



Competition, growth and yield of faba bean (*Vicia faba* L.)

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Abstract

This paper reviews current knowledge regarding the influence of plant density on the growth and yield of the faba bean crop (*Vicia faba* L.). An analysis is also made of sowing rate and other factors that may modify optimum plant density, including environmental conditions; in this sense, should be made a differentiation between faba crops grown in temperate conditions and those grown in Mediterranean and semi-arid conditions. The genotype also prompts variations in optimum plant density, depending on the botanical type (*mayor*, *equina* or *minor*) and the growth habit (determinate versus indeterminate) of the cultivar selected. Sowing date also influences optimum seeding rate, which is lower for autumn–winter sowing under temperate and Mediterranean conditions and increases as the sowing date is delayed. For the spring-sown crops typical of temperate conditions, optimum plant density will be higher due to the shorter growing season. With a longer growing season and under optimum environmental conditions, there is normally no additional response to densities over 20 plants m⁻², while in suboptimal conditions, optimum plant density may increase to over 60 plants m⁻². Although the faba bean crop displays considerable plasticity in response to variations in plant density, mainly with regard to number of pods per square meter, it is not wholly clear to which component of yield this should really be ascribed. Number of stems per plant appears to be the most influential factor, although further research is required to confirm this.

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Keywords: Growth; Seed yield; Sowing rate; Sowing date; Climate; Botanical type

Abbreviations: CGR, crop growth rate (g m⁻² d⁻¹); GAI, green area index; HI, harvest index (%); LAD, leaf area duration (days); LAI, leaf area index; LAR, leaf area ratio (cm² g⁻¹); NAR, net assimilation rate (g m⁻² d⁻¹); PAR, photosynthetically active radiation (MJ); RGR, relative growth rate (g g⁻¹ d⁻¹); RUE, radiation use efficiency (g MJ⁻¹)

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1. Introduction

Grain legumes are a major source of protein in human and animal nutrition and play a key role in crop rotations in most parts of the world. When grown in rotation with other crops, under certain environmental conditions, they can improve soil fertility and reduce the incidence of weeds, diseases and pests (Mwanamwenge et al., 1998).

Although today, faba bean is the second widely-grown dry grain legume in EU (15), the EU (15) is the world's fourth largest producer (FAO, 2003), little is known about the growth and development of this crop. It is grown in climates ranging from temperate to semi-arid, using different cultivars and relatively different crop-management techniques. One such difference is in the selection of sowing-rate, which directly determines plant density and is influenced to a great extent by the cultivar used, the environment and the sowing date.

In general, and for any crop, intra-specific plant-to-plant competition affects production of biomass and crop yield as well as economic profitability. A number of classic models examine the relationship between crop yield and plant density (Bleasdale and Nelder, 1960; Willey and Heath, 1969). The plants forming a crop compete with each other for light, nutrients and available soil water. Of these, the most important factor for agronomic crop productivity is the amount of radiation intercepted by the leaf surface (Williams et al., 1965; Hawtin, 1982); this is also the factor in which man has most effectively intervened (Evans, 1980). One of the crop-management techniques that most influences the amount of light intercepted by crops is the choice of plant density, which modifies canopy structure and the duration of vegetative growth. In nature, plant communities self-thin to an optimum plant density, which differs according to the size of individual plants. According to the empirical law that describes this process, the optimum population density is lower for larger plants (Harper, 1977). At the same time, the environment – through its effect on plant size – may influence the optimum plant density.

The present review has compiled all the information available until the current time about the influence of plant density on growth and yield of faba bean crop. It has been organized as following: Section 1, Introduction (see above); Section 2, Factors influencing plant density; Section 3, Growth and development; Section 3.1, Emergence and establishment, Section 3.2, Vegetative growth; Section 3.3, Leaf area development; Section 3.4, Interception of solar radiation; Section 3.5, Dry matter production; Section 3.6, Dry matter partitioning; Section 3.7, Canopy structure and characteristics; Section 3.8, Reproductive period; Section 3.8.1, *Podding-node formation*; Section 3.8.2, *Flowers and pods drop*; Section 3.8.3, *Premature flower abortion*;

Section 3.8.4, *Pod and seed filling*; Section 4, Seed yield and yield components; Section 4.1, Seed yield; Section 4.1.1, *Environmental influence*; Section 4.1.2, *Influence of cultivar*; Section 4.1.3, *Influence of sowing date*; Section 4.2, Harvest index (HI); Section 4.3, Seed yield components; Section 4.3.1, *Number of podding nodes per plant*; Section 4.3.2, *Number of pods per podding node*; Section 4.3.3, *Number of pods per plant*; Section 4.3.4, *Number of seeds per pod*; Section 4.3.5, *Mean seed weight*; Section 5, Conclusions.

2. Factors influencing plant density

For most crops, including grain legumes, the choice of sowing rate is an important agronomic practice, influencing plant density and crop establishment. In the faba bean, according to Loss et al. (1998a), plant density can affect canopy development, radiation interception, dry matter production, evaporation of water from soil under the crop, weed competition, the development of fungal and viral diseases, plant and first pod height, seed yield and ultimately, the economic productivity of a crop in the farming system.

A key component of seed yield is the number of plants per square meter. It is the first component to be established, at the start of the crop cycle and is largely dictated and controlled by the farmer himself; the environment plays a less important role in the final number of plants per square meter (Dantuma and Thompson, 1983). The other components of seed yield that determine the final output are established at a later stage in the course of the crop cycle and are dependent on the number of plants per square meter.

According to Bond et al. (1985), a wide range of densities is commonly used, from 15 to 60 plants m⁻², depending on the cultivar and the region. However, numerous studies undertaken in different environments provide more precise data on optimum density, which depends strongly on the cultivar used, the environmental conditions and the sowing date (Table 1).

The species *Vicia faba* L. comprises four botanical types (*mayor*, *equina*, *minor* and *paucijuga*), which differ from each other mainly with regard to seed size, a trait closely linked to genotype. However, crossing of botanical types has made it difficult to distinguish between them solely on the basis of seed size (a quantitative trait), especially as size may vary

Table 1

Influence of plant density of faba bean (*Vicia faba* L.): summary of experiments in various environments

Authors	Variety	Climate	Sowing date	Plant density	Conclusions
Marcellos and Consable (1986)	Fiord (<i>minor</i> , IDT ^a)	Mediterranean (New South Wales, Australia)	Autumn/winter-sown (range April–August)	Range 10–60 plants m ⁻² (inter-rows space 18 and 33 cm)	Optimum sowing in late April and early May. Under the highest yielding conditions, 20 plants m ⁻² but for a wide range of conditions, 30–35 plants m ⁻²
Coelho (1987)	Tapada da Ajuda (<i>minor</i> , IDT)	Mediterranean (Lisbon, Portugal)	Autumn-sown (December)	Range 10–50 plants m ⁻² (inter-rows space 50 cm)	Highest yields are reached with densities above 40 plants m ⁻²
Salih (1989)	cv. BF 2/2 (<i>minor</i> , IDT)	Arid (Sudan)	Autumn-sown (range October–November) under irrigation	Range 16.6–49.9 plants m ⁻² (inter-rows space 60 cm)	Highest yields are reached with 49.9 plants m ⁻² and sowing at the end of October
Pilbeam et al. (1990)	Ticol (<i>minor</i> , DT ^b); TP 667 (<i>minor</i> , DT); Maris Bead (<i>minor</i> , IDT); M 5.1 (<i>equina</i> , IDT)	Temperate (Sutton Bonington, UK and Dijon, France)	Spring-sown (March–April)	Range 10–100 plants m ⁻² (inter-rows space: 11.9 cm in UK and 17.5 cm in France)	Weather conditions exert higher influence on yield than plant density. Determinate cultivar is less productive. Optimum density is highest for determinate cultivar. Generally, yield raised with density increase
Pilbeam et al. (1991a,b)	Bourdon (<i>minor</i> , IDT); 858 (<i>minor</i> , DT)	Temperate (Sutton Bonington, UK)	Autumn-sown (October)	Range 10–80 plants m ⁻² (inter-rows space 13.4 and 11.9 cm)	Highest yield of indeterminate cultivar. Plant density does not affect yield. Optimum density is 10–20 plants m ⁻² for both determinate and indeterminate cultivars
Stützel and Aufhammer (1992)	Herz Freya (<i>minor</i> , IDT) Ticol (<i>minor</i> , DT)	Temperate (Hohenheim, Germany)	Spring-sown (April)	18.5 and 74.0 plants m ⁻² with three plant distributions: isometric stand, 25 and 12.5 cm; single rows, 40 cm; double rows, 80 cm	No influence of plant distribution on yield. Highest yield of indeterminate cultivar. Yield raised with density increase, being higher for determinate than indeterminate cultivar
Aguilera-Díaz and Recalme-Manrique (1995)	Alameda (<i>equina</i> , IDT)	Mediterranean (Granada, Spain)	Autumn-sown (December), under supplementary irrigation	Range 10–30 plants m ⁻² (inter-rows space 50 cm)	Lower yield for high densities and low N rates. Optimum density: 10 plants m ⁻²
Almeida et al. (1995)	Alameda (<i>equina</i> , IDT)	Mediterranean (Córdoba, Spain)	Autumn-sown (November)	Range 20–60 plants m ⁻² (inter-rows space 50 cm)	Highest yields are reached with densities above 40 plants m ⁻²
Quaglietta-Chiarandà et al. (1995a,b)	Gemini (<i>equina</i> , IDT)	Mediterranean (Southern Italy)	Autumn-sown	Range 7–100 plants m ⁻²	Until 35 plants m ⁻² , seed yield raises with density increase
Adisarwanto and Knight (1997)	Fiord (<i>minor</i> , IDT)	Mediterranean (Adelaide and Strathalbyn, Australia)	Autumn/winter-sown (range April–June)	Range 20–56 plants m ⁻² (inter-rows space 25 cm)	Highest yields are reached with lowest plant density (20 plants m ⁻²) and earliest sowing date (April). For April sowing, yield decreased with plant density increase. From May sowing, yield raised with the plant density increase until 49 plants m ⁻²
Loss et al. (1998a,b)	Fiord (<i>minor</i> , IDT)	Mediterranean (various sites of South-western Australia)	Autumn-sown (May)	Range 70–270 kg ha ⁻¹ (8–16 to 41–49 plants m ⁻²), Loss et al. (1998b) (inter-rows space 18 cm)	Most cases, optimum plant density is 45 plants m ⁻² (nowadays 30 plants m ⁻² is used for cv. Fiord)

^a IDT: indeterminate cultivar.^b DT: determinate cultivar.

considerably as a function of environmental conditions. Therefore, for crop-management purposes, reference is made only to cultivar seed size regardless of botanical type, being classified as large-seeded (>1.0 g seed $^{-1}$), medium-seeded (1.0 – 0.5 g seed $^{-1}$) and small-seeded (>0.5 g seed $^{-1}$). Large-seeded cultivars generally provide greater seed yields, both in Mediterranean (Robertson and El-Sherbeeney, 1993) and humid conditions (Mwanamwenge et al., 1998); at the same plant density, they also produce a larger amount of dry matter and display a larger green area index (GAI) than other cultivars. This is because the plant is larger and has larger leaves, enabling it to compensate better for low plant density (Lamb and Poddar, 1992). As a result, it is common practice to use different densities depending on cultivar seed size, the most common densities being 15 plants m $^{-2}$ for large seeds, 20 plants m $^{-2}$ for medium-size seeds and 30 plants m $^{-2}$ for small seeds. Mwanamwenge et al. (1998) suggest that variation in optimum plant density as a function of cultivar seed size has not yet been addressed in any depth and merits further research. Most studies dealing with plant density in faba beans use *minor* or small-seeded cultivars.

Within each type of faba bean, there are winter cultivars grown in temperate and Mediterranean environments and spring cultivars, grown mainly in temperate regions. Optimum plant density is different for the two groups. Winter cultivars sown at densities of over 25 plants m $^{-2}$ run the risk of a higher proportion of flowers fall and a greater incidence of disease (Bond et al., 1985).

New cultivars of determinate type have been obtained, based on the *ti* mutant, in which the apex is replaced by a terminal inflorescence after production of a number of nodes (Sjödin, 1971). These determinate cultivars display different growth habits; they are smaller, have fewer nodes per stem and develop a different canopy structure by producing a greater number of branches per plant (Pilbeam et al., 1989b). Side branches are reproductively inferior to the main stem, and their production can be curtailed by increasing plant density, effectively replacing them by a larger number of main stems and thus improving seed yield (Pilbeam et al., 1990).

Environmental conditions govern seed yield and thus influence the optimum density required to maximize yield. While in temperate regions, such as Northern Europe, the chief limiting factors are low tem-

perature, reduced intensity of incident radiation and excessive environmental moisture, in Mediterranean conditions, the limiting factor is low rainfall during spring and summer, particularly since the faba bean is regarded as a drought-sensitive crop (Grasshoff, 1990); the amount of water available from the start of flowering to harvesting partly determines seed yield (Mwanamwenge et al., 1998), and it is during this period that rainfall is lowest; however, according to López-Bellido et al. (2003), it improves as January through April rainfall increases (approximately from four leaves to pod set). Faba beans are reportedly tolerant to mild frosts during flowering in Mediterranean countries (Loss and Siddique, 1997).

According to Adisarwanto and Knight (1997), the numerous studies undertaken, particularly in Europe and North America, on the effects of sowing date and density on yield are not relevant to Australian conditions, since when faba beans are grown as a winter crop in temperate regions, responses to density are confounded by winterkill and disease; when they are sown as a spring crop, temperature and daylength are very different from winter conditions in a Mediterranean-type environment.

For small-seeded cultivars in the Mediterranean-type environments of Southern Australia, plant density of 30 plants m $^{-2}$ is generally targeted by farmers, but in medium to low rainfall areas or situations, where the risk of fungal diseases is large, densities of 15–25 plants m $^{-2}$ are also used (Loss et al., 1998a). Lower densities are preferred for large-seeded cultivars.

The response of seed yield to changes in plant density varies not only between autumn and spring sowing but also depending on the sowing date within each sowing season. In the United Kingdom, optimum plant density for spring sowing ranges from 45 to 65 plants m $^{-2}$, depending on cultivars, location and year (Pilbeam et al., 1991a). However, according to McEwen et al. (1988), the optimum seeding rate is lower for winter sowing (24 seeds m $^{-2}$), although this depends on the exact sowing date. A lower seeding rate is required for early sowing (12 seeds m $^{-2}$) than for late sowing (36 seeds m $^{-2}$).

Inter-row spacing commonly used for faba bean crops ranges between 10 and 50 cm. This appears to have little effect on the response to varying plant densities, according to McEwen (1973). For a given sowing rate (40 plants m $^{-2}$), variation in inter-row spacing

apparently had no effect on growth indices, final dry matter production, harvest index* or seed yield, for spring-sown determinate or indeterminate cultivars in the United Kingdom (Pilbeam et al., 1989a). Increasing linear density affected only the seedling mortality rate, which increased with linear density and on increasing inter-row spacing to 50 cm for the same plant density, due – according to Pilbeam et al. (1989a) – to greater plant-to-plant competition. Studies of spring-sown faba bean, undertaken by Stützel and Aufhammer (1992) in Germany, used both determinate and indeterminate cultivars at two different densities (18.5 and 74 plants m^{-2}); their findings bore out the results indicated above, i.e. that seed yield and yield components were not influenced by changes in plant distribution, although double rows (80 cm between each pair of rows) tended to produce lower yields than single rows (inter-row spacing of 40 cm) and isometric rows (12.5 and 25 cm).

3. Growth and development

3.1. Emergence and establishment

Germination and initial growth of the faba bean crop is mainly related to temperature, and more particularly, daytime temperature, where water is not a limiting factor (Dantuma and Thompson, 1983). Generally speaking, the seed germination and establishment rate is not affected by increasing the sowing rate, except where different weather conditions (Amato et al., 1992) or poor seed quality (Pilbeam et al., 1990) lead to losses in germination and seedling emergence which are greater at higher sowing rates. Low temperatures at autumn–winter sowing may prompt greater seedling mortality, although the rate is not influenced by sowing rate (Pilbeam et al., 1991a). In Mediterranean climate conditions, Loss et al. (1998a) report a positive linear correlation between sowing rate and plant density, though with a small trend towards greater mortality at higher sowing rates. These authors report an average emergence rate of 71%. Similar results were obtained for the same type of climate by Aguilera-Díaz and Recalme-Manrique (1995), who stress that seed proximity is an important limiting factor for emergence rates, which decline as density increases or inter-row spacing is increased for the same sowing rate.

According to Hegarty (1977) and Rowland and Gusta (1977), reduced germination is due to greater conductivity of solutes from the seeds themselves. Excessive seed proximity, together with low soil water availability for germination, thus, prompts greater conductivity of this water and a decrease in the germination rate. Once emergence has taken place, excessive reduction of intra-row spacing leads to greater mortality due to increased plant-to-plant competition (Pilbeam et al., 1989a).

3.2. Vegetative growth

During the early stages of vegetative growth, there is a linear correlation between dry matter accumulation and number of plants per square meter. High sowing densities will prompt higher leaf area index (LAI) and dry matter values during this stage, while relative growth indices remain similar. After a certain point and depending on sowing density, competition arises between plants for light and other resources, leading to a decrease in the relative growth of individual plants; the correlation between dry matter accumulation and density ceases to be linear and becomes asymptotic. Above a certain minimum, dry matter production will tend to equal out for different densities (Dantuma and Thompson, 1983). As plant density increases, competition between plants becomes more intense, affecting the growth, development and production of each plant. Faba bean crop output is governed by a number of compensatory factors. Some of these are fixed in the vegetative period, such as number of plants per square meter and number of stems per plant (both inversely related), through competition between plants for various resources, as indicated earlier. Coelho and Pinto (1989) note that the faba bean displays great plasticity in response to variations in plant density.

The duration of the vegetative period and the weather conditions during vegetative growth are of great importance for the compensatory capacity of faba beans, since they affect the number of stems per plant. In a longer growing season and given optimum growing conditions, plants grown at low density can effectively compensate for deficiencies with respect to those grown at high densities, by fully developing a larger number of side branches. In this regard, the crop cycle (autumn–winter sowing versus spring sowing) can affect the length of the vegetative period, and in

both cycles, the growing season can be prolonged by earlier sowing. Marcellos and Constable (1986) report that early autumn sowing in Mediterranean conditions (April in the Southern Hemisphere) prolongs the growing season with respect to later sowing (July–August in the Southern Hemisphere), resulting in larger plant size and higher average yields. However, Adisarwanto and Knight (1997), under similar conditions, found that sowing date had little influence on time from emergence to first flower.

Growth during this period is usually limited by competition between plants for solar radiation, when environmental conditions are favorable. In Mediterranean conditions, individual plant growth may be limited by lack of rainfall, particularly at high plant densities, while competition for radiation is low (Loss et al., 1998b).

3.3. Leaf area development

According to Poulain et al. (1986), development of the LAI depends mainly on environmental temperature (day and night temperature), water available to the crop and plant density. Generally speaking and for all conditions, the maximum LAI (GAI) is always achieved with higher plant densities (Singh et al., 1988; Quaglietta-Chiaranda et al., 1995a; Tuttobene and Vagliasindi, 1995), although Loss et al. (1998b) report that the highest values are recorded in the most favorable environ-

ments regardless of plant density. Maximum LAI is achieved during the state of flowering and until the start of pod filling, and it is the index that best accounts for differences in the other crop growth indices (Coelho and Pinto, 1989). Table 2 shows values for LAI_{max} (GAI_{max}) achieved at different densities by different authors.

For autumn-sown in temperate climates (United Kingdom), for determinate and indeterminate forms, the LAI increases rapidly from 170 DAS (days after sowing), from values of <1.5 to a maximum often greater than 4 (220–230 DAS); thereafter, values decline rapidly. Until flowering, the highest values are achieved at the highest densities; however, during pod development, the reverse is the case, i.e. final LAI is greater at lower densities (Pilbeam et al., 1991b). These findings match those reported by Dantuma and Thompson (1983), who conclude that the densities providing the highest seed yield are those which record the lowest LAI during the period from flowering to pod maturation. According to these authors, LAI is affected by others factors, including genotype. High input use increases LAI values, but not seed yield, which require a lower LAI; water supply is the main factor controlling the vigorous growth of stems and leaf surface.

Variation in sowing density prompts changes in the crop microclimate, modifying the values of some parameters. High densities increase photosynthesis, reducing respiration and photorespiration (Poulain et al.,

Table 2
Growth indices in faba bean (*Vicia faba* L.) crop in relation with plant density

Autors	Density (plant m ⁻²)	Total dry matter (g m ⁻²)	LAI _{max}	LAD (days)	Height plant (cm)	Height 1st pod (cm)	HI (%)
Coelho (1987)	10–50	1038–2311	–	–	–	–	46–47
Salih (1989)	–	–	–	–	–	–	–
Pilbeam et al. (1990)	10–100	759–908	–	–	85.1–107.1	–	52–40
Pilbeam et al. (1991b)	10–80	1678–1462	5.6–10.5	524–511	–	–	–
Stützel and Aufhammer (1992)	18.5–74.0	815–1442	–	–	–	–	40–41
Aguilera-Díaz and Recalme-Manrique (1995)	10–30	463–508	3.1–3.5	–	–	–	59–56
Almeida et al. (1995)	20–60	684–1555	3.7–7.1	180–376	79–85	23–35	51–25
Quaglietta-Chiaranda et al. (1995a)	7–100	519–738	1.0–2.5	–	50.8–69.9	–	36–41
Adisarwanto and Knight (1997)	20–56	980–1120	–	–	–	–	50–43
Loss et al. (1998a,b)	70–270 kg ha ⁻¹ 8–16 to 41–49 plants m ⁻²	395–623	1.9–3.3 (GAI)	–	45–66	10–18	52–49

1986); at the same time, they accelerate maturing of the crop (Stringi et al., 1986; Amato et al., 1992). Coelho and Pinto (1989) report rapid leaf senescence due to the swift decline in growth indices and an increase in the net assimilation rate (NAR). As a result, in winter, faba bean crops under Mediterranean climate conditions, there is no evidence of competition for light or nutrients; rapid senescence of the crop at high plant densities is probably due to inter-plant competition for available soil water at the end of the growth season.

Leaf area duration (LAD) is greater at higher plant densities during the vegetative stage, resulting in greater total biomass at these densities (Ishag, 1973; Almeida et al., 1995). Thereafter, there is no correlation between LAD during seed filling and seed yield (Pilbeam et al., 1991b).

Inter-plant competition for light increases with density, and therefore, leaf area ratio (LAR $\text{cm}^2 \text{g}^{-1}$) also increases. Production of leaves with high LAR values as a response to shading has been confirmed in faba beans (Kasim and Dennett, 1986). However, Pilbeam et al. (1991b) report that in some cases there is no clear effect of plant density on leaf area ratio.

The behavior of other growth indices in response to variation in plant density is generally linked to the dry matter and LAI values attained over the various crop stages. Polignand and Uggenti (1989) report different LAR, NAR and relative growth rate (RGR) values for different botanical types (*major*, *equina* and *minor*). With regard to plant density, Singh et al. (1992) and Tuttobene and Vagliasindi (1995) detected an increase in crop growth rate (CGR), when sowing rate was increased, while Singh et al. (1992), and in some cases, El-Zahab et al. (1981) observed a decrease in RGR and NAR values. However, Coelho and Pinto (1989) failed to find any significant difference in NAR for the different densities studied.

3.4. Interception of solar radiation

Crop canopy dry matter production depends on the interception of photosynthetically active radiation (PAR) and on the efficiency with which energy is used for the production of dry matter. Both interception and conversion are influenced by canopy characteristics, which can, in turn, be modified by plant density and by the use of cultivars with different growth habits, such as determinate cultivars. Consequently,

both factors will also influence dry matter production and seed yield (Stützel and Aufhammer, 1992). High plant density favors rapid canopy closure and an early maximization of light interception. Subsequently, however, under these conditions there is excessive shading between leaves, leading to insufficient carbon fixation and increased respiration rate. Thus, a more efficient use of light energy (interception and conversion) may be achieved with a lower plant density (Pilbeam et al., 1991b). According to Sprent et al. (1977), at densities of up to 66 plants m^{-2} , competition between faba bean plants for light has no apparent effect.

In faba beans, as in other crops, there is a linear correlation between dry matter production and accumulated intercepted PAR (Loss et al., 1998b). The slope of this correlation, radiation use efficiency (RUE), in the faba bean crop varies with season and environment, water reserves (Green et al., 1985), plant population density (Kasim and Dennett, 1986) and sowing date (Fasheun and Dennett, 1982). Values generally lie within the range 1.61–5.54 g MJ^{-1} (Pilbeam et al., 1991b). However, according with Loss et al. (1998b), sowing rate does not affect RUE, which displays an average value of 1.30 g MJ^{-1} in South-western Australia, with no significant difference between years.

The amount of PAR absorbed at high plant densities is greater than at lower densities; PAR values follow a pattern similar to that reported for GAI (Mwanamwenge et al., 1998). Early canopy closure at higher plant densities prompts greater use of available incident radiation (Pilbeam et al., 1990) and increases the % PAR absorbed in the absence of water stress (Lawn, 1989). Maximum absorbed PAR can attain values of 75–85%, matching maximum GAI values, in winter crops under Mediterranean conditions (Loss et al., 1998b). Similar findings are reported by Silim and Saxena (1992).

3.5. Dry matter production

Most authors agree that total dry matter production over the crop season behaves in a similar manner to LAI, higher values always being attained at higher densities, across a wide range of seeding rates tested in both temperate and Mediterranean conditions (Poulain et al., 1986; Coelho and Pinto, 1989; Singh et al., 1992; Gurung and Katwal, 1993; Siddique et al., 1998;

Pilbeam et al., 1991b; Stützel and Aufhammer, 1991; Silim and Saxena, 1992; Aguilera-Díaz and Recalme-Manrique, 1995) (Table 2). However, high densities do not always result in increased yields; indeed, the response is often negative (Donald, 1963).

Accumulation of dry matter per square meter is initially slow. Only a certain time after emergence, it increases rapidly, which continues until flowering-start of pod filling, when maximum values are recorded regardless of plant density. Prior to that peak, higher values are obtained at high plant densities (Pilbeam et al., 1991b). Thereafter, dry matter decreases until harvesting due to the fall of senescent leaves and to net loss of dry matter in leaves, stems and pod cases prompted by retranslocation of assimilates towards seeds, not existing differences in proportion among densities (Stützel and Aufhammer, 1992). According to McCree (1986), half the dry matter mobilized is lost through respiration, and these losses increase considerably during senescence. Photosynthesis at this stage is unable to make up for the loss. During the grain-filling stage, the decrease in dry matter is less marked at low plant densities. Although final dry matter of the crop is generally greater at higher densities, the reverse has occasionally proved to be the case. Total dry matter per plant is always greater at lower plant densities.

For many crops, final dry matter production (biological yield) increases curvilinearly with density until inter-plant competition limits any additional production; biomass values from that point onwards remain constant over a range of densities. The combination of optimum growing conditions, a long growing season and early sowing lead to profuse growth and severe inter-plant competition, giving rise to constant biomass values at normal densities (Donald, 1963). This behavior has often been observed in the faba bean crop. For early autumn sowing in Mediterranean conditions, with >600 mm rainfall in the growing season, final biomass production is greater and is not affected by plant density; with later sowing dates, biomass values are lower but increase with density because inter-plant competition is more moderate (Fig. 1). Under these conditions, biomass values reach a plateau at a density of 20 plants m⁻² (Adisarwanto and Knight, 1997). In regions, where high biomass values are not attained due to a number of growth-limiting factors, main among which is water

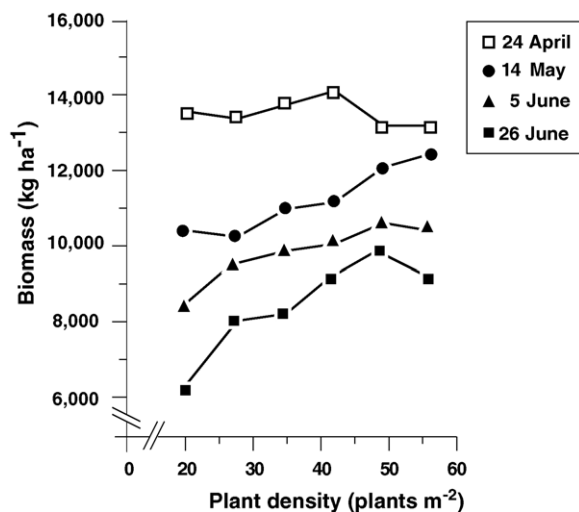


Fig. 1. Relation between biomass (kg ha⁻¹) and density for sowings on 24 April, 14 May, 5 June and 26 June. Standard errors (S.E.) for each sowing date–density value for the respective sowing date were: (24 April) 0.66, (14 May) 0.43, (5 June) 0.47, (26 June) 0.49. Waite Agricultural Research Institute, Adelaide, South Australia (in 2 years) (Adisarwanto and Knight, 1997).

shortage, increasing plant density always prompts an increase in biomass production, dry matter content or mass values do not reach a plateau until very high plant densities.

3.6. Dry matter partitioning

Although leaf dry matter per square meter behaves in a similar manner to total dry matter throughout the crop cycle (Pilbeam et al., 1991b), at high plant densities, a large proportion of final dry matter is due to the stems (Loss et al., 1998b). During the early stages of the crop season (vegetative growth), stem dry matter per square meter behaves like total dry matter, with no difference between the percentage of total dry matter contributed by leaves and stems. Only after the start of pod setting, as the distance between nodes increases, more biomass is produced in stems and branches, particularly at high densities. For autumn-sown crops, pod dry weight per square meter is initially greater at higher plant densities, but later on values are gradually reversed until the greatest weight is achieved at lower densities. Dry pod weight per plant is generally greater at lower plant densities.

3.7. Canopy structure and characteristics

During the vegetative period, the compensatory factor that, by optimizing crop use of environmental resources in response to variation in density, best accounts for differences in leaf and canopy development is the total number of stems per square meter or number of stems (main stem + side branches) per plant (Poulain et al., 1986). This will later have an effect on the reproductive period, by varying the total number of nodes per square meter, given the relationship existing between the number of stems per plant and the number of podding nodes at flowering. High plant densities lead to less branching of the plant across a range of environmental conditions (McEwen et al., 1988; Aguilera, 1987; Amato et al., 1992) and reduce leaf surface per plant (Poulain et al., 1986) (Table 3). Loss et al. (1998b), in a study of autumn-sown crops in Mediterranean-type conditions, found a linear decrease in the number of branches per plant as plant density increased. This could be advantageous, since side branches contribute less than the main stem to seed yield (Ingram, 1976; Pilbeam et al., 1989b). At low plant densities, the number of stems per plant increases over the crop cycle, while at high densities, the number decreases; the higher the density, the faster the decrease. This loss of branches takes place on the uppermost nodes (nodes 2 and 3, taking the main stem

as 0 and numbering the branches upwards along the main stem); the ratio of main stems to first branches per square meter increases over time at higher densities. Generally speaking, high densities result in taller plants (Pilbeam et al., 1990; Quaglietta-Chiaranda et al., 1995a), although in autumn crops sown in a temperate climate Pilbeam et al. (1991b) found no difference in height as a function of plant density (Table 2). Loss et al. (1998b) found that this greater crop height was not due to a larger number of nodes per stem, since the node appearance rate was relatively constant at all the sowing rates tested, but to a greater separation between nodes. Thus, the distance from the ground to the first pod increases with rising density (from 10 to 18 cm in Mediterranean conditions in Southern Australia), so facilitating mechanized harvesting. However, greater plant height renders the crop more susceptible to lodging, particularly, when indeterminate cultivars are used. Determinate cultivars tend to respond to variations in density much in the same way as conventional cultivars, except that they are shorter and have fewer nodes.

3.8. Reproductive period

This stage involves the establishment of the remaining components of crop yield (number of podding nodes per stem, number of pods per podding node,

Table 3
Seed yield and yield components in faba bean (*Vicia faba* L.) crop in relation with plant density

Authors	Density (plant m ⁻²)	Seed yield (kg ha ⁻¹)	Stems plant ⁻¹ (no.)	Nodes plant ⁻¹ (no.)	Pods node ⁻¹ (no.)	Pods plant ⁻¹ (no.)	Seeds pod ⁻¹ (no.)	Mean seed weight (g)
Coelho (1987)	10–50	4750–10950	4.7–2.2	–	–	32.1–13.4	3.0–3.0	0.53–0.54
Salih (1989)	16.6–49.9	1904–2245	–	–	–	23.0–15.6	2.6–2.5	0.43–0.42
Pilbeam et al. (1990)	10–100	4243–3827	–	15.9–2.5	1.9–1.3	29.0–3.3	3.5–2.9	0.55–0.43
Pilbeam et al. (1991a)	10–80	4033–5183	3.4–1.5	17.5–4.5	–	26.0–5.5	2.9–2.5	0.68–0.65
Stützel and Aufhammer (1992)	18.5–74.0	3295–5980	–	–	–	17.5–6.6	3.1–2.9	0.40–0.41
Aguilera-Díaz and Recalme-Manrique (1995)	10–30	4635–5084	–	–	–	–	–	–
Almeida et al. (1995)	20–60	3446–3897	–	–	–	12.3–7.6	3.1–3.1	0.75–0.71
Quaglietta et al. (1995a)	7–100	1920–2660	–	–	–	9.0–2.5	–	–
Adisarwanto and Knight (1997)	20–56	4925–4780	3.1–2.2	–	–	–	2.5	0.48–0.43
Loss et al. (1998a)	70–270 kg ha ⁻¹ 8–16 to 41–49 plants m ⁻²	1379–2672	–	–	–	13.7–7.5	1.8–2.6	0.32–45

number seeds per pod and mean seed weight); these, together with those fixed in the vegetative period, form seed yield (Aguilera, 1987). The formation and variation of these components is affected by plant density; some components will compensate for others in order to optimize use of the available environmental resources.

Flowering, pod filling and pod maturation are very long phases in the faba bean and are prolonged in autumn-sown crops, mediating the crop response to variations in plant density. In Mediterranean conditions, crops sown early in autumn display a prolonged reproductive period (Adisarwanto and Knight, 1997), resulting in larger plants and higher yields with respect to later sowings (Marcellos and Constable, 1986).

Throughout the reproductive period, both flowers and pods will be lost through inter-plant competition due to intrinsic, environmental and crop-related factors (Amato et al., 1992). Dantuma and Thompson (1983) suggest that transfer of assimilates to reproductive sinks is blocked by the good conditions in which the crop develops; water availability appears to be particularly relevant. These authors suggest that budding takes priority over assimilate supply during early pod growth. However, Baker et al. (1984) consider that vegetative growth does not reduce the amount of assimilates available to the reproductive sinks. Although this has not been sufficiently confirmed, early competition for assimilates may account for the high levels of flower abortion and pod fall in many crops; assimilation of reserves by pods may pose a greater problem than availability of assimilates for pod filling. This competition for assimilates during a short but critical phase (start of pod development) may be a major determinant of seed yield.

3.8.1. Podding-node formation

The number of sinks per plant is a major determinant of faba bean yield (Bond et al., 1985). Poulain et al. (1986) report that plant density affects the source/sink ratio, altering intra-plant competition for assimilates (Pilbeam et al., 1991b); at low sowing densities, fewer sinks are produced, which do not utilize all the available assimilates. As plant density increases, there is a decrease in number of nodes per plant and number of productive nodes per plant (Hodgson and Blackman, 1956; Tuttobene and Vagliasindi, 1995), leading to a lower number of flowers per plant and of pods per plant,

because the assimilate reserve of an individual plant is not sufficient to maintain many vigorous vegetative or reproductive sinks. This is less evident in determinate cultivars, since there is less internal competition for assimilates due to the presence of fewer reproductive sinks per plant. The number of podding nodes on a stem reflects the order of insertion; there are more on the main stem than on the first branch and so on, until the third branch. Loss of podding nodes takes place uniformly over all reproductive stems. Therefore, there will be a larger number of podding nodes per plant at lower densities. However, the number of podding nodes on the main stem contributes more to the total number of podding nodes per plant, further increasing its share of the total at high plant densities. On the contrary, the share of the total corresponding to side branches decreases with increasing plant density because of the absence of branches higher up the plant as density increases.

3.8.2. Flowers and pods drop

The factors responsible for abscission or pod retention are not yet clear (Stützel and Aufhammer, 1992). Coelho and Pinto (1989) suggest that high plant densities prompt greater competition among sinks for assimilates, causing more severe abscission of flowers and young pods in the absence of environmental crop stress. Tuttobene and Vagliasindi (1995) report similar results, with higher pod fall at higher plant densities, the pod setting coefficient (PSC) declined as density increased. Within the same plant, this coefficient also varied as a function of podding node position. By contrast, Amato et al. (1992) found that flower formation levels did not vary with plant density, observing no clear change in the percentage flower fall as a response to varying density. Pod abscission also appears to be influenced by the interaction of environment and crop factors (sowing density). Quaglietta-Chiarandá et al. (1995b) report no difference in percentage pod fall as a function of the extreme densities studied.

Pod loss is greater in determinate cultivars sown at low densities. This is because reduced apex activity improves illumination at the base of the main stem; this, together with canopy opening, stimulates axillary shoots under favorable conditions. Developing branches then enter into competition with young pods for assimilates. This effect is less marked at standard

densities, where base illumination is less intense (Stützel and Aufhammer, 1992).

3.8.3. *Premature flower abortion*

Premature flower abortion (buds and flowers before anthesis) in faba beans is generally due to a lack of insect pollinators (Kambal, 1969; Free and Williams, 1976), low levels of solar radiation (Plancquaert and Raphalen, 1984; Stoddard, 1993), intra-plant competition between vegetative and reproductive structures for assimilates (Gates et al., 1983) and high moisture levels (El-Beltagy and Hall, 1974). Flower fertilization is also affected by temperature. During flowering, low temperatures may create conditions unfavorable for pollination; high temperatures at flowering increase the rate of pod setting (Aguilera-Díaz and Recalme-Manrique, 1995). By contrast, excessive temperatures and water stress at this stage lead to a decline in pod formation.

This situation may be due both to environmental conditions during the crop season and to sowing date and may indirectly modify the effects of variation in plant density. Adisarwanto and Knight (1997) report that at the highest densities, environmental conditions for the lower flowers are not favorable for pod setting and maturation; although competition for light is probably important, other factors, such as inhibition of bee activity may play a certain role.

3.8.4. *Pod and seed filling*

Within certain limits, the number of seeds per pod is largely determined by genotype (Bond et al., 1985). Dantuma and Thompson (1983) report that this yield component is not visibly affected by factors, such as inter-plant competition for light, water balance or seeding density; they regard this component as the most stable in the faba bean crop, although – surprisingly – the number of seeds per pod varies considerably between different nodes on the same plant, a lower number of seeds per pod being common on the uppermost nodes, where wilting due to ovule drying is usual.

Rapid accumulation of dry matter in the seed starts 25–35 days after flowering in many cultivars of different seed sizes (Adler and Müntz, 1983). Abortion may still occur below a certain size or age.

Pod set is possibly a function of the growth rate during flowering (Stützel and Aufhammer, 1992). Seed filling and subsequent seed size and final unit weight are like number of seeds per pod, largely determined

by cultivars, although once the number of seeds per pod is fixed, competition takes place between seeds for assimilates. Within a given cultivar, competition may vary considerably depending on environmental factors, of which the water regime after flowering is the most influential. Low rainfall or lack of irrigation in the post-flowering period causes rapid leaf senescence, leading to lower seed weight (Dantuma and Thompson, 1983). According to these authors, weight per seed is the yield component that compensates for early pod loss, since it is the last to be formed, and under certain environmental conditions, may considerably increase final yield.

4. Seed yield and yield components

4.1. *Seed yield*

In faba bean crops, final seed yield increases with plant density up to a plateau beyond which density ceases to exert any influence or even prompts a decline in seed yield due to excessive inter-plant competition. This maximum yield plateau is reached at a range of plant densities, depending on genotype and on environmental and crop-related factors. Yield response to increasing plant density is generally asymptotic (Pilbeam et al., 1990; Marcellos and Constable, 1986; Loss et al., 1998a), although in some cases the response curve may resemble a parabola. This latter response, typical of seed crops, is reported by Pilbeam et al. (1990) for spring-sown faba bean crops in temperate climates.

According to a study by Loss et al. (1998a), in Mediterranean-type conditions and for autumn-sown crops, asymptotic models indicated how yields continued to increase as plant density was increased above the commonly recommended 30 plants m^{-2} . The economic optimum density (assuming a 10% opportunity cost) predicted by these models was in some cases well beyond the range of sowing-rates tested and varied considerably with location and year, from 31 to 63 plants m^{-2} (Fig. 2).

In numerous experiments undertaken across a wide range of plant densities, in different locations with very different soil–climate conditions and using different cultivars, yield always increased with plant density (Hodgson and Blackman, 1957; Day et al., 1979; Coelho, 1987; Salih, 1989; Stringi et al., 1986; Coelho and Pinto, 1989; Pilbeam et al., 1990; Almeida, 1993;

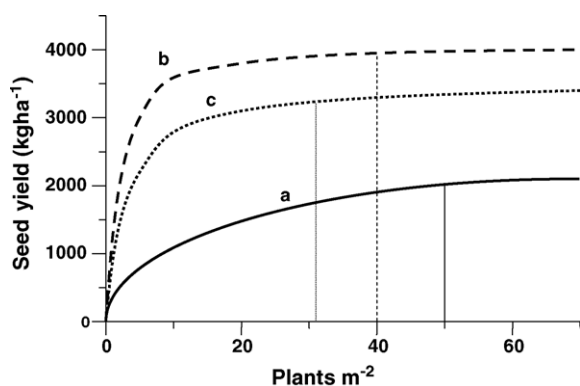


Fig. 2. The fitted curves of seed yield response to plant density at Dongara (South-western Australia) in (a) 1994 (rainfall May–October 201 mm), (b) 1995 (390 mm) and (c) 1996 (480 mm). Dotted lines indicate estimated economic optimum density (estimated as point on the response curve, where the cost for sowing additional seed equals the return from the additional grain produced, allowing a 10% opportunity cost for investing the additional money required for the extra seed (Loss et al., 1998a).

Quaglietta-Chiaranda et al., 1995a; Tonev, 1995; Loss et al., 1998a). However, other studies failed to find any yield response to variation in plant density (Pilbeam et al., 1991a; McEwen, 1973), while still others have even reported a negative response (Aguilera-Díaz and Recalme-Manrique, 1995). These differences in yield response to variation in plant density may be due to the limitations of the studies themselves, which have only enabled analysis of one segment of the real response curve under the conditions tested (Table 3).

4.1.1. Environmental influence

The environment greatly influences the response of faba bean yield to increased plant density or sowing rates. According to Pilbeam et al. (1990), seed yield is influenced by the year \times location and by density \times cultivar interactions; density has less influence on yield than environmental effects (year and to a lesser extent location). One characteristic of faba bean is the considerable and unpredictable year-on-year variation in seed yield, despite adequate control of pests and diseases. Under irrigation, this may be attributed to premature senescence caused by early high temperatures (McEwen et al., 1981). In rainfed conditions, the most influential environmental factor is rainfall from flowering to harvesting or soil water reserves during that period. Tonev (1995) reports that with minor varia-

tions in plant density around the optimum level, differences in yield are less evident; yield shows a greater response to yearly environmental conditions (rainfall and maximum daily temperatures). However, under drought treatments, increasing plant density prompts significant increases in seed yield (Kuraczyk, 1995).

In Mediterranean conditions, since faba bean crops are always sown in autumn and often on rainfed land, rainfall is the most influential environmental factor; variations in rainfall give rise to variations in yield, curtailing yield at high plant densities due to increased water requirements (Stringi et al., 1986).

In Southern and South-western Australia (Baldwin, 1979) and in Syria (Saxena et al., 1981) over a wide range of conditions, maximum yields are achieved with densities ranging between 30 and 35 plants m^{-2} , while in high-yielding situations (optimum environmental conditions), optimum densities are lower (20 plants m^{-2}). However, according to Loss et al. (1998a), under the Mediterranean-type conditions of South-western Australia, the optimum density (usually sown at a density of 30 plants m^{-2}), proved to be 45 plants m^{-2} for most of the locations studied. Saxena et al. (1991) found a similar response for large-seeded cultivars in Northern Syria, with an optimum density of 20–26 plants m^{-2} under supplementary irrigation, whereas a higher density of 44 plants m^{-2} is recommended under dryland conditions. In Spain, optimum density under irrigation, using an *equina* type, was found to be as low as 10 plants m^{-2} , higher densities providing lower yields (Aguilera-Díaz and Recalme-Manrique, 1995).

Although Day et al. (1979) suggest that yield is not affected by densities >18 plants m^{-2} , in the Mediterranean-type conditions of South-western Australia seed yield increased with density in the range 10–50 plants m^{-2} (Marcellos and Constable, 1986) and in some cases even higher.

4.1.2. Influence of cultivar

The influence of botanical type used on yield is greater than that of plant density and comparable to that of environmental effects. The greater seed weight of *equina* types means that yields are greater than those of *minor* types.

At the same plant density, seed yield is lower in determinate than in indeterminate cultivars (Stützel and Aufhammer, 1992), both for spring-sown and

autumn-sown crops. Difference in yield is attributed to differences in all yield components. Pilbeam et al. (1991b) report that there is no interaction between density and genotype for autumn sowings under temperate conditions, optimum density for both types of bean being lower than 18 plants m^{-2} or in the range 10–20 plants m^{-2} . However, for spring sowing, a density of 20–60 plants m^{-2} is recommended in order to attain maximum yields with indeterminate cultivars (Hebblethwaite et al., 1983). Determinate cultivars will require higher densities (Pilbeam et al., 1990).

4.1.3. Influence of sowing date

In temperate climates, the optimum density of the spring-sown faba bean crop is 45–65 plants m^{-2} , depending on location, year and cultivar. This range of densities has been reported in a number of experiments undertaken in similar conditions: 30–40 plants m^{-2} (Caballero, 1987), 30 plants m^{-2} (Graf and Rowland, 1987), 33–54 plants m^{-2} (Kondra, 1975). However, for autumn sowing in temperate climates, yield response to increasing density is less marked; optimum densities are lower than for the spring-sown crop, and high densities may even prompt a drop in yield due to disease. McEwen et al. (1988) conclude that the optimum mean seeding rate is 24 seeds m^{-2} , although this, in turn, depends on sowing date. Early sowing requires a lower seeding rate (12 seeds m^{-2}) than later sowing (36 seeds m^{-2}). Decreases in yield have been reported with increased density (Ingram and Hebblethwaite, 1976), but could also be attributed to chocolate spot (*Botrytis fabae*), lodging or winterkill (Adisarwanto and Knight, 1997). In the absence of chocolate spot, optimum plant density is between 12 and 30 plants m^{-2} (Ingram and Hebblethwaite, 1976). This figure agrees with the 10–20 plants m^{-2} proposed by Pilbeam et al. (1990). However, if the crop is sown before the end of October optimum plant density is 12 plants m^{-2} (McEwen et al., 1988).

In Mediterranean conditions, delayed sowing over the autumn and winter months modifies optimum plant density, which increases with the delay. In general, early sowing (late April and May in the Southern Hemisphere) produces greater yields than late sowing, by increasing the length of both the vegetative and the reproductive stages, thus achieving larger plants (Marcellos and Constable, 1986). According to Baldwin (1980) and Marcellos and Constable (1986),

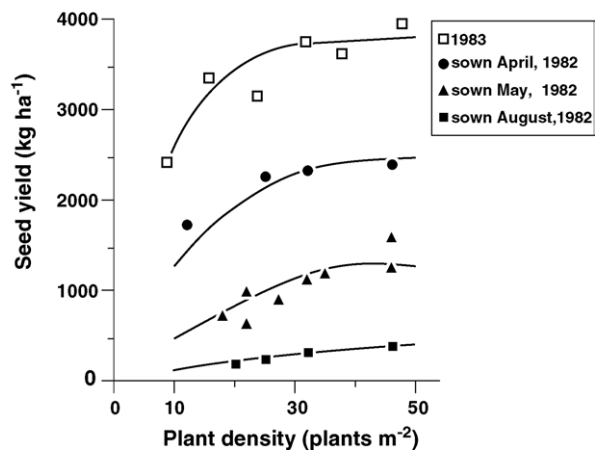


Fig. 3. Influence of plant density on seed yield of faba beans cv. Fiord in 1983 and 1982 (sowing date: April, May and August). Mediterranean Climate, Australia (Marcellos and Constable, 1986).

with early sowing, yield increased with density to an asymptote at about 30 plants m^{-2} ; however, with late sowing (July or August in the Southern Hemisphere) yields increased with density through the range 10–50 plants m^{-2} (Fig. 3). These findings have subsequently been confirmed by a number of authors under similar environmental conditions. Adisarwanto and Knight (1997) report that the highest seed yields for early sowing are obtained at a density of 20 plants m^{-2} , yield decreasing as density increases. This trend gradually changes as the sowing date is delayed, so that by the last sowing, there is a marked increase in yield with increasing density, although the increase in density cannot make up for the yield loss with respect to early sowing. Therefore, yield may either increase or decrease with density, depending on sowing date.

4.2. Harvest index

Although there is a certain correlation in faba bean crops between dry matter production and seed yield as reported by López-Bellido et al. (2003), high dry matter yield does not necessarily imply high seed yield. Final dry matter simply indicates efficiency in crop vegetative growth. Therefore, the productive capacity of the faba bean depends, apart from photosynthetic efficiency, on an effective translocation of assimilates to the seeds. This efficiency is measured for the crop as a whole by the harvest index. Partitioning of

assimilates between the vegetative and reproductive parts of a crop may be modified by agronomic practices, such as choice of sowing density, fertilization, irrigation, choice of sowing date and choice of cultivar. Excessive availability of water for the faba bean crop may lead to greater vegetative development at the cost of seed yield for the same dry matter production, prompting a decrease in the HI. This effect is heightened in association with higher sowing densities (Sau and Minguez, 2000). A number of authors (Sinha, 1978; Coelho and Pinto, 1989; Pilbeam and Hebblethwaite, 1990; Katyar and Singh, 1990) place the upper limit for HI in faba beans at around 50%.

The question is whether the harvest index can be increased by increasing plant density, since inter-plant competition may suppress excessive stems formation in faba beans, as it does in cereals. For most crops, under favorable conditions, dry matter production increases with density to a plateau above which inter-plant competition limits any further production. Thereafter, HI tends to decline and seed yield often displays a negative response to increasing sowing rates (Donald, 1963).

For spring-sown faba bean crops in temperate climates, Pilbeam et al. (1990) found that HI decreased with increasing plant density, since high densities increased total dry matter rather than seed yield. Determinate cultivars displayed a lower HI, although their response to varying density was identical to that of indeterminate cultivars (Stützel and Aufhammer, 1992). Similar findings are reported by Pilbeam et al. (1990) for autumn sowing under similar conditions (Table 2).

However, opinions are divided with regard to the behavior of the HI for autumn-sown crops in Mediterranean conditions. Aguilera-Díaz and Recalme-Manrique (1995) and Adisarwanto and Knight (1997) report lower HI at higher densities. However, Loss et al. (1998a) report that this trend is less marked, with almost constant HI values in all plant densities. Coelho (1987) found that HI was not significantly altered by plant density. Quaglietta-Chiaranda et al. (1995a) detected slight increases in HI with increasing plant density, although greater variations were noted for year (Table 2).

For autumn-sown crops under Mediterranean-type conditions, lower HI values are obtained for earlier sowing dates, while values rise with delayed sowing; HI is reported to decline with increasing density at all sowing dates (Fig. 4) (Adisarwanto and Knight, 1997). This

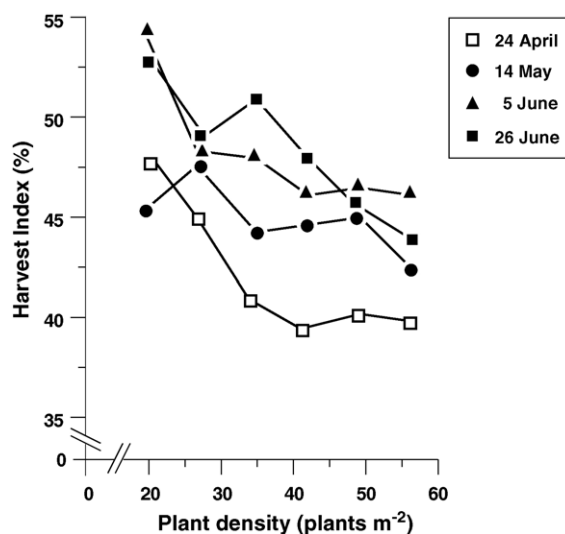


Fig. 4. Relation between harvest index (%) and density for sowings on 24 April, 14 May, 5 June and 26 June. Waite Agricultural Research Institute, Adelaide, South Australia (in 2 years) (Adisarwanto and Knight, 1997).

agrees with the findings reported for various crops by Donald (1963), who concludes that early sowing, when combined with good conditions and a long growing season, leads to profuse growth and severe inter-plant competition. Harvest index under these conditions of severe competition is low and declines with density.

4.3. Seed yield components

Faba bean seed yield is the product of several components: plant density, podding nodes per plant, pods per podding node, seeds per pod and mean seed weight (Bago et al., 1987). In response to increasing plant density, the behavior of these components tends to be predictable; seeds per pod and mean seed weight tend to display the most stable response to the environment, while plant density is the most susceptible to modification by man through variation of the sowing rate. Both number of podding nodes per plant and number of pods per podding node display considerable genotypic and environmental variations (Bond et al., 1985). Generally speaking, increased plant density prompts a decrease in number of podding nodes per plant (Barry and Storey, 1979) and number of pods per podding node (Thompson and Taylor, 1977), while number of seeds per pod and mean seed weight tend to remain

constant (Graf and Rowland, 1987; Seitzer and Evans, 1973; Hodgson and Blackman, 1956). An increase in one component of yield is compensated for by a decrease in one or more of the others, producing what is known as a “compensatory or plastic effect”. Thus, for the same overall yield, each component may have differing values. The basis of this compensatory capacity lies in the sequential development of successive components of yield; changes in one component affect successive developments. This influence is achieved by the utilization of assimilates from a common but limited pool. However, the compensatory effect is not always wholly effective, and under certain circumstances, increasing plant density cannot make up for the difference in seed yield sufficiently to ensure high values. Optimum density, therefore, will be the minimum density at which maximum yield is achieved. The real effectiveness of the compensatory effect in the faba bean is measured by number of pods per square meter and number of seeds per square meter, if mean seed weight is considered not to vary in response to varying plant density.

4.3.1. *Number of podding nodes per plant*

The number of pod-bearing nodes and number of pods (per plant or per square meter) are crucial determinants of yield in faba beans (Thompson and Taylor, 1977; Kambal, 1969; Yassin, 1973). Number of podding nodes per plant is the least stable component of yield. The lowest values for this component are usually achieved at higher plant densities (Table 3). This apparent contradiction is due to a trade-off between the components of yield; an increase in one component is associated with a decrease in another, possibly resulting in a negative correlation between adjacent components and a positive correlation between alternate components (Adams and Grafius, 1971). A given plant density is considered optimum, when it provides the maximum number of podding nodes per square meter. According to Pilbeam et al. (1991a), maximum yields are attained at higher densities, since these curtail the production of side branches which have fewer podding nodes per branch than the main stem and the first branch.

For autumn-sown crops in Mediterranean-type conditions, yield differences for different sowing dates can be partly explained by a greater number of pod-bearing nodes per plant with earlier sowing; the decrease with

delayed sowing is not fully compensated by an increase in the number of pods per node with later sowing, although high plant densities help to palliate these losses (Adisarwanto and Knight, 1997).

Since determinate cultivars have fewer pod-bearing nodes per stem, they produce fewer pods and fewer seeds, thus giving rise to a lower seed yield (Pilbeam et al., 1991a). Therefore, to maintain the number of potential reproductive sites per unit area, it is theoretically necessary to grow determinate plants at a higher density. It has been reported that the number of podding nodes per square meter shows no clear difference between determinate and indeterminate cultivars. So the creation of more podding sites cannot necessarily be used as an argument for sowing determinate cultivars at a higher density. However, most of the podding nodes on these cultivars, especially at lower plant densities, are on reproductively inferior branches, and so higher densities are required to minimize branching and thus enhance yield (Pilbeam et al., 1990). According to Pilbeam et al. (1991a), for autumn sowings under temperate conditions, there is no difference in optimum density for determinate and indeterminate cultivars, indeterminate plants always recording greater yield.

4.3.2. *Number of pods per podding node*

Like the previous component, number of pods per podding node decreases with increasing plant density (Barry and Storey, 1979). These two components display a similar response to variations in plant density. Moreover, there is a trade-off between number of podding nodes per plant and number of pods per podding node due to inter-plant competition for environmental factors at various stages of the crop cycle (Ishag, 1973).

Different densities have a different influence on number of pods per podding node, depending on the sowing date. For autumn-sown crops in Mediterranean conditions, early sowing and high densities prompt a decrease in pods per node on the lower nodes, but an increase on the upper nodes. With later sowing dates, however, number of pods per node is not influenced by plant density (Adisarwanto and Knight, 1997).

4.3.3. *Number of pods per plant*

Due their considerable variability, the previous two yield components are not often used; the most widely utilized parameter is a product of the two, number of pods per plant.

An increase in the number of pods per plant generally means an increase in faba bean yield (Meneses, 1977). Under most environmental conditions, number of pods per plant decreases with increasing density, compensating the number of plants per square meter (Salih, 1989; Miccolis et al., 1983; Stringi et al., 1986; Ishag, 1973; Seitzer and Evans, 1973) (Table 3). According to Stringi et al. (1986), beyond a given plant density, this component shows no further decrease. The decreases in number of pods per plant is due to a reduction in the number of stems per plant at higher densities (McEwen et al., 1988), there being no major variation in the number of pods per stem (Coelho, 1987). By contrast, Pilbeam et al. (1991a) report that high plant densities also reduce the number of pods per stem as well as the number of pods per plant. Adisarwanto and Knight (1997) found a strong correlation between seed yield and number of pods per plant for different densities and sowing rates for an autumn-sown crop in Mediterranean conditions.

Number of pods per square meter is the factor most closely correlated with seed yield (Stützel and Aufhammer, 1992), and the most effective component for detecting the plastic or compensatory effect in the faba bean crop. In general, and despite considerable variation, number of pods per plant decreases with increasing density, but is compensated by a larger number of plants per square meter, resulting in a larger number of pods per square meter and thus greater yields, although at very high plant densities this component shows no clear trend. When growth is limited by dry conditions, delayed sowing or other factors, there is little inter-plant competition; there is thus a greater difference in number of pods per square meter between high and low densities. Differences in seed yield as a function of various factors, such as sowing date or the use of cultivars with different growth habits (indeterminate versus determinate), are attributable to differences in number of pods per square meter.

4.3.4. Number of seeds per pod

Seeds per pod have been noted to be a component of yield that shows little variation across environments (Thompson and Taylor, 1977). Within any given faba bean cultivar, number of seeds per pod shows a relatively stable response to variations in sowing date or plant density (Stringi et al., 1986; Graf and Rowland, 1987; Salih, 1989; Coelho and Pinto, 1989) (Table 3),

since it is linked more to genotype than to environment (Newton, 1979).

Pilbeam et al. (1991a) reported that number of seeds per plant is the component displaying the strongest and most consistent correlation with yield and is arguably the most important determinant of yield. This component decreases with increasing plant density (Ishag, 1973; Seitzer and Evans, 1973).

4.3.5. Mean seed weight

There is evidence relating large seed size and weight to high yields. Mean seed weight is mainly linked to genotype, although to a lesser extent than number of seeds per pod for the same cultivar, since this is the last component to be fixed in the crop cycle (Pocsai, 1985). Environmental conditions during the growth season have some effect on mean seed weight (McEwen, 1973). Generally, and across a range of environmental and crop conditions, this component is not significantly influenced by plant density (Table 3). However, in some cases it is reported to decline as planting density increases (Salih, 1989). According to a study by Amato et al. (1992), mean seed weight responds differently to plant density depending on the year; dryness during the seed filling period prompts lower seed weights at higher densities, while in normal conditions seed weight is not affected by density. Sowing date may also influence mean seed weight (Poulain and Connen, 1992). For autumn-sown crops in Mediterranean conditions, later sowing is associated with a greater reduction in mean seed weight, due mainly to decreased seed size in the uppermost pods; by contrast, with early sowing, seed size is more uniform over the plant (Adisarwanto and Knight, 1997). These authors, however, detected no difference in mean seed weight as a function of different plant densities over all the sowing dates tested. Plant density also had no effect on mean seed weight at each node.

5. Conclusions

The effect of faba bean crop plasticity in response to variations in plant density depends largely on the duration of the vegetative and reproductive phase of the crop and on weather conditions during vegetative growth, more specifically on heat and water availabilities.

In longer growing seasons and given optimum growing conditions, the effect of crop plasticity is more evident, maximum grain yield being obtained at very low plant densities. Yields remain constant at higher densities and may even decline mainly due to the incidence of disease. For autumn–winter sown crops, particularly for those sown early in autumn, under optimal weather conditions (mild temperatures in temperate climates and sufficient rainfall/irrigation in Mediterranean or semi-arid climates) grain yield displays no response to increased planting density over roughly 20 plants m⁻².

Crop plasticity starts to be less effective, when any of the requirements indicated above are not met; in such situations, yield responds positively to increased plant density. In temperate climates, delayed sowing of the winter faba bean crop, spring sowing or excessive cold may prompt an increase in optimal density to anywhere between 30 and 60 plants m⁻². Similar behaviour is observed in Mediterranean conditions, when autumn sowing is delayed or when rainfall during the growing season is insufficient in rainfed areas; here, one of the most influential factors is rainfall from flowering to harvesting or soil water reserves over that period. The interaction between sowing date, plant density and incidence of disease should, therefore, be more closely addressed in future faba bean research.

Large-seeded cultivars are known to develop greater plant cover and require lower plant densities to achieve high grain yields. However, most studies dealing with plant density in faba beans use *minor* or *small-seeded* varieties. Further research on plant density should, therefore, be broadened to include cultivars with different seed sizes (*major* and *equina*).

Determinate cultivars generally display clear differences in grain yield as compared to indeterminate cultivars, optimal plant density being similar for the two types. At the same plant density, grain yield tends to be lower in determinate than that in indeterminate cultivars. For spring sowing, however, determinate cultivars require higher plant densities than indeterminate cultivars in order to achieve acceptable grain yields.

The mechanism governing grain yield response to variations in plant density involves the yield component number of pods per plant, which is inversely correlated with number of plants per square meter. These two yield components are largely responsible for the plastic or compensatory effect in the faba bean crop, since the

other components (number of seeds per pod and mean seed weight) are mainly genotype-dependent.

For a better understanding of the plastic effect in the faba bean crop, further research is required into the genesis and development of the component number of pods per plant, which is itself the product of three components: number of stems per plant, number of podding nodes per stem and number of pods per podding node. It has been found that side branches produce fewer podding nodes per branch than the main stem and that the number of pods per podding node does not display a clear response to variations in plant density; thus, number of stems per plant may be the major factor in determining the crop's ability to compensate for variations in plant density. A longer growing season, together with optimum growing conditions, may lead to the fuller development of a larger number of side branches at low plant densities; LAI and dry matter values are similar to those recorded at high plant densities, but are reached later in the crop cycle. Side branches may compensate more efficiently for the smaller number of podding nodes by an increase in the number of stems per square meter.

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