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Yield determination in olive hedgerow orchards. I. Yield and profiles of yield components in north–south and east–west oriented hedgerows

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Abstract. A study of the vertical distribution of flowering and fruit set and of components of yield (fruit numbers, fruit size, and fruit oil content) was maintained for 2 years in N–S- and E–W-oriented olive hedgerows of comparable structure (row spacing 4 m, hedgerow height to 2.5 m, width *c.* 1 m) near Toledo, Spain (39.9°N). Mean yield of the N–S orchard was 1854 kg oil/ha without difference between sides or years. Yield of the E–W orchard was greater in 2006, producing 2290 kg/ha, but only 1840 kg/ha in 2007, the same as the N–S orchard. The S side of the E–W orchard yielded more (59%) than the N side in 2007. In both orchards and years, most fruit was produced at 1.0–2.0 m height and fruit density was the most influential component in these differences, reflecting more intense bud initiation in these upper layers. Other components that determined fruit number, fertile inflorescences, fruits per fertile inflorescence, and fruit drop were not significantly different between layers. Fruit characteristics depended on hedgerow position. In both N–S and E–W hedgerows, fruit high in the hedgerow was the largest, most mature, and with highest oil content. These differences were more marked in N–S than in E–W hedgerows. Fruit growth and development were concentrated from the middle of September until the end November. Oil content per fruit increased linearly during that period when 65% of final oil content was accumulated. Similar patterns were observed between sides. The results of yield and yield profiles are discussed in the general context of light interception. The results suggest the importance of hedgerow porosity, and distinct penetration patterns of direct-beam radiation through N–S and E–W hedgerows, as the basis for explanation of the high yield of the N side of E–W hedgerows.

Additional keywords: *Olea europaea* L., superintensive olive orchard, row orientation, yield profiles.

Introduction

Olive has been grown commercially for over 4000 years and until recently was largely restricted to the Mediterranean region where it was grown in low density orchards, often 100/ha or less, in areas of low rainfall (Connor and Fereres 2005). Under those conditions, trees were little, or not at all, limited by radiation and indeed few studies have reported interest or data on the relationship between productivity and irradiance. Exceptions are records of distribution of fruit production around the periphery of individual vase-shaped trees (Ortega-Nieto 1945; Acebedo *et al*. 2000), revealing more fruit and oil on upper and southern sides in these Northern Hemisphere observations. Production methods are now changing rapidly, however, both in the Mediterranean region and also in new areas where olive production is expanding, e.g. USA, South America, South Africa, and Australia. Requirements for new orchards are for early yield after planting, high yield when established, and mechanisation, especially for harvesting. The consequence is a shift in production strategy away from isolated, vase-pruned trees to dense, central-leader hedgerows grown with irrigation or fertigation.

The first experimental olive hedgerow orchard was planted in Italy (Morettini 1972) but commercial hedgerow orchards, also called super-high-density (714–1975 olive/ha), have been planted in Spain since the early 1990s. Commercial expansion now underway there and elsewhere is also experimental. Orchards have been planted at row spacings ranging from 8 to 3 m, with consequent effect on row heights that can be adequately illuminated for productivity and the machinery required to manage them. Some narrow-row plantings showed the importance of illumination as the productive part of the canopy moved upwards with tree growth. This is not surprising given that physiological studies have shown that leaf photosynthesis reaches a maximum at around 900 μmol/m^2.s photosynthetically active radiation (PAR), one-third of full sunlight (Bongi and Palliotti 1994), and that bud development and shoot growth, floral initiation and differentiation, inflorescence development, flowering and fruit-set, and fruit dry matter and oil content (Tombesi and Standardi 1977; Tombesi and Cartechini 1986; Tombesi *et al*. 1999) are also responsive to illumination.

While most hedgerows are planted north–south (N–S), there are situations where this is not possible and also there are

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apparently opportunities to manipulate row illumination to advantage. At high latitudes there is opportunity to increase interception and yield during autumn with E–W orientation, while studies in more temperate environments identify the possibility of reducing radiation load and water demand during hot summer afternoons with orientations trending W of N (Goodwin 2004), although there have been studies to the contrary (Christensen 1979; Khemira *et al*. 1993). Devyatov and Gorny (1978) reported greater yield of apples on E–W than on N–S hedgerows (16–35%) at latitudes of 53.8°N. These observations are consistent with measurements and model studies of interception by hedgerows of various orientations (Cain 1972; Jackson and Palmer 1972). Palmer (1989) concluded that effect of row orientation in radiation interception and distribution is more important in low latitude, tall hedgerows and small row spacing. So far there are no reports of row orientation effects in olive hedgerow orchards.

Wider-planted hedgerows have presented different challenges. There, tall trees are required to use available radiation and, whereas short trees can be harvested with modified grape harvesters, orchards of tall trees require larger, specialised harvesting machinery. Many combinations of height and row width are now in commercial practice but so far no design criteria have been formulated for any geographic region. Fortunately, additional requirements for commercial success of hedgerow orchards, *viz*. low vegetative vigour, high self compatibility, and consistent annual bearing, have limited the choice of cultivars used in hedgerow plantings around the world. Even so, possible combinations of structural, cultivar, and climatic possibilities are large and the search for optimum design requires systematic experimentation and evaluation.

Connor (2006) proposed a method to evaluate optimum canopy structure of hedgerow orchards in terms of combinations of row height, width, spacing, and orientation, which would maximise, not just interception of radiation, but also productivity for the solar environment of any location. The method extends the approach of an earlier study of illumination in apple orchards (Cain 1972). It calculates profiles of illumination on canopy walls and combines them with productive responses of individual cultivars to evaluate optimum structure. The objective of the present study is to develop experimental protocols and to provide data on cultivar response that can be used to evaluate the effect of canopy structure on productivity of olive hedgerows. For this, it presents a set of parameters to define hedgerow structure and a methodology to measure vertical profiles of yield-determining steps of shoot growth, flowering, fruit set, fruit retention, and fruit and oil yield on individual sides of hedgerow orchards. Data are presented here from two orchards of cv. Arbequina of comparable row structure but contrasting orientation over a 2-year period. A subsequent paper will analyse production profiles against canopy interception patterns to establish the nature of their responses in cv. Arbequina.

Materials and methods

Site

The experiment was established in central Spain in a commercial orchard near Carpio de Tajo, Toledo (39.9°N, 4.5°W; alt. 480 m). The climate is semi-arid with annual average rainfall and reference evapotranspiration (ETo) of 359 and 1180 mm, respectively. Summer rainfall is negligible. Average maximum and minimum daily temperatures are 23 and 9°C. During the course of the experiment, a weather station 5 km from the site registered wind speed and direction, rainfall, temperature, humidity, and global radiation every 30 min, and calculated ETo by the Penman-Monteith method (Allen *et al*. 1998) from these climatic variables.

The orchards were managed according to local agronomic practices. In winter, branches extending towards the centres of rows were eliminated and hedgerows were topped at 2.00 m height (hedgerow heights recorded here were measured in summer). Irrigation was applied by drip lines from May until end of September.

The orchards

Olive cv. Arbequina was planted in spring 1998 over 25 ha at a spacing of 4.0 by 1.5 m (1667 trees/ha), with rows orientated north–south, except for 1 ha that was planted 20°NE–SW. Orientations are referred to as N–S and E–W, respectively. The observations reported here were collected in 2006 and 2007, when trees were 8 and 9 years old, in 4 randomly selected blocks of 10 trees per orientation. The foliage architecture of 2 trees of average height and width was described in each block (control trees) on 11.vii.06 and 17.ix.07. For this, height of top and bottom foliage was measured in 9 positions per tree, above the trunk and at distances of 0.2, 0.4, 0.6, and 0.8 m on both faces. Hedgerow width was measured at 0.5, 1.0, 1.5, and 2 m height at 3 positions of the same trees, beside the trunk and at 0.4 m on each side.

Hedgerow external surface area and canopy volume were calculated for a rectangular shape. Hedgerow leaf area was estimated by measuring the diameter of all branches on all control trees and applying the regression:

$$\text{Leaf area}\,(\text{m}^2) = 0.0019x^{1.94} \quad (R^2 = 0.79^{**})$$

where x is branch diameter (mm), obtained on 15 branches at the site. Branch diameters were measured at the base (below the first leaf) and all leaves were removed and areas measured with a meter (Li-3100; Li-Cor, Lincoln, NE, USA). This then allowed further calculation of leaf area density and number of effective leaf layers horizontally through the canopy. On 05.x.2007, two digital photographs of each layer of control trees were taken against a red sheet suspended behind the hedgerow. Porosity (horizontal gap) of each layer was calculated using the digital analysis program Erdas Imagine version 9.1 (Leica Geosystems Geospatial Imaging, Georgia, USA).

Yield and its development

Phenological development was recorded during 2006 and 2007 as occurrence of the stages, mean budburst, bloom, end of fruit drop, pit hardening, and veraison.

Fruit growth was recorded during 2006 by sampling 100 olives at regular intervals from 13.ix.06 until 21.xi.06 (commercial harvest date) from each side of hedgerows in each block, but avoiding control trees. Olives were weighed and maturity index was determined based on colour of skin and pulp (Uceda and Frías

1975). Three subsamples of 25 g from each sample were weighed fresh and again after oven-drying at 105°C. Oil content was measured in dry subsamples by nuclear magnetic resonance (MiniSpec MQ-10; Bruker, Madison, WI, USA) using the method described by del Río and Romero (1999).

Final harvests were made on 09.xi.06 and 05.xi.07 when fruit was removed from 8 control trees separately from either side of the hedgerows. In 2006, harvest was made in 3 layers, 0.5–1.0, 1.0–1.5, and 1.5–2.0 m above ground. In 2007, trees were taller so an additional layer (>2 m) was harvested. There were few fruits below 0.5 m so harvests from the two sides of that layer were combined to complete total production from the hedgerows. Yield of each layer and side was weighed fresh on collection. Olive number, fresh and dry weight, maturity index, and oil content were determined on 3 subsamples of 25 g from each layer and side. Mean fruit characteristics of either side were calculated as weighted averages of layers. Fruit number per layer was calculated from total production and mean olive weight.

Additional data were collected in 2007 to define profiles of yield development. On 23.iii.07, three shoots were selected at random and tagged on each side on control trees at 0.75, 1.25, and 1.75 m, and shoot length and number of buds were measured. Later, in sequence, number of inflorescences per shoot was counted on 24.iv.07 and number of fruits per shoot on 29.vi.07 and 05.xi.07 (harvest). Total length of new shoots and number of buds were counted on 27.xii.07. These observations were used to calculate percentages of buds that developed an inflorescence, inflorescences that set fruit on at least one flower, mean number of fruits per inflorescence, and fruit drop between 29.vi.07 and harvest (05.xi.07).

Data were subjected to analysis of variance using MSTAT-C (University of Michigan, USA). Effect of layers and sides was analysed using a split-plot model. Before analysis, percentage data were transformed to a normal distribution by arc-sin square-root. Least significant differences ($P < 0.05$) were used to separate means of parameters evaluated between layers and sides of the hedgerows using Duncan's multiple range test.

Results

Environmental conditions

The weather data for the site are summarised in Fig. 1 as monthly means of relative humidity (%), absolute minimum and maximum temperatures (°C), and monthly totals of rainfall (mm) and evaporation (mm). During the experimental period, highest temperature was recorded on 4 August 2007 (41.2°C) and lowest on 28 January 2006 (–7.0°C). July was the hottest month, with mean temperature of 26.6 and 25.7°C in 2006 and 2007, respectively. Evaporative conditions remained strong throughout the experimental period, with a cumulative ETo of 1222 and 1166 mm from November until October for 2006 and 2007 seasons, respectively. The dryer year was 2006, with 323 mm rainfall from November 2005 until October 2006, which fell mainly in autumn. In 2007, total rainfall of 479 mm fell mainly in spring, whereas autumn that year was exceptionally dry.

Hedgerow geometric characteristics, leaf area, and horizontal porosity

Although generally comparable in structure, measurements reveal significant differences between hedgerows and between years. The N–S and E–W hedgerows were both taller and wider in 2007 than 2006 (Table 1). The N–S hedgerows grew more, increasing in external surface area by 32% compared with

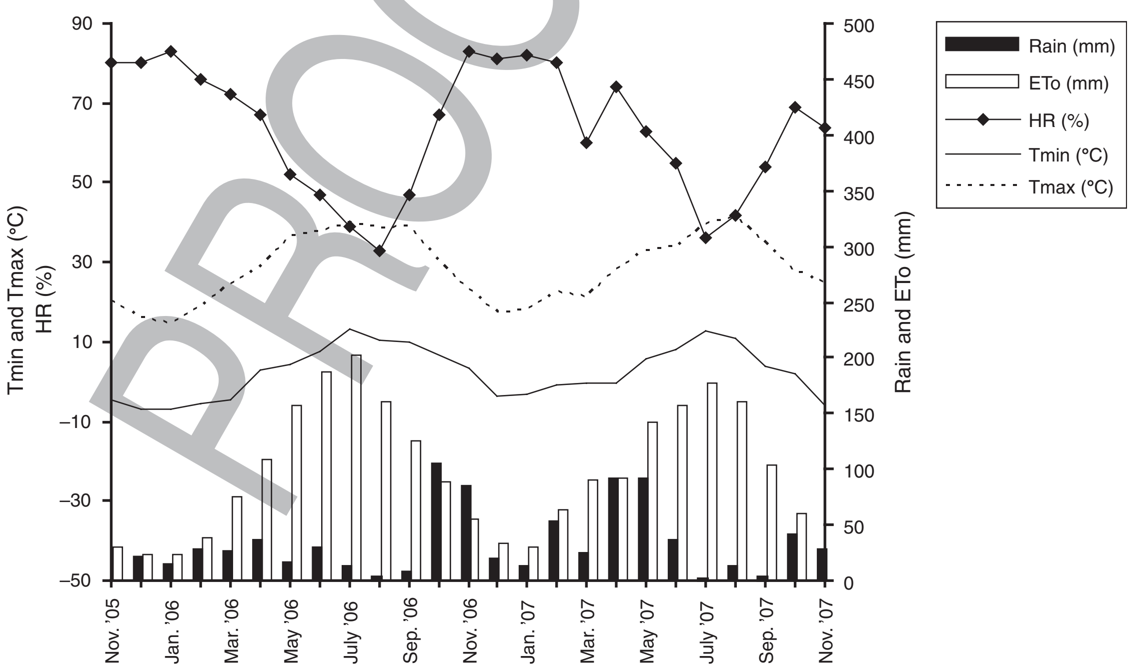

Fig. 1. Mean monthly relative humidity, absolute minimum and maximum temperature, and monthly rainfall and ETo from November 2005 to November 2007.

Table 1. Structure and leaf area characteristics of N–S and E–W olive hedgerows
Each point is a mean of 8 replicates ± standard error

Parameter	N–S 2006	N–S 2007	E–W 2006	E–W 2007
Top of hedgerow (m)	2.02 ± 0.02	2.43 ± 0.03	2.16 ± 0.05	2.46 ± 0.05
Base of canopy (m)	0.49 ± 0.02	0.40 ± 0.01	0.40 ± 0.02	0.40 ± 0.03
Hedgerow width (m)	0.71 ± 0.03	0.97 ± 0.04	0.97 ± 0.04	1.06 ± 0.04
Canopy depth/free alley	0.47 ± 0.01	0.67 ± 0.02	0.58 ± 0.02	0.70 ± 0.02
External surface area (m^2/m of hedgerow)	3.78 ± 0.07	5.02 ± 0.09	4.49 ± 0.09	5.19 ± 0.12
Canopy volume (m^3/m of hedgerow)	1.09 ± 0.06	1.97 ± 0.09	1.70 ± 0.08	2.18 ± 0.09
Leaf area (m^2/m of hedgerow)	4.02 ± 0.05	4.77 ± 0.22	4.26 ± 0.06	5.94 ± 0.42
Leaf area density (m^2/m^3)	3.77 ± 0.19	2.45 ± 0.14	2.54 ± 0.11	2.74 ± 0.20
Horizontal leaf layers (number)	2.63 ± 0.03	2.36 ± 0.11	2.43 ± 0.07	2.87 ± 0.17

16% in E–W. Hedgerows had 19 and 39% more leaf area in 2007 than 2006, for N–S and E–W, respectively. These differences in vegetative growth resulted in smaller leaf area density and fewer leaf layers in N–S hedgerows but increases in both parameters in E–W. The ratio of canopy depth/free alley width was greater in the E–W than in the N–S orchard and increased in both orchards in 2007.

Vertical distribution of horizontal porosity, measured in autumn 2007, was similar in both orchards (Table 2). Porosity was greater above 2 m (mean 37%) and in the small foliage layer below 0.5 m (mean 41%), but was not significantly different in the three intermediate (0.5–2.0 m) layers. Individual layers were not significantly different between N–S and E–W orchards, with average values of 15 and 18%, respectively.

Canopy walls were widest at 1.5 m height and narrowest at 0.5 m but essentially vertical with little width variation with canopy height (data not shown). The E–W hedgerow was wider than the N–S hedgerow in 2007, with mean values of 1.06 and 0.97 m (Table 1), respectively.

Table 2. Horizontal porosity of five canopy layers of N–S and E–W olive hedgerows in autumn 2007
Values with the same letter are not significantly different between hedgerows and layers by Duncan's test at $P < 0.05$. Values are means of 8 replicates

Layer (m)	N–S	E–W
>2.0	33.5a	40.3a
1.5–2.0	14.8b	18.2b
1.0–1.5	14.7b	16.0b
0.5–1.0	15.9b	20.2b
<0.5	39.0a	42.1a

Expressed per hectare, mean orchard characteristics were external surface area of 11527 m^2 and canopy volume of 4335 m^3.

Phenological development, vegetative growth, and reproductive components

In 2006, budburst occurred on 10.iii, bloom on 19.v, final fruit drop on 18.vi, and pit hardening on 15.vii. The crop was harvested before veraison. In 2007, budburst occurred on 16.iii, bloom on 28.v, final fruit drop on 29.vi, pit hardening on 20.vii, and veraison on 01.xi.

Observations on shoot growth and bud development on 1-year stems are presented in Tables 3 and 4. In 2007, mean shoot growth and number of buds were 6.4 and 5.6 cm and 13 and 10 in N–S and E–W orchards, respectively. Shoot growth and bud development were compared between layers and hedgerow sides. There were no differences in either parameter between layers or sides in the E–W orchard, but some differences were observed in both parameters between layers, but not between sides, in the N–S orchard. In that orchard, shoots grew more in the lower (0.5–1.0 m) than in the higher layers on both sides.

Total fruit number depends on buds that developed inflorescences (% buds initiated), inflorescences with at least one fruit (% fertile inflorescence), fruits/fertile inflorescence, and fruit drop. Overall in this experiment, 63 and 57% of winter buds developed an inflorescence, of these 53 and 52% set fruit with means of 1.3 and 1.1 fruits, but 29 and 32% of fruits dropped before harvest in N–S and E–W orchards, respectively. These productive components are compared between layers and sides (Tables 3 and 4). Significant differences between layers and sides were only observed in buds initiated. Highest values were

Table 3. Shoot growth (cm) and buds developed (number) on 1-year-old stems, percentage of winter buds that developed an inflorescence (buds initiated), percentage of inflorescences that developed one or more fruits (fertile inflorescence), number of fruits per fertile inflorescence, and percentage of fruit dropped during 2007 on three layers on both sides of N–S olive hedgerows
Values with the same letter are not significantly different between sides and layers of the hedgerow by Duncan's test at $P < 0.05$. Values are means of 8 replicates

Layer	Shoot growth		Buds developed		Buds initiated		Fertile inflorescence		Fruits per fertile inflorescence		Fruit drop	
	E	W	E	W	E	W	E	W	E	W	E	W
1.5–2.0	7.0ab	3.6b	15.6ab	10.2bc	59.5ab	71.2a	60.8	49.8	1.2	1.3	38.6	32.7
1.0–1.5	5.7b	3.9b	11.9abc	9.8c	64.1a	66.2a	50.8	46.4	1.2	1.3	28.1	33.9
0.5–1.0	10.6a	7.6ab	17.1a	15.1abc	49.2b	64.8a	60.7	49.1	1.2	1.4	24.0	18.1

Table 4. Shoot growth (cm) and buds developed (number) on 1-year-old stems, percentage of winter buds that developed an inflorescence (buds initiated), percentage of inflorescences that developed one or more fruits (fertile inflorescence), number of fruits per fertile inflorescence, and percentage of fruit dropped during 2007 on three layers on both sides of E–W olive hedgerows

Values with the same letter are not significantly different between sides and layers of the hedgerow by Duncan's test at $P < 0.05$. Values are means of 8 replicates

Layer	Shoot growth		Buds developed		Buds initiated		Fertile inflorescence		Fruits per fertile inflorescence		Fruit drop	
	N	S	N	S	N	S	N	S	N	S	N	S
1.5–2.0	5.1	3.1	7.0	7.9	63.3ab	67.2a	55.5	53.0	1.2	1.1	41.2	33.7
1.0–1.5	4.8	6.8	8.9	13.9	64.8a	58.3ab	52.2	50.0	1.2	1.0	34.9	23.3
0.5–1.0	6.7	6.2	12.1	10.2	44.2bc	40.9c	57.3	40.7	1.2	0.9	29.3	32.2

obtained in layers above 1 m but no significant differences were observed between sides of individual layers except in the lowest layer of the N–S orchard. There, more buds were initiated on the west (W) than east (E) side.

Fruit growth and development

Olive weight and oil content were determined for each layer of both orchards from 13.ix.06 until 21.xi.06, the commercial harvest date (Figs 2, 3). Olive weight increased only until 9.xi and was then maintained in both orchards and sides of hedgerows. Olives on south (S) sides in the E–W orchard were larger than on other sides of either hedgerow. In contrast, oil content increased linearly in both orchards during this period and 65% of final oil content was accumulated. Oil content (g/fruit) of the W side of the N–S orchard was lower than of all other sides of both N–S and E–W hedgerows.

There were few significant differences between sides of the orchards during the course of fruit development. Results reveal essentially similar patterns of growth and oil accumulation.

Fruit characteristics and distribution at harvest

Fruit characteristics of size (fresh and dry weight), oil content (g), and maturity index collected from all layers of both orchards are presented in Tables 5 and 6. Four layers were measured in 2006 and a fifth layer (>2 m) was added to account for hedgerow growth in 2007. Olives were harvested green (average maturity index MI = 1.0) in 2006 and nearly black (average MI = 3.0) in 2007. In 2006, olives were bigger (fresh weight) and less mature than in 2007. Olive dry weight was similar in the N–S between years, but in the E–W it was 13% greater in 2007 than 2006. Water content was greater in 2006 (mean 64%) than in 2007 (47%). Consequently, oil content per fruit in N–S was 6% greater in 2006 than in 2007 and it was 12% lower in the E–W hedgerow. Olives in the E–W hedgerow contained 14% more oil than in the N–S.

Overall, significant differences were observed between sides in the E–W but not in the N–S orchard. Oil content per fruit (g) was significantly greater on the S than the N side in both years (mean value of 6% greater). Fruit fresh and dry weight was significantly greater on the S side in 2007, mainly due to differences in the upper layers.

Significant differences were observed between layers of individual sides in the N–S and E–W orchards in 2006. Maturity, size, and oil content were greater for the upper layers. Oil content increased by 28 and 49% from the lower to the upper layers in both N–S and E–W orchards, respectively.

Olive and oil yield and distribution

Yield components (fruit density, fruit size, and oil content per dry weight) of productivity, and their distribution between hedgerow sides and layers are presented in Tables 7 and 8.

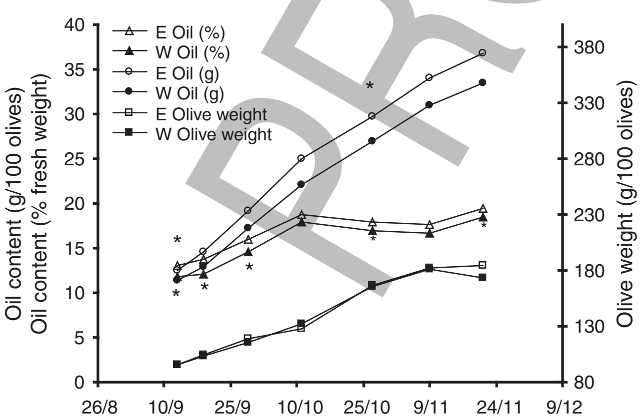

Fig. 2. Evolution of olive fresh weight and oil content by weight and % fresh weight, on both sides of a N–S olive hedgerow orchard in 2006. *Significant differences at $P < 0.05$. Values are means of 4 replicates.

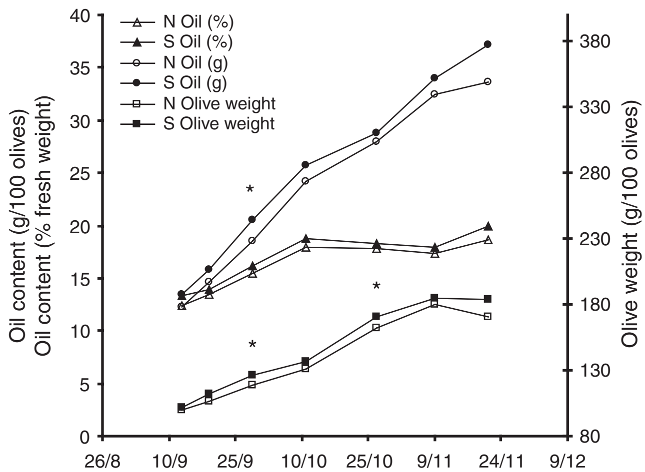

Fig. 3. Evolution of olive fresh weight and oil content by weight and % fresh weight, on both sides of an E–W olive hedgerow orchard in 2006. *Significant differences at $P < 0.05$. Values are means of 4 replicates.

Table 5. Fruit characteristics in four or five layers of fresh and dry weight (g/100 olives), oil content (g/100 olives), and maturity index of olives on both sides of a N–S hedgerow olive orchard in 2006 and 2007

Values with the same letter are not significantly different between sides and layers of the hedgerow by Duncan's test at $P < 0.05$. n.s., Non-significant differences between sides at $P < 0.05$. Values are means of 8 replicates

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Year	Layer	Fresh weight		Dry weight		Oil content		Maturity index	
		E	W	E	W	E	W	E	W
2006	1.5–2.0	176a	174ab	68.0a	66.3a	33.9a	32.6b	1.20a	1.10a
	1.0–1.5	163c	169b	59.2b	60.4b	28.6c	28.5c	0.83b	0.83b
	0.5–1.0	159cd	161cd	54.5c	55.7c	25.2d	24.8e	0.64bc	0.48c
	<0.5 m	156d		53.3c		23.7f		0.23d	
	Average	166	168n.s.	60.3	60.6n.s.	29.1	28.4n.s.	0.87	0.79n.s.
		167		60.5		28.8		0.84	
2007	>2.0	125a	120b	71.0a	67.4b	35.1a	32.4b	3.93a	3.59ab
	1.5–2.0	120b	118b	66.9b	64.9b	31.6c	30.2d	3.39b	2.93c
	1.0–1.5	105cd	109c	57.2c	58.2c	25.7f	26.4e	2.83c	2.60c
	0.5–1.0	101de	101de	53.4d	52.8d	23.5g	22.0h	2.48c	1.86d
	<0.5 m	98e		50.5d		21.5i		1.84d	
	Average	110	111n.s.	60.1	59.3n.s.	27.5	26.7n.s.	2.96	2.52n.s.
		110		59.7		27.1		2.74	

Table 6. Fruit characteristics in four or five layers of fresh and dry weight (g/100 olives), oil content (g/100 olives), and maturity index of olives on both sides of an E–W hedgerow olive orchard in 2006 and 2007

Values with the same letter are not significantly different between sides and layers of the hedgerow by Duncan's test at $P < 0.05$. n.s., Non-significant or * significant differences between sides at $P < 0.05$. Values are means of 8 replicates

Year	Layer	Fresh weight		Dry weight		Oil content		Maturity index	
		N	S	N	S	N	S	N	S
2006	1.5–2.0	174a	178a	65.1b	67.7a	31.8b	33.7a	1.25b	1.48a
	1.0–1.5	170ab	172ab	60.9d	63.0c	29.0d	30.8c	1.14bc	1.25b
	0.5–1.0	164b	166b	57.7g	59.3e	26.8f	28.3e	0.90d	0.96cd
	<0.5 m	176a		58.5f		26.7g		0.79d	
	Average	170	172n.s.	61.6	63.2n.s.	29.5	30.9*	1.13	1.24n.s.
		171		62.3		30.1		1.18	
2007	>2.0	138bcd	152a	73.5b	79.0a	38.6ab	41.6a	4.30a	4.13a
	1.5–2.0	138bcd	145ab	71.4bc	75.0ab	35.3bc	37.1b	3.35b	3.37b
	1.0–1.5	131cd	140bc	65.8de	70.2bcd	31.6de	33.6cd	3.07b	3.13b
	0.5–1.0	130d	136cd	63.5e	67.8cde	29.7e	32.0cde	3.05b	3.13b
	<0.5 m	132cd		64.2e		30.0e		2.98b	
	Average	134	141*	67.7	71.7*	32.9	35.0*	3.18	3.29n.s.
		138		70.2		34.2		3.25	

Olive dry matter yield was greater in the N–S orchard in 2007 than in 2006, but yields were reversed in the E–W. For N–S, yield was 1560 and 1656 g/m hedgerow, in 2006 and 2007, respectively. Comparative values for E–W were 1910 and 1517 g/m. These values correspond to 3.90, 4.14, 4.78, and 3.79 t/ha of dry matter yield. In contrast, oil yield was similar in both years in the N–S orchard, 740 and 748 g/m hedgerow for 2006 and 2007, respectively, whereas in E–W hedgerows, yield in 2006 (921 g/m) exceeded that in 2007 (736 g/m). Again, expressed per orchard area, these yields of 1850, 1870, 2303, and 1840 kg oil/ha, respectively, are creditable for local conditions. The greatest oil and fresh and dry matter production was achieved in 2006 in the E–W orchard. At orchard level, the major contributor to variation in yield is found in fruit density (fruits/m hedgerow). This is especially evident in the E–W where the high yield of 2006 was obtained with 43% more fruit than in 2007. By comparison, fruit density was reversed between years in the N–S orchard, with 7% more fruit in 2007 than 2006.

There were no differences in productivity, or its components, between sides of the N–S orchard in either year, except oil content (% dry weight) in 2006 when fruit contained significantly more oil per dry weight on E than on W sides. In the E–W orchard, however, while sides performed similarly in 2006, there were differences in fruit number, dry weight, and oil yield in 2007. Perhaps high temperature (36.6°C) recorded on 17.v.06 with low relative humidity (17%), 2 days before mean full bloom, could explain fewer fruits on the exposed S face. In 2007, oil yield of the S side was 59% greater than of the N side, due to contributions mainly from greater fruit density (50%). Oil

Table 7. Distribution in four or five layers of fruit density (number/m of hedgerow), oil content (% of dry weight), dry olive weight (g/m of hedgerow), and oil content (g/m of hedgerow) on both sides of a N–S olive hedgerow in 2006 and 2007

Values with the same letter are not significantly different between sides and layers of the hedgerow by Duncan's test at $P < 0.05$. n.s., Non-significant or * significant differences between sides at $P < 0.05$. Values are means of 8 replicates

Year	Layer	Fruit density		Oil content		Dry olive weight		Oil	
		E	W	E	W	E	W	E	W
2006	1.5–2.0	363d	330f	49.9a	49.2b	244ab	213abc	122ab	105ab
	1.0–1.5	496a	402c	48.3c	47.2d	288a	243ab	139a	115ab
	0.5–1.0	434b	351e	46.2e	44.4f	239ab	191bc	111ab	85bc
	<0.5 m	270g		44.5f		142c		63c	
	Total or average	1428	1218n.s.	48.1	46.8*	842	718n.s.	404	336n.s.
		2646		47.5		1560		740	
2007	>2.0	64de	41e	49.3a	48.0b	45d	28d	22d	14d
	1.5–2.0	492a	460ab	47.2c	46.6d	328a	297ab	154a	138a
	1.0–1.5	473ab	434abc	44.9f	45.3e	260b	251b	116b	114b
	0.5–1.0	371bc	337c	43.9g	41.6i	194c	174c	85c	72c
	<0.5 m	164d		42.5h		79d		33d	
	Total or average	1482	1354n.s.	45.5	44.8n.s.	867	789n.s.	394	354n.s.
		2836		45.2		1656		748	

Table 8. Distribution in four or five layers of fruit density (number/m of hedgerow), oil content (% of dry weight), dry olive weight (g/m of hedgerow), and oil content (g/m of hedgerow) on both sides of an E–W olive hedgerow in 2006 and 2007

Values with the same letter are not significantly different between sides and layers of the hedgerow by Duncan's test at $P < 0.05$. n.s. Non-significant or * significant differences between sides at $P < 0.05$. Values for layers are means of 8 replicates

Year	Layer	Fruit density		Oil content		Dry olive weight		Oil	
		N	S	N	S	N	S	N	S
2006	1.5–2.0	585ab	407bcd	48.9b	49.7a	374a	272abc	183a	135abc
	1.0–1.5	650a	516abc	47.7c	48.9b	390a	322ab	186a	158ab
	0.5–1.0	397bcd	307cd	46.5d	47.7c	224bcd	178cd	104bcd	86cd
	<0.5 m	256d		45.6e		150d		6d	
	Total or average	1760	1358n.s.	47.8	48.8n.s.	1063	847n.s.	508	413n.s.
		3118		48.3		1910		921	
2007	>2.0	71e	130de	52.3b	52.5a	49d	103cd	25d	54cd
	1.5–2.0	305bc	437ab	49.3c	49.3c	219b	327a	107b	161a
	1.0–1.5	342abc	473a	47.9d	47.7e	220b	320a	105b	152a
	0.5–1.0	124de	240cd	46.6g	47.1f	78cd	159bc	37cd	75bc
	<0.5 m	65e		46.6g		42d		20d	
	Total or average	875	1312*	48.4	48.6n.s.	587	930*	284	452*
		2187		48.5		1517		736	

content (g) and olive dry weight (Table 6) were only 6% greater. Oil content (% dry weight) was not significantly different between N and S sides (Table 8).

Both orchards showed differences in performance between layers. Comparing layers of individual sides it was observed that both top (>2.0 m) and base layers had the lowest yield in 2007. In both orchards and years, highest yield was produced in layers 1.0–1.5 m and 1.5–2.0 m. In the N–S orchard with its similar yield and side performance in both years, some compensating differences between layers of individual sides were evident. Thus, in 2006, differences in fruit number were insufficient to overcome the similarity in fruit size and oil content (g and % dry weight) (Tables 5, 7), so oil production was not significantly different between layers (Table 7). The most important differences were detected between second (0.5–1.0 m) and third (1.0–1.5 m) layers. The former produced 23 and 32% less oil than the latter in 2006 and 2007, respectively. Again, fruit density was the most influential component.

Differences were more marked in the E–W orchard, with greater differences between layers on individual sides. The 0.5–1.0 m layer produced 45 and 58% less oil than the upper layer in 2006 and 2007, respectively. Fruit density was again the most influential component of yield. In 2006 there was 39% less fruit on both sides; in 2007, fruit density was reduced by 64 and 49% on N and S sides, respectively.

Discussion

Selection of cv. Arbequina for hedgerow orchards has been made on the basis of self compatibility, low vegetative vigour, early harvest, high yield, and small tendency for alternating yield (Barranco *et al.* 2005). High and consistent yields in 2 successive years in 10-year-old orchards studied here are consistent with those characteristics. Yields were between 1850 and 2303 kg oil/ha in both years without evidence of alternating production (Tables 7, 8), while vegetative growth (6 cm/shoot) was surprisingly low (Tables 3, 4).

Differences in climatic conditions between the 2 years (Fig. 1) modified the morphology of the hedgerows and affected reproductive development. Compared with 2006, good spring rainfall in 2007 promoted growth so that hedgerows of both orchards were taller, wider, and with more leaf area than in 2006 (Table 1). The ratio of canopy depth to free alley width that determines penetration of radiation to lower canopy layers increased from 0.47 to 0.67 (42%) in the N–S and from 0.58 to 0.70 (21%) in the E–W. Despite this increase, values remained less than those used to characterise adequate illumination of lower layers of vineyards (= 1, Smart and Robinson 1991) or cherry hedgerows (= 2, Flore *et al*. 1996). This index is so far untested in olive hedgerows. In contrast, the dryer and warmer spring of 2006 hastened development so that while pit hardening was more advanced than in 2007, a subsequent cool autumn associated with rainfall slowed development and delayed veraison so that olives were harvested green in 2006 compared with nearly black in 2007. In 2006, olives were bigger, less mature, and with greater water and lower oil content than in 2007 (Tables 5, 6).

The present discussion seeks a general analysis of yield response to orchard structure and orientation. A detailed analysis of the relationship of yield components to the radiation regime within the hedgerows will be included with data from other hedgerows in a subsequent paper (Connor *et al*. 2009, this issue).

In the N–S orchard there was no difference in oil yield between years, nor was there any difference between yields of the two sides (Table 7). This is consistent with equality of radiation incident on either face during the course of each day and the fact that the orchard was well irrigated. Irrigation has the effect of minimising a potentially major difference between microenvironment on opposing faces, *viz*. higher temperature that the W face experiences when intercepting equivalent solar radiation during the afternoon. Analysis of profiles of yield components reveals differences that are subjectively consistent with patterns of canopy illumination (Tables 5, 7). Fruit density, fruit dry matter, and fruit oil content, although not fruit density in the sparse layer above 2 m, all decreased with depth in canopy. In this, the greatest effect was in fruit density. Phenological data reveal that differences in bud initiation were the primary determinant of fruit number because there were no differences in fruit set or fruit drop (Tables 3, 4). Tombesi and Standardi (1977) and Tombesi and Cartechini (1986) have previously reported greater sensitivity of bud initiation to low radiation compared with vegetative growth, fruit set, size, and oil content. In those studies, influence of illumination on bud initiation was greater when shading occurred between July and October. Overall, however, there were sufficient compensating responses among yield components in 2006 to obviate a significant profile in oil yield per layer. In 2007, when harvest was made of mature fruit, and hedgerow was taller and wider (Table 1), more distinct profiles of yield components contributed to a distinctly declining profile of oil yield per layer.

The E–W orchard experiences a completely distinct radiation environment. Only the S face receives direct radiation except for short periods in the early morning and late afternoon during summer when the beam radiation reaches the N face. The N face is thus dependent upon diffuse radiation from the sky, reflected radiation from the adjacent sunlit hedgerow, and radiation that penetrates through from the sunlit side. At the latitude of this experiment, the S face of an E–W orchard receives greater illumination than either face of a N–S orchard from September to April, with the difference increasing for this orchard structure to a maximum of 164% in December–January (calculated from Connor 2006). The large yield of the sunlit S side of the E–W orchard is, therefore, consistent with the strong radiation regime, during the period of major oil accumulation (Figs 2, 3). What cannot be explained by incident radiation, however, is the large yield of the N side in both years, even though it was, more expectedly, out-yielded by the S side in 2007. The data collected here suggest that an explanation of yield performance based on radiation must also pay attention to transmission through the canopy to the usually shaded N face. Since transmission of radiation through individual olive leaves is low (Bongi and Palliotti 1994), transmission through the canopy will mainly depend on leaf arrangement and the distribution of gaps. Light penetration also occurs within N–S hedgerows, but with two differences. First, penetration is symmetrical so both faces are illuminated equally. Second, the path length is longer in N–S hedgerows so penetration through to the shaded side is less. The major difference is seen in late autumn to early spring months when the S face of E–W hedgerows is illuminated at large angles of incidence during the central part of the day. Comparable angles of incidence and short path lengths are only achieved in N–S hedgerows for short periods during early morning and late afternoon when solar irradiance is low.

In contrast to some studies with different fruit trees discussed earlier, the present data do not support the proposition that light interception and distribution are the major factors that determine yield of individual hedgerow faces or layers. Other factors such as weather conditions and sink strength must be considered. For example, high temperature during bloom in 2006 could have reduced fruit-set on the S relative to the N side of the E–W hedgerow (Table 8). Further, low radiation during the rainy autumn of 2006 (Fig. 1), the period of oil synthesis, would minimise differences in interception between individual faces and orientations. Finally the assumption inherent in the present analysis that each layer is an independent productive unit relying for productivity on its own photosynthesis is only a first approximation. In olive, Proietti and Tombesi (1996) report that shoot growth and bud differentiation are highly dependent on assimilate provided by individual shoots, but fruit on poorly illuminated shoots can attract assimilates from nearby shoots. Such responses may have operated in this study, especially in E–W hedgerows.

This study has established general features of yield determination in olive orchards of distinct orientation and its relationship to interception of solar radiation. That yield on either side of the N–S orchard was equal in both years is consistent with equal receipt of solar radiation. Likewise the greater yield of the S side of the E–W orchard that was achieved in 2007 is consistent with greater radiation receipt, but that response was not repeated in the previous year. Evidence suggests that these two orchards are well illuminated to depth in the canopy because the free alley width is large (Smart and Robinson 1991; Flore *et al*. 1996) relative to canopy height and the relatively porous canopies allow transmission of solar radiation through to the shaded face. The latter effect is more important in E–W orchards because the geometrical relationship with the solar trace presents a small path length through the hedgerow during the fruit growth and oil formation period of autumn. In hedgerows generally, it is obvious that yield performance is the sum of contributions from canopy layers and that orchard structure (canopy height *v.* free alley width) will determine illumination patterns and hence yield performance. Data from more orchards of different structure and latitudinal locations, including densely planted orchards, are required to resolve these issues. Data from this detailed experiment and fragmentary data from other studies will be used to investigate relationships between yield and solar radiation in the second paper (Connor *et al*. 2009, this issue).

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