed, taller plants. A taller crop increases the risk of lodging (Pilbeam et al., 1990) but can also produce pods higher on the stem, which is favoured by growers for mechanical harvest. Bean plants are quite adaptable to their surroundings and when plant populations are low, they tend to branch to increase their canopy size and subsequently their leaf areas. This enables each plant to capture more radiation. Branching also allows each plant to produce more pods in the same way as more wheat tillers lead to more ears. This plasticity means that low plant populations can often offer competitive yields (Robinson and Conley, 2007).

3.5 Effect of sowing date on growth and development

Sowing date has been found to have a great influence on biomass, grain yield and yield components (Confalone et al., 2010). These authors also reported that studying a range of sowing dates provided a wide range of environmental conditions. As sowing date was delayed, the crop was exposed to higher values of radiation, air temperature and a longer photoperiod resulting in a shortening of the crop cycle.

Sowing date can have a profound influence upon the course of leaf area development. It has been observed that delaying sowing date for spring cereals causes an acceleration of crop development and results in lower maximum LAI values (Hay and Walker, 1989). Until the flowering stage, the highest LAI values are achieved at the higher plant densities. Husain et al. (1988) found that sowing date affected both canopy architecture and the green area necessary to absorb the available radiation.

As field beans are grown in a wide range of environmental conditions across the world, it is not possible to generalise the effect of sowing date. Optimal sowing dates for field beans sown in various countries are presented in Table 1. Several studies have shown the effect of sowing date on field beans in different countries. For example, in Western Canada, sowing date was found to be a more important factor than seed rate in affecting final yield (McVetty et al., 1986). More arid climates like Sudan, can experience higher temperatures at the early growth stages which can increase disease pressure (Salih and Ageeb, 1983). In France, early sowing is recommended in spring to avoid water stress and high temperatures during the flowering period and pod setting (Berthelem, 1980), whereas in southern Italy, which has a more semi-arid climate, an autumn sowing is preferred to a spring sowing to allow a longer growing season and better utilisation of water, giving higher yields and an increase in protein content (Ziliotto and Toniolo, 1979).

Table 2. Examples of optimum sowing dates for spring and winter varieties of field beans in different countries.

Sowing	Country	Recommended sowing time	Reference
Spring	France	February to March	Plancquaert et al. (1978)
	United Kingdom	Late February to mid-March	Thompson and Taylor (1977)
	Southern Chile	End July to mid-September	Krarup (1984)
Winter	France	Mid October to mid-November	Plancquaert et al. (1978)
	South Australia	End May	Baldwin (1980)
	Sudan	Mid to end October	Salih and Ageeb (1983)
	Spain	September to November	Moreno and Cubero (1982)

4. Yield

4.1 Components of yield

Like most crops, field beans have been difficult to breed for increased yield due to their low heritability and environmental interaction with the yield trait (Neal and McVetty, 1984). This problem has been approached by the attempt to further quantify yield by measuring morphological and physiological traits, i.e. yield components. This approach was first suggested in cereal crops by Engledow and Wadham (1924). They explained that yield differences in cereals could be described on the basis of three yield components: average number of ear bearing tillers, average number of grains per ear, and average weight of a single grain. Breeders have continued to adapt this concept in their breeding programs throughout the years with varying levels of success.

The concept of using yield components to study yield variation in field beans is more recent and less detailed than previous studies on cereals. Rowland (1955) reported that the three primary components of yield in field beans were: number of pods per plant, number of seeds per pod and seed size, which in turn were influenced by first flowering and podding nodes, the number of nodes per plant, plant height and number of branches (Kambal, 1969a). Field beans are known for their high variation in yield from year to year. This variation in yield has been found to be associated with the variation in pod and seed number per plant (Kambal, 1969a, Pilbeam et al., 1991b, Stützel and Aufhammer, 1992). Furthering the research carried out by Rowland (1955), Kambal (1969a) found that pod number per plant showed the highest correlation with yield. Positive correlations found between yield and pod and seed numbers indicate that there is a strong association between yield and these yield components. Dantuma and Thompson (1983) reported seed number per pod as the most stable yield component followed by mean seed weight, and the main yield-determining component was pod number per plant. Since seeds per pod were generally found to be stable, the seeds per plant will depend on the number of pods developed per plant.

The production of mature pods has been found to be dependent on the effect of the internal physiological factors and external environmental conditions on the crop's development from the early vegetative phase (Hodgson and Blackman, 1956).

Hodgson and Blackman (1956) also stated that the main stem together with the axillary branches provide the framework for the production of flowers and in turn with final pod production, suggesting that they believe the production of flowers to be the main component of yield in their studies.

Pilbeam et al. (1990) sums up the matter of yield components as a determinant of final yield in field beans concluding that there is a difficulty in pinpointing one particular yield component as the determinant of yield in field beans. This illustrates the plasticity of the yield components of the field bean crop. This plasticity dilutes the effects of the selection pressures used by plant breeders in an attempt to increase yield. The basis of this compensatory capacity lies in the sequential development of successive components of yield.

4.2 Dry matter

Yield can also be considered in terms of the accumulation and partitioning of dry matter. Yield potential is determined by the efficiency with which the plant uses the available light for dry matter production. The development of flowers and seeds are key processes in the formation of yield in field beans and other grain legumes (Patrick and Stoddard, 2010). As in many crops, an increase in plant density leads to an increase in total dry matter until a level of yield is reached after which increasing density does not lead to further increase in yield (Kirby, 1969).

The production of dry matter is a function of the interception of light and the efficiency with which the light is used by the plants. Silim and Saxena (1992) reported that dry matter production in field beans was strongly correlated with cumulative intercepted PAR and Husain et al. (1988) stated that total dry matter production was also strongly related to radiation absorbed by green surfaces of the crop. This has been shown to be constant in field beans that are grown under stress-free conditions (Stützel and Aufhammer, 1991).

During the early periods of vegetative growth, there is a linear relationship between accumulation of dry matter and the number of plants per square metre. This reflects the direct relationship between radiation interception and dry matter production, with higher plant populations intercepting more light. High dry matter production before the start of the reproductive phase is important for ensuring development of the reproductive structures, and crop yield. Strong correlations have been found between seed yield and total dry matter in field beans (Silim and Saxena, 1992).

4.3 Source-sink limitation

Variations in grain yield can be analysed in terms of the crop carbon economy during the grain filling period. This approach, known as the source-sink relationship, identifies when grain yield is limited by the supply (source capacity) or the demand (sink strength) of assimilates during the grain filling period (Tollenaar, 1977). For example, in maize, source capacity is identified by assimilate production by crop photosynthesis during the grain filling period. Sink strength is defined by the ability of the growing grains to accommodate these assimilates. Maize grain yield has been generally reported to be sink limited (Bonelli et al., 2016, Tollenaar, 1977).

In theory, an increase in photosynthesis should lead to increases in yield; however, there is an on-going debate about whether plant growth is limited by the source or the sink. In crops, the production of dry matter is dependent on the source – sink concept, where a source has the potential for photosynthesis and the sink has the potential to utilise the photosynthetic products produced by the source. Typical primary sources include green material such as leaves and stems. Sinks include roots and underground structures, fruits, grain, developing buds and flowers (Venkateswarlu and Visperas, 1987). Both source and sink are important and need to be considered in the production of biomass (Evans, 2013).

As individual leaves mature, they convert from sink to source (Turgeon, 1989). This transition from sink to source demonstrates an important transition in the physiology of the leaf (Turgeon, 1989). Trying to manipulate photosynthesis at the leaf level will only be beneficial if it makes an improvement in the whole plant canopy. Once crop canopy closure occurs and the plants have intercepted all available radiation, the challenge is to convert that energy into biomass with the greatest efficiency (Evans, 2013) and it was found by Venkateswarlu and Visperas (1987) that slow senescence is an advantage for prolonged source-sink efficiency.

Photosynthesis can be limited by sink capacity (Long et al., 2006). After anthesis, the most important sink in grain crops is the potential size and number of the seeds formed. Analysis of changes in seed dry weight in response to manipulations in assimilate availability during seed filling for wheat (*Triticum aestivum*), maize (*Zea mays L*.) and soybean (*Glycine max L*.) concluded that for all three crops, yield is usually more limited by sink than by source during grain development (Borrás et al., 2004).

Sink activity is the capacity of the sink to create a translocation gradient from the source to the centre of accumulation. The source is sink-dependent, since assimilates move from the source to the sink regardless of its location. The source-sink relationship between the leaf and other plant organs is complex. Most of the metabolic sinks in the plants are connected with the source by the phloem elements in the vascular strands.

In wheat, grain yield improvement is usually most closely related to grain number per unit area (Brancourt-Hulmel et al., 2003, Peltonen-Sainio et al., 2007, Sayre et al., 1997, Shearman et al., 2005). Evidence suggests that grain sink strength remains a critical yield-limiting factor (Borrás et al., 2004, Miralles and Slafer, 2007, Slafer and Savin, 1994) and that sink capacity will need to be improved if improvements in biomass and radiation use efficiency are to be fully exploited (Acreche and Slafer, 2009, Reynolds et al., 2005). Increasing the partitioning of assimilates to the developing spike and grain has been seen to have the greatest impact on improving yield potential in wheat, not only under optimal yielding conditions (Brancourt-Hulmel et al., 2003) but also under stressful and harsh environments like the Mediterranean regions (Loss and Siddique, 1997).

In common bean (*Phaseolus vulgaris*), a previous study found that reducing the amount of radiation intercepted by the plants increased LAI, duration of grain filling and mean grain weight but no significant effect of shading on yield was noted (Hadi et al., 2006). Conversely, grain yield of chickpea was decreased by shading in New Zealand (Verghis et al., 1999).

The most recent study carried out by Lake et al. (2019) extensively studied the effect of shading on field beans in Australia and Chile, using sequential 14-d shading periods in locally adapted bean varieties grown in five locations. They found that shading was most severe during the flowering to pod emergence phase and effected yield the most during this time. The study showed that seed size was slightly increased when shaded before flowering, and again after pod set. In comparison with other studies by Lake and Sadras (2014), chickpea increased seed size in response to shading after, but not before flowering. Field beans were also less sensitive to reductions in seed per pod later in the season compared with chickpea (Lake and Sadras, 2014).

However, to date there is not enough data regarding the source-sink response of field beans and the effect of reducing radiation during critical growth periods in temperate climates. Specific causes for yield sensitivity in field beans around the critical period deserve further research.

5. Environmental influences

Like most crops, field beans are drought sensitive (Grashoff, 1990). Water reaches the seed through contact with the soil or germinating medium. Once the germination process begins, an adequate moisture level must be maintained throughout seedling growth, loss of moisture can result in death of the seed or seedling. Moisture is the most important prerequisite for germination, however, too much moisture can cause the soil to become saturated and this deprives the seed of oxygen, leading to death (Chong et al., 2002). In soybeans (*Glycine max*), Dornbos Jr and Mullen (1991) reported that water and high air temperature stresses that occur during seed fill greatly reduce seed yield.

Where adequate moisture is provided, the next most important requirement for germination is temperature. Hartmann and Kester (1975) describe temperature as the single most important influence in the regulation of the timing of germination. High temperatures generally encourage dormancy while low temperatures overcome dormancy. Most seeds can tolerate prolonged hot weather if they are kept dry, and some can withstand even greater weather extremes of hot or cold (Hartmann and Kester, 1975).

Temperature can also have a major environmental influence on the production of leaves. The influence of air temperature on the production of new leaves in crops has been well-documented (Milthorpe, 1959, Robson, 1972). The rate at which the new leaves unfold in field beans was found to be determined solely by air temperature, provided that the crop is not subject to any stress (Dennett et al., 1979). Mohammed

Yusoff et al. (2013) found that field beans have a phyllochron, that is the rate of leaf expansion in degree days (degree-days leaf^{-1}), of 66 ± 1 for field beans, compared with 123 ± 3.90 for oats, and 120 ± 4.21 for Italian ryegrass. There is little evidence that other environmental factors such as interception of solar radiation, water supply or availability of nutrients have an influence on the production of leaves (Hay and Walker, 1989).

Rapid and uniform seed germination and seedling emergence under varied environmental conditions is a desirable characteristic for crops. The rate of seed germination and crop emergence is usually determined and controlled by the temperature of the soil (Probert, 2000) and the temperature of the soil is principally controlled by the time of year. There are numerous agronomic management techniques used for the growth of crops including choice of cultivar, seeding rate, and application and timing of fertilizer. However, sowing date is probably the most vulnerable to variation. Temperature conditions have a relevant role in the crop yield, together with environmental factors (De Ron et al., 2016) such as weather before and after sowing as well as ground conditions at time of sowing can have an effect on germination and seed emergence (Hay and Walker, 1989). This can impact greatly on the potential yield of the crop. In wheat, it has been observed that delayed sowing, beyond a given sowing date, can have a considerable impact on the crop and reduce the potential yield (Green et al., 1985).

Seeds require a suitable supply of oxygen during germination. Oxygen is essential for plant respiration and allows the oxidation of starches, fats, and other food reserves (Hopkins, 1999). If enough moisture is available and the temperature is correct, most seeds will germinate equally well in darkness or light. Some seeds are partially or completely inhibited by light or require it to germinate (Chong et al., 2002).

Temperature and light interact together to determine growth and development of crops. Field beans are grown in a wide range of climates, from arid and semi-arid conditions to the milder temperate conditions of north western Europe. The use of crop management techniques such as choice of cultivar that are tolerant to low temperatures during the germination and emergence stages and optimal seeding rates can make field beans a manageable crop in these different climatic conditions and need to be improved for the success of the bean crop (De Ron et al., 2016).

6. Conclusions

With the introduction of the protein grant as part of the CAP greening measures in 2015, and the increasing interest in growing beans in Ireland, crop suitability to specific environments must be studied and established. The drive to increase home-grown protein and reduce imports for animal feed has opened the opportunity for this study to optimise the growth and development of high energy, high protein grain legumes such as the field bean for growth in the temperate Irish climate. However, compared to crops such as wheat and oilseed rape, there has been relatively little research on field beans and the yield of field beans which is highly variable from year to year. I propose that, through an improved understanding of crop physiology, agronomic practices can be developed to improve both yield and yield stability of field beans in the temperate Irish climate and growers can reap the benefits of having this protein crop in their rotations.

7. Hypotheses

Following this review of the literature, the following hypotheses were devised to better understand the interactions between sowing date, seed rate and variety and their impact on canopy size, components of yield and final harvest yield in *Vicia faba*.

I. Delaying sowing date for of *Vicia faba* will lead to a reduction in final yield.
II. Economic optimum plant populations will be higher in spring sown *Vicia faba* than winter sown *Vicia faba*.
III. Yield of *Vicia faba* is stable across a wide range of plant populations.
IV. Yield of *Vicia faba* is primarily driven by pod number.
V. *Vicia faba* are predominantly source-limited.
VI. Fresh leaf biomass can be used to accurately predict green area index (GAI).
VII. Using a model to predict GAI from fresh leaf biomass can therefore be used as a surrogate for GAI and a management tool for growers of field beans.

8. Thesis overview

This thesis is written in paper format. Chapters are written in the format for submission for review to relevant journals.

Chapter 2 – "Yield response of field beans (*Vicia faba*) to plant population and sowing date in a temperate climate."

This paper discusses the influence of sowing date and seed rate on crop establishment, growth, yield and profitability.

Chapter 3 – "Yield of field beans (*Vicia faba*) is determined by light interception during the pod development phase."

This paper investigates further the studies in Chapter 2, with the in-depth study of yield components to understand the impact of canopy size on yield and to identify the key components of yield in field beans.

Chapter 4 – "Predicting Green Area Index (GAI) from leaf biomass in field beans (*Vicia faba*)."

This chapter discusses the relationship between biomass and Green Area Index (GAI) in the efforts to utilise biomass as a predictor of GAI, and in turn use GAI as a precursor to determine final yield.

To conclude, the results of all the work conducted are summarised in a general discussion in Chapter 5.

As the chapters are being submitted for publication, references can be found at the end of each chapter.

9. References

Acreche, M. M. & Slafer, G. A. 2009. Grain weight, radiation interception and use efficiency as affected by sink-strength in Mediterranean wheats released from 1940 to 2005. *Field Crops Research,* 110**,** 98-105.

Adisarwanto, T. & Knight, R. 1997. Effect of sowing date and plant density on yield and yield components in the faba bean. *Australian Journal of Agricultural Research,* 48**,** 1161-1168.

Aguilera-Diaz, C. & Recalde-Manrique, L. 1995. Effects of plant density and inorganic nitrogen fertilizer on field beans (Vicia faba). *The Journal of Agricultural Science,* 125**,** 87-93.

Aguilera Díaz, C. 1987. Estudio, por medio de un modelo estadístico multivariante del desarrollo de la cosecha, de las respuestas a la densidad de siembra ya la fertilización nitrogenada de los cultivos de habas (Vicia faba, L.).

Amato, G., Cibella, R., Giambalvo, D. & Gristina, L. Observations of the reproductive development in faba bean (Vicia faba L. var. equina) in relation to plant density. Proceedings of the First European Conference on grain legumes, 1992. 1-3.

Baker, D., Chapman, G., Standish, M. & Bailey, M. 1984. Growth habit in relation to assimilate partitioning and some consequences for field bean breeding. *Vicia faba: Agronomy, physiology and breeding.* Springer.

Baldwin, B. 1980. Time of sowing-a major factor influencing the yields of Vicia faba in South Australia. *FABIS newsletter*.

Berry, P. M. & Spink, J. H. 2006. A physiological analysis of oilseed rape yields: Past and future. *The Journal of Agricultural Science,* 144**,** 381-392.

Berthelem, P. 1980. The major agronomic problems of the cultivation of faba bean (Vicia faba L.) in France. *FABIS Newsletter (ICARDA)*.

Bishop, J., Garratt, M. P. D. & Breeze, T. D. 2020. Yield benefits of additional pollination to faba bean vary with cultivar, scale, yield parameter and experimental method. *Scientific Reports,* 10**,** 2102.

Bonelli, L. E., Monzon, J. P., Cerrudo, A., Rizzalli, R. H. & Andrade, F. H. 2016. Maize grain yield components and source-sink relationship as affected by the delay in sowing date. *Field Crops Research,* 198**,** 215-225.

Borrás, L., Slafer, G. A. & Otegui, M. E. 2004. Seed dry weight response to source–sink manipulations in wheat, maize and soybean: a quantitative reappraisal. *Field Crops Research,* 86**,** 131-146.

Brancourt-Hulmel, M., Doussinault, G., Lecomte, C., Bérard, P., Le Buanec, B. & Trottet, M. 2003. Genetic improvement of agronomic traits of winter wheat cultivars released in France from 1946 to 1992. *Crop science,* 43**,** 37-45.

Cernay, C., Ben-Ari, T., Pelzer, E., Meynard, J.-M. & Makowski, D. 2015. Estimating variability in grain legume yields across Europe and the Americas. *Scientific reports,* 5**,** 1-11.

Coelho, J. & Pinto, P. 1989. Plant Density Effects on the Growth and Development of Winter Faba Bean (Vicia faba L. var. minor). *Fabis***,** 26-30.

Confalone, A., Lizaso, J. I., Ruiz-Nogueira, B., López-Cedrón, F.-X. & Sau, F. 2010. Growth, PAR use efficiency, and yield components of field-grown Vicia faba L. under different temperature and photoperiod regimes. *Field Crops Research,* 115**,** 140-148.

CSO. 2020. *Area, Yield and Production of Crops* [Online]. CSO Ireland. [Accessed 09/09/2020 2020].

Cubero, J. 2011. The faba bean: a historic perspective. *Grain legumes,* 56**,** 5-7.

Dantuma, G. & Thompson, R. 1983. Whole-crop physiology and yield components. *The faba bean*, 143-158.

De Ron, A. M., Rodiño, A. P., Santalla, M., González, A. M., Lema, M. J., Martín, I. & Kigel, J. 2016. Seedling Emergence and Phenotypic Response of Common Bean Germplasm to Different Temperatures under Controlled Conditions and in Open Field. *Frontiers in Plant Science,* 7.

Dean, J. R. & Clark, K. W. 1980. Effect of low level nitrogen fertilization on nodulation, acetylene reduction and dry matter in fababeans and three other legumes. *Canadian Journal of Plant Science,* 60**,** 121-130.

Dennett, M., Elston, J. & Milford, J. 1979. The effect of temperature on the growth of individual leaves of Vicia faba L. in the field. *Annals of Botany,* 43**,** 197-208.

Dornbos Jr, D. & Mullen, R. 1991. Influence of stress during soybean seed fill on seed weight, germination, and seedling growth rate. *Canadian Journal of Plant Science,* 71**,** 373-383.

Egli, D. B. 2010. 6 Soybean Yield Physiology: Principles. *The Soybean: Botany, Production and Uses***,** 113.

Engledow, F. & Wadham, S. 1924. Investigations on yield in the cereals 1. I. *The Journal of Agricultural Science,* 14**,** 66-98.

Evans, J. R. 2013. Improving photosynthesis. *Plant physiology,* 162**,** 1780-1793.

FAO. 2018. *Production quantities of Broad beans, horse beans, dry by country* [Online]. FAO: FAO. Available: http://www.fao.org/faostat/en/#data/QC/visualize [Accessed November 2020].

Grashoff, C. 1990. Effect of pattern of water supply on Vicia faba L. 2. Pod retention and filling, and dry matter partitioning, production and water use. *NJAS wageningen journal of life sciences,* 38**,** 131-143.

Green, C., Paulson, G. & Ivins, J. 1985. Time of sowing and the development of winter wheat. *The Journal of Agricultural Science,* 105**,** 217-221.

Hadi, H., Ghassemi-Golezani, K., Khoei, F. R., Valizadeh, M. & Shakiba, M. R. 2006. Response of common bean (Phaseolus vulgaris) to different levels of shade. *Journal of Agronomy,* 5**,** 595-599.

Hartmann, H. T. & Kester, D. E. 1975. *Plant propagation: principles and practices*, Prentice-Hall.

Hay, R. K. M. & Walker, A. J. 1989. *Introduction to the physiology of crop yield,* Harlow, Longman Group UK Limited.

Hodgson, G. & Blackman, G. 1956. An Analysis of the Influence of Plant Density on the Growth of Vicia faba: I. THE INFLUENCE OF DENSITY ON THE PATTERN OF DEVELOPMENT. *Journal of Experimental Botany,* 7**,** 147-165.

Hopkins, W. G. 1999. *Introduction to plant physiology*, John Wiley and Sons.

Husain, M. M., Hill, G. D. & Gallagher, J. N. 1988. The response of field beans (Vicia faba L.) to irrigation and sowing date. 2. Growth and development in relation to yield. *The Journal of Agricultural Science,* 111**,** 233-254.

Kambal, A. E. 1969. Components of yield in field beans, Vicia faba L. *The Journal of Agricultural Science,* 72**,** 359-363.

Kirby, E. 1969. The effect of sowing date and plant density on barley. *Annals of Applied Biology,* 63**,** 513-521.

Krarup, A. 1984. Effect of sowing date on yield of faba bean (Vicia faba major) at Valdivia, Chile. *Faba Bean Information Service*.

Kulig, B., Ko£Odziej, J., Andrzej, O., Kolodziejczyk, M. & Sajdak, A. 2011. INFLUENCE OF THE WEATHER CONDITIONS ON FABA BEAN YIELDING. *ECOLOGICAL CHEMISTRY AND ENGINEERING A,* 18**,** 1-7.

Lake, L., Godoy-Kutchartt, D. E., Calderini, D. F., Verrell, A. & Sadras, V. O. 2019. Yield determination and the critical period of faba bean (Vicia faba L.). *Field Crops Research,* 241**,** 107575.

Lake, L. & Sadras, V. O. 2014. The critical period for yield determination in chickpea (Cicer arietinum L.). *Field Crops Research,* 168**,** 1-7.

Lambers, H., Chapin III, F. S. & Pons, T. L. 2008. *Plant physiological ecology*, Springer Science & Business Media.

Lancashire, P. D., Bleiholder, H., Boom, T. V. D., Langelüddeke, P., Stauss, R., Weber, E. & Witzenberger, A. 1991. A uniform decimal code for growth stages of crops and weeds. *Annals of Applied Biology,* 119**,** 561-601.

Long, S. P., Zhu, X.-G., Naidu, S. L. & Ort, D. R. 2006. Can improvement in photosynthesis increase crop yields? *Plant, Cell & Environment,* 29**,** 315-330.

Loomis, R. & Connor, D. 1992. Crop ecology: productivity and management in agricultural systems Cambridge University Press. *New York, NY*.

López-Bellido, F. J., López-Bellido, L. & López-Bellido, R. J. 2005. Competition, growth and yield of faba bean (Vicia faba L.). *European Journal of Agronomy,* 23**,** 359-378.

Loss, S., Siddique, K., Jettner, R. & Martin, L. 1998a. Responses of faba bean (Vicia faba L.) to sowing rate in south-western Australia I. Seed yield and economic optimum plant density. *Australian Journal of Agricultural Research,* 49**,** 989-997.

Loss, S., Siddique, K., Martin, L. & Crombie, A. 1998b. Responses of faba bean (Vicia faba L.) to sowing rate in south-western Australia II. Canopy development, radiation absorption and dry matter partitioning. *Aust. J. Agric. Res,* 49**,** 999-1008.

Loss, S. P. & Siddique, K. H. M. 1997. Adaptation of faba bean (Vicia faba L.) to dryland Mediterranean-type environments I. Seed yield and yield components. *Field Crops Research,* 52**,** 17-28.

Marcellos, H. & Constable, G. 1986. Effects of plant density and sowing date on grain yield of faba beans (Vicia faba L.) in northern New South Wales. *Australian Journal of Experimental Agriculture,* 26**,** 493-496.

McEwen, J. 1970. Fertilizer nitrogen and growth regulators for field beans (Vicia faba L.):I. The effects of seed bed applications of large dressings of fertilizer nitrogen and the residual effects on following winter wheat. *The Journal of Agricultural Science,* 74**,** 61-66.

McEwen, J., Bardner, R., Briggs, G., Bromilow, R., Cockbain, A., Day, J., Fletcher, K., Legg, B., Roughley, R. & Salt, G. 1981. The effects of irrigation, nitrogen fertilizer and the control of pests and pathogens on spring-sown field beans (Vicia faba L.) and residual effects on two following winter wheat crops. *The Journal of Agricultural Science,* 96**,** 129-150.

McVetty, P., Evans, L. & Nugent-Rigby, J. 1986. Response of faba bean (Vicia faba L.) to seeding date and seeding rate. *Canadian journal of plant science,* 66**,** 39-44.

Meier, U., Bleiholder, H., Buhr, L., Feller, C., Hack, H., Heß, M., Lancashire, P. D., Schnock, U., Stauß, R. & Van Den Boom, T. 2009. The BBCH system to coding the phenological growth stages of plants–history and publications. *Journal für Kulturpflanzen,* 61**,** 41-52.

Milthorpe, F. 1959. Studies on the expansion of the leaf surface: I. The influence of temperature. *Journal of Experimental Botany,* 10**,** 233-249.

Miralles, D. J. & Slafer, G. A. 2007. Sink limitations to yield in wheat: how could it be reduced? *Journal of Agricultural Science, 2007, vol. 145, núm. 2, p. 139-149*.

Mohammed Yusoff, M., Moot, D. J., McKenzie, B. A. & Hill, G. D. 2013. Quantification of vegetative development of faba bean, oats, and Italian ryegrass. *Crop and Pasture Science,* 63**,** 1097-1105.

Moreno, M. & Cubero, J. 1982. Faba beans: The Spanish crop systems. *FABIS Newsletter*.

Mwanamwenge, J., Loss, S. P., Siddique, K. H. M. & Cocks, P. S. 1998. Growth, seed yield and water use of faba bean (Vicia faba L.) in a short-season Mediterranean-type environment. *Australian Journal of Experimental Agriculture,* 38**,** 171-180.

Nachi, N. & Le Guen, J. 1996. Dry matter accumulation and seed yield in faba bean (Vicia faba L) genotypes. *Agronomie, EDP Sciences,* 16 (1)**,** pp.47-59.

Neal, J. R. & McVetty, P. B. E. 1984. Yield structure of faba beans (Vicia faba L.) grown in Manitoba. *Field Crops Research,* 8**,** 349-360.

Ort, D. & Long, S. 2003. Converting solar energy into crop production. *Plants, Genes, and Crop Biotechnology (240-269). Edited by Chrispeels MJ, Sadava DE. Jones and Bartlett Publisher International*.

Patrick, J. & Stoddard, F. 2010. Physiology of flowering and grain filling in faba bean. *Field Crops Research,* 115**,** 234-242.

Peltonen-Sainio, P., Kangas, A., Salo, Y. & Jauhiainen, L. 2007. Grain number dominates grain weight in temperate cereal yield determination: Evidence based on 30 years of multi-location trials. *Field Crops Research,* 100**,** 179-188.

Pilbeam, C. J., Duc, G. & Hebblethwaite, P. D. 1990. Effects of plant population density on spring-sown field beans (Vicia faba) with different growth habits. *The Journal of Agricultural Science,* 114**,** 19-33.

Pilbeam, C. J., Hebblethwaite, P. D., Ricketts, H. E. & Nyongesa, T. E. 1991. Effects of plant population density on determinate and indeterminate forms of winter field beans (Vicia faba) 1. Yield and yield components. *The Journal of Agricultural Science,* 116**,** 375-383.

Plancquaert, P., Girard, C., Lemaire, L., Menessier, P. & Picard, J. 1978. Culture du pois et de la feverole. *Perspectives Agricoles,* 13**,** 24-35.

Poulain, D. 1984. Influence of density on the growth and development of winter field bean (Vicia faba). *Vicia faba: Agronomy, Physiology and Breeding.* Springer.

Probert, R. J. 2000. The role of temperature in the regulation of seed dormancy and germination. *Seeds: the ecology of regeneration in plant communities,* 2**,** 261-292.

Reckling, M., Döring, T. F., Bergkvist, G., Stoddard, F. L., Watson, C. A., Seddig, S., Chmielewski, F.-M. & Bachinger, J. 2018. Grain legume yields are as stable as other spring crops in long-term experiments across northern Europe. *Agronomy for sustainable development,* 38**,** 1-10.

Reynolds, M., Pellegrineschi, A. & Skovmand, B. 2005. Sink-limitation to yield and biomass: a summary of some investigations in spring wheat. *Annals of Applied Biology,* 146**,** 39-49.

Robinson, A. P. & Conley, S. P. 2007. Plant populations and seeding rates for soybeans. https://www.extension.purdue.edu/extmedia/ay/ay-217-w.pdf: Purdue Univ., West Lafayette, IN. .

Robson, M. 1972. The effect of temperature on the growth the S. 170 tall fescue (Festuca arundinacea). I. Constant temperature. *Journal of Applied Ecology*, 643-653.

Roques, S. E. & Berry, P. M. 2016. The yield response of oilseed rape to plant population density. *The Journal of Agricultural Science,* 154**,** 305-320.

Rowland, D. G. 1955. The problem with yield in field beans. *Agric. Prog.,* 30**,** 137-147.

Salih, F. & Ageeb, O. 1983. Effect of sowing date, watering regime and mulching on yield of faba beans [in the Gezira region of Sudan]. *FABIS Newsletter ICARDA*.

Savonen, C. 2003. *What are short day and long day plants?* [Online]. Oregon State University Extension Service. Available: https://extension.oregonstate.edu/news/what-are-short-day-long-day-plants [Accessed].

Sayre, K. D., Rajaram, S. & Fischer, R. 1997. Yield potential progress in short bread wheats in northwest Mexico. *Crop science,* 37**,** 36-42.

Scott, R., Stokes, D., McWilliam, S., Spink, J. & Clare, R. Yield improvement through canopy management. Proceeding of the 10th International Rapeseed Congress, 1999. 313-318.

Shearman, V., Sylvester-Bradley, R., Scott, R. & Foulkes, M. 2005. Physiological processes associated with wheat yield progress in the UK. *Crop science,* 45**,** 175-185.

Silim, S. & Saxena, M. 1992. Comparative performance of some faba bean (Vicia faba) cultivars of contrasting plant types. 2. Growth and development in relation to yield. *The Journal of Agricultural Science,* 118**,** 333-342.

Slafer, G. A. & Savin, R. 1994. Source—sink relationships and grain mass at different positions within the spike in wheat. *Field Crops Research,* 37**,** 39-49.

Sprent, J. I., Bradford, A. M. & Norton, C. 1977. Seasonal growth patterns in field beans (Vicia faba) as affected by population density, shading and its relationship with soil moisture. *The Journal of Agricultural Science,* 88**,** 293-301.

Stringi, L., Sarno, R., Amato, G. & Gristina, L. 1986. Effects of plant density on Vicia faba L. equina and Vicia faba L. minor in a semi-arid environment in Southern Italy. *Faba Bean Information Service*.

Stützel, H. & Aufhammer, W. 1991. Light interception and utilization in determinate and indeterminate cultivars of Vicia faba under contrasting plant distributions and population densities. *The Journal of Agricultural Science,* 116**,** 395-407.

Stützel, H. & Aufhammer, W. 1992. Grain yield in determinate and indeterminate cultivars of Vicia faba with different plant distribution patterns and population densities. *The Journal of Agricultural Science,* 118**,** 343-352.

Sylvester-Bradley, R., Spink, J., Foulkes, M., Bryson, R., Scott, R., Stokes, D., King, J., Parish, D., Paveley, N. & Clare, R. Sector challenge project—canopy management in practice. Proceedings HGCA 2000 Crop Management into the Millennium Conference'.(Home-Grown Cereals Authority: London), 2000.

Teagasc 2018. Teagasc Specialist, Tillage CROPS Report, Harvest Report.

Thompson, R. & Taylor, H. 1977. Yield components and cultivar, sowing date and density in field beans (Viciafaba). *Annals of Applied Biology,* 86**,** 313-320.

Tollenaar, M. 1977. Sink-source relationships during reproductive development in maize. A review. *Maydica,* 22**,** 49-75.

Turgeon, R. 1989. The sink-source transition in leaves. *Annual review of plant biology,* 40**,** 119-138.

Venkateswarlu, B. & Visperas, R. M. 1987. Source-sink relationships in crop plants.

Verghis, T., McKenzie, B. & Hill, G. 1999. Effect of light and soil moisture on yield, yield components, and abortion of reproductive structures of chickpea (Cicerarietinum), in Canterbury, New Zealand. *New Zealand journal of crop and horticultural science,* 27**,** 153-161.

Watson, C. A., Reckling, M., Preissel, S., Bachinger, J., Bergkvist, G., Kuhlman, T., Lindström, K., Nemecek, T., Topp, C. F. E., Vanhatalo, A., Zander, P., Murphy-Bokern, D. & Stoddard, F. L. 2017. Chapter Four - Grain Legume Production and Use in European Agricultural Systems. *In:* SPARKS, D. L. (ed.) *Advances in Agronomy.* Academic Press.

Whaley, J. M., Sparkes, D. L., Foulkes, M. J., Spink, J. H., Semere, T. & Scott, R. K. 2000. The physiological response of winter wheat to reductions in plant density. *Annals of Applied Biology,* 137**,** 165-177.

Zadoks, J. C., Chang, T. T. & Konzak, C. F. 1974. A decimal code for the growth stages of cereals. *Weed research,* 14**,** 415-421.

Ziliotto, U. & Toniolo, L. 1979. Field trials on time of sowing field beans (Vicia faba var. minor) and broadbeans (Vicia faba var. major) at Padova in 1976 and 1977. *Some current research on Vicia faba in Western Europe, edited by DA Bond, GT Scarascia-Mugnozza and MH Poulsen; sponsored by the Commission of the European Communities, Directorate-General for Agriculture, Coordination of Agricultural Research*.

Chapter 2

Yield response of field beans (*Vicia faba*) to plant population and sowing date in a temperate climate.

This chapter has been prepared as a journal article for submission to the Irish Journal of Agricultural and Food Research (IJAFR).

Yield response of field beans (*Vicia faba*) to plant population and sowing date in a temperate climate

L.C. Murphy[1,2], D.L. Sparkes[2], J.H. Spink[1*] and S. Alves[1]

[1] Teagasc, Crops, Environment & Land Use Programme, Oak Park Crops Research Centre, Carlow, Ireland

[2] University of Nottingham, Sutton Bonington, Loughborough, LE12 5RD, United Kingdom

Abstract

Sowing date and seed rate influence crop establishment, growth, yield, and profitability. The growth and yield of field beans in response to sowing date and seed rate was examined over three seasons in Teagasc, Oak Park, Carlow, Ireland. Six sowing dates between October and April were studied along with three seed rates (20, 40 and 60 seeds m^{-2}). An additional two seed rates (10 and 80 seeds m^{-2}) were included in October and March only. Both a winter and a spring variety were sown in October and November and spring variety only from January to April. The economic optimum plant population was estimated for the October and March sowing dates, by fitting a standard (linear + exponential) curve.

There is no published information on the optimum plant populations for field beans in Ireland and we believe we are the first to report these findings. The estimated economic optimum plant populations, varied between 13 – 38 plants m^{-2} for both varieties, with an average optimum of 25.5 plants m^{-2}. This range falls in the current recommendations for sowing field beans in Ireland, demonstrating that increasing plant populations above the current commercial practice for field beans in Ireland, will not increase yield or profitability.

Keywords: Field beans; Yield; Establishment; Economic optimum; Plant populations; Temperate climate.

*Corresponding author

Email: John.Spink@teagasc.ie

1. Introduction

Field beans have the potential to produce high yields in temperate climates to supply home grown protein for animal feed. However, this potentially valuable crop is not popular among growers because of its perceived year on year variability in comparison to cereals. However, in response to support for the crop by the introduction of the protein grant as part of the CAP greening scheme, field bean area in Ireland increased rapidly from 3,500 hectares in 2014 to its highest of c.12,000 hectares in 2017 (CSO, 2020).

Achieving an optimal crop canopy is important for sufficient interception of radiation, and production of assimilates, however, too large a canopy can also lead to problems such as lodging and high disease pressure (Loss et al., 1998b, Pilbeam et al., 1990). In a leguminous crop like field beans, which fix their own nitrogen and hence do not receive nitrogenous fertiliser, the most efficient way to adjust the size of the crop canopy is through the seeding rate which, along with establishment, determines the number of plants per square metre. One of the main determinants of establishment is sowing date, as optimal conditions for germination and early plant development depend on the soil and air temperature when the sowing takes place.

Studies have shown that there are advantages to sowing higher plant populations. In soy beans, Robinson and Conley (2007) found that higher plant populations lead to quicker canopy closure. This results in early maximisation of light interception and less competition from weeds. However, having a higher plant population does not necessarily mean an increase in yield. Lower plant populations tend to produce more branches which allows each plant to produce more leaf area for light interception and to produce more pods per plant (Robinson and Conley, 2007). Higher plant densities can cause problems such as competition between plants for light, water, and other nutrients (Pilbeam et al., 1991a), as well as an increase in the risk of lodging.

Sowing date can have a profound influence upon the course of plant development. It has been observed in wheat that delaying sowing date for spring cereals causes an acceleration of crop development and results in lower maximum green area index (Hay and Walker, 1989). It has been repeatedly found that there is an interaction between sowing date and optimum plant populations (Adisarwanto and Knight, 1997, Baldwin, 1980, Green et al., 1985, Kirby, 1969, Spink et al., 2000), as at later sowing dates individual plants are less able to increase growth to compensate for reduced plant density.

It is not known, however, how Ireland’s temperate maritime climate with relatively warm winters and cool springs and summers affect the bean crop’s ability to compensate for reduced plant population density. Nor is it known in these conditions how sowing date affects the yield potential of the crop or its ability to compensate for reduced plant populations.

This chapter focuses on hypotheses 1, 2 and 3:

1. Delaying sowing date for of *Vicia faba* will lead to a reduction in final yield.
2. Economic optimum plant populations will be higher in spring sown *Vicia faba* than winter sown *Vicia faba*.
3. Yield of *Vicia faba* is stable across a wide range of plant populations.

2. Materials and methods

2.1 Agronomy

Field experiments were carried out for three consecutive years in Teagasc, Oak Park, Carlow, Ireland, following oats in 2016, spring barley in 2017, and winter barley in 2018. P and K were maintained on all sites following national guidelines on soil fertility (Teagasc, 2016). Soil organic matter ranged from 3.9-4.8% and pH ranged from 6.4-7.1.

For all field experiments, certified seed of winter variety (cv. Wizard), spring varieties cv. Fuego (2016 and 2017) and cv. Fanfare (2018) was used. The change in spring variety for the third year was due to unavailability of cv. Fuego. Germination rate was ≥85% for all seed. Experimental areas were cultivated with a conventional plough and one pass power harrow system. Plots were sown using a Wintersteiger plot drill (Wintersteiger AG, Austria). The seed was drilled between 7-10 cm deep. A prophylactic programme of chemicals was used to minimise weeds, pests, and diseases throughout the season.

2.2 Bird damage control

In 2017, netting was erected over the November sown plots, and a bird scarer was also placed in the field. Nets were also erected over February 2019 plots to deter bird attacks on the plots.

2.3 Experimental design

The experiments were arranged in a randomised, incomplete split-split plot design with four replications. The main plot treatment was time of sowing (TOS), sub plot treatment was variety and sub-sub plot treatment was seed rate (SR). Plot size was 5m x 24m, which was split in half lengthways (2.5m x 24m); one side of the plot was used for destructive samples and the other side for combine yield. In the last season, due to field restrictions and shortage of seed, the field experiment was divided into two incomplete split-split-plot designs with four replications.

Field experiments consisted of six sowing dates from October to April, five seed rates between 10 and 80 seeds m^{-2} and two varieties. The five seed rates were only sown in October and March; at the remaining sowing dates only three seed rates (20, 40 and 60 seeds m^{-2}) were sown. The spring variety was sown at all sowing dates, but the winter variety was only sown in October and November.

In the last season (2018-2019), two trials were sown, to reduce the size of the trial and hence variability for the comparison of the full range of seed rates. The first trial comprised of two sowing dates (October and March), two varieties (Wizard, sown in October only and Fuego, sown at both sowing dates) and five seed rates (10-80 seeds m^{-2}). The second trial included the six sowing dates, two varieties (Wizard sown in October and November, and Fanfare sown in all sowing dates) and three seed rates (20, 40 and 60 seeds m^{-2}).

2.4 Crop establishment and plant population

Plant counts for crop establishment were taken at the second leaf stage of growth (GS12; BBCH scale, Lancashire et al. (1991)). Establishment was assessed by randomly throwing a 1m^2 plastic hoop into the plot. Ten counts were taken throughout the plot and an average plant population and percentage establishment was calculated per plot.

2.5 Combine harvest

Plots were harvested mid-September each year when the crop was dry, black, and seed was hard using a plot combine (Deutz-Fahr, Germany). A minimum area of 52-57 m^2 was harvested from each plot. As plots were harvested, moisture and weight were recorded on an attached handheld computer (Allegro, Juniper Systems, Austria) with accompanying software (Field Research Software (FRS) for GrainGage, Juniper systems, Austria).

2.6 Meteorological data

Meteorological data was taken from the onsite weather station in Oak Park, Carlow, Ireland. Rainfall (mm), temperature (°C) and solar radiation (mJ m^{-2}) were recorded over the three seasons 2016-2019. Historical weather data was obtained from the Irish Meteorological Service, Met Éireann, for long term monthly rainfall and temperature averages from 2007-2019.

2.7 Statistical analysis

Analysis of variance (ANOVA) and regression analyses were carried out using the statistical software GenStat, version 20 from VSN International and Microsoft Excel, Office 365 from Microsoft Corporation. Analysis of variance was carried out across the experiments in the first 2 years and the second experiment in the final year. Winter and spring varieties were compared by analysing the 20, 40 and 60 seed rate treatments for October and November sowings only. All sowing dates were compared using the 20, 40 and 60 seed rates for the spring variety only. Where the full range of seed rates were compared the analysis was restricted to winter and spring varieties in the October sowing and spring cultivar for the March sowing from the first 2 years and experiment 1 in the final year.

2.8 Economic optimum plant population

The economic optimum was estimated for the winter and spring varieties in the October sowing and spring cultivar for the March sowing date for the five seed rates over the three seasons. A standard curve (linear + exponential) was fitted using Genstat version 20 (VSN International). Economic optimum populations were estimated at the highest point on the response curve. Assuming a return from the harvested grain of €170 t^{-1}, a seed cost of €205 t^{-1}, (S. Phelan, Teagasc, personal communication) a mean seed weight of 0.63g and a 60% establishment rate was used to convert seed cost into the cost per plant, this was calculated using the equation:

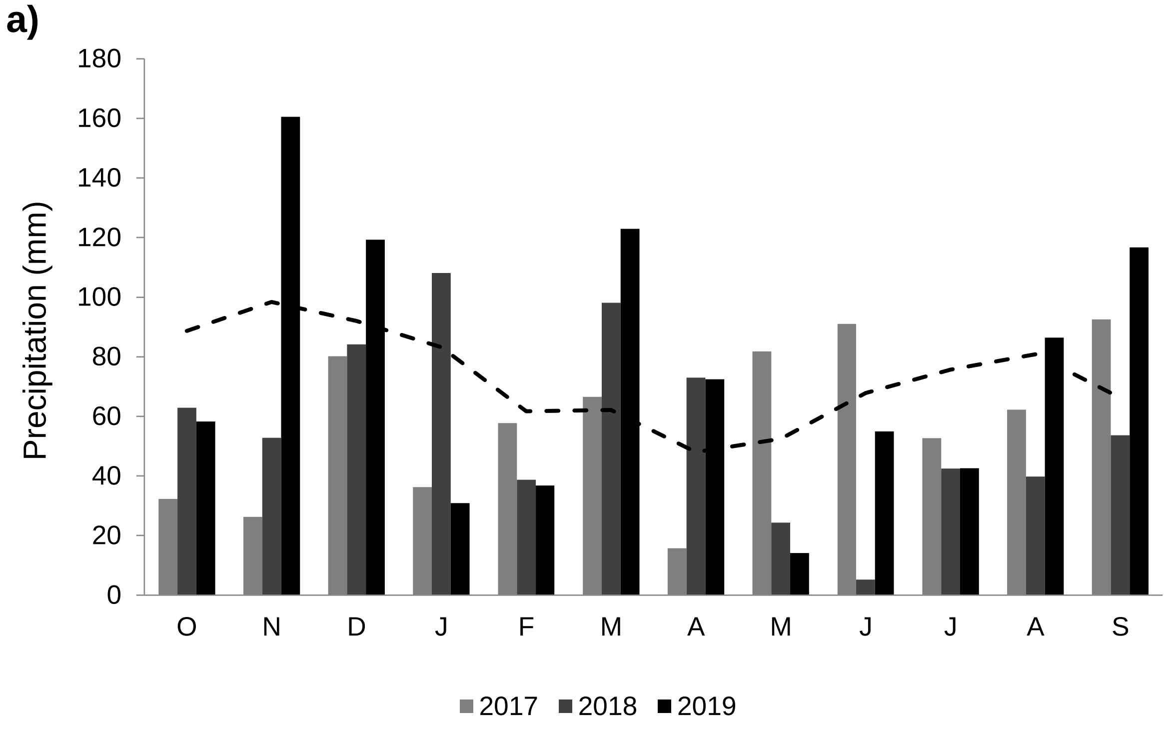
$$A+B(R^{**}X) + C^{*}X$$

Where A, B, C and R are the estimates of the parameters and X is plant number.

3. Results

3.1 Meteorological data

Temperature and radiation for the three years showed a typical trend for the moist maritime climate of Ireland (Figure 1b; Figure 1c) and typically followed the long-term average. However, large variations in rainfall were observed over the three seasons. In 2018, rainfall between May and September was much lower than the average, with the lowest of 5.2mm in June 2018 compared to the 67.8mm long term average (2007-2019; MetÉireann (2019)) for the same month (Figure 1a).



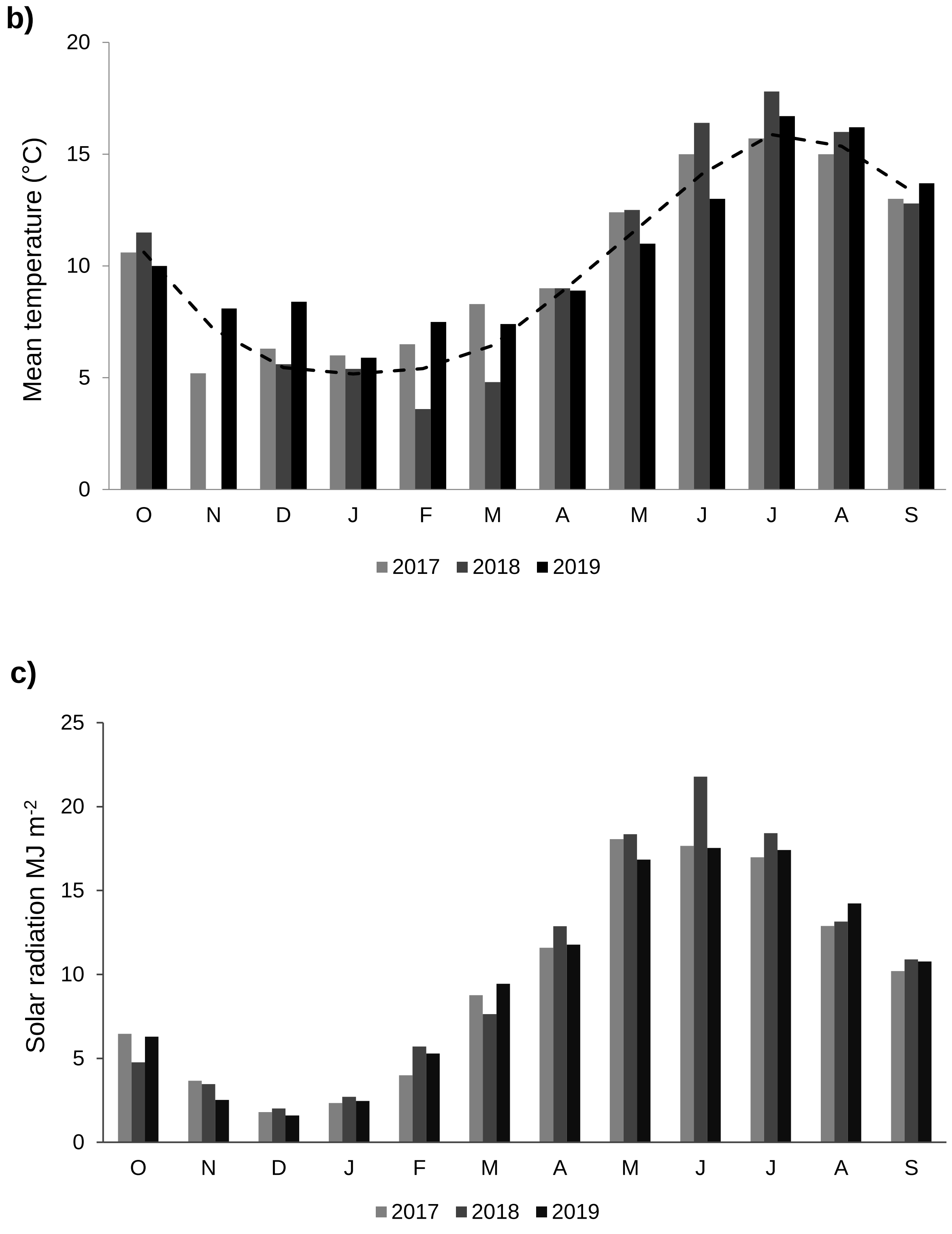


Figure 1. Meteorological data taken from the onsite weather station at Oak Park, Carlow showing a) monthly accumulated rainfall (mm); b) monthly mean temperature (°C); c) mean daily solar radiation (MJm^{-2}) from October to September across three

seasons 2017-2019. Dashed line shows monthly average from 2007-2019 (MetÉireann, 2019).

3.2 Yield

There were large differences in yield between the three seasons with average yields across sowing dates and varieties of 6.2 t ha^{-1}, 1.7 t ha^{-1} and 4.7 t ha^{-1} for 2017, 2018 and 2019, respectively ($P<0.001$). The impact of sowing date on yield across the three seasons and treatments can be seen in Figure 2. There were significant differences in yield between sowing dates, but the ranking changed between years ($P<0.001$). For the spring variety, in 2017, the October sowing yielded highest, followed by the November (netted), March and April sowings, with January and February yielding the lowest ($P<0.001$). In 2018, yields were much lower than in 2017 or 2019, with the October sowing producing the greatest yield ($P<0.001$). The January sowing date yielded less than February but there were no other significant differences. In 2019, February yielded the highest, followed by November and March, then October and January, with April giving the lowest yield in that year ($P<0.001$, Figure 2a).

For the winter variety, there was a strong interaction between year and sowing date ($P<0.001$). In 2017, there was no significant difference found in yield between the October and November sowing dates (Figure 2b). In 2018, the October sown treatment yielded more than the November sown treatment (Figure 2b). In 2019, the November sown crop yielded more than the October sown crop (Figure 2b).

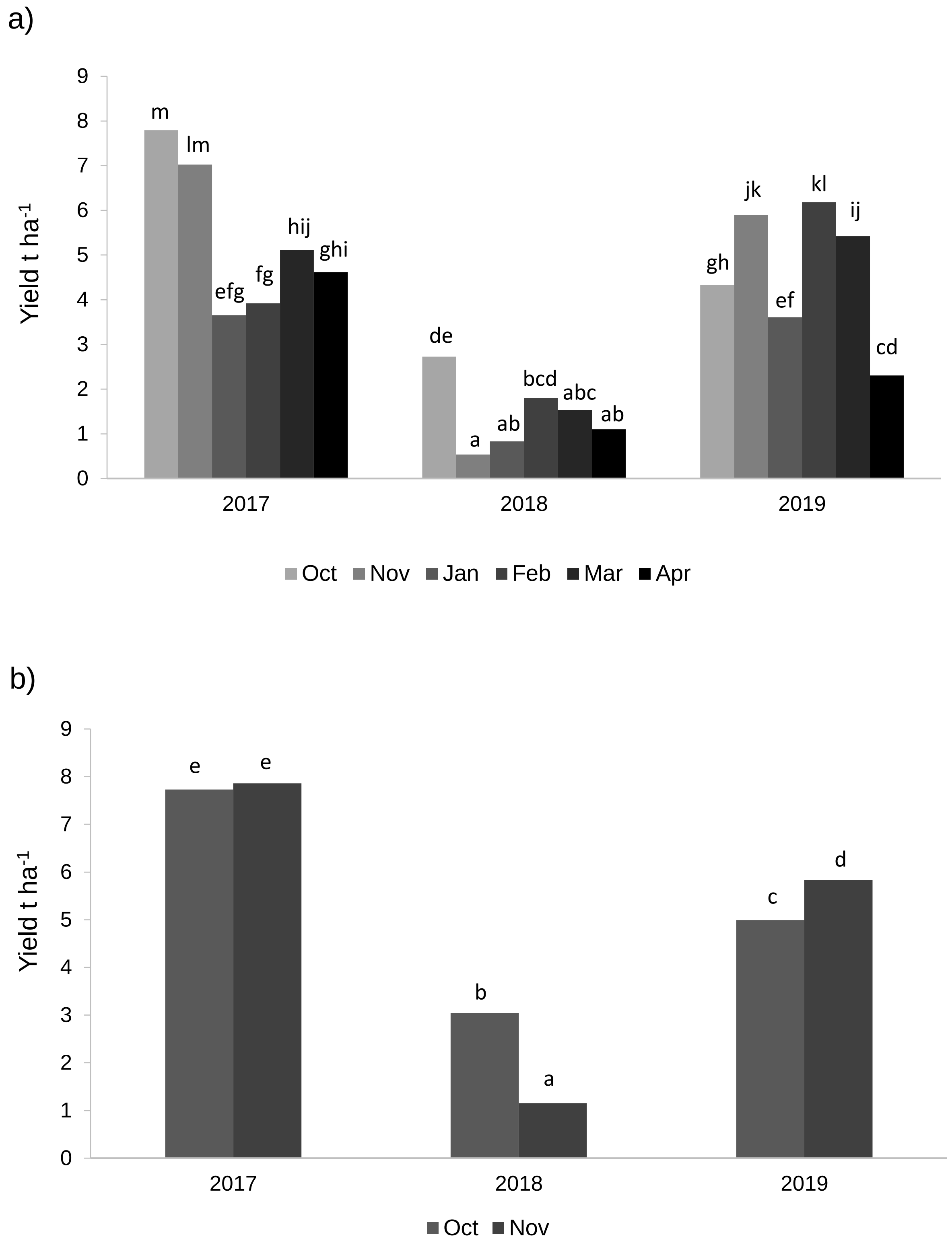


Figure 2. Average yield of a) October, November, January, February, March, and April sowings (l-r) for the spring variety (Fuego/Fanfare) and b) winter sown treatments in October and November for the winter variety (Wizard) over three seasons 2017-2019

at 15% moisture. Different letters represent significant differences (at 5.0%) between treatments using Fisher's unprotected LSD multiple comparison test.

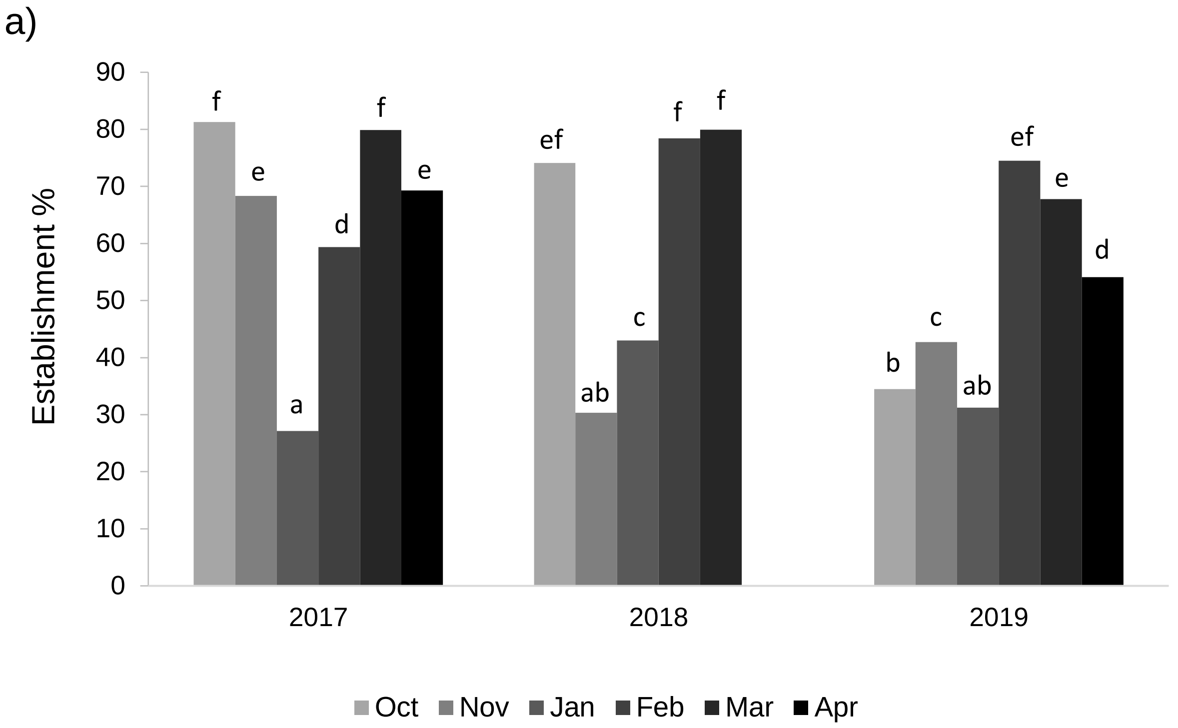
Yield increased significantly with seed rate between 20, 40 and 60 seeds m^{-2} in the spring sown treatments, with average values of 2.7 t ha^{-1}, 3.7 t ha^{-1}, and 4.1 t ha^{-1} respectively (P<0.001). Yield also increased with seed rate in the winter sown treatments, with average values of 4.5 t ha^{-1}, 5.3 t ha^{-1}, and 5.9 t ha^{-1} for 20, 40 and 60 seeds m^{-2}. This was supported in the broader seed range of 10 – 80 seeds m^{-2} sown in October and March, with average values of 3.5 t ha^{-1}, 4.3 t ha^{-1}, 5.3 t ha^{-1}, 5.8 t ha^{-1}, and 5.9 t ha^{-1}. Average values for yield for each year, sowing date, seed rate and variety are presented in Supplementary Table 1.

3.3 Crop Establishment

Because crop establishment dictates the plant population density, which is known to be a major factor in the determination of yield, it was important to study how this parameter varied with year, sowing dates, seed rates and variety. Averaged across sowing date (October - April), seed rate (20-60 seeds m^{-2}), and variety, overall establishment varied significantly between years with highest establishment in 2017 of 71%, compared to 60% in 2018 and 47% in 2019 (P<0.001).

For the spring variety, in 2017, October and March sowings established significantly better than the other sowing dates followed by April and November with January giving the poorest establishment. In 2018, October, February, and March established best, followed by January. There was no establishment data taken for April in 2018, due to severe weed infestation in plots at early growth stages. In 2019, February and March had the highest establishment followed by April. All of the earlier sowings (November, December, and January) had poor establishment (Figure 3a).

In the winter variety treatments, establishment varied with year (P<0.001), sowing date (P<0.001) and seed rate (P=0.009), in the 20-60 seeds m^{-2} range, with significant interactions found between year with sowing date (P<0.001) as presented in Figure 3b. In 2017 and 2018, the October sowing established significantly better than the November sowing (P<0.001). In 2019, the November sowing established higher than the October sowing (Figure 3b).



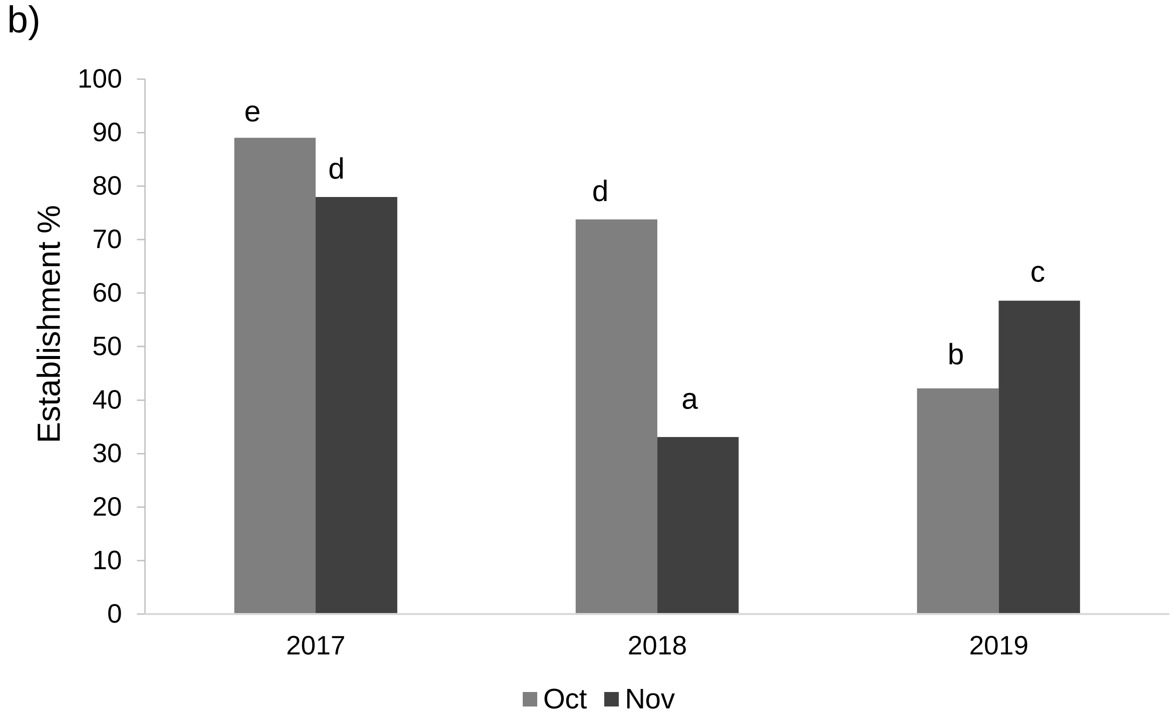


Figure 3. Average crop establishment of a) spring variety (cv. Fuego/Fanfare) treatments sown in October, November, January, February, March, and April (l-r)) and b) winter variety treatments (cv. Wizard) sown in October and November) over three

seasons 2017-2019. Different letters represent significant differences (at 5.0%) between treatments using Fisher's unprotected LSD multiple comparison test.

3.4 Variation of plant population with seed rate

As expected, plant population (plant m^{-2}) varied directly with the seed rate (seed m^{-2}), however, a large variation in the plant population from individual seed rates was achieved. Regression analysis using all data, with plant density as the dependent variable and seed rate as the independent variable, showed a linear relationship, with a slope of 0.60 ($P<0.001$) and intercept not significantly different from zero, that explained 64% of the variation. Further grouping of the data by years showed comparable slopes of 0.74 and 0.63, for 2017 and 2018, respectively, while a much lower slope of 0.43 was observed in 2019 ($P<0.001$). Grouping by years, explained 73% of the variation in plant density with seed rate.

Due to the large variation in establishment between years, sowing dates and seed rates, actual plant populations were used in the subsequent analysis rather than seed rate.

3.5 Economic optimum plant population

The relationship between plant population density and yield for the October winter and spring varieties and the March spring variety showed that generally as plant population increased, yield increased (Figure 4) until 20 plants per square metre for the October spring variety and 40 plants per square metre for the March spring variety with no significant difference found ($P>0.001$).

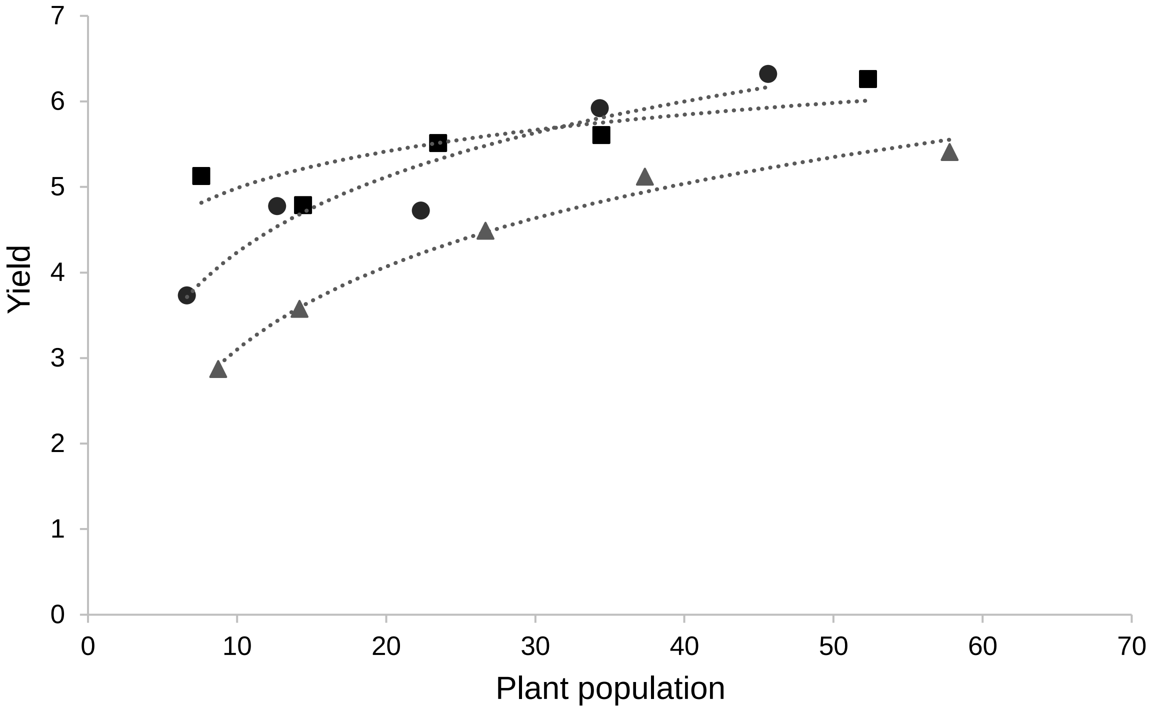
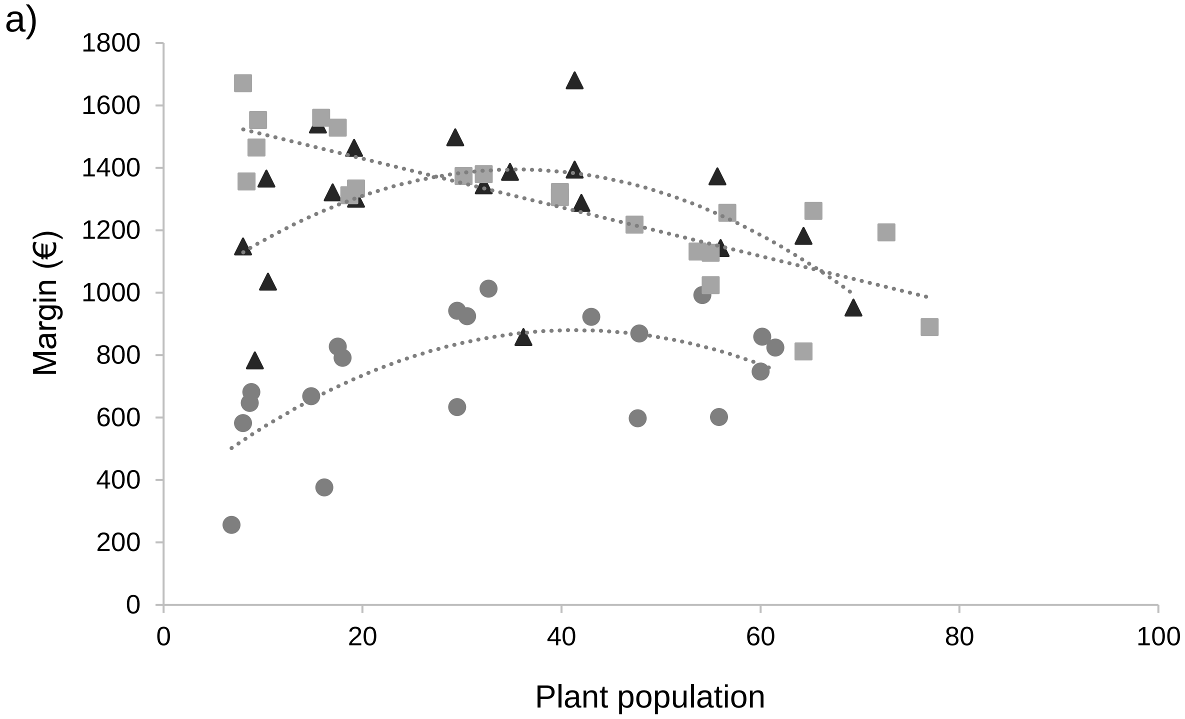


Figure 4. Relationship between plant population and yield, averaged across seed rates and years, 2017-2019, for October Fuego, October Wizard, and March Fuego

Fitted linear plus exponential curves for the winter and spring cultivar sown in October and the spring cultivar sown in March over the three seasons are given in Figure 7.

In 2017, the March sown Fuego gave an economic optimum plant population of 38 plants m^{-2}, and the October sown Fuego gave an optimum of 24 plants m^{-2}. For the October sown Wizard there was no increase in margin across the five seed rates and therefore no optimum could be calculated (Figure 7a). In 2018, due to extreme drought conditions causing the crop to senesce earlier than expected, the economic optimum was found to be lower than the lowest plant population in the experiment (Figure 7b). In 2019, the March sown Fuego gave an optimum plant population of 27 plants m^{-2}, the October sown Fuego gave an optimum plant population of 31 plants m^{-2}, and the October Wizard gave an optimum plant population of 13 plants m^{-2} (Figure 7c).

Overall, there was good consistency between years for each variety/sowing date combination, excluding the 2018 season. March and October (cv. Fuego) sown plots resulted in an optimum of 27-38 plants m^{-2} and 24-31 plants m^{-2} respectively. Giving an overall range of 24-38 for the spring variety across years. Wizard sown plots gave an economic optimum population of 13 plants m^{-2} in 2019 and could not be calculated in 2017 due to a flat response. This effectively means that the lowest plant population density (PPD) of 10 plants m^{-2} was the most cost effective that year.



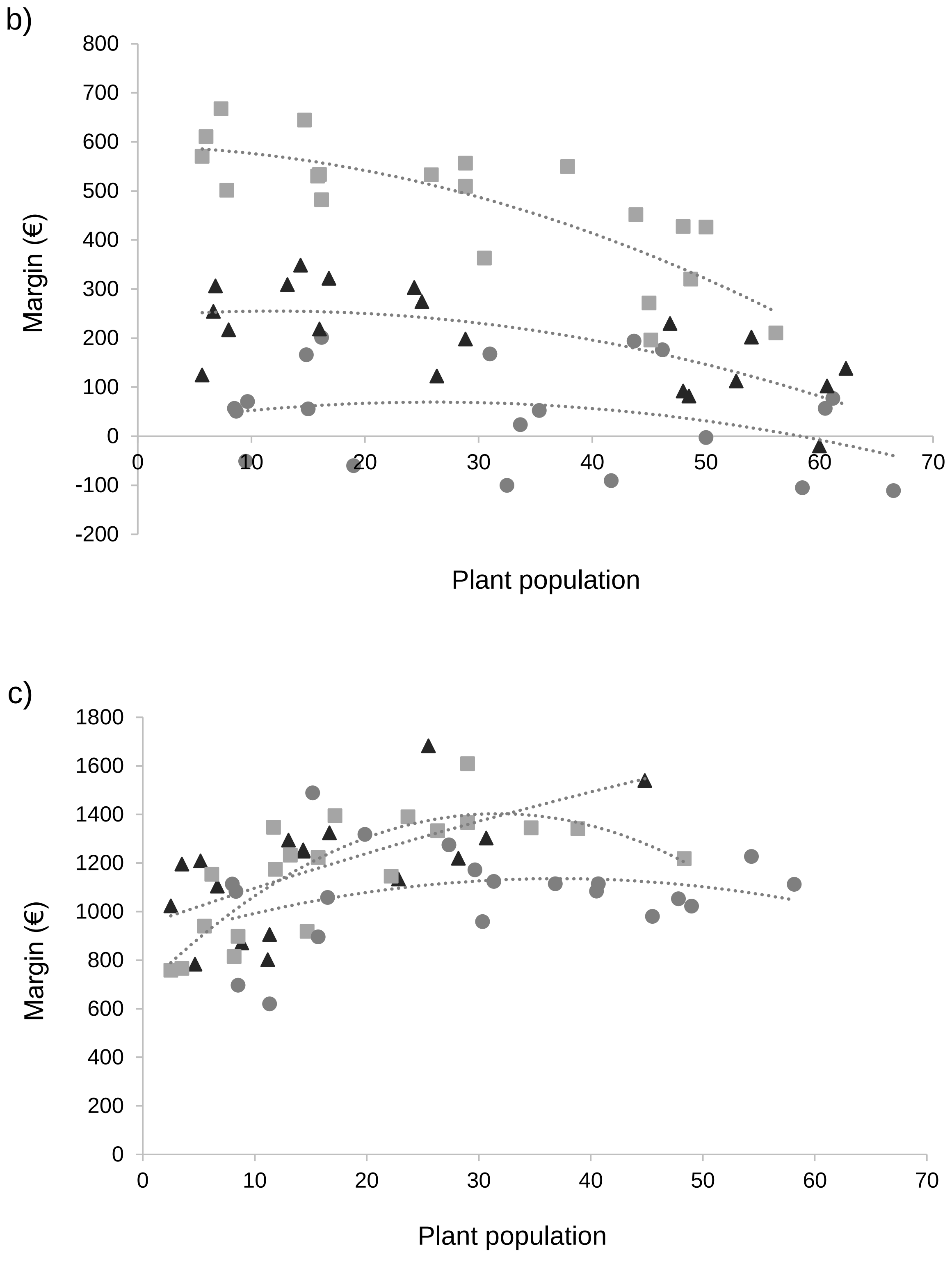


Figure 5. Linear + exponential curve fitting between gross profit margin (€/plant m^{-2}) and plant populations (plants m^{-2}) for October Fuego (▲), October Wizard (■) and March Fuego (●), across five seed rates for a) 2017, b) 2018 and c) 2019 season.

4. Discussion

In Ireland, the recommended sowing window for field beans is from the second week of October to mid-November for winter beans and the end of February to the end of March for spring beans (Teagasc, 2017). However, growers might sow later in winter or earlier/later in spring depending on sowing conditions, with the knowledge that early sown crops are more susceptible to bird damage and high disease pressure.

The consistently poor establishment in late winter and early spring sowings was related to bird damage, wet ground conditions during sowing and colder weather. This is contrary to Loss et al. (1998a), who attributes poor establishment to physical damage to the seed caused by harvest, cleaning, and mechanical sowing. Establishment was also lower than the overall establishment rate of 71% reported for 19 field experiments conducted by Loss et al. (1998a) over 3 years in south-western Australia but with similar variation between years. There was no difference in establishment between sowing in October and November in 2017 but the October sowing established significantly better in 2018. Later winter sowings risk bird damage and wetter ground conditions which often negatively impacted establishment. Sowing in March generally gave better establishment rates for spring varieties. February and April sowings gave inconsistent results which varied year to year due to bird damage in the former and wet ground conditions when sowing in the latter.

Bird damage was clearly seen when comparing establishment in plots sown in November 2017, 2018 and 2019. The 2017 November sown plots were covered by netting giving establishment values of 73% compared to 32% in 2018 and 51% in 2019 when the plots were not netted. In January, combined effects of wet conditions and/or bird damage resulted in establishment values below 43%. Poor establishment in April sown plots in 2018 and 2019 may be related with wet conditions at sowing as well as weed growth in the plots during early crop growth.

Previous studies have found that sowing date has a significant influence on biomass production, grain yield and yield components (Confalone et al., 2010). The six sowing dates across the three seasons provided a wide range of environmental conditions for the performance of the crop which was found to be a contributing factor for the final crop yield. Field bean yield was poorest in 2018 when lower than average precipitation from pre-flowering to harvest reduced the national average yield from 6.7 t ha^{-1} in 2017 to 2.5 t ha^{-1} (Teagasc, 2018). Yield in this study averaged 1.7 tha^{-1} in 2018 compared to 6.2 t ha^{-1} in 2017 and 4.7 t ha^{-1} in 2019. The hot, dry conditions in 2018 accelerated the flowering period and stunted crop growth, with the crop receiving 111.8 mm of rainfall over this growth period compared to the long-term average of 276.7 mm. This was most notably detrimental in June 2018, during the crop's flowering period, when the crop received 5.2 mm of rain compared to 67.8 mm long term average for the month of June.

In 2017, when the November-sown plots were netted to prevent bird damage, October and November-sown plots had comparable yields. In 2018, October-sown plots yielded significantly more than those sown in November when not netted. However, in 2019, November-sown plots yielded 5.9 t ha^{-1} compared to 4.7 t ha^{-1} for those sown in October. February, March, and April gave comparable yields, with March generally yielding the highest for the spring sown treatments across the three years, except for 2019 when February yielded the most. January typically gave the worst conditions for sowing. Ground conditions were not optimum, resulting in very damp, large aggregated soil after ploughing, making it difficult to reach the required seed depth of 7-10 cm. For autumn sowings the recommended window by the Department of Agriculture, Food and Marine (DAFM) of October to November seems correct but it is important to have the correct conditions for sowing and control bird damage in later winter sowings. For spring sowing there seems to be quite a wide window from February to April with good ground conditions for ploughing and sowing probably being more important than the actual sowing date. Several studies have shown the effect of sowing date on field beans in different countries. McVetty et al. (1986) found that in Western Canada, sowing date was a more important factor than seed rate in affecting final yield. Other parts of Europe such as France, recommended an early sowing in spring to avoid water stress and high temperatures during the flowering period and pod setting (Berthelem, 1980), whereas in southern Italy, with a much warmer, semi-arid climate, an autumn sowing is preferred to a spring sowing, allowing a longer growing season and better utilisation of water, often resulting in higher yields (Ziliotto and Toniolo, 1979).

A key component of yield is the number of plants per square metre (López-Bellido et al., 2005). Considering the variation in crop establishment over the three years, yield was examined against plant populations instead of seed rate. There were significant interactions found between plant populations with year, variety, and sowing date. The general trend showed that as plant populations increased, yield increased. The exception for this was found in 2017 for the winter variety when no significant difference was found in yield with plant populations ranging from 12 – 57 plants per m^{-2}. This agrees with previous work (Sprent et al., 1977, Pilbeam et al., 1991a, Robinson and Conley, 2007), which reported that at low plant populations, yield can be maintained as the crop is able to compensate through physiological processes such as branching and increased leaf area per plant. The variation in yield response to sowing date between years could be due, at least in part, to variation in crop establishment with the same seed rate achieving different plant densities in each year.

As far as we are aware, this is the first study to examine the effect of plant populations on profitability of field bean production in Ireland. Although the estimated economic optimum plant population varied across the three seasons, from 24 - 38 plants m^{-2} in 2017 to 28 - 31 plants m^{-2} in 2019 for the spring variety and 13 plants m^{-2} in 2019 for the winter variety, the current study shows that the yield and profits of field bean crops in Ireland will not improve by increasing seed rate. The results from this study show that the estimated economic optimum for the spring variety generally falls in the recommended range of 25-30 plants, taking into account 25-37.5% field losses after sowing (DAFM, 2020), suggesting that sowing higher than the recommended 40 seeds m^{-2} for spring beans will not increase yields or profits for field bean crops. For the winter variety however, the optimum of 13 plants m^{-2} or less falls below the recommendations, suggesting that there may be an opportunity to lower plant populations in winter sowings, resulting in lower seed costs for growers. In contrast to this, in Australia studies by Loss et al. (1998a) found a mean economic optimum plant population of 45 plants m^{-2}. This indicates that in Ireland's temperate maritime climate the crop is better able to compensate for lower plant populations, presumably due to cooler conditions in Ireland providing more time for compensatory growth.

In conclusion, field bean yields were found to be variable from year to year due to ground conditions at sowing, crop establishment and environmental factors throughout crop growth and development, with low water availability being the most detrimental to final yield as seen in the 2018 season. With October generally yielding highest for the winter sown treatments and February/March for the spring sown treatments, it is recommended to aim for these sowing dates when planting field beans in Ireland. The economic optimum plant populations after field losses for spring beans range from 24 – 38 plants m^{-2}, and 13 plants m^{-2} or less for winter beans. This coincides with the current recommendations for spring beans from the Department of Agriculture, Food and Marine, to sow 40 seeds m^{-2} to achieve 25-30 plants m^{-2}, but there may be an opportunity to reduce the plant population of winter beans without affecting final yield and profits. This study confirms that in Ireland, there is no benefit to sowing higher plant populations than currently recommended, as no profit is gained from higher sowing rates; indeed, it may be possible to improve profitability of winter sown crops by reducing seed rate with no negative impact on yield.

5. Acknowledgments

This work was supported by the Walsh Scholars Association and the Irish Farmers Association. The authors would like to acknowledge the Teagasc farm manager, farm staff, technicians and summer interns for their help in this study. A particular thanks to Kevin Murphy and Frank Ryan for their constant help and support throughout the entirety of this project.

6. References

Adisarwanto, T. & Knight, R. 1997. Effect of sowing date and plant density on yield and yield components in the faba bean. *Australian Journal of Agricultural Research,* 48**,** 1161-1168.

Baldwin, B. 1980. Time of sowing-a major factor influencing the yields of Vicia faba in South Australia. *FABIS newsletter*.

Berthelem, P. 1980. The major agronomic problems of the cultivation of faba bean (Vicia faba L.) in France. *FABIS Newsletter (ICARDA)*.

Confalone, A., Lizaso, J. I., Ruiz-Nogueira, B., López-Cedrón, F.-X. & Sau, F. 2010. Growth, PAR use efficiency, and yield components of field-grown Vicia faba L. under different temperature and photoperiod regimes. *Field Crops Research,* 115**,** 140-148.

CSO. 2020. *Area, Yield and Production of Crops* [Online]. CSO Ireland. [Accessed 09/09/2020 2020].

DAFM. 2020. *Field Beans Recommended List 2020* [Online]. Department of Agriculture. Available: https://www.agriculture.gov.ie/media/migration/publications/2020/1SpringBeanRecommendedList2020130120.pdf [Accessed 20/08 2020].

Green, C., Paulson, G. & Ivins, J. 1985. Time of sowing and the development of winter wheat. *The Journal of Agricultural Science,* 105**,** 217-221.

Kirby, E. 1969. The effect of sowing date and plant density on barley. *Annals of Applied Biology,* 63**,** 513-521.

Lancashire, P. D., Bleiholder, H., Boom, T. V. D., Langelüddeke, P., Stauss, R., Weber, E. & Witzenberger, A. 1991. A uniform decimal code for growth stages of crops and weeds. *Annals of Applied Biology,* 119**,** 561-601.

López-Bellido, F. J., López-Bellido, L. & López-Bellido, R. J. 2005. Competition, growth and yield of faba bean (Vicia faba L.). *European Journal of Agronomy,* 23**,** 359-378.

Loss, S., Siddique, K., Jettner, R. & Martin, L. 1998a. Responses of faba bean (Vicia faba L.) to sowing rate in south-western Australia I. Seed yield and economic optimum plant density. *Australian Journal of Agricultural Research,* 49**,** 989-997.

Loss, S., Siddique, K., Martin, L. & Crombie, A. 1998b. Responses of faba bean (Vicia faba L.) to sowing rate in south-western Australia II. Canopy development, radiation absorption and dry matter partitioning. *Aust. J. Agric. Res,* 49**,** 999-1008.

McVetty, P., Evans, L. & Nugent-Rigby, J. 1986. Response of faba bean (Vicia faba L.) to seeding date and seeding rate. *Canadian journal of plant science,* 66**,** 39-44.

MetÉireann. 2019. *Met Éireann historical data* [Online]. Met Éireann. Available: https://www.met.ie/climate/available-data/historical-data [Accessed 2019].

Pilbeam, C. J., Duc, G. & Hebblethwaite, P. D. 1990. Effects of plant population density on spring-sown field beans (Vicia faba) with different growth habits. *The Journal of Agricultural Science,* 114**,** 19-33.

Pilbeam, C. J., Hebblethwaite, P. D., Nyongesa, T. E. & Ricketts, H. E. 1991. Effects of plant population density on determinate and indeterminate forms of winter field beans (Vicia faba) 2. Growth and development. *The Journal of Agricultural Science,* 116**,** 385-393.

Robinson, A. P. & Conley, S. P. 2007. Plant populations and seeding rates for soybeans. https://www.extension.purdue.edu/extmedia/ay/ay-217-w.pdf: Purdue Univ., West Lafayette, IN. .

Spink, J. H., Semere, T., Sparkes, D. L., Whaley, J. M., Foulkes, M. J., Clare, R. W. & SCOTT, R. K. 2000. Effect of sowing date on the optimum plant density of winter wheat. *Annals of Applied Biology,* 137**,** 179-188.

Sprent, J. I., Bradford, A. M. & Norton, C. 1977. Seasonal growth patterns in field beans (Vicia faba) as affected by population density, shading and its relationship with soil moisture. *The Journal of Agricultural Science,* 88**,** 293-301.

Teagasc 2016. *Major and micro nutrient advice for productive agricultural crops,* Johnstown Castle, Enviromental Research Centre, Co. Wexford.

Teagasc. 2017. *Field Beans* [Online]. Available: https://www.teagasc.ie/crops/crops/research/research-programme/cropquest/field-beans/ [Accessed 05/08 2020].

Teagasc 2018. Teagasc Specialist, Tillage CROPS Report, Harvest Report.

Ziliotto, U. & Toniolo, L. 1979. Field trials on time of sowing field beans (Vicia faba var. minor) and broadbeans (Vicia faba var. major) at Padova in 1976 and 1977. *Some current research on Vicia faba in Western Europe, edited by DA Bond, GT Scarascia-Mugnozza and MH Poulsen; sponsored by the Commission of the European Communities, Directorate-General for Agriculture, Coordination of Agricultural Research*.

7. Supplementary material

Supplementary table 1. Average yield for sowing dates, seed rates and varieties for three seasons 2017,2018 and 2019.

Harvest Year	Sowing date	Seed rate	Variety	Average yield
2017	Apr	20	Fuego	3.85
2017	Apr	40	Fuego	4.64
2017	Apr	60	Fuego	5.36
2017	Feb	20	Fuego	3.32
2017	Feb	40	Fuego	4.07
2017	Feb	60	Fuego	4.70
2017	Jan	20	Fuego	2.43
2017	Jan	40	Fuego	3.86
2017	Jan	60	Fuego	4.65
2017	Mar	10	Fuego	2.96
2017	Mar	20	Fuego	3.89
2017	Mar	40	Fuego	5.46
2017	Mar	60	Fuego	5.98
2017	Mar	80	Fuego	5.98
2017	Nov	20	Fuego	6.16
2017	Nov	40	Fuego	7.50
2017	Nov	60	Fuego	7.40
2017	Oct	10	Fuego	5.65
2017	Oct	20	Fuego	7.54
2017	Oct	40	Fuego	7.48
2017	Oct	60	Fuego	8.35
2017	Oct	80	Fuego	8.32
2018	Feb	20	Fuego	1.08
2018	Feb	40	Fuego	1.72
2018	Feb	60	Fuego	2.49
2018	Jan	20	Fuego	0.51
2018	Jan	40	Fuego	0.73
2018	Jan	60	Fuego	1.13
2018	Mar	10	Fuego	0.64
2018	Mar	20	Fuego	1.07
2018	Mar	40	Fuego	1.45
2018	Mar	60	Fuego	2.09
2018	Mar	80	Fuego	2.28
2018	Nov	20	Fuego	0.13
2018	Nov	40	Fuego	0.51
2018	Nov	60	Fuego	0.56
2018	Oct	10	Fuego	1.36

2018	Oct	20	Fuego	3.27
2018	Oct	40	Fuego	2.10
2018	Oct	60	Fuego	3.44
2018	Oct	80	Fuego	2.79
2019	Mar	10	Fuego	5.02
2019	Mar	20	Fuego	5.17
2019	Mar	40	Fuego	6.10
2019	Mar	60	Fuego	7.33
2019	Mar	80	Fuego	7.96
2019	Oct	10	Fuego	4.19
2019	Oct	20	Fuego	5.82
2019	Oct	40	Fuego	6.52
2019	Oct	60	Fuego	7.68
2019	Oct	80	Fuego	7.86
2019	Apr	20	Fanfare	1.87
2019	Apr	40	Fanfare	2.53
2019	Apr	60	Fanfare	2.52
2019	Feb	20	Fanfare	5.54
2019	Feb	40	Fanfare	6.38
2019	Feb	60	Fanfare	6.62
2019	Jan	20	Fanfare	2.35
2019	Jan	40	Fanfare	3.58
2019	Jan	60	Fanfare	4.57
2019	Mar	20	Fanfare	4.18
2019	Mar	40	Fanfare	4.93
2019	Mar	60	Fanfare	5.08
2019	Nov	20	Fanfare	4.11
2019	Nov	40	Fanfare	6.84
2019	Nov	60	Fanfare	6.70
2019	Oct	20	Fanfare	2.47
2019	Oct	40	Fanfare	2.79
2019	Oct	60	Fanfare	4.21
2017	Nov	20	Wizard	7.90
2017	Nov	40	Wizard	7.71
2017	Nov	60	Wizard	7.96
2017	Oct	10	Wizard	7.63
2017	Oct	20	Wizard	7.63
2017	Oct	40	Wizard	7.73
2017	Oct	60	Wizard	7.82
2017	Oct	80	Wizard	7.76
2018	Nov	20	Wizard	1.08
2018	Nov	40	Wizard	0.67
2018	Nov	60	Wizard	1.47
2018	Oct	10	Wizard	3.12
2018	Oct	20	Wizard	2.04
2018	Oct	40	Wizard	3.49

2018	Oct	60	Wizard	2.51
2018	Oct	80	Wizard	3.64
2019	Oct	10	Wizard	4.63
2019	Oct	20	Wizard	6.45
2019	Oct	40	Wizard	6.66
2019	Oct	60	Wizard	6.81
2019	Oct	80	Wizard	7.40
2019	Oct	20	Wizard	3.03
2019	Oct	40	Wizard	4.17
2019	Oct	60	Wizard	5.30
2019	Nov	20	Wizard	4.98
2019	Nov	40	Wizard	5.64
2019	Nov	60	Wizard	6.82

Chapter 3

Yield of field beans (*Vicia faba*) is determined by light interception during the pod development phase

This chapter has been prepared as a journal article but has not yet been submitted for review.

Yield of field beans *(Vicia faba)* is determined by light interception during the pod development phase

L.C. Murphy[1,2], S. Alves[1*], J.H. Spink[1] and D.L. Sparkes[2]

[1] Teagasc, Crops, Environment & Land Use Programme, Oak Park Crops Research Centre, Carlow, Ireland

[2] University of Nottingham, Sutton Bonington, Loughborough, LE12 5RD, United Kingdom

Abstract

This paper reports the results of three years of field experiments (2017-2019), carried out in Teagasc Oak Park, Carlow, examining the effect of sowing date and plant population on yield and yield components in two varieties of field beans, cv. Wizard and cv. Fuego. The aim of this study was to understand the impact of canopy size on yield of beans by creating a range of canopies using seed rates, sowing dates and varieties. The second part of this study aimed to identify the key components of yield in field beans and the mechanisms by which they are determined.

Across the three years, there was a strong, linear relationship between pod number and final yield of beans. In most cases, pod number was linearly related to green area index during the pod development phase but, for crops sown in winter 2016, which had very large GAIs during pod development, this relationship was not found. This led to the hypothesis that light interception during the pod development phase determined pod number and thereby yield. Our shading experiment supported this when incident light was reduced by 60% during flowering/early pod development, yield was reduced by 27%, resulting from a 38% reduction in pod number which was compensated by a 14% increase in seed size.

Keywords: Time of sowing, Seed rate, Agronomy, Physiology, Yield components, Field beans

*corresponding author

Email address: Sheila.Alves@teagasc.ie

1. Introduction

Field beans *(Vicia faba)*, also known as faba beans or broad beans, are a major source of protein and play a key role in human and animal diets worldwide, as well as having the benefit of being an efficient break crop in arable rotations. Field beans have been found to improve soil fertility and biodiversity and help to reduce the occurrence of weeds, diseases and pests (Mwanamwenge et al., 1998).

One characteristic that is well recognised of field beans is the considerable and unpredictable year-on-year variation in seed yield (López-Bellido et al., 2005). They are vulnerable to biotic and abiotic stresses which can lead to low profitability and unreliable yields (Mwanamwenge et al., 1998). Yield variation has been reported to be associated with variation in pod and seed number (Kambal, 1969b, Pilbeam et al., 1989).

Yield is a complex characteristic, defined by numerous yield components. Yield component studies in crops such as wheat, oilseed rape and other grain legumes such as soybeans are well supported (Carpenter and Board, 1997a, Whaley et al., 2000, Berry and Spink, 2006, Roques and Berry, 2016). It has been established in wheat that yield is mainly determined by grain number per unit area, whereas Berry and Spink (2006) found that yield in oilseed rape is split into two main components: seed number/m^2 and individual seed weight and concluded that yield is maximised by the production of 6000-8000 pods/m^2. Carpenter and Board (1997a) reported that the main determinant of yield in soybean was pods per plant.

The study of yield components in field beans has received less attention than in other crops. In 1955, Rowland determined that the primary components of yield in field beans were number of pods per plant, number of seeds per pod and seed size. Kambal (1969a) and Husain et al. (1988) agreed with this, reporting pod number per plant as having consistently strong correlations with yield. Kambal (1969a) also found that these primary yield components are influenced by the first flower and podding node, number of nodes per plant, plant height and number of branches. They also reported that between 95 – 98% of yield variability was explained by seed number, pod number and seed size. However, Salih and Salih (1980) found that there was no relationship between seed size and final yield, with pod number explaining most of the variation in yield.

Examining the effect of plant density on yield components in field beans, Pandey (1981) found a significant decrease in pods per plant at high densities with number of seeds per pod and seed size unaffected. Bean plants adapt to their surroundings, and when plant populations are lowered, they increase their leaf area by producing branches which allows each plant to produce more pods. This plasticity means that low plant populations can often produce similar yields to higher populations (López-Bellido et al., 2005, Robinson and Conley, 2007). The plasticity of field beans in response to variations in density depends largely on the duration of the vegetative and reproductive stage of the crop. The weather conditions during vegetative growth also have an impact on this plasticity, especially temperature and water availability during this critical growth phase (López-Bellido et al., 2005). Stresses such as drought and nutrient deficiency reduce the rate of canopy expansion and with more severe stress to the crop, radiation use efficiency can also be decreased (Lake et al., 2019). López-Bellido et al. (2005) noted that at low plant densities, the number of stems per plant increased over the crop cycle, while at higher plant densities, the number decreases; the higher the density, the faster the decrease. Similarly, in soybeans, Carpenter and Board (1997b) found that as soybean plant population changed the main driver of yield was pods per plant, with little change in seed size or seeds per pod.

In wheat, Whaley et al. (2000) found that as plant density was reduced, grain number per ear increased. Whaley also found that planting density affected the potential sink size of the crop as early as the formation of the spikelet primordia and that more spikelets were initiated at lower plant densities compared with higher plant densities. An 18-fold reduction in plant density of winter wheat led to only a six-fold reduction in green area index (GAI) at GS31. The lower plant populations had increased their GAI by this stage mainly through a prolonged tillering phase. As the season progressed, the differences in GAI between the high and low plant densities were proportionately reduced through an increase in green area per shoot, extended duration of tillering and increased shoot survival enabling low plant densities to achieve a similar yield as high densities (Whaley et al., 2000). They concluded that both radiation capture and radiation use improved when the crop was grown at reduced plant densities. In oilseed rape, Lunn et al. (2003) found that at flowering the optimum canopy structure of oilseed rape was a GAI of about 4, where three units were leaf and one unit was stem.

López-Bellido et al. (2005) concluded that to better understand the plasticity of field beans, further research is required into the development of number of pods per plant, which they considered is the product of three components: number of stems per plant, number of podding nodes per stem and number of pods per podding node.

This current study utilised a combination of variety, sowing date and seed rate to create a range of field bean canopies with the aim of understanding the impact of canopy size on yield. A further aim was to identify the key components of yield and the mechanisms by which they are determined.

This chapter focuses on hypothesis 4 and 5:

4. Yield of *Vicia faba* is primarily driven by pod number.
5. *Vicia faba* are predominantly source-limited.

2. Materials and methods

2.1 Experimental design

Field trials were carried out for three consecutive years in Teagasc, Oak Park, Carlow, Ireland. Crops were rotated according to the farm rotation with the experiments following oats in 2016, spring barley in 2017, and winter barley in 2018. All sites had sufficient P and K, with organic matter ranging from 3.9-4.8% and pH ranging from 6.4-7.1.

The experiments were arranged in a randomised, split-split plot design with four complete replications. The main plot treatment was time of sowing (TOS), sub plot treatment was seed rate (SR) and sub-sub plot treatment was variety. Plot size was 5m x 24m, which was split in half lengthways (2.5m x 24m); one side of the plot was used for destructive samples and the other side for combine yield.

2.2 Field trials

Field trials consisted of six sowing dates from October to April, five seed rates between 10 and 80 seeds m^{-2} and two varieties, Wizard (winter variety) and Fuego (spring variety). This paper will focus on the October and March sowing dates. Sowing dates were between 21 and 25 October and the 20 and 21 March each year.

Trials were sown with a conventional plough and one pass power harrow system. Plots were sown using a Wintersteiger plot drill (Wintersteiger AG, Austria), which was tractor-mounted, for precision sowing of smaller research plots. The seed was drilled approx. 7-10 cm deep. A prophylactic programme of chemicals was used to minimise weeds, pests, and diseases throughout the season.

A supplementary experiment (Figure 1.) was carried out in 2018-2019 where March sown plots had superimposed shading treatments. The plots were sown at a commercial seed rate of 40 seeds m^{-2} using cv. Fuego, using a plough and one pass system. The plots were shaded by an open weave polystyrene shade netting material which was attached to a 2m x 3m metal frame, suspended 0.5m above the crop canopy using rope tied to 1.2 m high stakes. This netting material blocked c.60% of the incident. Plots were shaded through two critical growth stages: vegetative growth and flowering. Shades were erected above the plots at the second/third leaf stage (GS 13; BBCH growth scale) and shaded throughout the vegetative period until flower buds were visible (GS 51) when the shade was removed. The shades were moved to the second shade timing, the flowering phase, which was shaded from the opening of the first flowers (GS60) until the end of flowering/start of pod development (GS 69).

Figure 1. Supplementary shading experiment: shades placed over the crop through the vegetative phase (top) and reproductive phase (bottom) reducing the radiation intercepted by the crop by c.60%.

2.3 Sampling method

Destructive samples (2x1 m²) were taken at five developmental stages: vegetative growth, flowering, pod development, pod fill and pre-harvest. The samples were taken to the laboratory for further analysis. Due to drought conditions and subsequent early ripening, there were only four samples, including pre-harvest, taken during the 2017-2018 growing season.

Using the same methodology, samples were taken from the supplementary shading trial. A sample was taken from the plot before the shade was put in place. Once the shade was removed, a sample was taken from the middle area under the shade, to avoid an edge effect and from an unshaded area of the plot. A preharvest sample was also taken at the end of the season from the area that was shaded and an unshaded area of the plot.

2.4 Laboratory analysis

In the laboratory, the full sample was weighed, the total numbers of stems counted, then c.20% of the total fresh weight was taken as a subsample for further analysis. The total number of stems in the subsample was counted before the sample was broken down into its individual yield components of leaf and stem, and pod, and seed in the later samples. The fresh weights of each individual component were weighed using a two-decimal balance (OHAUS, Switzerland). Pods were then counted. Leaf and stem material were passed through an image analysis system (Delta-T Devices Ltd, Cambridge, UK), that allowed the green area of the leaf and stem to be measured using the accompanying software WinDIAS. Each component was then bagged, labelled then placed in a drying oven at 70ºC until constant weight. In the pre-harvest sample only, 50% of the pods from the subsample were opened and the seed removed, counted, weighed, and dried until constant weight and reweighed.

2.5 Combine harvest

Plots were harvested mid-September each year when the crop was dry, black, and seed was hard using a plot combine (Deutz-Fahr, Germany). A minimum area of 52-57 m^2 was harvested from each plot. As plots were harvested, moisture and weight were recorded on an attached handheld computer (Allegro, Juniper Systems, Austria) with accompanying software (Field Research Software (FRS) for GrainGage, Juniper systems, Austria).

2.6 Statistical analysis

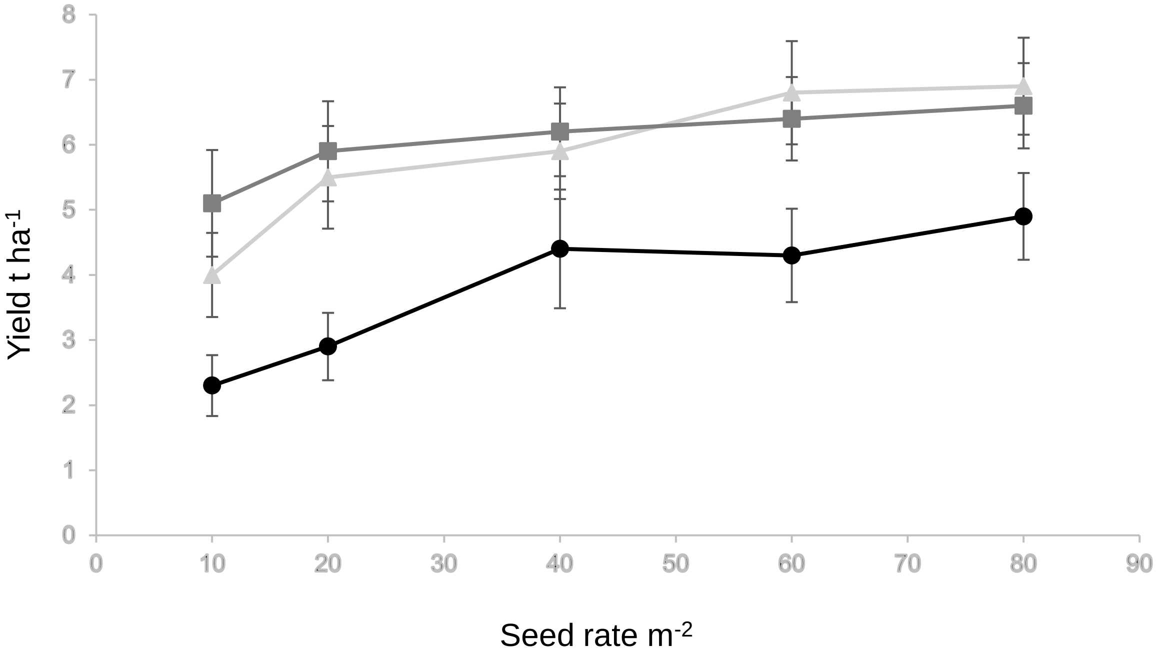
Analysis of variance (ANOVA) appropriate for the split-split plot design and linear regression analyses were carried out using the statistical software GenStat, version 20 from VSN International and Microsoft Excel, Office 365 from Microsoft Corporation.

3. Results

3.1 Yield

When combine yield was averaged across the three years, the October sown plots yielded more than the March sown plots (Figure 2a; $P<0.001$). The October sown treatments showed an increase in yield until 20 seeds m^{-2} before reaching a plateau while the March sown treatments increased until 40 seeds m^{-2} and then plateaued. The pattern was very similar with the quadrat yields but with more variation, as would be expected given the smaller sample area (Figure 2b).

a)



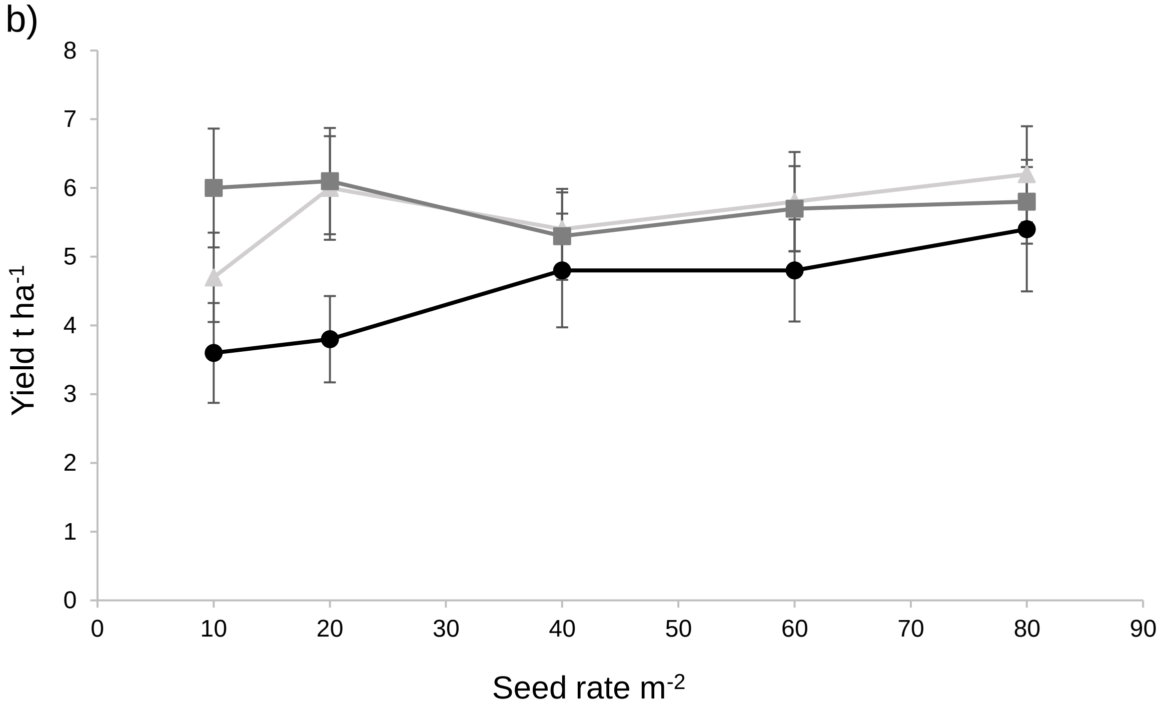


Figure 2. a) Combine yield of October sown Wizard (■),October sown Fuego (▲) and March sown Fuego (●) for five seed rates (10, 20, 40, 60 and 80 seeds m^{-2}); b) Quadrat yield of October sown Wizard (■), October sown Fuego (▲) and March sown Fuego (●)for five seed rates (10, 20, 40, 60 and 80 seeds m^{-2}). Error bars show standard error of means.

While the response to seed rate was similar in all three years, the average yield was significantly different between years (P<0.001; Table 1).

Table 1. Combine yield over three seasons for the three sowing date/variety combinations, 2017-2019.

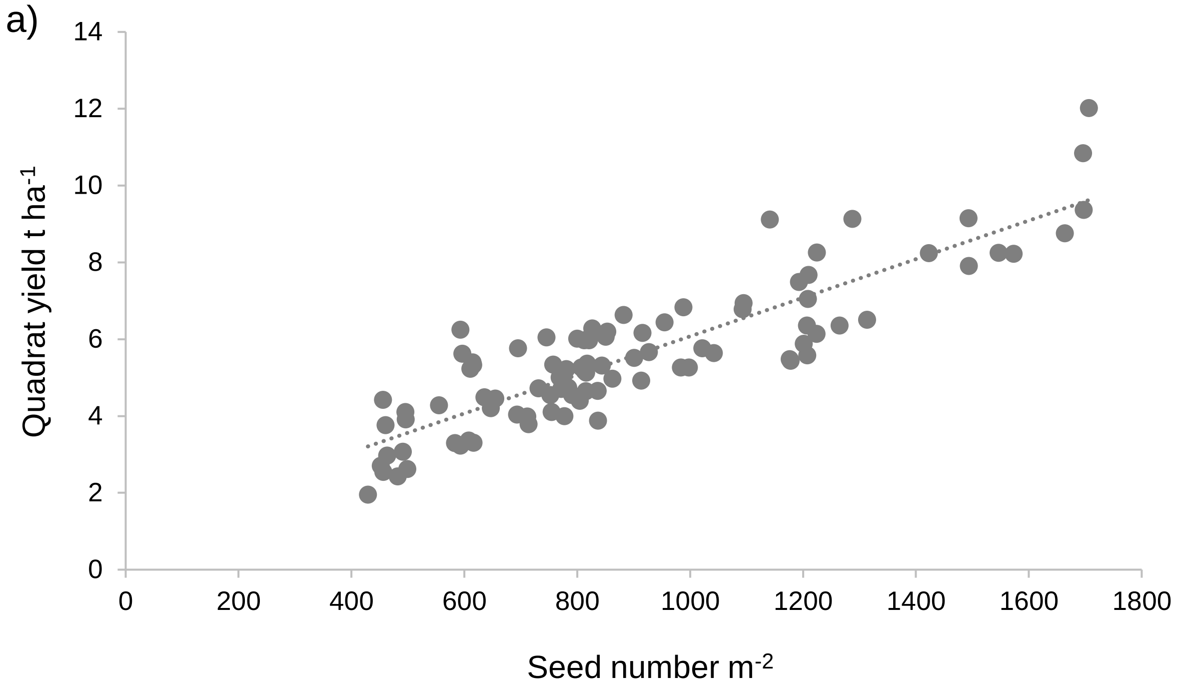
Sowing date/variety	2017	2018	2019
October cv. Wizard	8.6	3.1	6.4
October cv. Fuego	8.3	2.7	6.4
March cv. Fuego	6.0	1.5	3.8
Mean	7.63	2.43	5.53
P value	<0.001	<0.001	<0.001

Due to the differences between combine and quadrat yield, all yield component analysis is based on the quadrat samples.

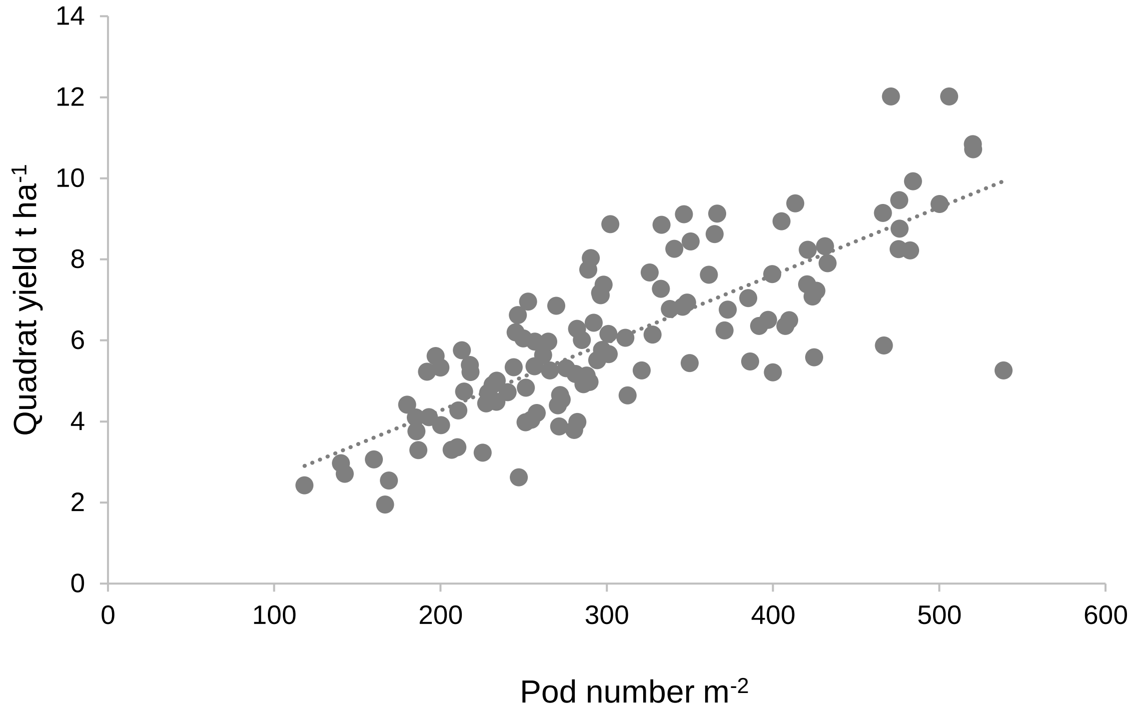
3.2 Yield components

Yield of October sown field beans was linearly related with seed number m^{-2} (P<0.001, R^2= 0.77; Figure 3a) and pod number m^{-2} (P<0.001, R^2=0.62; Figure 3b). For the March sown field beans, the relationship between yield and seed number m^{-2} and yield with pod number m^{-2} was linear up to c.800 seeds m^{-2} (P<0.001, R^2=0.76; Figure 3c) and c.250 pods m^{-2} (P<0.001, R^2=0.72; Figure 3d) when it was then found to plateau.

a)


14
12
10
8
6
4
2
0
Quadrat yield t ha^{-1}
0
200
400
600
800
1000
1200
1400
1600
1800
Seed number m^{-2}

b)


14
12
10
8
6
4
2
0
Quadrat yield t ha^{-1}
0
100
200
300
400
500
600
Pod number m^{-2}

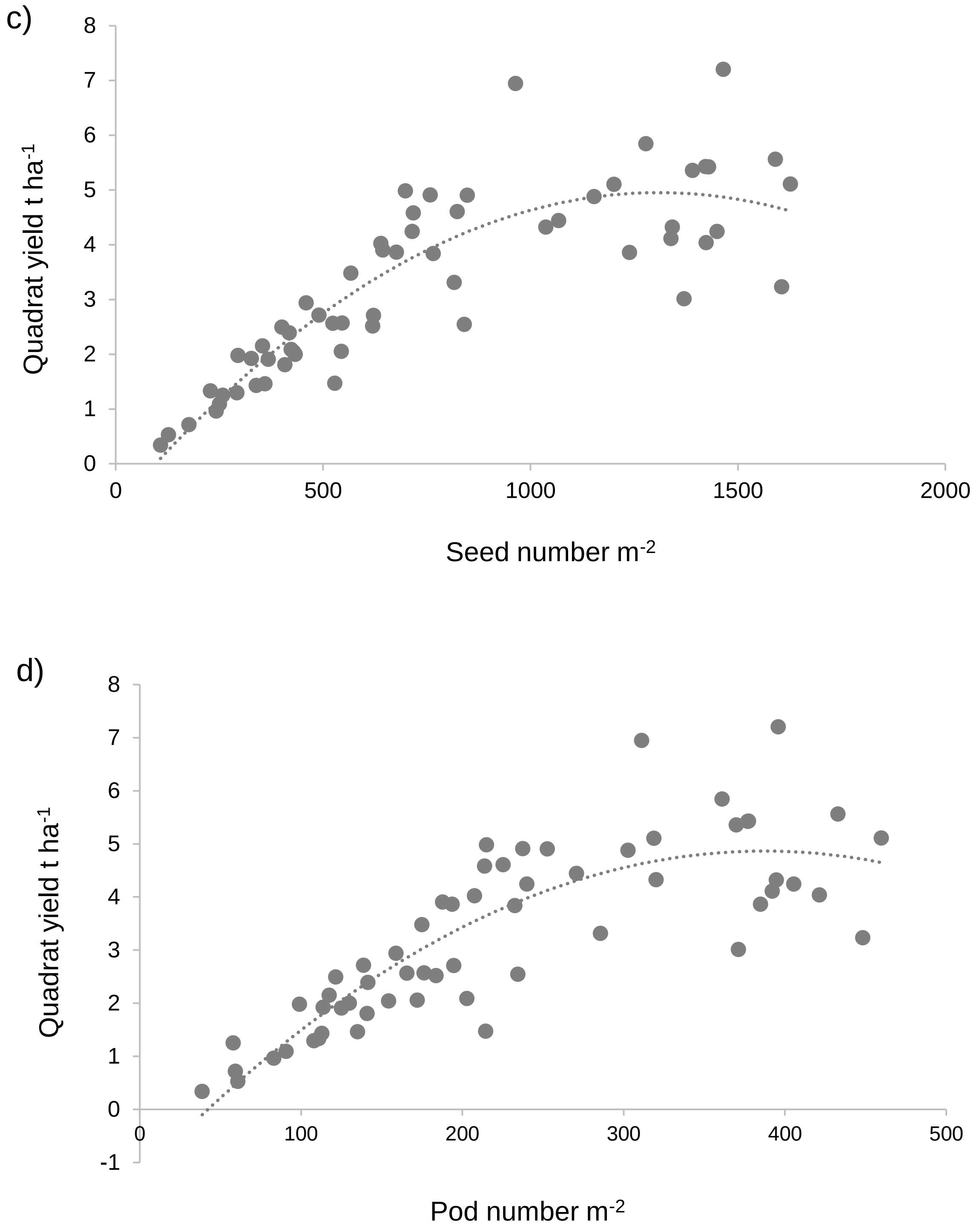


Figure 3. The relationship between (a) seeds m^{-2}, R^2 = 0.77; (b) pods m^{-2}, R^2 = 0.62 and quadrat yield for October sown plots and (c) seeds m^{-2} R^2 = 0.77 (d) pods m^{-2}, R^2 = 0.72 and quadrat yield for March sown plots. Data averaged across three years and two varieties.

3.2.1 Seed number per pod and seed size

Neither seed number per pod nor seed size responded to changes in seed rate. Seed number per pod was significantly greater in 2017 than 2018 and 2019 ($P<0.001$) and slight differences between varieties ($P=0.046$). Average seed size was much greater in 2019 (0.72g) than 2018 (0.52g) and 2017 (0.43g) ($P<0.001$). October sown beans had, on average, larger seeds than March sown beans, 0.60 and 0.48g respectively ($P=0.004$). There was also a significant difference in seed size between varieties with the October sown Wizard producing larger seeds than the October sown Fuego and the March sown Fuego (0.66, 0.53 and 0.48g) ($P<0.001$). As seed number per pod and seed size were relatively stable. The focus was turned to the determination of pod number.

Table 2. Seed size and number over three seasons 2016-2019, seed rates and two varieties (Wizard and Fuego).

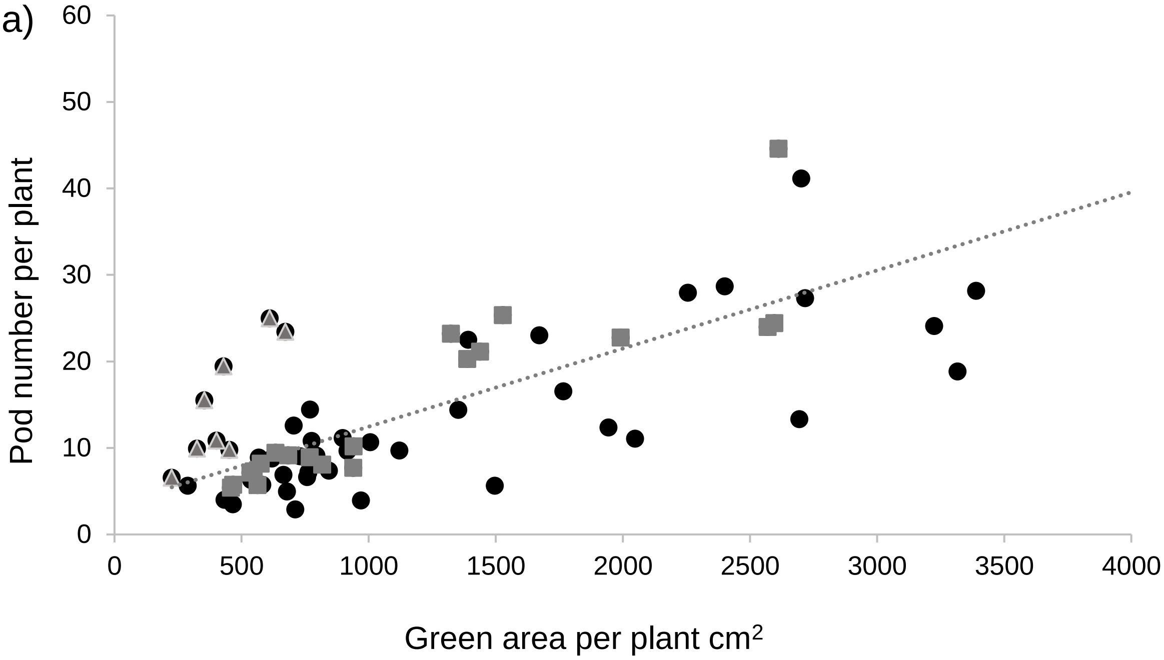
	Seeds per pod					Seed size (g)				
Sowing date/variety	2017	2018	2019	P value	LSD	2017	2018	2019	P value	LSD
October cv. Wizard	3.60	3.05	3.05	<0.001	0.243	0.49	0.62	0.87	<0.001	0.079
October cv. Fuego	3.33	2.82	3.09	<0.001	0.239	0.42	0.51	0.68	<0.001	0.055
March cv. Fuego	3.36	2.90	3.21	<0.001	0.240	0.39	0.43	0.61	<0.001	0.032
Mean	3.43	2.92	3.12			0.43	0.52	0.72		

3.3 Determination of pod number

3.3.1 Green Area

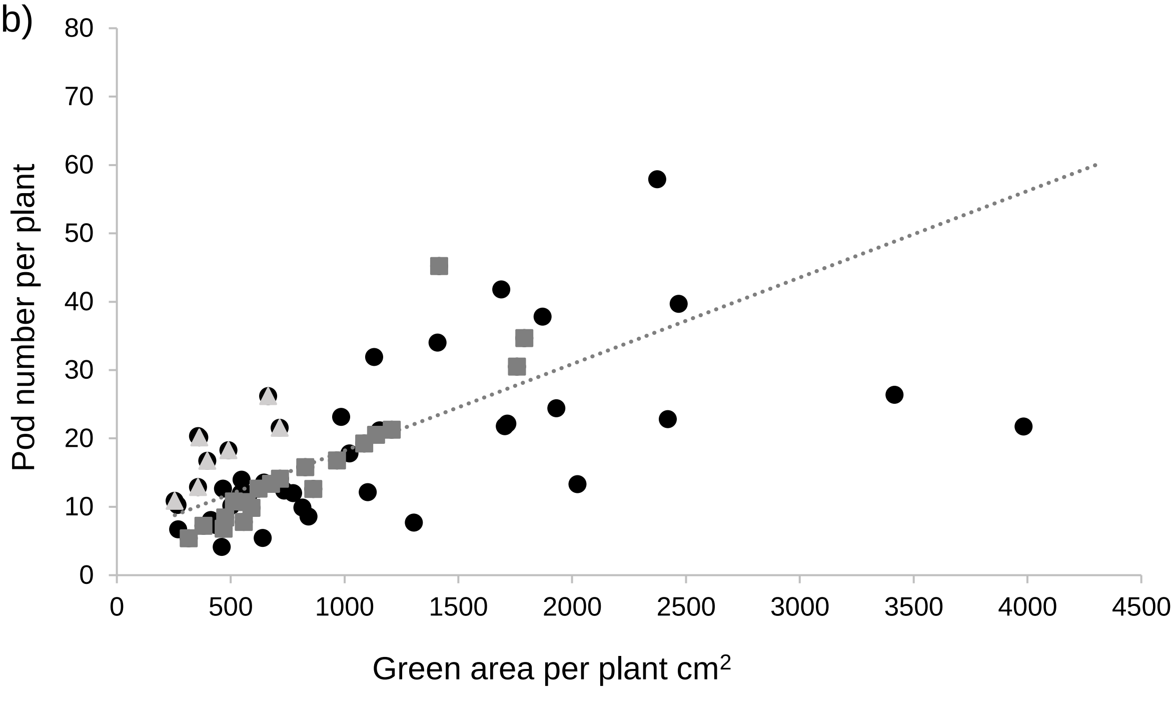
Both October and March sown plots showed a strong linear relationship between green area per plant and pods per plant over three years (Figure 4). March sown Fuego had the strongest relationship ($P<0.001$, $R^2=0.88$), while October sown Wizard and Fuego also showed a positive relationship ($P<0.001$, $R^2= 0.64$ and $P<0.001$, $R^2= 0.53$).

a)



60
50
40
30
20
10
0
Pod number per plant
0
500
1000
1500
2000
2500
3000
3500
4000
Green area per plant cm2

b)



80
70
60
50
40
30
20
10
0
Pod number per plant
0
500
1000
1500
2000
2500
3000
3500
4000
4500
Green area per plant cm2

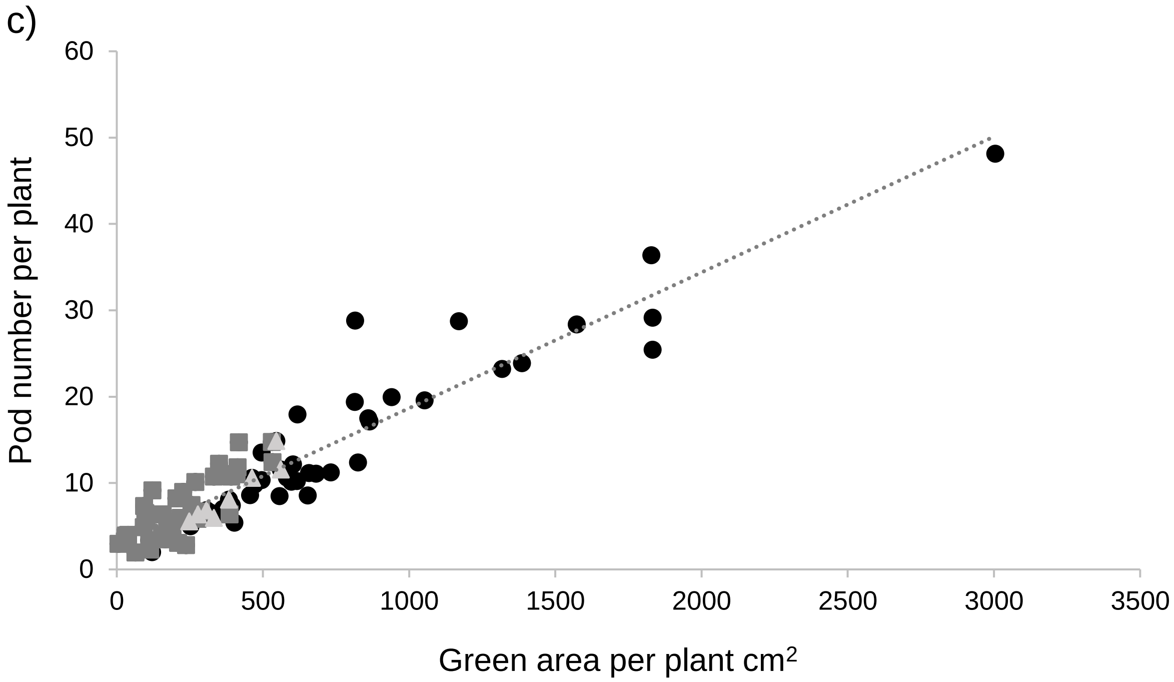


Figure 4. Relationship between green area per plant cm^2 and number of pods per plant for (a) October sown Wizard; (b) October sown Fuego; (c) March sown Fuego over three seasons, 2016-2017(●), 2017-2018 (■) and 2018-2019 (▲). R^2 values of 0.64, 0.53 and 0.88 repectively.

While the relationship between green area per plant and pod number per plant was consistent across varieties, sowing dates, and seed rates, when examined as green area index (GAI) against pod number m^{-2}, the relationship was less consistent (Figure 5).

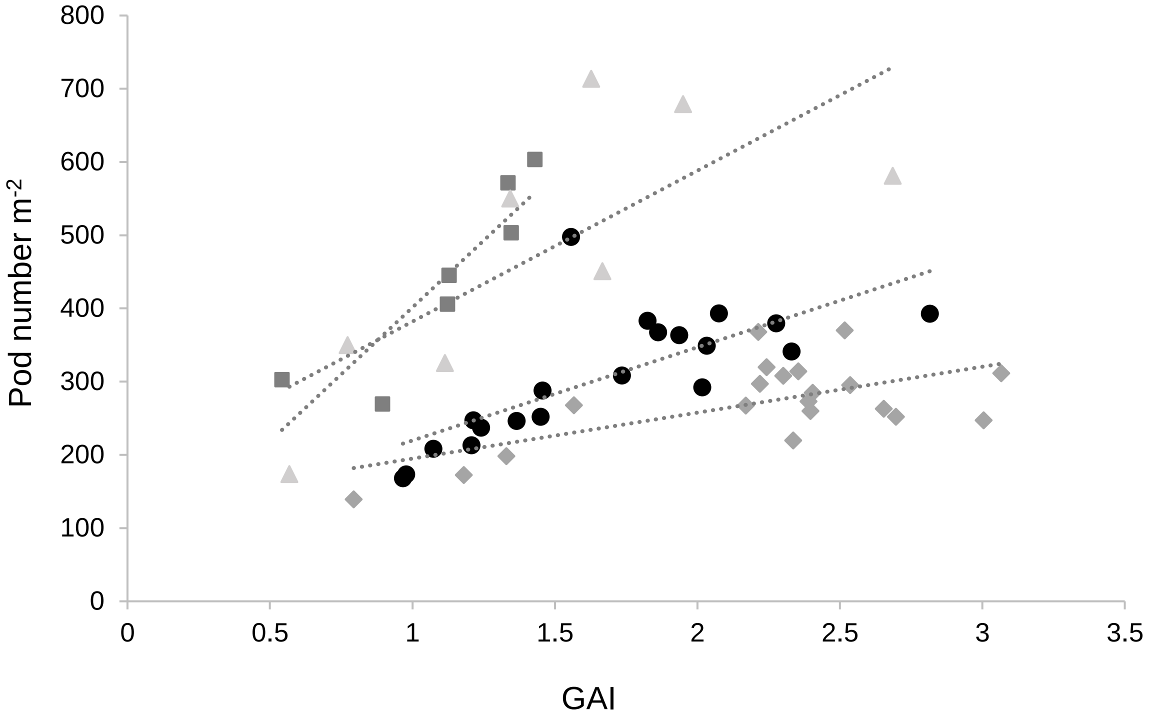


Figure 5. Relationship between final pod number m^{-2} and GAI for October Fuego 2018 (●); October Fuego 2019 (■); October Wizard 2018 (♦); October Wizard 2019 (▲).

The relationship between pod number m^{-2} and GAI was analysed at pod development and pod filling stages. The relationship was found to be stronger at the pod development stage when the October sown Fuego showed positive relationships between pod number m^{-2} and GAI for both the 2018 ($P<0.001$, $R^2 = 0.54$) and 2019 ($P<0.001$, $R^2 = 0.79$) season. The October sown Wizard also showed a positive relationship between pod number m^{-2} and GAI for 2018 ($P<0.001$, $R^2 = 0.39$) and 2019 ($P<0.001$, $R^2 = 0.56$). However, no relationship between GAI and pod number was found in 2017 for either variety sown in October.

Comparative analysis showed that the relationship between pod number m^{-2} and GAI for the March sown Fuego was consistently strong across all three years at the pod development stage ($P<0.001$, $R^2=0.77$) (Figure 6).

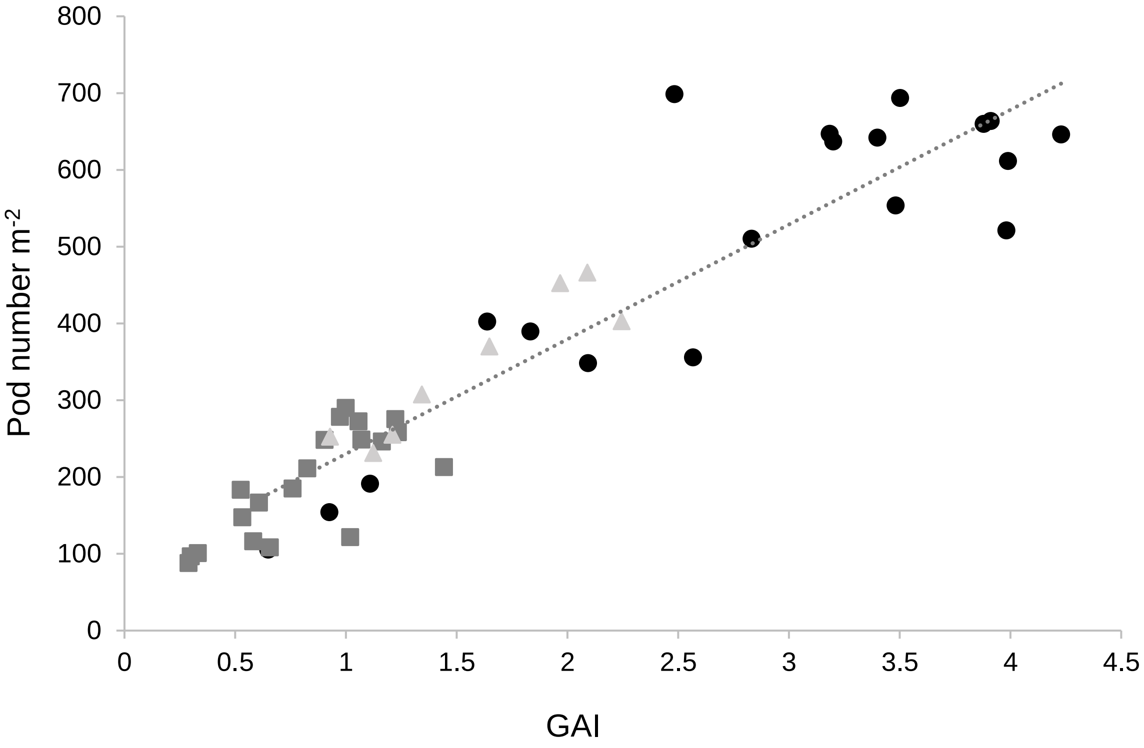


Figure 6. Pod number m^{-2} against GAI for March Fuego over three seasons 2017 (●), 2018 (■) and 2019 (▲).

3.3.2 Intercepted radiation

The strong relationship between GAI and pod number led to the hypothesis that pod number is determined by the amount of radiation intercepted at critical developmental stages. Through the supplementary shading trial, 60% of the incident radiation through the vegetative and flowering phases was removed during that growth period. Shading during the vegetative stage did not influence pod number or yield but when shaded during the flowering stage, yield and pod number were reduced by 27% (P=0.035) and 38% (P=0.025) respectively (Table 3). Shading had no effect on seeds per pod, while seed size was larger in the shaded plots, regardless of timing (P<0.001). However, the impact on seed size was greater for plants that were shaded at flowering (P=0.03).

Table 3. Pod number m^{-2} for shaded and unshaded treatments during vegetative stage of growth and flowering period in 2018-2019. P value represents the interaction between the growth stage and treatment.

	Yield (t ha^{-1})		**Pod m^{-2}**		**Seeds per pod**		**Av seed size (g)**	
	veg	flower	veg	flower	veg	flower	veg	flower
Unshaded	2.07	2.51	106.6	123.7	3.24	3.30	0.603	0.613
Shaded	2.40	1.84	120.1	76.2	3.18	3.41	0.639	0.712
P value	0.035		0.025		0.508		0.030	
LSD	0.646		36.44		0.406		0.039	

Maximum GAIs at flowering were higher in 2017, reaching an average across all treatments of 5.0 in 2017 compared to 3.9 in 2018 and 2.6 in 2019. This led to large differences in radiation interception. Between the flowering and pod filling developmental stages, the 2017 crop intercepted 1153.86 MJ on average compared to 483.48 MJ in 2018 and 584.66 MJ in 2019. There are no direct measurements of light interception available due to instrument malfunction.

4. Discussion

Using a range of seed rates to manipulate the structure of the crop canopy showed that there was an increase in yield between 10 and 20 seeds m^{-2} for the October sown treatments (cv. Wizard and cv. Fuego), and an increase between 10, 20 and 40 seeds m^{-2} for the March sown treatments (cv. Fuego). However, there was no yield benefit with increasing seed rates above 20 seeds/m^2 for the October sown treatments and 40 seeds/m^2 for the March sown treatments. This is possibly due to plant competition at higher plant densities, competing for light and other assimilates. Field observations have shown that at higher plant densities, field beans will only set pods higher up on the stem, whereas at lower densities, plants have room to branch and produce more pods per plant lower on the stem. In this way, the lower densities have been seen to compensate and be competitive with the higher densities. This concurs with Carpenter and Board (1997b) who that found that soybeans will compensate for space by branching, resulting in no yield response from increasing seed rate.

Previous studies have shown that the variation in seed yield in field beans from year to year was associated with pod number and seed number per unit area (Kambal, 1969a, Pilbeam et al., 1989). Results from this study agree with these findings with the number of seeds m^{-2} and pods m^{-2} being strongly related to final yield across the three seasons, suggesting that yield is driven by these yield components. With seed number per pod unchanged across a wider range of plant densities, we focussed on the determination of pod number to explain variation in final yield.

From the supplementary shading trial, pods m^{-2} were reduced by 38% when the crop was shaded throughout the flowering period, which was then compensated by a 14% increase in seed size, leading to a 27% yield loss overall. Shading did not affect the number of seeds per pod through either the vegetative or flowering phase with no significant differences found. These results confirm the conclusions of Agung and McDonald (1997) who reported that for any given cultivar of field bean, the average number of seeds per pod remained relatively stable. The increase in seed size is probably a result of shading changing the source-sink balance. Shading led to a reduced pod number then, once the shade was removed, the greater assimilate supply per pod during the pod filling stage, led to larger seeds than the unshaded control.

The results of shading during the critical developmental stages reinforces the hypothesis that radiation intercepted by the crop throughout the flowering phase determines pod number and therefore is a key driver of final yield. This concurs with the recent study carried out in the Mediterranean-type climate of Chile and the humid subtropical climate of Australia by Lake et al. (2019). They discovered that yield response to shading was most severe during the flowering to pod development stage, with the more severe yield loss found in the Australian experiments where 90% of the light was reduced, compared to the Chile experiments where 75% of the light was reduced. This agrees with Board and Tan (1995) who suggest that soybeans are source limited with yield more restricted by assimilatory capacity during the flowering and pod development phase.

Previous work has shown that the number of pods per plant was determined by the green area per plant (Husain et al., 1988). Our work confirmed this finding and went on to show that, when considered on an area basis, green area index was strongly related to pods m^{-2} in the March sown plots in all years and in the October sown plots in 2018 and 2019. The GAI of the October sown crop in 2017 was higher than subsequent years, leading to the crop intercepting nearly double the amount of radiation during pod development than in 2018 and 2019. We therefore propose that the lack of relationship between GAI and pod number m^{-2} in 2017 was because light interception was not limiting, even at the lower seed rates.

In conclusion, the yield of field beans was determined by pod number per unit area which was in turn determined by light interception during flowering and early pod development. The seed rates, sowing dates and varieties used in these experiments created a range of canopy sizes and showed that, in most cases, GAI (and hence light interception) at early pod development determined pod number, and thereby yield. However, for winter sown crops in 2017, there was no relationship found between pod number and GAI. Studying the weather data for each year showed that the crop was intercepting over double the amount of incident radiation between the flowering and pod filling phase in 2017 compared to 2018 and 2019. GAI for 2017 was also much higher between the flowering and pod development phase than in subsequent years suggesting that light interception was not limiting because GAI was so high.

5. Acknowledgements

This work was supported by the Walsh Scholars Association and the Irish Farmers Association. The authors would like to acknowledge the Teagasc technicians, farm manager, farm staff and summer interns for their help in this study. A particular thanks to Kevin Murphy and Frank Ryan for their constant help and support throughout the entirety of this project.

6. References

Agung, S. & McDonald, G. K. 1997. Effects of seed size and maturity on the growth and yield of faba bean (Vicia faba L.). *Australian Journal of Agricultural Research,* 49**,** 79-88.

Berry, P. M. & Spink, J. H. 2006. A physiological analysis of oilseed rape yields: Past and future. *The Journal of Agricultural Science,* 144**,** 381-392.

Board, J. E. & Tan, Q. 1995. Assimilatory Capacity Effects on Soybean Yield Components and Pod Number. *Crop Science,* 35**,** cropsci1995.0011183X003500030035x.

Carpenter, A. C. & Board, J. 1997a. Branch Yield Components Controlling Soybean Yield Stability across Plant Populations. *Crop Science - CROP SCI,* 37.

Carpenter, A. C. & Board, J. E. 1997b. Branch Yield Components Controlling Soybean Yield Stability across Plant Populations. *Crop Science,* 37**,** cropsci1997.0011183X003700030031x.

Husain, M. M., Hill, G. D. & Gallagher, J. N. 1988. The response of field beans (Vicia faba L.) to irrigation and sowing date. 2. Growth and development in relation to yield. *The Journal of Agricultural Science,* 111**,** 233-254.

Kambal, A. E. 1969a. Components of yield in field beans, Vicia faba L. *The Journal of Agricultural Science,* 72**,** 359-363.

Kambal, A. E. 1969b. Flower drop and fruit set in field beans, Vicia faba L. *The Journal of Agricultural Science,* 72**,** 131-138.

Lake, L., Godoy-Kutchartt, D. E., Calderini, D. F., Verrell, A. & Sadras, V. O. 2019. Yield determination and the critical period of faba bean (Vicia faba L.). *Field Crops Research,* 241**,** 107575.

López-Bellido, F. J., López-Bellido, L. & López-Bellido, R. J. 2005. Competition, growth and yield of faba bean (Vicia faba L.). *European Journal of Agronomy,* 23**,** 359-378.

Lunn, G. D., Spink, J. H., Wade, A. & CLARE, R. W. 2003. Spring Remedial Treatements to Improve Canopy Structure and Yield in Oilseed Rape. *HGCA Project Report No. OS64.* London: Home-Grown Cereals Authority.

Mwanamwenge, J., Loss, S. P., Siddique, K. H. M. & Cocks, P. S. 1998. Growth, seed yield and water use of faba bean (Vicia faba L.) in a short-season Mediterranean-type environment. *Australian Journal of Experimental Agriculture,* 38**,** 171-180.

Pandey, R. K. 1981. Growth, dry matter and seed yield of faba beans (Vicia faba) as influenced by planting density. *Fabis,* 3**,** 37-38.

Pilbeam, C. J., Hebblethwaite, P. D. & Ricketts, H. E. 1989. The response of determinate and semi-determinate faba bean varieties to different sowing dates in the spring. *Annals of Applied Biology,* 114**,** 377-390.

Robinson, A. P. & Conley, S. P. 2007. Plant populations and seeding rates for soybeans. https://www.extension.purdue.edu/extmedia/ay/ay-217-w.pdf: Purdue Univ., West Lafayette, IN. .

Roques, S. E. & Berry, P. M. 2016. The yield response of oilseed rape to plant population density. *The Journal of Agricultural Science,* 154**,** 305-320.

Rowland, D. G. 1955. The problem with yield in field beans. *Agric. Prog.,* 30**,** 137-147.

Salih, F. A. & Salih, S. H. 1980. Influence of seed size on yield and yield components of broad bean (Vicia faba). *Seed Science and Technology,* 8**,** 175-181.

Whaley, J. M., Sparkes, D. L., Foulkes, M. J., Spink, J. H., Semere, T. & Scott, R. K. 2000. The physiological response of winter wheat to reductions in plant density. *Annals of Applied Biology,* 137**,** 165-177.

Chapter 4

Predicting Green Area Index (GAI) from leaf biomass in field beans (*Vicia faba*)

This chapter has been prepared as a journal article but has not yet been submitted for review.

Predicting green area index (GAI) from leaf biomass in field beans *(Vicia faba)*

L.C. Murphy[1,2], S. Alves[1*], J.H. Spink[1] and D.L. Sparkes[2]

[1] Teagasc, Crops, Environment & Land Use Programme, Oak Park Crops Research Centre, Carlow, Ireland

[2] University of Nottingham, Sutton Bonington, Loughborough, LE12 5RD, United Kingdom

Abstract

At present, there is a limited understanding of the factors influencing crop development and canopy management in field beans. Field experiments were carried out over three seasons in Teagasc, Oak Park Carlow, Ireland to observe the effect of variety, sowing date and seed rate on crop and canopy development in field beans. This paper focuses on the hypothesis that plant fresh biomass can be used as a predictor of leaf green area and in turn be utilised as a tool for growers in canopy management. Destructive samples were taken from field experiments and the green area of the different plant components were measured. The results suggest that the leaf, making up the majority of the green fresh biomass in the crop throughout the growing season, is strongly related to green area and hence could be used to predict GAI in the early stages of developing crop.

To test this hypothesis, a model was developed using the relationship between leaf fresh biomass and leaf green area giving the equation $y = 0.0021x - 0.0734$. Data from an independent data set consisting of three years of field beans experiments, was fitted into the original data set model to validate the model. The results showed a strong correlation between measured leaf green area and predicted leaf green area with an $R^2=0.92$ and RMSE of 0.38.

Keywords: Field beans; Green area index; Canopy management; Biomass.

*Corresponding author: Sheila.Alves@teagasc.ie

1. Introduction

Green area of a canopy is involved in key processes including photosynthesis, respiration, and evapotranspiration. It reflects the potential growth of the canopy and is a key variable when modelling biomass production as well as yield and yield loss (Verger et al., 2014). Green Area Index (GAI) is the ratio of green canopy area to the area of ground it covers (Black et al., 2009) and is often assessed indirectly by measurement of the fractional interception by a crop, which together with an assumed extinction coefficient, can be used to predict GAI. The alternative approach is to measure canopy green area directly which is laborious and time consuming. In other broadleaf crops like oilseed rape, GAI has been studied as a useful tool for canopy management. Studies have found that a GAI of 4 prior to flowering indicates that the crop is on track for good final yields (Berry and Spink, 2006). This technique of tracking GAI in oilseed rape has even been made into a tool for growers by taking photos through a mobile application (BASF, 2018).

Field beans have the potential to produce high yields in a temperate climate; however, yields can be highly variable from year to year (López-Bellido et al., 2005). Studies have shown that in field beans, a GAI of c.3.5 is needed for the crop canopy to fully intercept and utilize solar radiation (Thomson and Siddique, 1997) which is influenced by plant population. In higher plant populations, canopy closure is quicker, allowing the crop to maximise interception of radiation earlier in the season but leading to leaves lower in the canopy being heavily shaded. Lower plant populations take longer to achieve canopy closure but allow radiation to be transmitted to lower parts of the canopy.

The leaf may be considered the most important organ for plants to transfer solar energy to biological energy by means of photosynthesis (Huang et al., 2019). Leaf weight and leaf area are both measures of leaf size, which is important for the amount of solar radiation intercepted by the plant. Generally, when leaf dry mass increases, the leaf area decreases, impacting the leaf’s photosynthetic capacity. Leaves with a large surface will have an increased area to intercept the light and enhance the photosynthetic potential (Smith et al., 1997). If leaves become too large, water evaporation may be a problem, which can cause plants to die of dehydration (Huang et al., 2019). Large leaves can increase light utilization efficiency of the leaf surface, but because of their larger size, they also need more input of biomass to increase leaf area. However, leaf water content plays an important role in photosynthesis. It does not proportionally increase with increasing leaf dry weight (Niklas et al., 2007). This means that the ratios of leaf dry weight to fresh weight are not a constant. Many studies have used leaf dry weight when studying the relationship between leaf biomass and area. Huang et al. (2019) draw the conclusion that, in 15 broad leaf species under study, using leaf fresh weight data is better than using leaf dry weight when examining this relationship. This means that if leaf fresh weight can be accurately measured, then it is better to use leaf fresh weight to represent leaf area than to use leaf dry weight to examine the relationship with leaf area for broad-leaved species.

Chapters 2 and 3 of this thesis investigated the effect of sowing dates, varieties and seed rates on canopy size in field beans. The aim of this chapter was to develop a predictive model for green area based on plant fresh biomass for field beans, that could be applicable to different varieties, sowing dates, and cultivation systems. This chapter focuses on hypotheses 6 and 7:

6. Fresh leaf biomass can be used to accurately predict green area index (GAI).

7. Using a model to predict GAI from fresh leaf biomass can therefore be used as a surrogate for GAI and a management tool for growers of field beans.

2. Materials and methods

2.1 Experimental design

Field trials were carried out for three consecutive years in Teagasc, Oak Park, Carlow, Ireland. Crops were rotated according to the farm rotation with the experiments following oats in 2016, spring barley in 2017, and winter barley in 2018. All sites had sufficient P and K, with organic matter ranging from 3.9-4.8% and pH ranging from 6.4-7.1.

The experiments were arranged in a randomised, split-split plot design with four complete replications. The main plot treatment was time of sowing (TOS), sub plot treatment was seed rate (SR) and sub-sub plot treatment was variety (winter and spring). Plot size was 5m x 24m, which was split in half lengthways (2.5m x 24m); one side of the plot was used for destructive samples and the other side for combine yield.

2.2 Field trials

Field trials consisted of October and March sowing dates, five seed rates from 10 – 80 seeds m^{-2} and two varieties, Wizard (winter) and Fuego (spring). Trials were sown with a conventional plough and one pass power harrow system. Plots were sown using a Wintersteiger plot drill (Wintersteiger AG, Austria), which was tractor-mounted, for precision sowing of smaller research plots. The seed was drilled approx. 7-10 cm deep.

The independent validation data set was taken from field trials that consisted of three sowing dates in October, February and March, four cultivation systems (conventional and minimum tillage) and two varieties, Wizard (winter) and Fanfare (spring). There were four trial sites across two locations (Teagasc, Oak Park Carlow and Lyon’s Research Farm, Dublin) from 2017-2019.

A prophylactic programme of chemicals was used to minimise weeds, pests, and diseases throughout the season in all experiments.

2.3 Sampling method

Samples were collected over the growing season, across all field bean trials, over the three seasons. Destructive samples were taken at targeted growth stages: vegetative growth, flowering, pod development, and pod set. Samples were taken using 2 x 1m^2 quadrats, one from the top of the plot and one from the bottom of the plot. Plants were counted inside the quadrat and cut at the base of the stem above the ground. The samples were bagged, labelled, and stored at 4-8°C.

2.4 Laboratory analysis

The fresh weight of the full sample was recorded and a subsample (~20%) was taken from each field sample. Sub samples were broken down into leaves, stems, and pods later in the season. Leaf, stem and pod material from each sub sample was scanned through a leaf area meter (Delta-T Devices Ltd, Cambridge, UK) to measure the projected green area of each component. Using the accompanying image analysis computer software WinDias 3, (Delta T, Cambridge, UK), the green area of each sub-sample was recorded in cm^2. The green colours were selected in the software by passing the leaf under the camera allowing the software to pick up the different green colours in the leaf. Using this output, the GAI for each component (leaf, stem, and pod) was calculated. The green area of the pods was only measured in 2018. Each component was weighed (fresh weight) and bagged for drying. Dry weights of all plant components were recorded after drying at 70°C until a constant weight.

2.5 Statistical analysis and validation

Data analysis was done using the statistical software GenStat, version 20 from VSN International. ANOVA and regression analysis were used to study the relationship between biomass and GAI.

The variances were found to be not homogeneous. Transformations were applied to the data (Log_{10}, Ln, square root, reciprocal and weighted regression) none of which resulted in homogeneous variances. The data was therefore used without transformation for analysis in the model.

To evaluate the agreement between estimated and measured values of the validation set, the model was tested using an independent data set using the equation from the model:

$$\text{LAI} = 0.0021 \times \text{leaf fresh biomass (g/m2)} - 0.0734$$

The independent data set consisted of variation in site, variety, cultivation systems, seed rates and sowing dates over three years to test the robustness of predicting GAI using measured leaf fresh weight.

3. Results

3.1 Biomass

Both total biomass and total green area increased over time; however, the contribution of each plant component varied over the growing season. The green leaf area was the major contributor to the total plant green area in all growth stages, ranging from 75 to 90% of the total plant green area, while the maximum contribution recorded for stems and pods was c.21 and 4%, respectively (Figure 1). Even though leaf biomass decreased over the growing season, between the pre-anthesis and pod fill stage from c.67% to c.24%, leaf green area remained the highest contributor to the total plant green area.

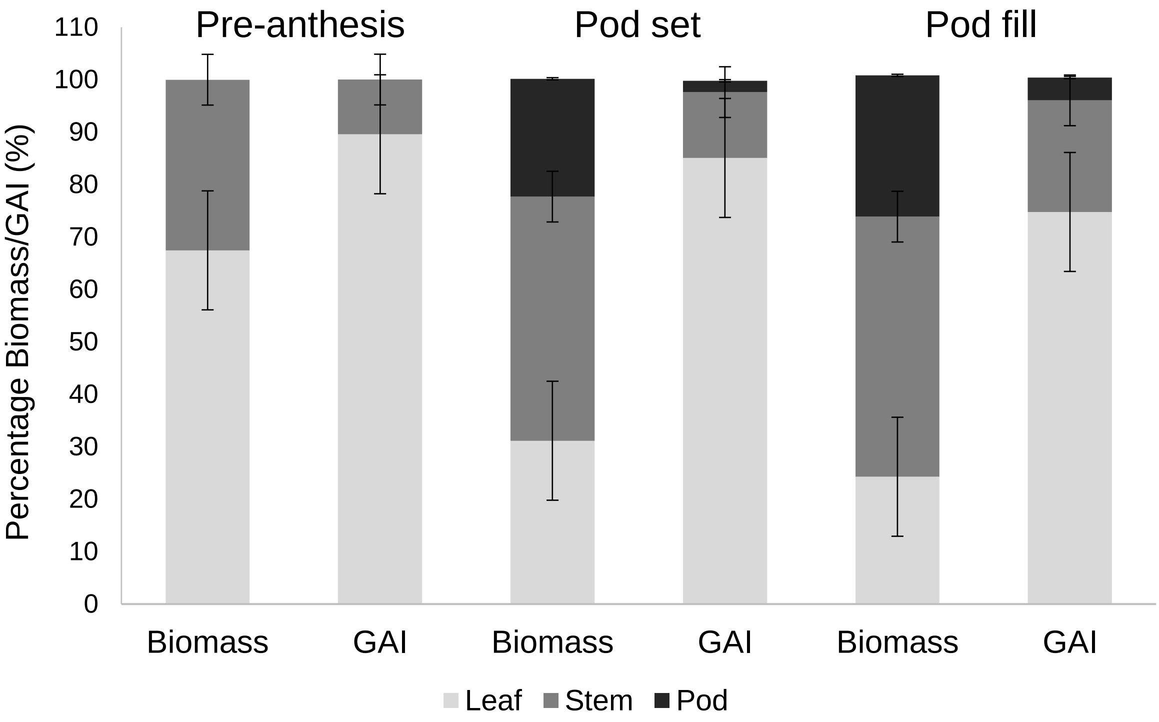


Figure 1. Average percentage contribution of leaf, stem, and pod fresh biomass and green area index (GAI) pre-anthesis, at pod set and pod fill stages of growth, across

sowing dates, and varieties over three seasons, 2017-2019. Error bars show standard error of means.

Looking at the components individually, the fresh biomass of each plant component under study; leaf, stem, and pod, were found to be positively related to their corresponding GAI. Moreover, all relationships were found to be positively linear (Figure 2), with R^2 values of 0.88 for leaf, 0.87 for stem and 0.58 for pods.

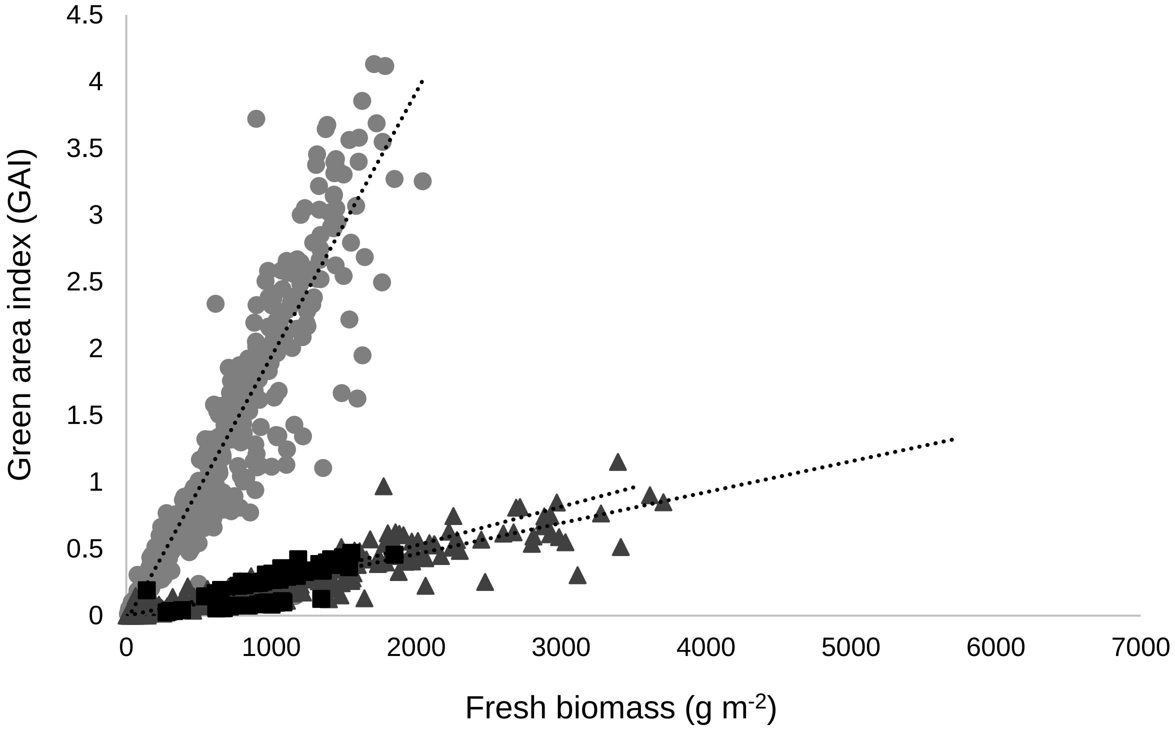
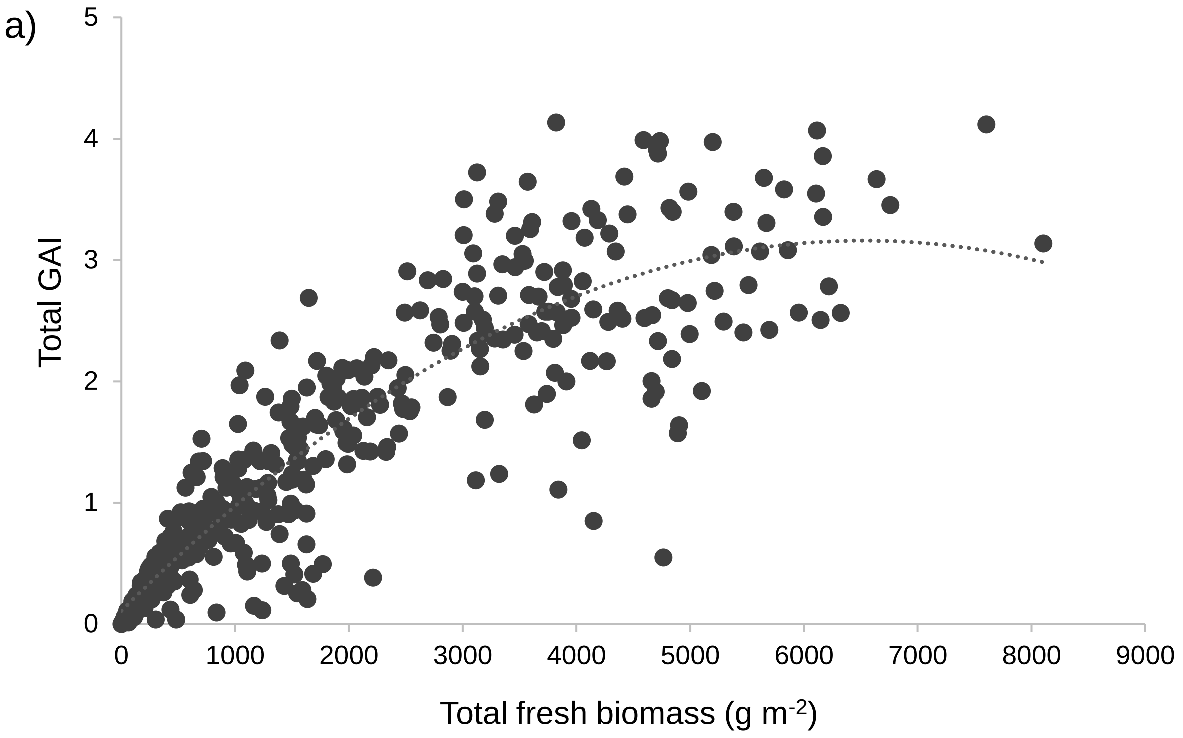


Figure. 2. The relationship between leaf (●) and stem (▲) fresh biomass and green area index (GAI) for each component for three seasons (2017-2019) and pod (■) fresh weight for 2018 against GAI. R^2 values of 0.88 for leaf, 0.87 for stem and 0.58 for pods.

Total fresh biomass was strongly related to total GAI, that is the biomass and green area of combined leaf, stem, and pod ($P<0.001$ $R^2=0.83$) (Figure 3a). However, as leaf material was the main contributor to the total GAI, and was found to have a stronger, linear relationship, the leaf biomass and GAI data was used to analyse the relationship between biomass and leaf GAI across seasons, sowing dates, and varieties (Figure 3b). Regression analysis showed that there was no significant difference between the three seasons. All years showed a strong positive relationship between fresh biomass and GAI ($P<0.001$, $R^2 = 0.94$) (Figure 3b). ANOVA analysis was also carried out on the varieties and sowing dates. The winter and spring varieties had a similar relationship between fresh leaf biomass and GAI with and R^2 value of 0.95 for the spring variety and 0.92 for the winter variety, with no significant difference between varieties. The analysis for the October and March sowing dates showed that leaf fresh weight had a strong positive correlation with GAI with an R^2 of 0.93 for October and 0.97 for March. There was no significant difference between sowing dates. Comparative analysis showed no differences between years, sowing dates and varieties across the three seasons.


a)
Total GAI
0
1
2
3
4
5
0
1000
2000
3000
4000
5000
6000
7000
8000
9000
Total fresh biomass (g m-2)

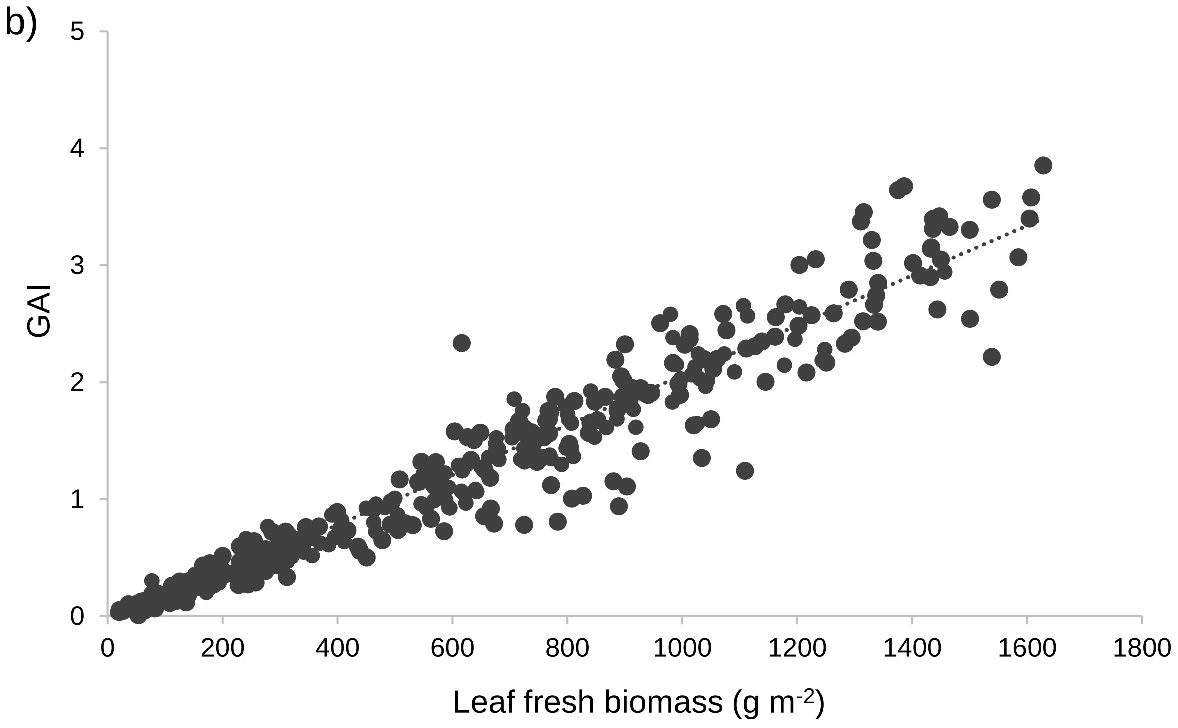

b)
GAI
0
1
2
3
4
5
0
200
400
600
800
1000
1200
1400
1600
1800
Leaf fresh biomass (g m-2)

Figure 3. The relationship between a) total biomass and total Green Area Index (GAI) for three seasons (2017-2019), R^2= 0.78, P<0.001, and b) leaf fresh biomass and total leaf Green Area Index (GAI) across all treatments and years, with R^2= 0.94, P<0.001.

3.2 Validation

As the analysis found that the relationship between leaf fresh biomass and canopy green area was strong (Equation 1; P<0.001, R^2 = 0.94) and consistent across all years, seed rates, sowing dates and varieties, this was then tested using the validation data set.

Equation 1: GAI = 0.0021 x leaf fresh biomass (g m^{-2}) - 0.0734

The results shown in Figure 4, show a strong positive correlation between measured leaf green area and the predicted leaf green area with an R^2 = 0.92 using the equation from the model. The error between the predicted and measured values for the independent data set was calculated using the Root Square Mean Error (RSME) resulting in an RSME of 0.38. This value shows that the ability of the model to accurately predict the data is good.

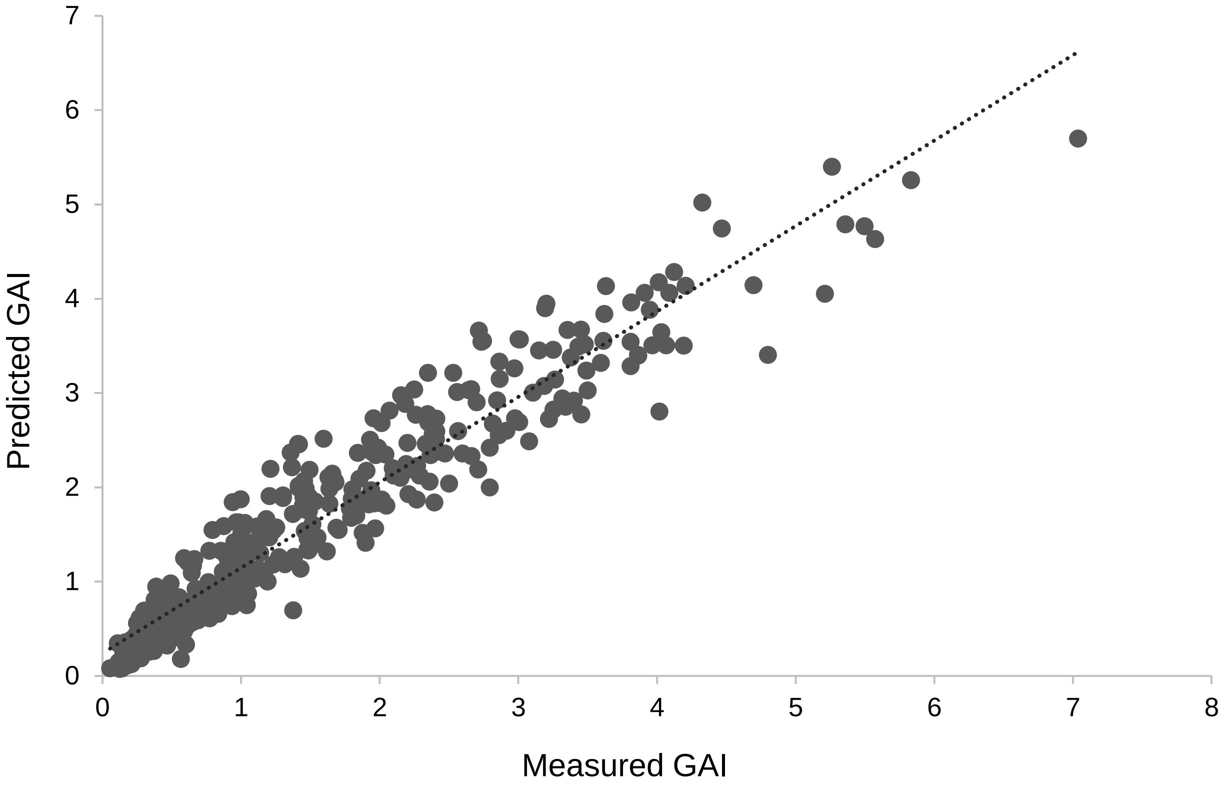


Figure 4. Predicted GAI against measured GAI using the model equation y = 0.0021x – 0.0734 from leaf fresh weight with R^2 = 0.91. Data collected from an independent data set including sowing dates, seed rates, varieties, locations, and cultivation systems.

4. Discussion

Canopy management, where crops are managed to achieve a target GAI, has been proposed for wheat (Spink et al., 2000), and subsequently extended to OSR (Lunn et al., 2003) and other crops. The key principle of canopy management is to produce a canopy large enough to intercept enough incident radiation, and utilise this efficiently, while avoiding overly large canopies that would be prone to lodging. In wheat the optimum GAI was found to be c.6 (The wheat growth guide, 2008) while in oilseed rape, a GAI of 3-4 is sufficient (Lunn et al., 2003). Growers can use these optimum GAIs to modify their crop management but measurement of GAI can be slow and laborious, especially through measurements of light interception in the canopy, hence rapid assessments are required.

In cereals, Hay and Walker (1989) observed that most of the solar radiation absorbed by a crop's canopy is intercepted by its leaves. The leaf can be considered to be most important organ for plants to transfer solar energy to biological energy by means of photosynthesis (Huang et al., 2019). From this study, it was found that the leaves make up the majority of green area in the bean crop and therefore have the most photosynthetic capacity. The proportion of leaf green area continued to increase as the weight of the leaves increased throughout the season across all treatments. However, a different trend was observed in the stem. The proportion of stem green area was found to increase slowly to a certain point before plateauing, however, the stem biomass continued to increase. This suggests that at some point in the season, the stem no longer contributes to the addition of green area for photosynthesis, but the weight of the stem increases and in turn adds to the sturdiness of the plant, making the stem more rigid to support the weight of this tall crop and facilitate translocation of assimilates to the different parts of the plant. The pods made up a small percentage of the overall green area and biomass in the later stages of the growing season. They have the capacity to photosynthesise but their contribution is most likely minimal and very limited as the time between pod development and ripening is around one month and do not remain green for very long once they begin to fill.

In other broadleaf crops such as oil seed rape, GAI is used as a critical benchmark in growth and development for final yield. Additionally, in oil seed rape, GAI is used as an indicator for the amount of nitrogen that is available in the crop. For every 1 unit of GAI, it is estimated that the crop contains 50kg N/ha (Lunn et al., 2003). In this way, GAI can be used to determine the amount of fertiliser that needs to be applied to the crop and as an indicator of the crop's progress throughout the season, to meet benchmark targets and maximise final harvest yields.

Using GAI targets for N application is not applicable to field beans, however. As an N fixing crop, there is no need for additional application of fertiliser. Even though GAI targets cannot be used in the same ways as OSR for application of fertiliser, they can be used by growers to track crop and canopy development. From this study, highest GAIs were found in 2017 to be ~ 3-4 during the reproductive phase leading to yields of 6 tha^{-1} on average. Providing that the conditions for growth were optimal, GAI can be used to track the canopy size and act as a benchmark at certain growth stages for production of final yield.

In a similar way, using leaf weight in field beans at different stages of growth to predict GAI could be used as a helpful tool in predicting final yields. This method of taking biomass samples to gather data on the crop canopy as it develops throughout the season is an easy and robust method. This could also be used to improve field bean crop management throughout the season. In this study, a strong relationship was found between leaf biomass and leaf green area. Using the equation from the regression analysis on the independent data set to predict GAI using leaf biomass proved successful in this incidence in a temperate environment, however, the parameters could be different in other environments and may not fit this model.

As far as we are aware, there have been no studies on this relationship in field beans or other crops. Research has been found on remote estimation of leaf area and biomass in Maize and Mountain Birch (Gitelson et al., 2003, Heiskanen, 2006) but the relationship between the two has not previously been studied. Leaf area index (LAI) has been seen to be an important variable for climate modelling, agricultural yield forecasting, and many other diverse studies (Gitelson et al., 2003). Further research needs to be carried out on this topic in field beans and other crops to improve crop yields, create advice for growers and develop this method as a reliable management tool for tracking crop growth.

5. Acknowledgments

This work was supported by the Teagasc Walsh Scholars Association and the Irish Farmers Association. The authors would like to acknowledge the Teagasc farm manager, farm staff, technicians, and summer interns for their help in this study. A particular thanks to Kevin Murphy and Frank Ryan for their constant help and support throughout the entirety of this project.

6. References

BASF. 2018. *OSR GAI Online* [Online]. BASF Agricultural Solutions UK. Available: https://www.agricentre.basf.co.uk/en/Services/Online-Tools/OSR-GAI-Online/?fbclid=IwAR0oNo84dIPkx2QEhAEaravmplxK0dI49vqSVd9POtVVq1Ir5x-fmLPlPl0 [Accessed November 2020].

Berry, P. M. & Spink, J. H. 2006. A physiological analysis of oilseed rape yields: Past and future. *The Journal of Agricultural Science,* 144**,** 381-392.

Gitelson, A. A., Viña, A., Arkebauer, T. J., Rundquist, D. C., Keydan, G. & Leavitt, B. 2003. Remote estimation of leaf area index and green leaf biomass in maize canopies. *Geophysical Research Letters,* 30.

Hay, R. K. M. & Walker, A. J. 1989. *Introduction to the physiology of crop yield,* Harlow, Longman Group UK Limited.

Heiskanen, J. 2006. Estimating aboveground tree biomass and leaf area index in a mountain birch forest using ASTER satellite data. *International Journal of Remote Sensing,* 27**,** 1135-1158.

Huang, W., Ratkowsky, D. A., Hui, C., Wang, P., Su, J. & Shi, P. 2019. Leaf fresh weight versus dry weight: which is better for describing the scaling relationship between leaf biomass and leaf area for broad-leaved plants? *Forests,* 10**,** 256.

López-Bellido, F. J., López-Bellido, L. & López-Bellido, R. J. 2005. Competition, growth and yield of faba bean (Vicia faba L.). *European Journal of Agronomy,* 23**,** 359-378.

Lunn, G. D., Spink, J. H., Wade, A. & CLARE, R. W. 2003. Spring Remedial Treatements to Improve Canopy Structure and Yield in Oilseed Rape. *HGCA Project Report No. OS64.* London: Home-Grown Cereals Authority.

Niklas, K. J., Cobb, E. D., Niinemets, Ü., Reich, P. B., Sellin, A., Shipley, B. & Wright, I. J. 2007. “Diminishing returns” in the scaling of functional leaf traits across and within species groups. *Proceedings of the National Academy of Sciences,* 104**,** 8891-8896.

Smith, W. K., Vogelmann, T. C., DeLucia, E. H., Bell, D. T. & Shepherd, K. A. 1997. Leaf Form and Photosynthesis. *BioScience,* 47**,** 785-793.

Spink, J. H., Semere, T., Sparkes, D. L., Whaley, J. M., Foulkes, M. J., Clare, R. W. & SCOTT, R. K. 2000. Effect of sowing date on the optimum plant density of winter wheat. *Annals of Applied Biology,* 137**,** 179-188.

Thomson, B. D. & Siddique, K. H. M. 1997. Grain legume species in low rainfall Mediterranean-type environments II. Canopy development, radiation interception, and dry-matter production. *Field Crops Research,* 54**,** 189-199.

Verger, A., Vigneau, N., Chéron, C., Gilliot, J.-M., Comar, A. & Baret, F. 2014. Green area index from an unmanned aerial system over wheat and rapeseed crops. *Remote Sensing of Environment,* 152**,** 654-664.

Chapter 5

General Discussion

5.1 Introduction

The research described in this thesis was undertaken to gain a better understanding of the overall agronomy, physiology and canopy management of field beans sown in the temperate Irish climate. The manipulation of the crop canopy through various agronomic techniques such as sowing date and seed rate, allowed for the detailed study of the crop and its components of yield to answer the following research questions set out by the literature review in Chapter 1 and outlined again here:

I. Delaying sowing date for of *Vicia faba* will lead to a reduction in final yield.
II. Economic optimum plant populations will be higher in spring sown field beans than winter sown field beans.
III. Yield of *Vicia faba* is stable across a wide range of plant populations.
IV. Yield of *Vicia faba* is primarily driven by pod number.
V. *Vicia faba* are predominantly source-limited.
VI. Fresh leaf biomass can be used to accurately predict green area index (GAI).
VII. Using a model to predict GAI from fresh leaf biomass can therefore be used as a surrogate for GAI and a management tool for growers of field beans.

5.2 Impact of seed rate and sowing date on canopy structure

The structure of the crop's canopy has been found to be most easily manipulated by seeding rate and to a lesser extent, sowing date. Field beans have been found to modify their morphological structure depending on the space that is available to each plant (Poulain, 1984a). Sowing at a lower or higher seed rate decreases or increases the competition between plants for light and other nutrients needed for growth and development. Studying a broad range of seed rates from 10 – 80 seeds per square metre over the three seasons, showed many characteristics typical of low and high plant densities. The lower seed rates allowed for the development of axillary branches and in this way, the crop compensated for lower plant populations. Secondary branches developed more green area per plant and thickened the canopy, allowing a greater interception of radiation. This also helps with the reduction of weeds. A higher number of weeds would be found at lower seed rates but branching and increasing the size of the crop canopy will help to smother the weeds.

Too high a seed rate can also cause many complications. Even though high seed rates have been found to allow the crop canopy to close quicker, maximising the amount of intercepted radiation, higher plant populations compete for light and assimilates causing a higher rate of seedling death. The higher seed rates did not branch as much as lower seed rates and tended to be taller as the crop grew and stretched for light within the dense canopy. This often leads to weaker stems with a higher chance of the crop lodging. Higher seed rates also have a greater disease and pest pressure. Studies by Aguilera-Diaz and Recalde-Manrique (1995) found that seed proximity is critical for emergence and establishment of a crop. Higher seed rates resulting in excessive seed proximity, can lead to a decrease in germination rate.

Having a longer growing period by sowing in the winter, gave the crop an advantage of maximising the amount of radiation intercepted by the canopy during vegetative and reproductive growth compared to the later spring sowings, with the winter sowings yielding significantly higher than the spring sowings each year. Establishment rates decreased in late winter and early spring sowings, due to weather/ground conditions and bird attacks on the freshly sown seed and newly emerged seedlings. Optimal sowing dates were found to be in October and February/March for winter and spring sowings, coinciding with the current recommendations for field beans in Ireland (DAFM, 2020).

Previous research on field beans in Ireland by the Department of Agriculture, Food and Marine (DAFM) published the recommended seed rate of 40 seeds per square metre in guidelines for growers sowing spring and winter beans (DAFM, 2020). Using the range from 20-60 seeds per square metre and the broader range of 10-80 seeds per square metre made for an extensive study of the effect that seed rates have on crop growth, development, and final yield. The general consensus found in this research was that as seed rate increases, yield increased. The first year of the field experiments was the exception to this. In 2017, there was no significant increase found in yield with seed rate from 10 to 80 seeds per square metre. This agrees with previous work on seed rate and yield in field beans that observed that even at lower seed rates/plant populations, yield can be competitive with higher seed rates/plant populations (Pilbeam et al., 1991b, Robinson and Conley, 2007, Sprent et al., 1977).

5.3 Hypotheses 1, and 2:

The results from this research support the hypothesis that delaying sowing date for *Vicia faba* will lead to a reduction in final yield. From the three years of field experiments, it was found that having a wide range of sowing dates under study gave a mixture of climatic conditions and other external influences for the growth and development of the crop. These environmental factors proved to be significant for crop performance and yield over the three seasons under study. The varieties and seed rates performed differently across the sowing dates, with the spring variety showing a promising performance when sown in the autumn. Previous studies on sowing dates in field beans found that low temperatures over the winter period can delay germination leading to increased seedling mortality (López-Bellido et al., 2005). The work presented in this thesis found that both the spring and winter variety sown in the autumn, performed well during the winter months. However, the important thing to note here is that similar to the López-Bellido studies in Spain, Irish winters typically are not that severe, with very little frost or snow during the winter season which favours good seedling survival. Sowing field beans in the autumn gives a longer growing season and a better opportunity to obtain enough green area for intercepting radiation in the spring and summer months compared to plants sown in the spring. From the range of sowing dates studied, the autumn sowings performed the best over the three studied seasons, with the October and November plots generally yielding highest each year. Poorer ground conditions and bird damage in January resulted in the worst crop establishment and yield across the seasons. As the ground conditions improved in the spring months, it was found that March, having more optimal sowing conditions, yielded highest for the spring sowings where April, with only a month difference in sowings, yielded lower. Sowing field beans in April or later in the season results in the crop having to be manually ripened by a desiccant. This is done because the crop is not ready to harvest when the weather in Ireland is still dry and because of this the crops canopy does not have enough time to develop before pod setting and therefore the source is too small to feed the sinks. This agrees with Confalone et al. (2010), who reported that as sowing date was delayed, the crop was exposed to higher values of radiation, air temperature and a longer photoperiod resulting in a shortening of the crop cycle.

5.3.1 Economic optimum plant population

With the extensive work on field trials carried out over three seasons, we believe to be the first to report an economic planting optimum for field beans in Ireland. The recommended seed rate for spring and winter field beans in Ireland is 40 seeds per square metre to establish 25-30 plants per square metre after field losses (DAFM, 2020). This thesis reports that, taking into account field losses during germination and establishment, the optimum plant population for the spring variety ranged between 24 - 38 plants per square metre with an average economic optimum of 31 plants per square metre and the optimum plant population for the winter variety was 13 plants per square metre. This supports the hypothesis that economic optimum plant populations will be higher in spring sown field beans than winter sown field beans.

With the range for the spring variety falling in the current recommended guidelines, we concluded that increasing seed rate above current commercial practices will not increase yield or profitability for spring beans grown in Ireland. However, there is a possibility to lower the seed rate for winter beans. Loss et al. (1998a) found a contrasting result in Australia, where their experiments found an economic optimum of 45 plants per square metre, which was higher than the recommended guidelines for sowing field beans in Australia. Increasing the seed rate in Australia was found to increase yield and profit for growers of field beans. Having a lower economic optimum in Ireland's maritime climate indicates how the crop is better able to compensate at lower plant populations than that of the hotter, semi-arid climate of Australia. With a similar climate to Ireland, research from the UK by Processors and Growers Research Organisation (PGRO), suggest that the optimum plant populations in the UK for spring field beans is between 60-65 plant m^{-2} for maximum yields. But when taking into account seed cost and produce value, the economic target population is 50-55 plants m^{-2} for soils that produce typical bean growth. For fertile soils or areas that produce very vigorous growth, target populations should remain at 35-45 plants m^{-2}.

5.4 Hypotheses 3, 4 and 5:

Results from Chapters 2 and 3, partially support the hypothesis field bean yield is stable across a wide range of plant populations. In 2017, the hypothesis was fully supported but in 2018 and 2019, there was a decline in yield at the lower plant populations. This was ascribed to the smaller canopies on those years, which resulted in less light interception at the critical growth stages and, thereby fewer pods per unit area. The number of pods per unit area is the yield component most closely related to yield and hence by increasing pods per unit area, yield will increase. This validates the hypothesis that yield of *Vicia faba* is primarily driven by pod number. The concept of using yield components to study the yield variation in field beans has been found to be less detailed than that of cereals and other crops. Rowland (1955) first identified the main yield components of field beans were number of pods per plant, number of seeds per pod and seed size. Further progress in the study of Rowland's findings have been limited. Kambal (1969a) continued the study of field bean yield components to find pod number per plant showed the highest correlation with yield in field beans, with yield variation caused mainly by the pod number and seed number per unit area (Kambal, 1969a, Pilbeam et al., 1989). From the in-depth study of yield components in Chapter 3, it was found that seed number per square metre and pod number per square metre were strongly related with final yield across the three seasons of study, agreeing with the previous studies that these components are the drivers of yield in field beans. However, the seed number per pod remained relatively stable across the studied range of plant densities, therefore, the focus of the study was the determination of pod number in field beans to explain yield variation. The determination of pod numbers is directly influenced by the amount of radiation intercepted throughout the flowering period. This was found through the supplementary shading experiment when radiation was reduced by c.60% during the vegetative and flowering period. Results from the experiment found that pod number per square metre was reduced by 38% when shaded throughout the flowering period, leading to an overall reduction in yield of 27%. Less of an effect was found when the crop was shaded through the vegetative phase suggesting that the crop may be able to recover from the reduction in radiation when the shade was removed.

The results of the supplementary shading experiment support the fifth hypothesis that yield of field beans is predominantly source-limited. Reducing the amount of intercepted solar radiation by the crop's canopy by shading during the pod development phase led to fewer pods per unit area, thereby reducing final yield. This agrees with most recent studies by Lake et al. (2019) carried out in Australia and Chile, who found that yield response to shading was most severe during the flowering to pod development stage, conforming with other indeterminate crops such as oilseed rape and other legumes like soybeans. These findings also agree with earlier studies from Board and Tan (1995) on soybeans, who found that yield was more restricted by the assimilatory capacity during the reproductive phase. However, this contradicts research carried out by Nasrullahzadeh et al. (2007) who found that yield per unit area was higher in shaded plants than unshaded plants. Whereas Hadi et al. (2006) found no effect of shading on yield in common beans (*Phaseolus vulgaris)*, and Verghis et al. (1999) found an overall reduction in yield of chickpeas from shading.

We found that shading during the reproductive phase did not allow the crop to recover from the loss of radiation, but the crop compensated by a 14% increase in seed size. This was possibly due to the assimilate supply per seed being greater during the pod filling stage after the shade was removed. However, shading did not affect the number of seeds per pod, in line with previous work which found that the number of seeds per pod is the most stable yield component in field beans (Agung and McDonald, 1997, Dantuma and Thompson, 1983)

5.5 Hypotheses 6 and 7:

Furthering the results found from the supplementary shading experiment, it was also found that generally, pod number was linearly related to the green area index (GAI) during the pod development phase. However, in the season of 2017, crops which had a larger GAI did not show this relationship. GAI has been found to be a useful tool for growers for crop management and tracking canopy closure for optimum interception of radiation and yields. This led to the hypothesis that fresh leaf biomass can be used to accurately predict green area index (GAI) and from this a second hypothesis that using a model to predict GAI from fresh leaf biomass could be used as a surrogate for GAI and a management tool for growers of field beans. Previous studies have found that a GAI of 4 at flowering is on target for optimum yield in oilseed rape (Berry and Spink, 2006, Lunn et al., 2003). Adapting this to field beans could prove to be useful as a management tool for growers.

With leaf green area making up the majority of the total crop green area in this study, it can be said that the leaves have the most photosynthetic capacity for the production of assimilates. Leaf fresh weight showed a stronger relationship with GAI than dry weight. The GAI continued to increase as the leaf weight increased across seasons, showing a strong positive relationship between the two. Just as GAI is used in oilseed rape as a benchmark for growth and development, leaf biomass in field beans could also assist as a predictor of GAI and in turn, be used as a benchmark as in oilseed rape. Taking small biomass samples from the crop at different growth stages to gather data on the growing crop and predict GAI is an easy method for growers to better management of field bean crops in temperate climates. Using the equation from the regression analysis on an independent data set to predict GAI using leaf biomass was successful in this study and climate but could possibly be worth investigating to see would this be a universal method that could work in other environments and climates. These findings support the hypothesis in question to an extent. The model created was accurately able to predict GAI from measured GAI using leaf fresh biomass from the independent data set, however, this data set contained similar parameters to the original data set used to create the model. The model worked well in this instance but there is no confirmation that it would work on other field bean sites or other climates as accurately.

5.6 Conclusions

5.6.1 Key messages for growers and breeders

The research outlined in this thesis covers the basic agronomy and physiology of field beans in Ireland. As an up-and-coming crop in Irish agriculture, gaining popularity with Irish growers in the last five years, further research should be carried out in the area of field bean agronomy, crop management and future research into starting a breeding programme for breeding of desirable traits suitable for the Irish climate and optimising yields. Breeding varieties with specific traits for temperate environments like varieties with improved disease resistance for the main diseases found in field beans ie: aschochyta, chocolate spot, rust, and downy mildew, would offer benefits, as would early harvest varieties with more determinate growth characteristics.

For growers, sowing in optimum soil conditions at the right time of year will be beneficial in the management and yield of bean crops. Winter beans should be ideally sown in October, reducing the threat of bird attacks, and giving the seedling enough time to emerge before the colder weather sets in. Winter beans have been found to be desirable to growers with their early harvest, however the extra management throughout the winter period has deterred growers from sowing winter beans. With similar field equipment used for cultivation of cereal production also used for beans, spring crops are more desirable with a slightly later harvest time so that as soon as the cereal harvest is over, the same equipment can be used in the spring bean harvest, allowing machinery costs to be reduced. Spring beans should be sown at the end of February/early March to aim for a mid-September harvest.

The recommended seed rate by the Department of Agriculture, Food and Marine is 40 seeds per square metre, with the aim of establishing 25-30 plants per square metre (DAFM, 2020). Taking into account field losses, the economic optimum plant number found in this research was 31 plants per square metre, falling within the recommended range from DAFM. However, this was much lower for winter beans at around 13 plants per square metre. With spring beans, the most popular of the two sowing dates in Ireland, aiming for the recommended seed rate of 40 seeds per square metre or approx. 230 kg per hectare (for a TGW of c.650g), will give an optimum planting density, on target for high yield and profit.

The work carried out by Lake and Sadras (2014) on chickpea and Lake et al. (2019) on field beans on identifying the critical period in these crops can also aid in crop breeding by increasing the likelihood of successful selection strategies, and increasing the efficiency of screening by narrowing the focus to critical physiologically relevant stages. It will also aid in improved agronomy and stress mitigation practices (Andrade et al., 2005, Sandaña and Calderini, 2012).

5.6.2 Bird damage/preventative measures

Late winter sowings and early (Irish) spring sowings of field beans have a higher risk of being attacked by birds either directly after sowing or at early emergence. Research in this area is limited, with very little known about preventative measures for bird damage in field beans. From field observations over the three studied seasons, bird damage occurred from sowing up to the appearance of the second leaf. Freshly planted seeds and small seedlings are the target for birds, attacking most plots in the field experiments and in some cases fully decimating the plots. Preventative measures rarely achieve 100% protection. Bangers, whistling tape, and netting were all used to avoid damage to the plots from birds. This damage was clearly seen when comparing the crop establishment in 2017 against 2018. In 2017, netting was placed over the late winter sowing (November), and establishment was calculated at 73%. This was found to be drastically lower in 2018 when the plots were not netted with establishment at 32% for the November sown plots. Although the damage to the plots was severe, the experiment and plot size was small compared to a farm level when sowing a larger area of beans. The damage by birds may not be as severe across a larger area of beans sown on a farm scale compared to smaller plot areas.

5.6.3 Impact of weather

Yield was found to be the lowest in 2018 when the average precipitation from flowering to harvest was much lower than expected, with the national average yield falling from 6.7 tonnes per hectare in 2017 to 2.5 tonnes per hectare in 2018 (Teagasc, 2018). Crop growth was accelerated due to the hot, dry conditions and the crop was stunted, with some of the lower seed rates not achieving full canopy closure during the season. Studies carried out on soybeans found that water and high air temperature stresses can greatly reduce seed yield (Dornbos Jr and Mullen, 1991) which coincides with the findings of this thesis. Field beans prefer a heavier soil with greater water retention. In dry seasons like 2018 and on lighter soils, beans can suffer from drought.

5.6.4 Key messages for policy makers

Encouraging growers to incorporate field beans and other protein crops into their rotations will be beneficial for the addition of residual nitrogen in the soil, reduction of pests, and ultimately using home grown protein for animal feed, reducing Irish imports. The Irish climate is very suitable to growing field beans, with high yields possible and this should be exploited. The highest national yield for field beans in Ireland was 6.7 t ha^{-1} in 2017 (Teagasc, 2018) compared with the UK average of 5.6 t ha^{-1} (PGRO, 2017). In the UK, there was an initiative set up by PGRO to encourage growers to grow field beans and achieve a 10-tonne field bean crop by the end of 2020 called the “Bean Yield Challenge”. The highest yielding crop of 8.32 t ha^{-1} was achieved by a grower in North Yorkshire. This initiative gives great incentive for growers to take on the challenge of growing a 10-tonne field bean crop. A similar initiative could be implemented in Ireland, encouraging growers to grow field beans as a home-grown source of protein with the added incentive of winning a competition or the recognition of growing the highest yielding crop that year.

Funding and extending the protein grant as well as implementing targets or introducing the likes of the competition for the highest yielding crop could be introduced to educate and encourage growers to sow protein crops such as beans and reap the benefits of this crop in their rotations such as residual N for the following crop, weed control as well as using field beans as a break crop.

5.6.5 Future research

From the evidence found in numerous previous studies on field beans, as well as the results presented in this thesis, it is clear to say that field beans are a beneficial, high yielding, manageable crop given the right conditions. The main concern for field beans is their unreliable and variable yields from year to year, which has been ultimately found to be weather related. With three very different seasons and weather conditions from 2017-2019, the results of this thesis clearly show the impact of weather, more specifically, water and light availability to the crop during the reproductive phase, which was found to be impacted the most in 2018 during the unusual hot, and dry summer period. Although the weather cannot be controlled, what is possible is breeding varieties with specific traits suitable for variable climates. Setting up a bean breeding programme would be a good step forward in the right direction for the future of beans research.

Bean crops have the most potential as a native protein source. Protein content in field beans has been estimated at around 25-35% dry matter (Nachi and Le Guen, 1996), however, there is very little knowledge in the area of protein content in grain legumes such as field beans. Studying the protein content in field beans and other grain legumes would be useful for optimising animal feeds and increasing the amount of reliable protein feed from sustainable sources. There is scope to improve the traceability of Irish branded produce by replacing non-traceable imported protein with native bean crops. However, farmers need to be assured of the value of their feed and ensure a continued supply to consider beans as a significant ration component.

Residual nitrogen (N) content that is left in the soils after harvest of field beans crops has always been presumed rather than an absolute value with suggestions that there is about 20-30% residual N after harvest. Further research into how the rhizobia in the root nodules are fixing N during the crop cycle, soil analysis and the yields of the crop following field beans would all make for interesting research and furthering what is known about field beans and the benefits they bring to soil fertility.

GAI has been a useful tool for growers for crop management and tracking canopy closure for optimum interception of radiation and yields. This has been most useful so far in oilseed rape crops, even going so far as creating a GAI online tracking data base and an application for mobile phones as a quick in field indication tool for growers (BASF, 2018). The concept of this tool could be applicable to field beans, using a simple photograph of the growing canopy to track GAI at the early vegetative and reproductive phases as a benchmark for final harvest yields.

Overall, the research presented in this thesis has provided a good insight to the growth, development, and management of field beans in Ireland. The hypotheses set out at the beginning of this thesis were tested through the extensive field experiments, and study of the developing crop and yield components over three seasons. The supplementary field experiments carried out in conjunction with the main field experiments gave a more detailed insight to the growth and development of the crop, the green area needed for intercepting radiation, and the development of pods and seeds for optimising final harvest yields. This research is a good foundation for research on field beans in temperate climates such as Ireland. Building on this research, introducing the concept of a breeding programme and focusing on breeding for desired traits would lead to a more productive research on field beans in Ireland, with the ultimate goal of reducing our imports and replacing them with a reliable, home-grown protein source.

References

Aguilera-Diaz, C. & Recalde-Manrique, L. 1995. Effects of plant density and inorganic nitrogen fertilizer on field beans (Vicia faba). *The Journal of Agricultural Science,* 125**,** 87-93.

Agung, S. & McDonald, G. K. 1997. Effects of seed size and maturity on the growth and yield of faba bean (Vicia faba L.). *Australian Journal of Agricultural Research,* 49**,** 79-88.

BASF. 2018. *OSR GAI Online* [Online]. BASF Agricultural Solutions UK. Available: https://www.agricentre.basf.co.uk/en/Services/Online-Tools/OSR-GAI-Online/?fbclid=IwAR0oNo84dIPkx2QEhAEaravmplxK0dI49vqSVd9POtVVq1Ir5x-fmLPlPl0 [Accessed November 2020].

Berry, P. M. & Spink, J. H. 2006. A physiological analysis of oilseed rape yields: Past and future. *The Journal of Agricultural Science,* 144**,** 381-392.

DAFM. 2020. *Field Beans Recommended List 2020* [Online]. Department of Agriculture. Available: https://www.agriculture.gov.ie/media/migration/publications/2020/1SpringBeanRecommendedList2020130120.pdf [Accessed 20/08 2020].

Dantuma, G. & Thompson, R. 1983. Whole-crop physiology and yield components. *The faba bean***,** 143-158.

Dornbos Jr, D. & Mullen, R. 1991. Influence of stress during soybean seed fill on seed weight, germination, and seedling growth rate. *Canadian Journal of Plant Science,* 71**,** 373-383.

Hadi, H., Ghassemi-Golezani, K., Khoei, F. R., Valizadeh, M. & Shakiba, M. R. 2006. Response of common bean (Phaseolus vulgaris) to different levels of shade. *Journal of Agronomy,* 5**,** 595-599.

Husain, M. M., Hill, G. D. & Gallagher, J. N. 1988. The response of field beans (Vicia faba L.) to irrigation and sowing date:1. Yield and yield components. *The Journal of Agricultural Science,* 111**,** 221-232.

Kambal, A. E. 1969. Components of yield in field beans, Vicia faba L. *The Journal of Agricultural Science,* 72**,** 359-363.

López-Bellido, F. J., López-Bellido, L. & López-Bellido, R. J. 2005. Competition, growth and yield of faba bean (Vicia faba L.). *European Journal of Agronomy,* 23**,** 359-378.

Loss, S., Siddique, K., Jettner, R. & Martin, L. 1998. Responses of faba bean (Vicia faba L.) to sowing rate in south-western Australia I. Seed yield and economic optimum plant density. *Australian Journal of Agricultural Research,* 49**,** 989-997.

Lunn, G. D., Spink, J. H., Wade, A. & CLARE, R. W. 2003. Spring Remedial Treatements to Improve Canopy Structure and Yield in Oilseed Rape. *HGCA Project Report No. OS64.* London: Home-Grown Cereals Authority.

Nachi, N. & Le Guen, J. 1996. Dry matter accumulation and seed yield in faba bean (Vicia faba L) genotypes. *Agronomie, EDP Sciences,* 16 (1)**,** pp.47-59.

Nasrullahzadeh, S., Ghassemi-Golezani, K., Javanshir, A., Valizade, M. & Shakiba, M. 2007. Effects of shade stress on ground cover and grain yield of faba bean (Vicia faba L.). *Journal of Food Agriculture and Environment,* 5**,** 337.

Pilbeam, C. J., Hebblethwaite, P. D., Ricketts, H. E. & Nyongesa, T. E. 1991. Effects of plant population density on determinate and indeterminate forms of winter field beans (Vicia faba) 1. Yield and yield components. *The Journal of Agricultural Science,* 116**,** 375-383.

Poulain, D. 1984. Influence of Density on the Growth and Development of Winter Field Bean (Vicia Faba). *In:* HEBBLETHWAITE, P. D., DAWKINS, T. C. K., HEATH, M. C. & LOCKWOOD, G. (eds.) *Vicia faba: Agronomy, Physiology and Breeding: Proceedings of a Seminar in the CEC Programme of Coordination of Research on Plant Protein Improvement, held at the University of Nottingham, United Kingdom, 14–16 September 1983. Sponsored by the Commission of the European Communities, Directorate-General for Agriculture, Coordination of Agricultural Research.* Dordrecht: Springer Netherlands.

Robinson, A. P. & Conley, S. P. 2007. Plant populations and seeding rates for soybeans. https://www.extension.purdue.edu/extmedia/ay/ay-217-w.pdf: Purdue Univ., West Lafayette, IN. .

Rowland, D. G. 1955. The problem with yield in field beans. *Agric. Prog.,* 30**,** 137-147.

Sprent, J. I., Bradford, A. M. & Norton, C. 1977. Seasonal growth patterns in field beans (Vicia faba) as affected by population density, shading and its relationship with soil moisture. *The Journal of Agricultural Science,* 88**,** 293-301.

Teagasc. 2017. *Field Beans* [Online]. Available: https://www.teagasc.ie/crops/crops/research/research-programme/cropquest/field-beans/ [Accessed 05/08 2020].

Teagasc 2018. Teagasc Specialist, Tillage CROPS Report, Harvest Report.

Verghis, T., McKenzie, B. & Hill, G. 1999. Effect of light and soil moisture on yield, yield components, and abortion of reproductive structures of chickpea

(Cicerarietinum), in Canterbury, New Zealand. *New Zealand journal of crop and horticultural science,* 27**,** 153-161.