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Water requirements of subsurface drip-irrigated faba bean in California

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Abstract A 3-year study was done in central California to determine the water requirements for growing faba bean (*Vicia faba* L.) as a winter cover crop using subsurface drip irrigation (SDI). Water was applied at 0, 50, and 100% of the estimated crop evapotranspiration (ET_c) the first 2 years and 50, 100, and 150% ET_c the third year, with drip laterals installed 0.30, 0.45, or 0.60 m deep. Rainfall was above normal the first year (>330 mm) and irrigation had no effect on crop production. Irrigation improved production and water-use efficiency the following years, however. Production was higher when drip laterals were located at 0.30 or 0.45 m than at 0.60 m depth, even though roots tended to be concentrated near the laterals (later in the season) regardless of depth. Overall, well-irrigated faba bean required 231–297 mm of water to produce 3.0–4.4 t ha^{-1} of dry vegetative biomass.

Introduction

In California, faba bean is grown for seed production in the Salinas and Northern Sacramento Valleys, but in other parts of the state it is grown mostly as a cover crop or for green manure. It is a cool-season annual, usually planted in February and March for seed and September to November for cover crops. Vegetative yields typically produce about 20–40 t (fresh weight) of forage per hectare, and the leguminous nature of the plant can provide considerable amounts of nitrogen to the soil (Hickman and Canevari 1989). Once incorporated into the soil, faba bean, as with other cover crops, potentially increases soil organic matter and improves soil structure and tilth over time (Black 1973; Tisdale et al. 1985; Roberson et al. 1991).

Growth of faba bean is very sensitive to the level and pattern of water supply and is prone to drought stress (Hebblethwaite 1981; Husain et al. 1988b; Grashoff and Verkerke 1991; Xia 1994; De Costa et al. 1997a). Many studies have reported very substantial increases in faba bean seed yields as a result of proper irrigation, including studies in regions where rainfall is abundant throughout the growing season (Sprent et al. 1977; Krogman et al. 1980; Stock and El-Naggar 1980; McEwen et al. 1981; Day and Legg 1983; Hebblethwaite et al. 1984; Green et al. 1985; Husain et al. 1988a; Grashoff 1990; De Costa et al. 1997b). Water requirements have not been determined, however, when growing faba bean as a cover crop, nor have they been determined in California. Proper irrigation scheduling is expected to differ when the crop is grown as a cover crop compared with when it is grown for seed production. When growing faba bean for cover (or green manure), the primary goal is to maximize vegetative production by the crop, whereas production for seed requires that some level of water stress is imposed on the crop in order to limit excessive vegetative growth and stimulate early reproductive growth (De Costa et al. 1997b). Stock and El-Naggar (1980) concluded that the optimum soil water content during flowering was at 40–60% of the available water and that either higher or lower water content resulted in suboptimal seed yields.

The purpose of the present study was to determine the amount of irrigation required for growing faba bean as a winter cover crop in the San Joaquin Valley of central California. The crop was irrigated using a SDI system because, while flood or furrow systems are still the most common irrigation systems used in the region, SDI acreage is expanding, particularly for growing vegetable crops. The potential of SDI for increasing yield and water-use efficiency has been demonstrated for

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a variety of important vegetable and field crops grown in the Valley, including alfalfa, cantaloupe, cotton, tomato, and sweet corn (Ayars et al. 1999). SDI may also help reduce deep percolation and induce crop water use of shallow groundwater in areas where high groundwater tables exist (Ayars et al. 2001).

Materials and methods

A small-seeded, determinate variety of faba bean (*Vicia faba* L. cv. Bell) was grown as a winter cover crop for 3 years in a level 1.8 ha field located at the University of California West Side Research and Extension Center near Five Points, California, USA. Soil at the site is a Panoche clay loam (Typic Torriorthents) with relatively uniform water retention characteristics and high water-holding capacity, averaging over 425 mm in the top 2.5 m (Nielsen et al. 1973). Saline groundwater, which is characteristic of the west side of the San Joaquin Valley (Hanson and Trout 2001), was always deeper than 8 m during the study.

Each growing season, the field was first sprinkler-irrigated with 100 mm of water at 21–28 days prior to planting to refill the soil water profile. Granular 11:50:2 NPK fertilizer and trifluralin (α,α,α-trifluro-2,6-dinitro-*N*, *N*-dipropyl-*p*-toluidine) herbicide were then broadcast and disked into the top 0.1 m of soil at rates of 45 kg N ha^{-1} and 7.8–11.2 kg ha^{-1}, respectively, at 7 days prior to planting. Seed, pre-inoculated with *Rhizobium* spp. bacteria, was sown on 2 November 1997, 16 November 1998, and 14 September 1999. Two rows of seed spaced 0.5 m apart were planted to a depth of 0.04 m on 1.5 m wide × 91 m long beds and sprinkler-irrigated with 50 mm of water to encourage germination. The crop was thinned at 2 weeks after germination to one seedling every 0.2 m within a row.

Two weeks after emergence, irrigation treatments were initiated. Treatments were arranged in a randomized split-plot design with four replicated blocks. Each block contained three main plots with SDI tubing (GeoFlow, Charlotte, N.C.) buried 0.30, 0.45, or 0.60 m deep and three subplots irrigated at 0, 50, or 100% ET_c during the 1997/1998 and 1998/1999 growing seasons, and at 50, 100, or 150% ET_c during the 1999/2000 growing season. Main plots contained ten crop beds with one line of tubing permanently installed along the center of each bed. In-line turbulent flow emitters in the tubing were spaced 1.0 m apart and had a nominal flow rate of 2 l h^{-1} at a working pressure of 130 kPa. Subplots contained three or four beds each. Values of ET_c were calculated by multiplying potential evapotranspiration, downloaded from a CIMIS (California Irrigation Management Information System) weather station located in an adjacent field, by crop coefficients developed for dry beans (Pruitt et al. 1986). Water applications were controlled with manual valves and monitored using water meters (Sensus Technologies, Uniontown, Pa.). Irrigation was scheduled every 7 days throughout the growing season and adjusted for precipitation.

Changes in soil water content were measured every month during the growing season, beginning at planting, using a neutron probe (Troxler Model 4300; Troxler Electronic Laboratories, Research Triangle Park, N.C.) and PVC access tubes installed 3 m deep. Tubes were located in a middle bed of each subplot (within 0.15 m of the bed center, midway along the row). By using a middle bed, any potential effects from nearby treatments were minimized. Neutron counts (60-s intervals) were made at each 0.3-m depth increment between 0.15 and 2.25 m from the soil surface and converted to soil water content using a calibration curve developed for the site, following procedures outlined by Gardner (1986).

Seasonal water use in each plot was estimated by a water balance approach (Allen et al. 1998), which accounted for precipitation, irrigation, and soil water depletion calculated from changes in water content in the top 2.1 m of the soil profile (estimated root zone). Water loss by deep percolation was also accounted for when the amount of irrigation or rain received caused the soil water content to exceed field capacity within the root zone (Allen et al. 1998). Runoff and capillary rise from the groundwater table were considered negligible in the field plots.

A subsample of plants was harvested four to six times per growing season. At each harvest, six representative plants selected from a middle bed of each subplot were cut off at the soil surface, dried for 4–5 days at 55°C, and weighed. Soil cores (0.1 m diameter) were also collected from the middle bed of each subplot on 19 January 2000 to determine the root length distributions under each irrigation treatment. The cores were extracted in 0.1-m increments from the top 1 m of soil from a position located between two representative plants within a row. Roots were washed from the cores, imaged using a flatbed scanner (Epson Expression 1600; Epson America, Long Beach, Calif.), and measured for length using image analysis software (WinRhizo v. 4.0; Regent Instruments, Quebec). Root length was divided by soil volume to calculate root length density.

At the end of each growing season, approximately 5 months after emergence, the crop was allowed to dry and then mulched and disked into the soil. The field was left fallow during spring and summer months.

Analysis of variance (SAS general linear model procedures; SAS Institute 1988) was used to analyze the data and mean comparisons were made using Duncan's multiple range test (Gomez and Gomez 1984).

Results and discussion

Weather conditions

Long-term average climatic conditions for the study site are presented in Table 1. In an average year at the site, total precipitation during the winter growing season from November to April was 197 mm. De Costa et al. (1997a) found that faba bean grown for seed production used 302–472 mm of water under well irrigated conditions, which means that irrigation may be required to optimize growth of faba bean during the winter months in the San Joaquin Valley, particularly during dry years.

During the first year of the study in 1997/1998, winter precipitation was unusually high throughout the entire growing season, exceeding 330 mm by the end of the season (Fig. 1A). The 1998/1999 field season, however, was considerably drier than the previous year, with only 80 mm of rain falling between December and March, which is about 50% below normal (Fig. 1B). In 1999/2000, the crop was planted 2 months earlier than the previous 2 years, which consequently exposed the plants to higher solar radiation (Fig. 1D–F), warmer air temperatures (Fig. 1G–I), and drier conditions early on (Fig. 1C). Throughout the 1999/2000 season, there was only 37 mm of precipitation, most of which fell near the end of the season.

Potential evapotranspiration over each growing season was 277 mm in 1997/1998, 233 mm in 1998/1999, and 356 mm in 1999/2000.

Water balance

Crop water balances calculated for each year are presented in Table 2. Based on estimates of crop evapotranspiration calculated by multiplying potential

Table 1 Mean (standard error) precipitation, potential evapotranspiration (ET_o), solar radiation and air temperature at the UC West Side Research and Education Center from 1982 to 2001[a]

Month	Precipitation (mm)	ET_o (mm)	Solar radiation (W m^{-2} day^{-1})	Air temperature (°C)	
				Maximum	Minimum
January	47 (9)	34 (4)	84 (4)	13.1 (0.4)	2.9 (0.5)
February	44 (7)	53 (3)	134 (4)	17.0 (0.3)	4.8 (0.4)
March	45 (9)	100 (5)	198 (4)	20.6 (0.4)	6.7 (0.3)
April	12 (3)	157 (5)	268 (4)	24.5 (0.4)	8.3 (0.3)
May	7 (3)	207 (7)	314 (4)	28.7 (0.6)	11.4 (0.3)
June	2 (1)	222 (5)	339 (4)	32.1 (0.3)	14.2 (0.2)
July	0 (0)	226 (3)	327 (3)	34.4 (0.3)	16.3 (0.3)
August	1 (1)	205 (4)	294 (3)	34.1 (0.3)	16.1 (0.2)
September	8 (3)	157 (4)	239 (2)	31.7 (0.4)	14.1 (0.3)
October	17 (5)	114 (2)	179 (2)	27.0 (0.4)	9.9 (0.3)
November	23 (6)	60 (3)	117 (3)	18.7 (0.5)	4.8 (0.3)
December	26 (5)	35 (4)	79 (3)	12.8 (0.4)	1.7 (0.5)

[a] Data were collected by a CIMIS weather station

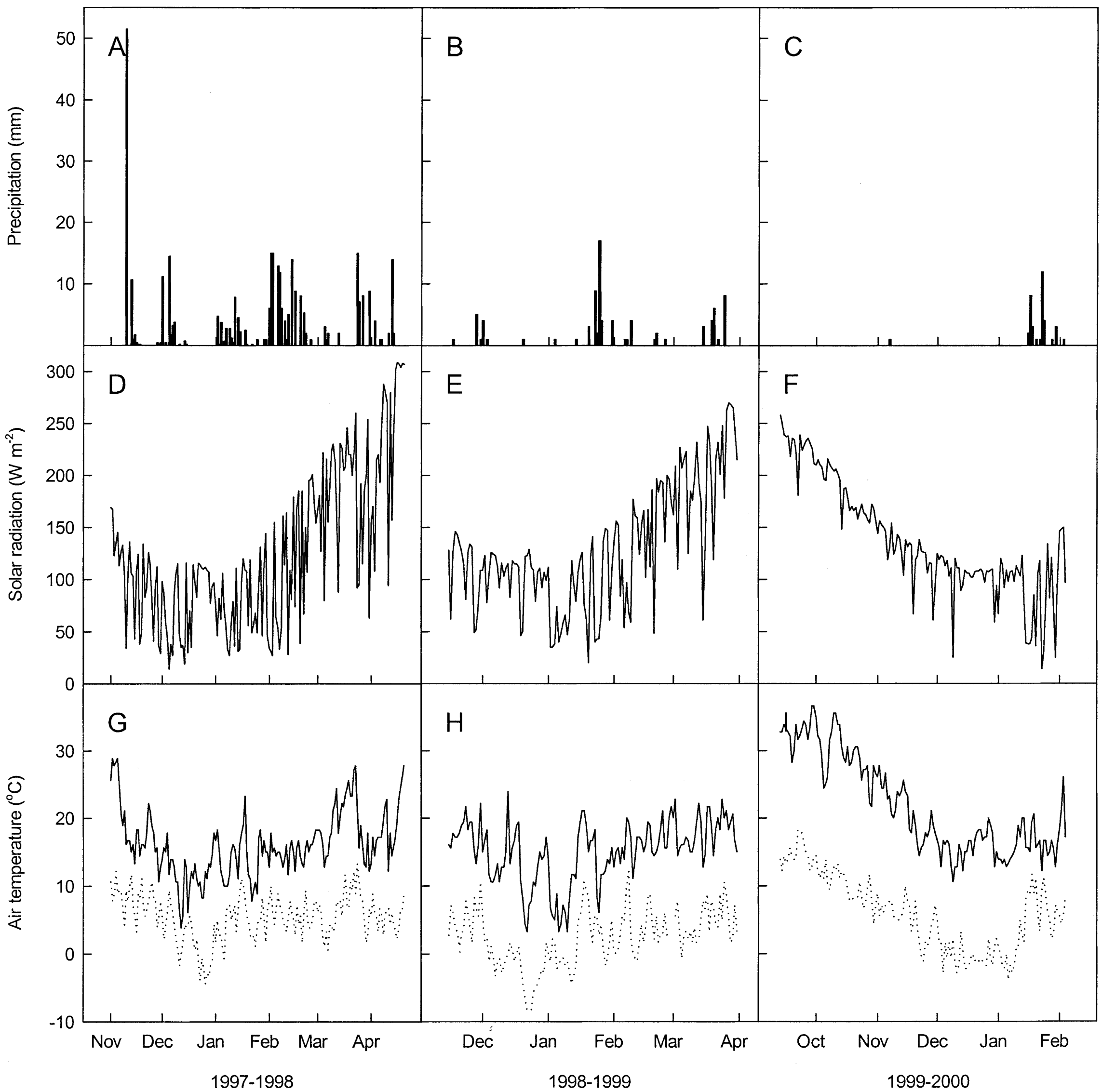

Fig. 1 Precipitation (**A**–**C**), solar radiation (**D**–**F**), and maximum (*solid line*) and minimum (*dotted line*) air temperatures (**G**–**I**) at the faba bean study site during the 1997/1998 (**A**, **D**, **G**), 1998/1999 (**B**, **E**, **H**) and 1999/2000 (**C**, **F**, **I**) winter field seasons

evapotranspiration by a published crop coefficient for winter dry bean production in central California (Pruitt et al. 1986), less water was applied to the irrigated treatments during the wet 1997/1998 field season than

Table 2 Water balance of faba bean planted as cover crop during the 1997/1998, 1998/1999, and 1999/2000 winter field seasons. The crop was irrigated each year at three different levels using subsurface drip irrigation (*SDI*) laterals installed 0.30, 0.45 or 0.60 m deep

Depth of SDI lines (m)	Irrigation level (% ET_c)	Irrigation (mm)			Soil water depletion (mm)			Deep percolation (mm)			Seasonal water use (mm)		
		97/98	98/99	99/00	97/98	98/99	99/00	97/98	98/99	99/00	97/98	98/99	99/00
0.30	0	0	0	#	120c[a]	130c	#	176	0a	#	273	209a	#
0.30	50	60	84	81	51b	90b	70c	179	0a	0a	261	253b	183a
0.30	100	119	168	162	52b	15a	30ab	165	18b	1a	335	244b	223b
0.30	150	#	#	243	#	#	13a	#	#	33c	#	#	254b
0.45	0	0	0	#	138c	147c	#	182	0a	#	285	226a	#
0.45	50	60	84	81	70b	106b	95d	181	0a	0a	278	269b	208a
0.45	100	119	168	162	28a	9a	48b	207	8ab	0a	269	248b	242b
0.45	150	#	#	243	#	#	13a	#	#	55d	#	#	232b
0.60	0	0	0	#	137c	138c	#	164	0a	#	302	217a	#
0.60	50	60	84	81	71b	117b	72c	169	0a	0a	291	280b	185a
0.60	100	119	168	162	32a	36a	43b	193	30c	8b	287	253b	229b
0.60	150	#	#	243	#	#	23a	#	#	63d	#	#	234b
Analysis of variance													
Depth					ns	ns	ns	ns	ns	0.01	ns	ns	ns
Level					0.001	0.001	0.001	ns	0.05	0.001	ns	0.01	0.001
Interaction					ns	ns	ns	ns	ns	ns	ns	ns	ns

[a] Within a column, means followed by the same letter are not significantly different at $P \leq 0.05$ using Duncan's multiple range test
Treatment not included in study
ns Not significant

was applied during the following 2 years. In general, faba bean acquired 120–147 mm of water from the top 2.1 m of the soil profile when the crop was not irrigated, and less water from the soil profile as more irrigation was applied. Deep percolation losses were high in 1997/1998, ranging from 164 to 207 mm among treatments, due to heavy rainfall. Much less water percolated below the root zone the following 2 years even when irrigations were scheduled at 150% ET_c in 1999/2000. Overall, irrigation had no effect on crop water use in 1997/1998, but significantly increased water use in 1998/1999 and 1999/2000. When the crop was irrigated at 100% ET_c, water use averaged 297 mm in 1997/1998, 248 mm in 1998/1999, and 231 mm in 1999/2000. Differences in water use among seasons corresponded with the length of the growing season each year. Soil evaporation is also expected to be higher during years with high rainfall.

Soil water depletion and water use were not affected by drip lateral depth. Deep percolation, however, was significantly higher when drip laterals were located at 0.60 m than when they were located at 0.30 or 0.45 m in the treatment irrigated at 150% ET_c in 1999/2000 (Table 2).

Crop production

Irrigation had no effect on crop production in 1997/1998 (Fig. 2A, D, G). Husain et al. (1988b) similarly found that irrigation had little effect on faba bean growth in New Zealand when precipitation was adequate early in the growing season. In 1998/1999, however, rainfall was more limited than the previous year, and the beans grew poorly and showed visual signs of water stress (i.e., wilting and leaf necrosis) without irrigation (Fig. 2B, E, H). Stem and leaf growth in faba bean tends to be very sensitive to small declines in leaf turgor caused by even the slightest water shortage (Grashoff 1990; Grashoff and Verkerke 1991). Growth was also reduced in 1999/2000 when irrigations were scheduled at 50% ET_c (Fig. 2C, F, I). As mentioned above, the beans were planted earlier in 1999/2000 than the previous 2 years, and there was no rain until the end of the growing season (Fig. 1C).

Drip lateral placement had a significant effect on dry matter production in 1998/1999 and 1999/2000 (Fig. 2). During these years, well-watered plants irrigated with laterals located at 0.60 m were smaller than plants irrigated with laterals located at 0.30 or 0.45 m, particularly early in the growing season. At 0.60 m, the laterals were well below most of the root system during the first few months of the growing season (data not shown). Faba bean tends to have a shallow root system (Heeraman and Juma 1993). However, by the end of the season, each treatment had well-developed root systems in the top meter of soil, even in the treatments where the drip laterals were placed 0.60 m deep (Fig. 3). Not surprisingly, roots tended to be concentrated near the drip laterals regardless of depth. Breeding programs aimed at improving root system development during early growth (e.g., varieties bred for dry-land farming) may increase the feasibility of using deeper lateral placement for growing faba bean under irrigated conditions (Bond et al. 1994).

Water-use efficiency

Water-use efficiency based on dry matter production was expressed as the ratio of aboveground biomass at final

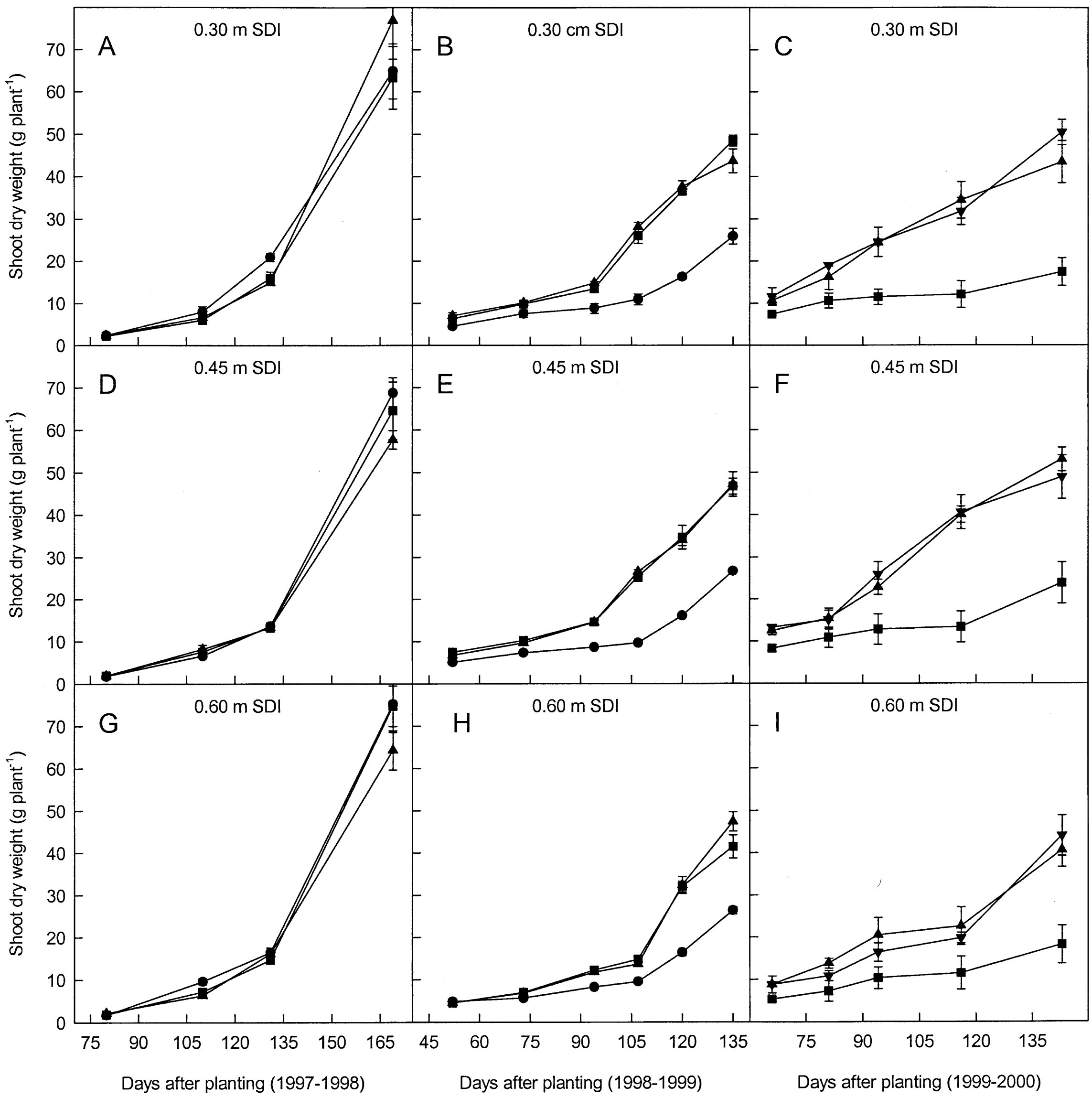

Fig. 2 Total aboveground biomass over time of faba bean grown during the 1997/1998 (**A**, **D**, **G**), 1998/1999 (**B**, **E**, **H**), and 1999/2000 (**C**, **F**, **I**) winter field seasons. Plants were irrigated each year at three different levels (*circles* 0% ET_c, *squares* 50% ET_c, *triangles* 100% ET_c, *inverted triangles* 150% ET_c) using subsurface drip irrigation (*SDI*) tubing installed 0.30 (**A**–**C**), 0.45 (**D**–**F**), or 0.60 (**G**–**I**) m deep. *Each symbol* represents the mean of four replicates per treatment and *error bars* represent one standard error

harvest to the total seasonal water use (Table 3). Irrigation significantly improved water-use efficiency in 1998/1999 and 1999/2000, but not in 1997/1998. Irrigation water-use efficiency was highest when plants were irrigated at 50% ET_c in 1998/1999 and at 100% ET_c in 1999/2000, but lower when drip laterals were located at 0.60 m than at 0.30 or 0.45 m (Table 3). At 0.60 m, laterals were too deep to supply water to the roots early in the season (as mentioned above) and deep percolation losses increased (Table 2). The water-use efficiency values reported in this study were similar to those reported for faba bean by others (ICARDA 1994; Loss et al. 1997).

Conclusions

Based on the data collected over 3 years, well-irrigated faba bean grown for winter cover crop used on average 231–297 mm of water for production. Irrigation improved production and crop water-use efficiency in 2 years of the study, but not the third. Evidence from the study indicates that farmers can reduce the need for irrigation by planting the crop later in the year when temperatures are cooler and winter rains are more reliable. In fact, with sufficient soil moisture available at the beginning of the season, it appears that the water requirements for growing faba bean can be adequately met by winter precipitation in central California, particularly when rainfall is above normal. However, if irrigation is required and subsurface drip is used, drip lateral depth is an important consideration. At our site, drip laterals located at 0.60 m were too deep to provide adequate moisture early when plants were small; plants grew

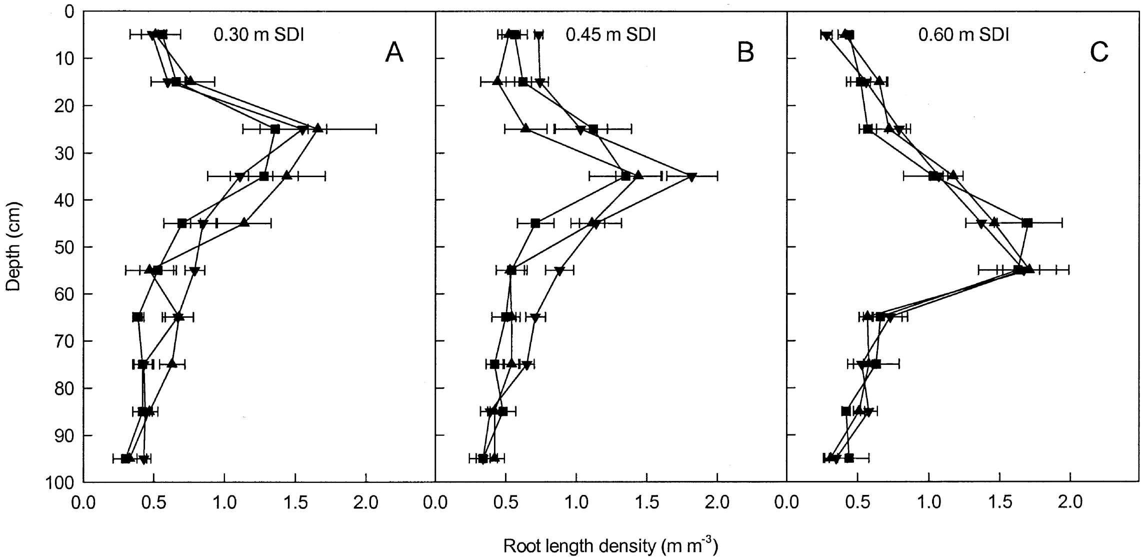

Fig. 3 Root length density as function of depth of faba bean grown during the 1999/2000 winter field season. Plants were irrigated at three different levels (*squares* 50% ET_c, *triangles* 100% ET_c, *inverted triangles* 150% ET_c) using subsurface drip irrigation (*SDI*) tubing installed 0.30 (**A**), 0.45 (**B**), or 0.60 (**C**) m deep. *Each symbol* represents the mean of four replicates per treatment and *error bars* represent one standard error

better when laterals were located at 0.30 or 0.45 m. Fortunately, most growers using subsurface drip for annual crop production in California tend to install drip laterals 0.25–0.30 m deep.

Analysis of nutrient composition of faba bean green material shows on average approximately 0.5 kg of nitrogen for every 100 kg of material turned under (Bond et al. 1985). Based on this rate, 152–218 kg N per hectare was produced each year of the study (in the highest yielding irrigation treatments) and incorporated into the soil. With proper irrigation, faba bean holds excellent promise as green forage, providing nitrogen for subsequently planted crops, as well as for improving organic matter content and tilth of the soil. Further study would be required to determine water requirements when growing faba bean for seed production in central California.

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Table 3 Water use efficiency of faba bean grown during the 1997/1998, 1998/1999 and 1999/2000 winter field seasons. The crop was irrigated each year at three different levels using subsurface drip irrigation (SDI) laterals installed 0.30, 0.45 or 0.60 m deep

Depth of SDI lines (m)	Irrigation level (% ET_c)	Water use efficiency[a] (kg m^{-3})			Irrigation water use efficiency[b] (kg m^{-3})		
		97/98	98/99	99/00	97/98	98/99	99/00
0.30	0	1.53	0.80a[c]	#	na	na	#
0.30	50	1.57	1.24c	0.62a	−0.68	1.71c	1.39c
0.30	100	1.56	1.16c	1.26bc	0.62	0.67a	1.73d
0.30	150	#	#	1.28bc	#	#	1.34c
0.45	0	1.56	0.76a	#	na	na	#
0.45	50	1.50	1.12bc	0.74a	−0.62	1.57c	1.90e
0.45	100	1.39	1.23c	1.41c	−0.72	0.80a	2.12f
0.45	150	#	#	1.36c	#	#	1.30b
0.60	0	1.61	0.78a	#	na	na	#
0.60	50	1.66	0.96b	0.64a	0.63	1.17b	1.46c
0.60	100	1.45	1.21c	1.14b	−0.32	0.81a	1.62d
0.60	150	#	#	1.21b	#	#	1.17a
Analysis of variance							
Depth		ns	ns	0.05	ns	0.01	0.01
Level		ns	0.001	0.001	ns	0.001	0.001
Interaction		ns	ns	ns	ns	0.05	0.05

[a] Calculated as the ratio of shoot dry mass produced to seasonal crop water use

[b] Calculated as the difference between biomass yields under irrigated and rain-fed conditions divided by the total amount of applied irrigation (Howell 2000); rain-fed yields during the 1999/2000 season was presumed to be zero

[c] Within a column, means followed by the same letter are not significantly different at $P \leq 0.05$ using Duncan's multiple range test

Treatment not included in study

na Not applicable

ns Not significant

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