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Effect of pattern of water supply on *Vicia faba* L. 1. Dry matter partitioning and yield variability

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Abstract

The effects of various amounts and timings of water supply during and after the flowering period on growth, total dry matter production and partitioning of dry matter, and variability of yield were studied in faba beans. In field experiments in 1980 and 1981, plenty of water during and after flowering (i-i) resulted in stimulation of vegetative growth, but reduced initial reproductive growth as well as final seed yield, compared with a control with mild water shortage during flowering but plenty of water after flowering (d-i). In further field experiments in 1982-1984, d-i resulted in high average seed yield of 7.0 t ha^{-1} (cv. Minica), optimum harvest index (HI) (0.61 g g^{-1}) and relatively small seed yield range over the experiments (2.2 t ha^{-1}). In i-i, average seed yield (7.1 t ha^{-1}) did not differ significantly from d-i and HI was lower (0.57) but seed yield range was small with 1.4 t ha^{-1}. D-d, i-d and natural rainfall control provided much lower average seed yields and a larger seed yield range; i-d also provided the lowest HI (0.54 g g^{-1}). Data for cv. Alfred showed the same trend as for cv. Minica. *It is concluded that differences in distribution pattern and amount of rainfall* are a major reason for the variability in seed yield of faba beans. During flowering a mild water shortage might be preferable to plenty of water, to limit vegetative growth and stimulate early reproductive growth. After flowering, plenty of water is crucial for high and stable seed yield responses.

Keywords: faba beans, *Vicia faba* L., irrigation, dry matter partitioning, seed yield, yield variability

Introduction

The area with seed legumes under cultivation in the European Community has increased importantly. In total in ten member-states 515 000 ha were grown in 1981 and 988 000 ha in 1986 (Anon., 1984-1988). This was mainly a result of financial support measures for protein crops as part of the plant productivity programme of the European Community. About a third of this area is cultivated with faba beans. In the Netherlands the area with faba beans has increased from about 30 ha in 1977 to 13 400 ha in 1988 (Anon., 1977-1988). The present increase followed after a steady decrease from 30 000 ha in the period around 1930.

Like in most European countries, a major reason for the decrease in area with faba beans in the Netherlands between 1930 and 1975 has been the high yield variability. The crop is still considered to be highly unreliable in this respect (Hawtin & Hebblethwaite, 1983). Much research has been undertaken to identify key factors influencing yield, and causing yield variability.

As it is generally accepted that water shortage is a major yield-determining factor (Day & Legg, 1983), the effect of water availability has been the subject of several studies. Attention has been paid to the identification of growth stages especially sensitive to lack of water.

Many authors have reported that irrigation had a positive effect on seed yield, regardless of time of application (Hebblethwaite et al., 1977; French & Legg, 1979; Farah, 1981). Krogman et al. (1980) found linear correlations between total water applied (irrigation and rainfall) and seed yield and also between water applied and straw yield. Results of other authors confirm this correlation (Day & Legg, 1983). Husain et al. (1983) stated that special moisture-sensitive phases did not exist in faba beans grown in New Zealand.

However, this conclusion is not generally accepted. Brouwer (1959) reported that especially irrigation during flowering provided high yield increments.

In contrast, also negative effects of irrigation on seed yield were reported. Yield depressions seem to be linked to irrigation before and during flowering (Stock & El-Naggar, 1980; Smith, 1982) or are described as rare deviations from a general positive effect (McEwen et al., 1981).

Smith (1982) reported that under West European conditions, irrigation applied during flowering may favour vegetative growth at the expense of reproductive growth. This conclusion was mainly based on reduced pod retention caused by irrigation during flowering.

In recent studies on productivity and yield variability in countries of the European Community, it was postulated that in some environments insufficient water supply is the major yield-limiting factor. However, in more maritime regions growing conditions could also lead to excessive vegetative growth and low seed yields (Dantuma et al., 1983).

The present study was carried out to gain a better understanding of the effects of various levels of water availability during and after flowering on dry matter partitioning and production throughout the growing season and to draw conclusions about water availability as a major limiting factor for yield and yield stability. In this paper (Part 1) these effects are discussed and integrated in a functional but qualitative way. In three following publications (Grashoff, in prep.) crucial details of this mechanism will be presented and discussed: pod retention, pod fill and yield components (Part 2) and dry matter partitioning in relation to plant water status (Part 3); a quantitative integration of growth processes that are affected by water availability will be presented in the form of a simulation study, (Part 4), and a generalization to other locations, climates and soil types will be given.

Materials and methods

Water supply treatments

Two groups of field experiments were conducted (Table 1). In the first group (in 1980 and 1981), the effect of full irrigation during and after flowering (further called i-i) was compared with a non-irrigated control. In the second group (1982-1984), five different combinations of soil water conditions during flowering and after flowering were created:

– d-d: a period with limited water availability from onset of flowering to the end of the growing season.
– i-d: irrigated to keep soil close to field capacity during flowering, followed by a period with limited water availability to the end of the growing season.
– d-i: a period with limited water availability during flowering, and irrigated after flowering to bring and keep soil water content close to field capacity.
– i-i: irrigated to keep soil close to field capacity from onset of flowering to the end of the growing season.
– natural rainfall: control treatment only exposed to rainfall conditions of the various experimental seasons.

Technical realization of treatments

The irrigation system consisted of perforated polythene tubes laid on the soil, connected to a central water pump. In each irrigation a quantity of 20 mm (20 kg m^{-2}) water was applied within half an hour. The frequency of application was one to three times a week, depending on the course of soil water content and reference

Table 1. Short description of water supply treatments, crop data collection, years, sites, cultivars, trial designs and number of replicates of the experiments in 1980-1984 with faba beans.

Water supply treatments	Crop data collection at	Year	Sites	Cultivars	Trial designs	Number of replicates
Control	14-day	1980	clay(N)	Minica	split plot	12
i-i	intervals	1981	sand(N)	Minica, Kristall	split split plot	4
Control	Final	1982	clay(N)	12[a]	trial in one-fold	
d-d	harvest	1982	sand(N)	12[a]	trial in one-fold	
d-i	only	1983	sand(N)	Minica, Alfred,	strip plot[b]	5[c]
i-d		1983	sandy loam(GB)	Optica and	strip plot	3
i-i		1984	sand(N)	Kristall	strip plot	5

[a] Cultivars obtained from colleagues involved in the EC joint field bean test, and cultivars Minica, Optica, Cebeco number (Alfred), and Kristall.
[b] A split plot with cultivars in horizontal, and water supply treatments in vertical strips.
[c] Two replicate blocks excluded (water logging; see text).

values of evapotranspiration provided by the Royal Dutch Meteorological Institute (KNMI). In all experiments, early-flowering cultivars and late-flowering cultivars were irrigated separately, to allow adaptation to the dates of onset and end of flowering.

The drying-out periods were realized by covering the soil between the plant rows with white polythene sheets to drain off about 80-90 % of rainwater. The period of soil covering depended on treatments. Sheets were not placed in the field before flowering to avoid effects on germination and early growth.

Locations, trial designs, fertilizers and drilling

Locations and trial designs are presented in Table 1. 'Sand(N)' is referring to the experimental farm Droevendaal on a humic sandy soil near Wageningen, Netherlands. 'Clay(N)' is referring to the experimental farm De Bouwing at heavy river clay (about 60 % lutum) in Randwijk, Netherlands. The 'Sandy Loam(GB)' location was the experimental farm of the University of Nottingham, UK, at Sutton Bonington (results of a joint experiment of the School of Agriculture of the University of Nottingham and the Centre for Agrobiological Research, Wageningen).

P and K fertilizers were applied according to the current recommendations which are based on soil testing. Depending on analysis of P and K soil test values, P application varied from 95 to 184 kg P_2O_5 per ha for the location on clay soil and from 38 to 133 kg P_2O_5 per ha for the location on sandy soil; K application varied from 120 to 480 kg K_2O per ha for the clay soil and from 52 to 182 kg K_2O per ha for the sandy soil.

Gross plot sizes varied from 6 m^2 in the experiments of 1980 to 15 m^2 in 1982-1984.

In all experiments in the Netherlands a precision drill was used (Vicon mono-air); plant density was 20 plants m^{-2} with 50 cm row spacing, which is usually practised in this country. In the experiment in England, plant density was 28 plants m^{-2} with 44 cm row spacing.

Plant material

The used cultivars were not the same in all experiments (Table 1), but cv. Minica was used as a standard each time. The large-seeded varieties Minica and Optica were obtained from Nickerson-Zwaan BV (Stompwijk, Netherlands). The smaller-seeded varieties Alfred and Kristall were obtained from Cebeco-Handelsraad (Lelystad, Netherlands). All other varieties were obtained by exchange between participants of the 'joint field bean trials' (Dantuma et al., 1983).

Measurements and data collection

In all experiments, soil water content was determined gravimetrically at weekly intervals and before each irrigation, and rainfall was recorded daily.

In 1980 and 1981, net plot samples of 1 m^2 were harvested at about 14-day intervals from beginning of June to the end of the growing season. In 1980, samples were divided into leaves, stems, pod walls and seeds and fresh and dry weight were determined. LAI, leaf size and stem length were recorded at each harvest. In 1981, samples were divided in straw and seed. In 1982-1984, more experimental treatments were included (Table 1) and only final harvest data could be obtained.

In all experiments, plant length, harvest index (HI) and seed yield were recorded at final harvest in net plots of 3 m^2. Detailed data on individual plants were obtained from samples of 10 to 20 plants. Details about these samples will be presented in Part 2 (Grashoff, in prep.).

Trial performance, crop protection and important dates

In all experiments, the crop grew without hail or frost damage. In 1983 the experimental field in Wageningen was waterlogged in two of the five replicate blocks, due to excessive rainfall in March-May. This resulted in very poor crop growth and high heterogenity in those two blocks, which were excluded from analysis. In 1982, in contrast with the standard water supply treatment description, the d-d treatments were irrigated two times after mid July under the polythene sheets to prevent the d-d crop from total failure.

Preventive measures for weed, disease and pest control were taken as much as possible. Weed control started before emergence with spraying of a prometryn/simazin mixture; after emergence dinoseb-acetate was applied. Weevils (*Sitona lineatus* L.) were sprayed with parathion at first visible damage of leaf edges. Pirimicarb was sprayed against black aphids (*Aphis fabae* Scop.) as soon as the first aphids were observed. In case of wet and cold weather, vinchlozolin, zineb or benomyl were sprayed preventively against fungal attack (mostly *Botrytis* spec.). Important damage by one of these pests or diseases did not occur in any experiment.

Over all experiments, dates of sowing ranged from 14 March to 9 April, emergence from 16 April to 6 May, onset of flowering from 27 May to 9 June, cessation of flowering from 17 June to 6 July and final harvest from 10 August to 10 September.

Results

Characterization of water supply in 1980 and 1981

In the months April to June total rainfall was 166 mm in 1980 and 123 in 1981, which is 10, respectively 53 mm lower than normal. Soil water content in the control steadily declined during the period of flowering and at the end of flowering (end of June) reached a minimum of 0.17 g g^{-1} in the clay (1980) and of 0.07 g g^{-1} in the sand (1981). Soil water contents in i-i treatments were kept at about 0.23 g g^{-1} (1980) and at 0.15 g g^{-1} (1981).

Due to heavy rains after the end of flowering, soil water content in the control treatment rose, reached the high values of i-i (in the first part of July) and did not decline again until mid July (in 1981) or August (in 1980). After this period, water

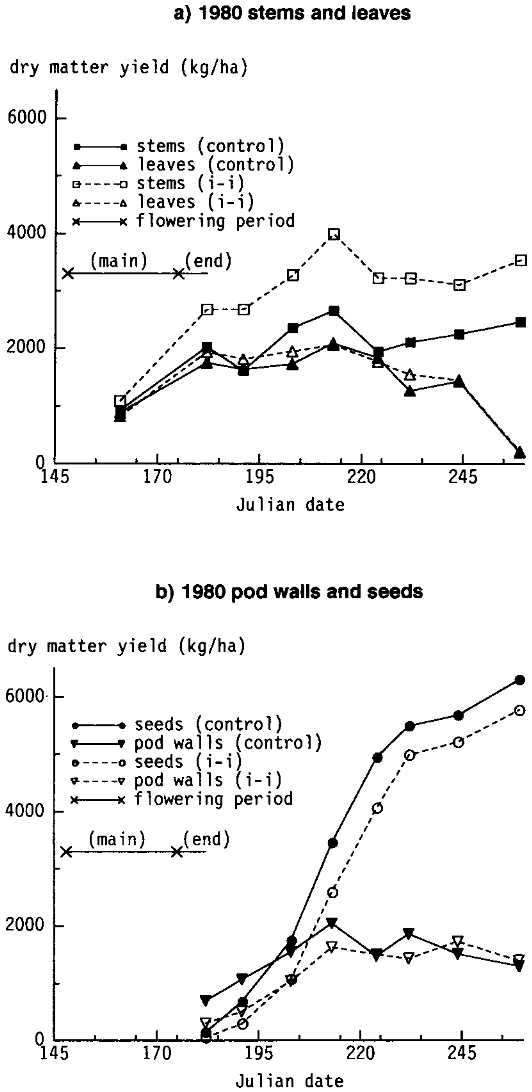


Fig. 1. Faba bean (cv. Minica) dry matter yields during the season 1980 in a field experiment with two water supply treatments. (a) stems and leaves; (b) pod wall and seed.

content in the control treatment remained only 0.02 g g^{-1} lower than in i-i in both years. The control treatments of 1980 and 1981 were characterized as a natural d-i situation.

Effects of irrigation on dry matter partitioning and on final yields

In the experiments of 1980 and 1981, irrigation did not affect the date of onset of flowering. The main flowering period was from day 150 (in 1980) or day 155 (in 1981) to day 175, but small numbers of open or rudimentary flowers were observed till about day 185, especially in i-i. Already during flowering, dry weight of stems in the i-i treatment of 1980 was larger than in the control treatment (Fig. 1a). Dry matter accumulation of stems was higher due to irrigation during flowering, and stems were longer from the first harvest onwards (Fig. 2a). Dry matter accumulation of leaves was little affected by irrigation (Fig. 1a), but leaf size and total leaf area were much larger (Figs. 2b, c), indicating a lower specific leaf weight.

In contrast, pod and seed weights in the i-i treatment were lower than in the control at the second harvest (which was the first possible weight analysis of those organs). Growth curves (Fig. 1b) indicate that irrigation during flowering resulted in a delay in pod and seed growth. In 1981 irrigation delayed and reduced early seed growth in the same way as in 1980 (Fig. 3b). In 1981 no significant variety × treatment interaction was found; therefore only results of Minica are presented.

In the phase of linear seed growth after flowering, both i-i and control resulted in high seed growth rates of 135 kg ha^{-1} d^{-1} (Figs. 1b, 3a). As the control was characterized earlier as a natural d-i treatment, the high rates of reproductive growth were the result of the high water availability after flowering in both treatments. Irrigation did not enhance further vegetative growth, as the plants terminated their elongation growth about two weeks after flowering (Fig. 2a).

However, seed growth in the i-i treatments was not continued long enough to catch up with the final seed production of the control treatments. Figures 3a and 3b show that in both years final seed yields of i-i were lower (significant at P = 0.01), but straw yields higher (P = 0.05) than in the controls. Final total yields of i-i treatments were slightly higher (only significant in 1980) than of the controls. Final harvest index (HI) of i-i was 0.53 in 1980 and 0.54 in 1981, which was significantly lower (at P = 0.005) than in the controls (0.62 in 1980 and 0.63 in 1981). High water availability during flowering not only reduced dry matter allocation to the seeds in a relative way (lower HI), by means of stimulation of vegetative growth and consequent delay of reproductive growth, but reduced seed yields in an absolute way as well.

Irrigation during flowering versus irrigation after flowering: experiments 1982-1984

In this series of experiments (with five different treatments) the effects of high water availability during flowering were separated from the effects of high water availability after flowering (after cessation of vegetative growth).

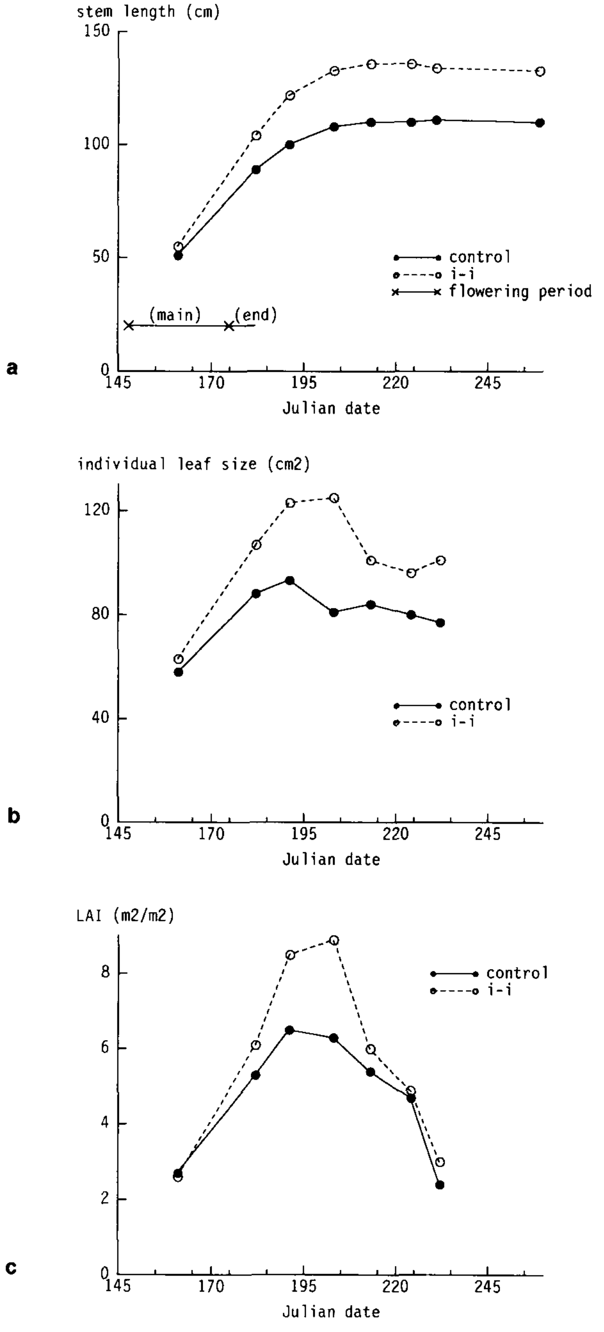


Fig. 2. Faba bean (cv. Minica) vegetative growth during the season 1980 in a field experiment with two water supply treatments. (a) stem length; (b) individual leaf size; (c) leaf area index.

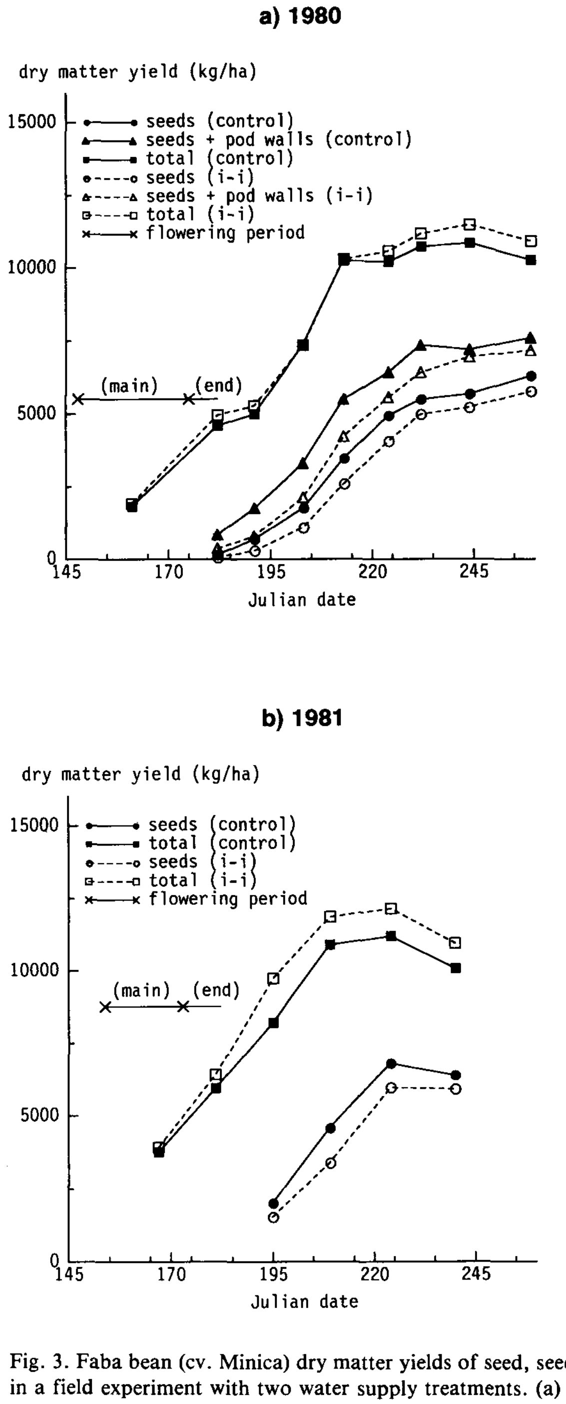


Fig. 3. Faba bean (cv. Minica) dry matter yields of seed, seed and pod wall, and total during the season in a field experiment with two water supply treatments. (a) season 1980 (clay); (b) season 1981 (sand).

Final stem length, harvest index and seed yield. Results of the five experiments are presented for cv. Minica (Fig. 4) as high-yielding standard cultivar and for Alfred (Fig. 5) as widely used cultivar in practice.

Averaged over the five experiments, final stem length in i-d and i-i treatments was 22 cm higher than in d-d and d-i treatments (Minica: Fig. 4b, and Alfred: Fig. 5b). In further comparison of d-d with d-i and of i-d with i-i, only a small additional effect of irrigation after flowering on average final stem length was observed: 4 cm for Minica (Fig. 4b) and 9 cm for Alfred (Fig. 5b). That confirms that vegetative growth is mainly enhanced by high water availability during flowering and is hardly affected by high water availability after flowering.

The d-i and i-i treatments both resulted in average seed yields which were 1.6 t ha^{-1} higher than in d-d and i-d (Minica: Fig. 4f, and Alfred: Fig. 5f). That confirms that seed production is mainly enhanced by high water availability after flowering. However, average total yield was higher in i-i than in d-i (Figs. 4h and 5h). So, total yield was enhanced by every irrigation during flowering and after flowering.

In d-i, reduced vegetative growth, due to reduced water availability during flowering, was followed by a high seed growth rate, due to high water availability after flowering. That resulted in a short-stem crop type (Figs. 4b and 5b), with most effi-

Table 2. Seed yields (t ha^{-1}, 86 % DM), plant length (cm) and harvest index (g g^{-1}) of an experiment with four faba bean cultivars grown under five different water supply treatments. Seed yields presented separately for each treatment and for each cultivar, and as average over cultivars (horizontally) or over treatments (vertically). Plant length and harvest index only presented as average over treatments or over cultivars. Results from sand(N) in the season 1984. Different letters (a, b, c, d) indicate significant differences at P = 0.05.

	Water supply treatments					Average seed yield	Average plant length	Average harvest index
	d-d	i-d	d-i	i-i	control			
Minica	6.4	6.6	8.2	7.8	7.0	7.2 (a)	151 (c)	0.53 (a)
Alfred	5.9	6.4	7.0	7.3	6.6	6.6 (b)	172 (b)	0.51 (b)
Optica	5.7	6.1	6.2	6.0	6.2	6.0 (c)	110 (d)	0.54 (a)
Kristall	5.8	5.9	6.1	6.0	6.3	6.0 (c)	192 (a)	0.47 (c)
Average seed yield	6.0 (c)	6.2 (bc)	6.9 (a)	6.8 (a)	6.5 (ab)			
Average plant length	149 (c)	161 (b)	154 (c)	169 (a)	149 (c)			
Average harvest index	0.51 (ab)	0.50 (b)	0.53 (a)	0.50 (b)	0.53 (a)			

Values of F-test on seed yield

Cultivar	32.7
Water treatment	11.9
Cultivar × treatment	4.5

cient dry matter partitioning (maximum harvest index, Figs. 4d and 5d) and average seed yield which was equally high as in i-i (Figs. 4f and 5f). In contrast, in i-d the stimulated vegetative growth followed by reduced seed growth resulted in a long-stem crop type, with the least efficient partitioning (minimum harvest index) and average seed yield which was equally low as in d-d. Both i-i and d-d showed sub-optimum dry matter partitioning (intermediate harvest indices; Figs. 4d and 5d). The two irrigations after flowering in the d-d treatments of 1982 had a strong positive effect on seed yield and harvest index for cv. Alfred (Figs. 5c and 5e).

Average seed yield of natural rainfall control (Figs. 4f and 5f) was only slightly higher than or equal to the d-d and i-d treatments. Irrigation after flowering resulted in yield enhancement of 1.5 t ha^{-1} (Minica) and of 1.7 t ha^{-1} (Alfred) compared with the control.

Effects of treatments on plant length, harvest index and yield were larger in experiments of 1982 and 1983 (England) than in 1983 (Netherlands) and 1984 (Figs. 4a, c, e and 5a, c, e).

However, the relatively small main effects of treatments in 1984 were significant (Table 2) and in agreement with the average effects presented above. Also, significant differences between cultivars were observed in 1984. For instance, Minica yielded higher than Alfred ($P = 0.05$) and Alfred higher than Optica and Kristall. Effects of treatment on growth and yield were larger in Minica and Alfred and smaller in Kristall and Optica. Those cultivar × treatment interaction effects were also significant, but, according to the *F*-values, main effects were stronger.

Variability of seed yield. Effects of water availability on variability of seed yield were studied within each experiment (over the five treatments) and within each treatment (over the five experiments).

Firstly, the yield variability expressed as the range of variation over the five treatments within one separate experiment was not equal for all experiments (Figs. 4e and 5e). But, within each experiment, highest yields were obtained in d-i or in i-i; lowest yields were always obtained in d-d, i-d or natural rainfall control (Figs. 4e and 5e). The yield responses to high water availability after flowering indicate that yield variability was related to variation in water supply, at least within each experiment.

Table 3. Total global radiation (kJ cm^{-2}), average daily temperature (°C) and rainfall (mm) in spring (April-June) and summer (July-September) for a normal 30-year standard and positive (+) or negative (−) deviations from that normal of the years 1982, 1983 and 1984. Standard (N-30) obtained from the Royal Dutch Meteorological Institute (KNMI) at De Bilt.

	Normal		1982		1983		1984	
	spring	summer	spring	summer	spring	summer	spring	summer
Radiation	147	128	+21	+ 13	− 15	+ 9	−17	−11
Temperature	11.8	15.7	+ 0.5	+ 1.5	norm.	+ 1.8	− 1.0	norm.
Rainfall	176	230	−41	−149	+123	−96	−39	−17

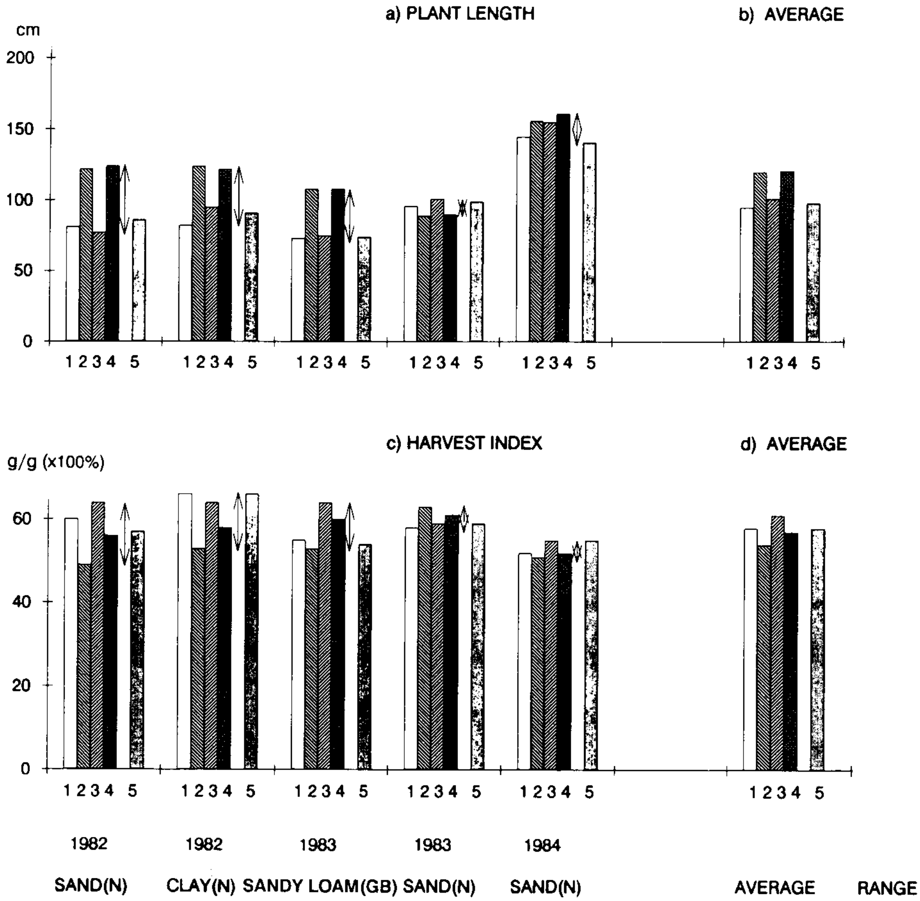


Fig. 4. Plant length (a,b), harvest index (c,d) seed yield (e,f) and total yield (g,h) of faba bean (cv. Minica) grown under five different soil water supply treatments in five experiments in 1982-1984. 1 = d-d; 2 = i-d; 3 = d-1; 4 = i-i; 5 = control. Arrows represent range over the five treatments of each experiment; 'Range' represents range for each treatment over the five experiments. Sand(N), clay(N) and sandy loam(GB) refer to the experimental sites (see Table 1 and text). In 1982 d-d got two irrigations after flowering.

Secondly, the relation between water supply and yield variability was confirmed by expressing the variability as the range from lowest to highest seed yield within one treatment over the five experiments. That range was largest in the control and small in both d-i and i-i treatments (Figs. 4f and 5f). High water availability after flowering not only increased average seed yield with 1.6 t ha^{-1}, but also reduced seed yield range over the five experiments with 2 t ha^{-1}, compared with the natural rainfall control. In contrast, total yield ranges were almost equal for all treatments (Figs. 4h and 5h).

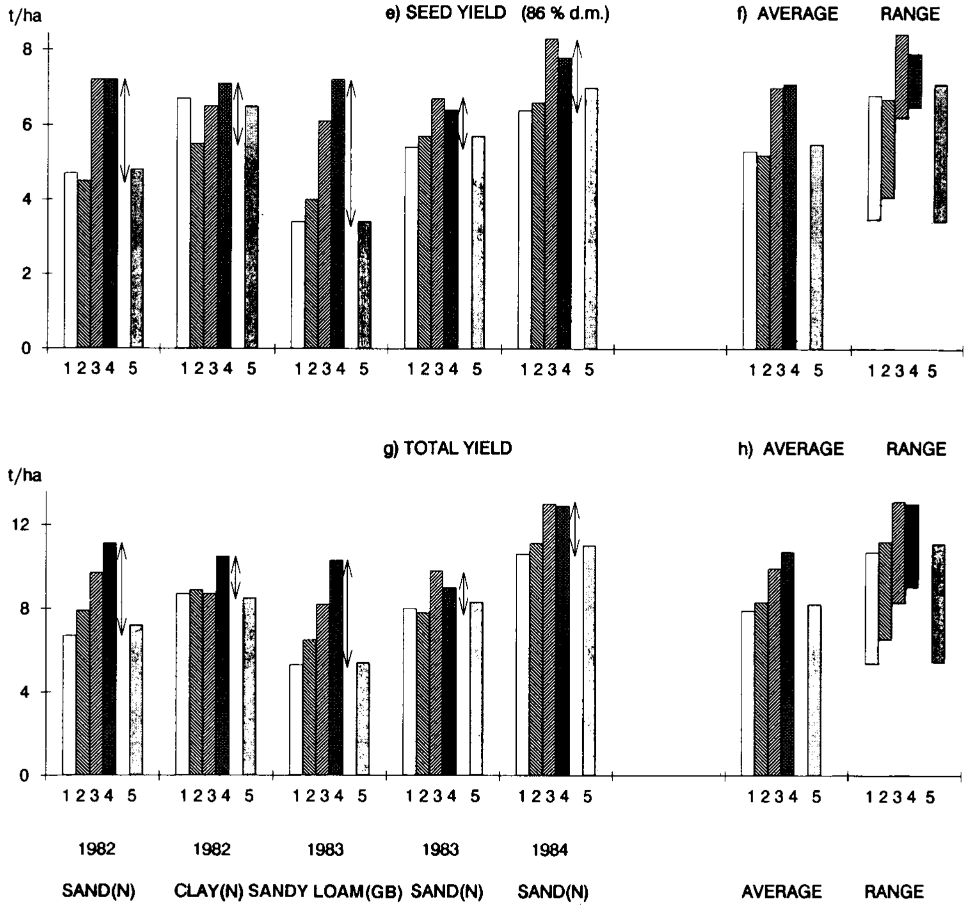


Fig. 4. Continued.

Growth and yield in relation with soil water content and weather. Both the unequal seed yield range for each separate experiment (Figs. 4e and 5e) and the large seed yield range in natural rainfall controls over all experiments (Figs. 4f and 5f) were related to differences in the course of soil water content and weather among the various experiments. In the sandy soils, detectable differences in plant water potential between irrigated and control field plots were only found below a soil water content of 0.10 g g^{-1} (Venekamp et al., 1987). This value, which corresponds to a pF of 3 for this soil type, was used for comparison of treatments in the experiments on

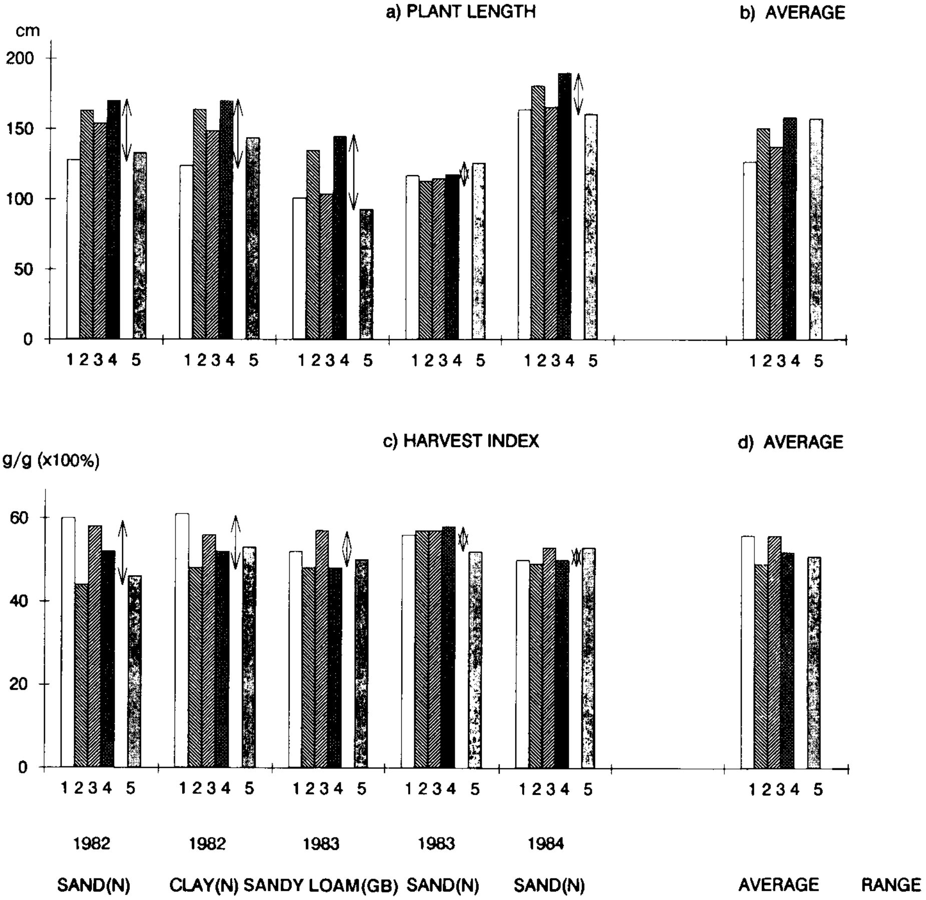


Fig. 5. As Fig. 4, for cv. Alfred.

sandy soils (1982-1984).

The growing season of 1982 as a whole was sunny, warm and dry (Table 3). In this season, soil water content of the natural rainfall control (Fig. 6a) underscored the value of 0.10 g g^{-1} much earlier than in 1983 (Fig. 6c), as the spring of 1983 was extremely wet (Table 3). In contrast, the summer of 1983 was very dry. In 1984 a second peak in control soil water content in July was recorded after a rainy period (Fig. 6e). The growing season of 1984 was dark, cold and slightly dry (Table 3). Seed yield of 1984 control was high, due to those moderate conditions; yield of the 1983 control was intermediate due to water shortage after flowering and yield of 1982 was low due to dry conditions during the whole growing season.

These weather conditions also interfered with the other treatments. Notwithstand-

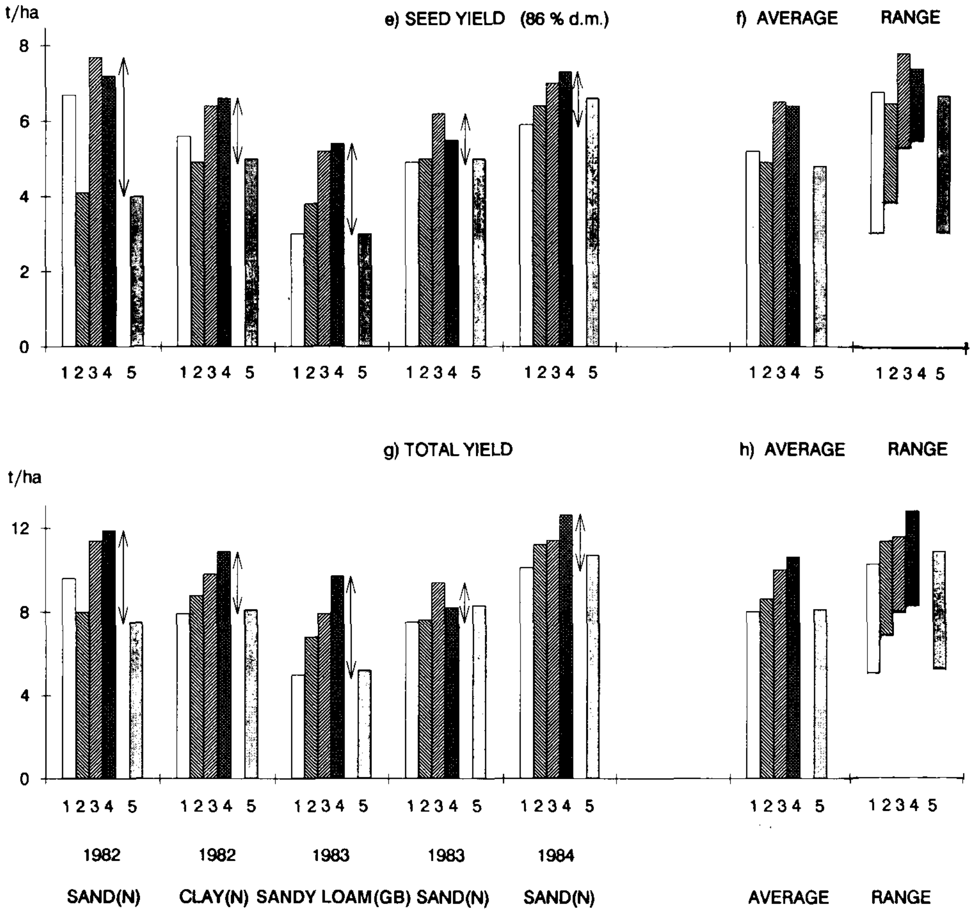


Fig. 5. Continued.

ing the polythene sheeting, water shortage (in d-i treatments, but also in d-d) during flowering was realized earlier in 1982 than in 1984 and was absent in 1983 (Fig. 6b, d, f). For that reason, differences in plant length and harvest index were expressed more clearly in the 1982 experiments.

In the treatments with planned water shortage after flowering (i-d), soil water content underscored the value of 0.10 g g^{-1} at about 18 days after the end of flowering (Fig. 6b, d, f). This explains why the treatment effect of water shortage after end of flowering on seed yield was clear in all experiments. However, this effect was smaller in 1984, as the cool and dark 1984 season moderated the water shortage, even in the d-d treatments.

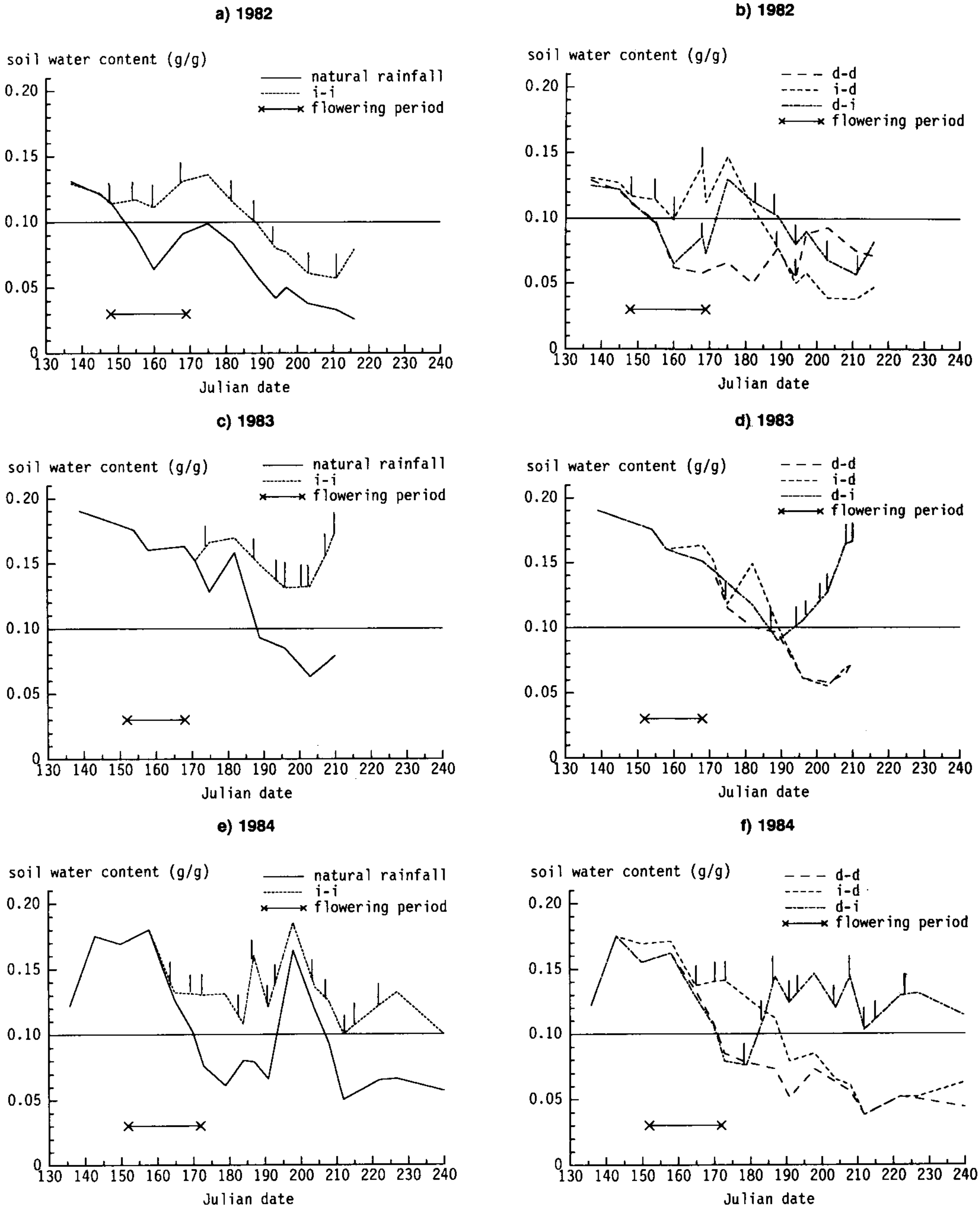


Fig. 6. Seasonal course of soil water content in faba bean experiments with different water supply treatments. Experiments on sand(N) 1982-1984; horizontal lines = soil water content at pF 3 (see text); vertical marks represent times of irrigation.

Discussion

The consequences of various amounts and timings of water supply on growth are arranged in a flow chart (Fig. 7). According to definitions of Hsiao et al. (1976a), in the chart two alternative situations for the crop during flowering are distinguished: absence of water shortage (the expansive growth is high) versus 'mild' water shortage (the expansive growth is reduced, but the rate of photosynthesis hardly).

Decrease of leaf expansion and reduction of stem extension due to water shortage were reported by Karamanos (1978), Elston et al. (1976) and Tamaki & Naka (1971). Extension rates of stems and leaves of faba beans were very sensitive to a small decline of leaf turgor caused by mild water shortage (Part 3; Grashoff, in prep.). Figure 2a (stem extension) and Figures 2b and 2c (leaf expansion) confirm that reduction of expansive growth is the earliest effect of water shortage on crop growth in the season, accompanied by reduced dry matter accumulation of stems (Fig. 1a), while total dry matter production is still nearly unaffected during flowering (1980: Fig. 3a; 1981: Fig. 3b). This is in agreement with Hsiao et al. (1976b) who concluded that a reduction in cell expansion is the first reaction to increasing water shortage. It confirms that water shortage in 1980 and 1981 was only 'mild'. In 1982-1984, soil water content during flowering in the sandy soil never reached importantly lower values than in 1981 (Fig. 6). For this reason, effects of water shortage during flowering were mainly caused by the 'mild' type of shortage, and effects of 'severe' water shortage during flowering (the rate of photosynthesis is reduced, Hsiao et al., 1976a) were not included in Figure 7. However, a more severe water shortage may have developed during flowering in clay(N) 1982, and in sandy loam(GB) 1983. This is discussed in Part 2 (Grashoff, in prep.).

Reduced expansive growth during flowering results in a smaller sink strength of the vegetative top (Hsiao & Acevedo, 1974). So, in situations with mild water shortage, more assimilates are available for organs at a lower plant position, as for instance young pods, which have a lower competitive strength (Jaquiéry & Keller, 1978; 1980). This was confirmed by the initial stimulation of dry matter increase of pods under mild water shortage (Figs. 1b, 3), which was accompanied by higher pod retention (and higher final seed yield) at early developed flowering nodes (Part 2; Grashoff, in prep.), and this supports the results of Smith (1982), who recorded higher pod retention in a natural d-i control than in treatments which were irrigated during and after flowering. Dependant on the water supply during flowering, a more vegetative crop type and a more reproductive type are distinguished at the end of flowering (Fig. 7), comparable with the situations in Figures 1, 2 and 3 at the end of flowering.

After flowering, expansive growth is terminated in both crop types (Fig. 2a), so the competition between vegetative top and reproductive organs is also terminated. In this period, the two extremes, water shortage versus absence of water shortage, are distinguished in the flow chart, for each of the two crop types. Water shortage now reduces rate and period of further reproductive growth, the extent depending on the severeness of the water shortage. That results in reduced number of later

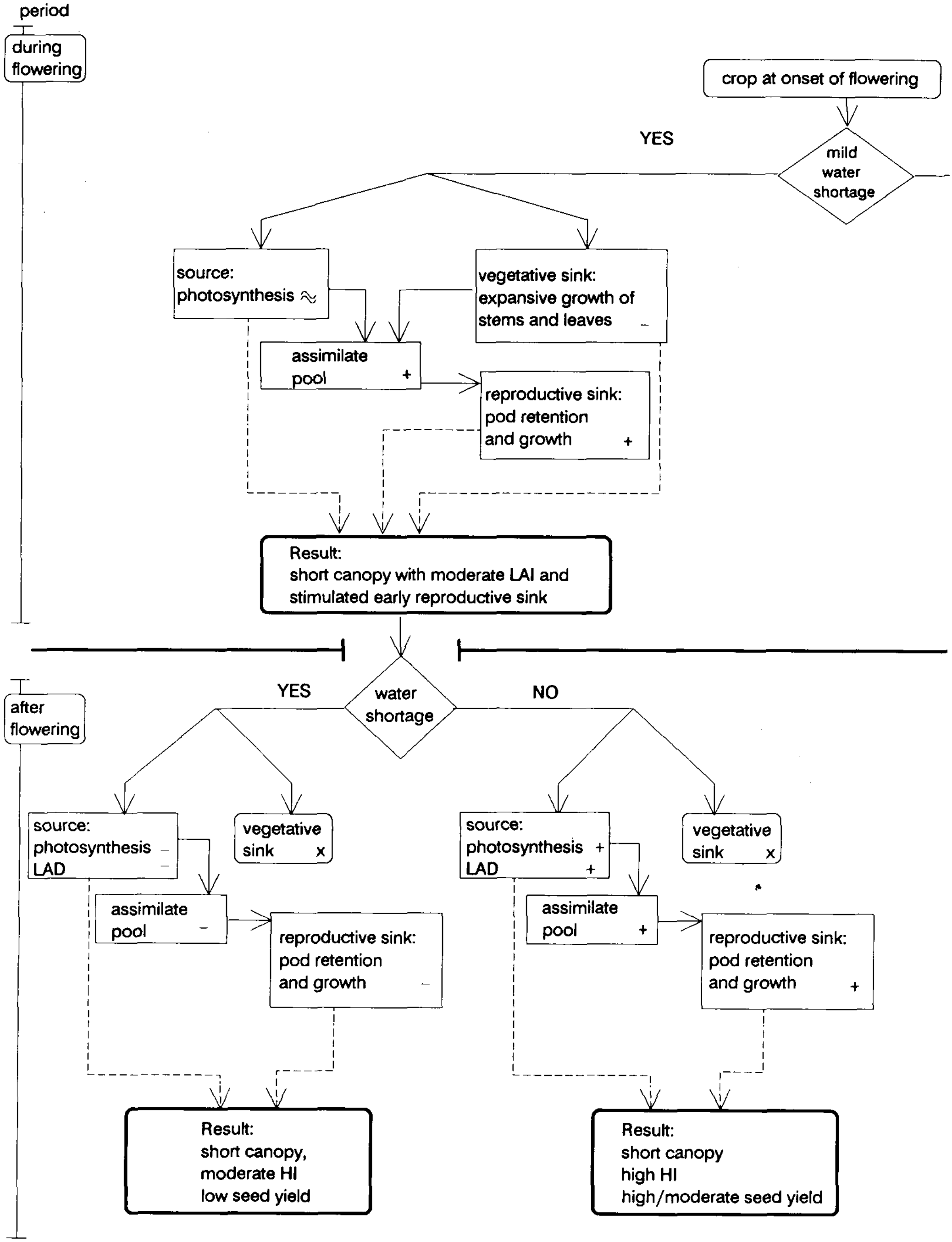
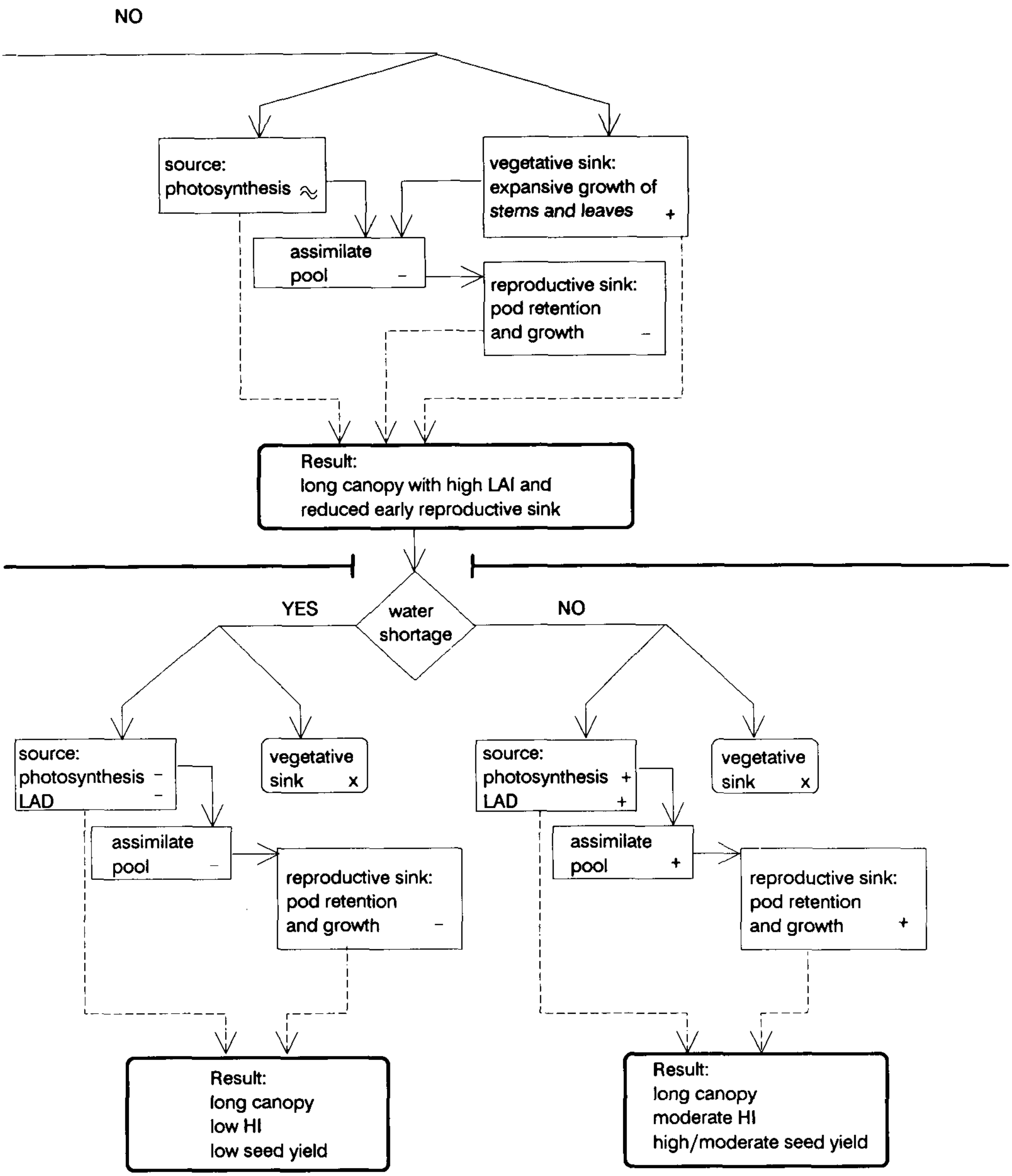


Fig. 7. Effects of different soil water contents on growth, dry matter partitioning and yield of faba beans summarized in a flow chart. Traced arrows = 'has influence on'; dotted arrows = 'has the following final result'; + = stimulated; – = reduced; × = terminated; ≈ = not changed.


NO
source:
photosynthesis ≈
vegetative sink:
expansive growth of
stems and leaves +
assimilate
pool –
reproductive sink:
pod retention
and growth –
Result:
long canopy with high LAI and
reduced early reproductive sink
YES
water
shortage
NO
source:
photosynthesis –
LAD –
vegetative
sink x
assimilate
pool –
reproductive sink:
pod retention
and growth –
Result:
long canopy
low HI
low seed yield
source:
photosynthesis +
LAD +
vegetative
sink x
assimilate
pool +
reproductive sink:
pod retention
and growth +
Result:
long canopy
moderate HI
high/moderate seed yield

formed pods and reduced pod fill (Part 2; Grashoff, in prep.). As a consequence, four extremes of final crop types are distinguished (Fig. 7), identical with the average results in Figures 4 and 5.

These results prove that differences in amounts and timings of water supply not only highly affect final seed yield but also initial dry matter partitioning, leading to differences in final harvest index. That contrasts with several reports which concluded that harvest index was not influenced (Krogman et al., 1980; Kogbe, 1972). However, other workers reported variable harvest indices as well. Our results confirm that the largest differences are most probably the result of natural i-d or d-i situations. Sprent et al. (1977) found a harvest index of only 0.24 g g^{-1} in 1974 and of 0.50 g g^{-1} in 1975 for the cultivar Maris Bead. Total rain, radiation and temperature were not much different for both years. However, in May and June 1975 (before and during flowering) there was much less rain than in those months in 1974. Thus, there is evidence to qualify these results of 1974 as i-d situations and 1975 as d-i situations.

Green et al. (1986) concluded from experiments in England with polythene sheeting and irrigation that dry matter partitioning and final harvest index were not systematically affected by different irrigation treatments. However, results of irrigation during flowering versus after flowering were not compared.

Figure 7 indicates why in some d-i situations higher seed yields than in i-i were found in combination with lower or equal average total dry matter production (Fig. 3; Fig. 4 1984 and Fig. 5 1982 sand). As total amount of applied water in i-i situations is higher than in d-i, it is assumed that the amount of consumed water in i-i is higher as well, which is confirmed by the higher total dry matter yield. This is in agreement with the conclusion of de Wit (1958), who found linear relationships between total dry matter yield and water use in many situations. However, in our experiments, mild water shortage during flowering is essential for high early pod retention (Fig. 7) which on its turn is a requirement for an early and strong reproductive sink. It results in the most efficient dry matter partitioning during the whole season and absolutely higher seed yields, even with slightly reduced total dry matter production.

It supports the statement of Smith (1982) and Dantuma et al. (1983) that irrigation during flowering favours vegetative growth at the expense of reproductive growth. So, correlation between seed yield and total water received may not be as close as between total yield and water.

These conclusions are in contrast with the conclusion of Day & Legg (1983) and Krogman et al. (1980). They found a linear relationship between seed yield and water use, and a near-constant value of harvest index of 0.45 g g^{-1} for crops, grown under a range of irrigation plus rain from 100-700 mm.

On the other hand, our conclusions are in agreement with the results of Stock & El-Naggar (1980) who concluded from regression analysis that the optimum soil water content during flowering was at 40-60 % of 'utilizable field capacity' (a concept, which is used by Stock & El-Naggar (1980) for the water content range between pF 2 and 4.2). Both higher or lower soil water contents resulted in sub-optimum seed yields. After the flowering period, a linear correlation between utilizable field capacity and seed yield was found. Stock & El-Naggar (1980) did not present data about straw yields, harvest index, or records on pod retention, but with our results and conclusions presented above, the graph made by Stock & El-Naggar (1980) can be hypothetically complemented with effects of water supply on total dry matter production and partitioning.

Based on total yields in Figures 4 and 5 and the conclusions of de Wit (1958), it is stated in Figure 8 that the relation between total dry matter production and utilizable field capacity is linear during flowering and after flowering (provided that water use is closely related with utilizable field capacity). Following the regression for seed yield and utilizable field capacity of Stock & El-Naggar (1980), Figure 8 shows that the correlation between seed yield and water use is also linear in the lower and middle range of amounts of used water during flowering. This represents situations with more or less severe water shortage and is in agreement with Krogman et al. (1980). In contrast with Krogman et al., the regression line for seed yield reaches an optimum at moderate levels of water used during flowering (that means with mild water shortage during flowering). The line then decreases at high amounts of used water (absence of any water shortage), due to vigorous vegetative growth and consequent processes described above (Fig. 7), while correlation between total dry matter production and water used remains positive. After flowering, linear relations are described in Figure 8 between water use and total yield and between water use and seed yield. The water supply patterns of Figures 3, 4 and 5 are placed in Figure 8, based on the description of the soil water content during and after flowering. Only a rough comparison can be made, but it is worth noting that the yield results of the i-i treatments can be compared with the left back corner of Figure 8 and those of the i-d treatments with the left front corner; d-i with the middle of the back side, and d-d with the middle of the front side of Figure 8.

Figure 8 has consequences for the analysis of maximum possible seed yield. If maximum total dry matter production (for Minica about 15 t ha^{-1}, obtained in 1984) could be combined with maximum harvest index (about 0.65 g g^{-1}) this should result in a potential seed yield of about 10 t ha^{-1}. However, Figure 8 indicates that it may not be possible to combine these two maxima in one crop.

The negative effects of irrigation during flowering are in contrast with the conclusion of Day & Legg (1983) that, in general, similar seed yield responses were observed to irrigation when water availability is limited in any time in the season. However, deviations from these general conclusions are only to be expected in the situation of absence of water limitation ('plenty of water') during flowering (Figs. 7 and 8). These conditions may occur more often in the temperate climate in Western Europe than in Egypt, Canada and the United States, on which the conclusions of Day & Legg were mainly based.

Although plenty of water during flowering has a negative effect on dry matter partitioning and seed yield, the most important negative effects on yield and yield stability were the result of water limitation after end of flowering (Figs. 4 and 5). The lower yield variability in combination with higher average yields in the d-i and i-i treatments (compared with the natural rainfall, i-d and d-d treatments) lead to the general conclusion that natural differences in distribution pattern and amount

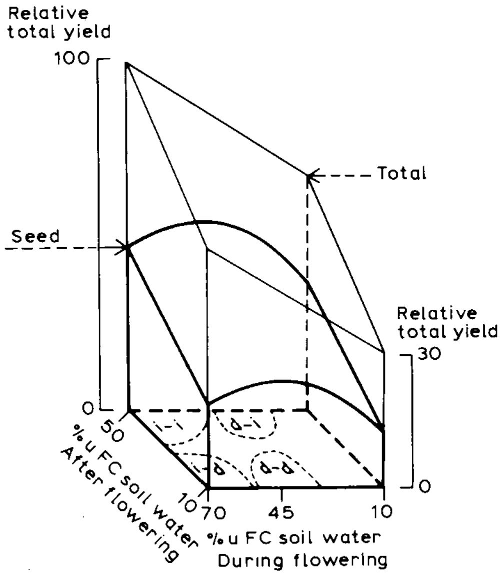


Fig. 8. Relation between relative yield of faba beans and water use, expressed as percentage of utilizable field capacity (% uFC) during and after flowering. Thick lines after Stöck & El-Naggar (1980) for seed yield; thin lines as hypothetical complement for total dry matter production. Symbols i-i, d-i, etc., correspond to four different water supply patterns (see text).

of rainfall are an important cause of the high natural yield variability of faba beans. During flowering a mild water shortage might be preferable to plenty of water, but after flowering plenty of water is essential for a high seed yield and low yield variability of faba beans.

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