Available online at www.sciencedirect.com
SCIENCE DIRECT®
Europ. J. Agronomy 24 (2006) 296–303
European Journal of Agronomy
www.elsevier.com/locate/eja

Modelling potential growth and yield of olive (*Olea europaea* L.) canopies

F.J. Villalobos[a,b,*], L. Testi[a], J. Hidalgo[d], M. Pastor[c], F. Orgaz[a]

[a] *Instituto de Agricultura Sostenible, CSIC. Apdo. 4084, 14080 Cordoba, Spain*
[b] *Dep. Agronomia, Universidad de Cordoba, Apdo. 3048, 14080 Cordoba, Spain*
[c] *IFAPA, Consejería de Innovación, Ciencia y Empresa. Junta de Andalucia, Apdo. 3092, 14080 Cordoba, Spain*
[d] *Servicio de Asesoramiento de Riegos, Caja Rural de Jaen, Paseo de la Estación, 23007 Jaen, Spain*

Received 3 February 2005; received in revised form 28 September 2005; accepted 31 October 2005

Abstract

The wide variability and complexity of olive orchards makes it difficult to provide solutions to the numerous management questions using a pure experimental approach. In this paper we calibrate and validate a simple model of olive orchard productivity based on the Radiation-Use Efficiency (RUE) concept of Monteith. A calibration experiment was performed in Cordoba from 1998 to 2001 with drip-irrigated olive trees cv. 'Arbequina'. Destructive samples of 18 trees and non-destructive measurements on 80 trees were used to determine RUE and dry matter partitioning coefficients. Validation experiments were performed in 18 drip-irrigated orchards of seven locations in Southern Spain, including two cultivars ('Arbequina' and 'Picual'). Average RUE was 0.86 g dry matter (MJ PAR)$^{-1}$ which is equivalent to 1.56 g glucose (MJ PAR)$^{-1}$. Aboveground accumulated biomass was allocated equally to fruits and vegetative growth, which in turn was partitioned into 30% for leaves and 70% for stems, branches and trunk. The fraction of oil in fruits was 0.38 which implies that the average ratio oil yield/intercepted PAR, which is an equivalent RUE for oil production (ε_o), is 0.17 g oil (MJ PAR)$^{-1}$. The prediction of oil yield as the product of 0.17 and total intercepted PAR was tested successfully in the validation experiments (relative RMSE = 0.26). Errors of this simple model were partly due to alternate bearing and partly to a decrease in ε_o as canopy size increases, which deserves further research. The concept of ε_o may be also useful for the evaluation of alternate bearing in olive trees.

Estimated potential carbon sequestration by intensive irrigated olive orchards in Southern Spain was 7 t CO_2 ha^{-1} year^{-1} which is much higher than that of other agricultural systems in Europe.

The simple model of growth and yield presented herein is the core of a complete model of olive growth and yield and may be useful not only for evaluating productivity at different scales but also for solving different management problems (nutrient requirements, plant protection, etc.)
© 2005 Elsevier B.V. All rights reserved.

Keywords: Radiation-Use Efficiency; PAR; Radiation interception; Carbon sequestration

1. Introduction

Olive (*Olea europaea* L.) trees are grown all over the Mediterranean basin, with around 9.5 million ha. Spain is the largest olive oil producer (2.4 million ha and more than 1 million t oil) (Civantos, 2004) with areas like the Jaen province where more than 90% of the agricultural area is dedicated to olive production. Olive cropping systems, which include agroforestry stands, traditional groves and new intensive orchards, are therefore of enormous importance in both economic and ecological aspects. Despite their relevance, eco-physiological information on olive orchards is scarce, partly due to the traditional low investment in research in the main producing countries and partly to the diversity and complexity of these systems.

Several major technological changes have occurred in the olive industry during the past two decades. The traditional rain fed orchard with low density (less than 100 olive trees/ha), intensive tillage, low inputs in fertilizer and pesticides and manual harvest is being substituted by new intensive (200–400 olive trees/ha) drip-irrigated plantations, with reduced tillage, high inputs and mechanical harvesting. This transition has caused a major increase in productivity from less than 1 to more than 2 t ha^{-1} of oil and generated a large number of questions for optimizing the management of olive orchards in relation to irrigation, fertilization and prunning. The classical experimental approach is inefficient and expensive in this case, due to the large variability in environmental conditions and orchard characteristics and to the perennial nature of the species. A possible alternative is

* Corresponding author. Tel.: +34 957 499232; fax: +34 957 499252.
E-mail address: ag1vimaf@uco.es (F.J. Villalobos).

1161-0301/$ – see front matter © 2005 Elsevier B.V. All rights reserved.
doi:10.1016/j.eja.2005.10.008

the development and use of a crop simulation model which, in combination with experimental work, allows the evaluation of responses of crop growth and yield to changes in management and environmental factors. This type of tool has been widely used in field crops (e.g. Ceres-Maize; Jones and Kiniry, 1986) and much less in forest (e.g. Hunt et al., 1991) and fruit trees (Grossman and DeJong, 1994).

The central element of most crop models is the simulation of biomass accumulation which usually follows the proposal of Monteith (1977) of the concept of Radiation-Use Efficiency (RUE) which is the ratio of biomass accumulation and radiation interception (a function of leaf area). Then biomass is allocated to the different plant organs using fixed or dynamic partitioning coefficients.

Other key components of crop models include water balance, nitrogen balance, phenology and responses of growth to water or N stress.

In the case of olive the only evaluation of RUE and partitioning has been the work of Mariscal et al. (2000b) with young trees before the onset of flower production. Other model components have been developed. The water balance of olive orchards has been the subject of much research. Olive transpiration has been studied by Villalobos et al. (2000) and Testi et al. (2004, 2006). Direct evaporation from the soil surface may be a significant fraction of total evapotranspiration and may be predicted following Bonachela et al. (1999) for rainfed orchards and Bonachela et al. (2001) for drip-irrigated plantations.

Simulation of phenological development of olive orchards may be performed using the model of Melo-Abreu et al. (2004) for flowering.

The objectives of this work were (a) to develop a simple model of potential growth and yield for olive orchards and (b) to test the model for yield prediction.

2. Materials and methods

2.1. Model description

Oil yield ($\mathrm{g\,m^{-2}}$) may be calculated as:

$$Y = R_{sp} Q_e \,\varepsilon\, \mathrm{HI}\, F_o \quad (1)$$

where R_{sp} is the annual incoming PAR ($\mathrm{MJ\,m^{-2}}$), Q_e the fraction of PAR intercepted by the canopy, ε the Radiation-Use Efficiency for above ground biomass production ($\mathrm{g\,MJ^{-1}}$), HI the Harvest Index (ratio of fruit yield and total biomass) and F_o is the fraction of oil in fruit dry matter.

This equation might be simplified to the following:

$$Y = R_{sp} Q_e \varepsilon_o \quad (2)$$

where ε_o is the equivalent RUE for oil production, that is, the amount of oil produced per unit of intercepted PAR.

2.2. Calibration experiment

The experiment was performed from 1997 to 2001 on a 4 ha flat uniform olive orchard (cv. "Arbequino") located in the Agricultural Research Center of Cordoba, Spain (37.85°N, 4.8°W, altitude 110 m). The climate in the area is typically Mediterranean, with rainfall concentrated from autumn to spring (Table 1), and an average annual reference evapotranspiration ($\mathrm{ET_0}$) of around 1400 mm. The orchard was planted in summer 1997 with a 3.5 m × 7 m spacing (408 olive trees/ha), which is typical for modern intensive plantations in this zone. The orchard was drip irrigated, without water restrictions: the amount of irrigation applied ranged from 4 to 6 mm per week (applied from 9 June to 16 October) in 1998, from 4.5 to 8 mm per week (applied from 3 March to 15 October) in 1999 and from 6.5 to 10 mm per week from April to October in 2000 and 2001. The irrigation system consisted of two emitters per tree with a flow rate of $4\,\mathrm{l\,h^{-1}}$. The fraction of soil wetted by the irrigation drippers varied from 7 to 14% depending on the amount of irrigation applied. Weed control was performed using herbicides. The soil is classified as Typic Xerofluvent of sandy-loam texture, with upper drained limit soil water content of $0.23\,\mathrm{m^3\,m^{-3}}$ and lower limit soil water content of $0.07\,\mathrm{m^3\,m^{-3}}$ (Testi et al., 2004).

Ten subplots of eight trees (two lines of four trees each) were marked within the orchard for non-destructive measurements such as fruit yield, trunk diameter at 0.3 m height, canopy dimensions (diameters in the *x*, normal to the row, *y*- and *z*-directions) and Leaf Area Density (LAD), i.e. leaf area per unit canopy volume.

Table 1
Average monthly weather conditions during the calibration experiment (1998–2001, Córdoba, Spain)

Month	R_s ($\mathrm{MJ\,m^{-2}\,day^{-1}}$)	T_{max} (°C)	T_{min} (°C)	Rainfall (mm)	Wind speed ($\mathrm{m\,s^{-1}}$)	Vapor pressure (kPa)
1	8.6	15.2	4.8	58	1.54	1.08
2	12.9	18.9	5.4	35	1.49	1.13
3	17.1	22.1	8.4	72	1.77	1.28
4	21.4	22.8	9.6	62	2.01	1.24
5	23.3	27.0	13.6	77	1.71	1.65
6	28.5	34.3	16.8	8	1.86	1.64
7	27.6	36.5	19.0	4	2.15	1.81
8	24.9	37.1	19.6	4	2.08	1.84
9	18.9	31.5	17.5	20	1.99	1.86
10	13.8	25.5	13.3	33	1.72	1.67
11	9.6	18.4	7.4	47	1.57	1.24
12	7.2	15.8	5.4	85	1.72	1.09
Total	17.8	25.4	11.7	505	1.80	1.46

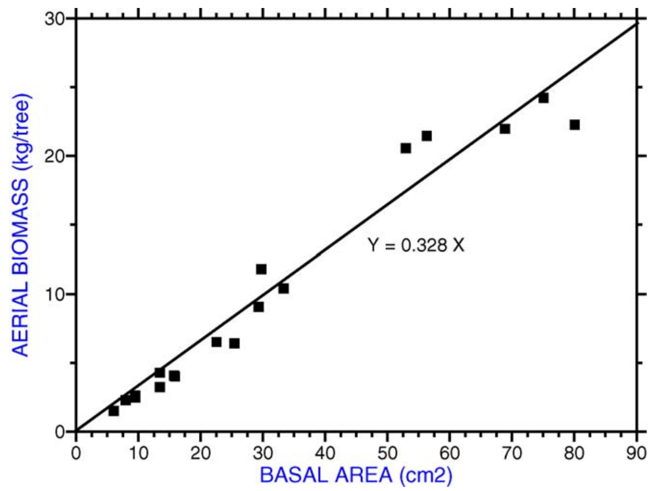

Fig. 1. Total above ground biomass of olive trees (cv. 'Arbequina') as a function of trunk sectional area. Calibration experiment (Cordoba, 1999–2001).

Harvests were performed in December 1999–2001 with the aid of a small vibrator. Total fresh fruit of single trees was weighed in the field and subsamples of 4 and 5 kg from each tree were taken to the laboratory for further processing (dry matter content, oil concentration, single fruit weight).

Leaf Area Index was calculated as the product of Leaf Area Density and crown volume. Leaf Area Density was determined using measurements of diffuse radiation interception performed with a Plant Canopy Analyzer (PCA, model LAI-2000, Li-Cor, Lincoln, NE, USA). Five fixed points were marked in the soil below the trees of each subplot. Diffuse radiation transmisivity at the five points was measured either on cloudy days or just before sunrise to avoid direct radiation. For each subplot, a model of olive radiation interception (Mariscal et al., 2000a) was used to determine the value of LAD that minimized the error in transmisivity using the measured tree dimensions as inputs. Tree dimension data collected at 2-month intervals and LAD of the 10 subplots were used to calculate intercepted PAR using the model of Mariscal et al. (2000a).

Destructive samples (whole trees) were collected on March 1999 (five trees), December 1999 (five trees), December 2000 (five trees), and December 2001 (three trees). The trees were cut at ground level, separated into trunk, branches, and shoots + leaves in the field and weighed. Fresh subsamples of 3 and 4 kg were then taken to the laboratory were shoots were separated from leaves and then all subsamples were oven dried at 80 °C for 72 h. Before drying, leaf area of all leaf subsamples was measured using an electronic area meter (model LI-3100, Li-Cor, Lincoln, NE, USA). The ratio of area and weight (Specific Leaf Area, SLA) was later applied to deduce total plant leaf area from total leaf mass. The 18 destructive samples were used to develop an empirical relationship between tree above ground biomass and trunk area (Fig. 1) with a Root Mean Square Error (RMSE) of 1.64 kg/tree and a relative RMSE of 0.15. It is clear that this relationship only holds for the trees in this orchard during the experimental period as prunning and age affect the relation between biomass and trunk dimensions (Villalobos et al., 1995).

This relationship was then used to calculate the above ground biomass of the 80 marked trees using the measured trunk diameter at 2-month intervals throughout the experimental period.

The destructive samples were also used to calculate the dry matter partitioning coefficients for leaves, stems, branches (including trunk) and fruits, by regressing the organ mass on total mass (including cumulative yield).

The conversion factor or production value (cvf: the amount of dry matter produced per gram of glucose, $\mathrm{g\,g^{-1}}$) was calculated for each organ according to the equation of Penning de Vries et al. (1974) using the data of Mariscal et al. (2000b) for the composition of vegetative parts and assuming 40% of oil in fruit dry matter:

$$1/\mathrm{cvf} = 2.1\,\mathrm{HI} + 1.5(1 - \mathrm{HI}) \qquad (3)$$

Radiation-Use Efficiency for dry matter production of a given year was calculated as the ratio of total increase in biomass (including yield and leaf losses) and total intercepted PAR. Leaf losses for 2000 and 2001 were estimated as the increase in leaf biomass (calculated according to the partitioning coefficient) in 1998 and 1999, respectively, based on an average duration of leaves of 2 years (Rapoport, 2004). Radiation-Use Efficiency for fruits and oil (ε_f and ε_o) were calculated as fruit yield and oil yield divided by intercepted PAR, respectively.

Harvest Index for each year (and for the whole experiment) was calculated as the ratio of yield and total biomass increase. Alternatively, HI was estimated as the partitioning coefficient for fruits, using the destructive samplings.

2.3. Model validation

Yield and canopy dimensions were recorded in 18 irrigated orchards (Table 2) in seven locations within the main olive producing areas of Southern Spain. The orchards were either of cv. 'Picual' (the main cultivar in Spain) or cv. 'Arbequina' (high yield expanding cultivar) and presented a wide variation in planting date (1900–1991) and planting density (65–450 olive trees/ha). The altitude of the locations ranges from 110 (Cordoba) to 794 m (Villacarrillo) while annual rainfall ranges from around 450 to 600 mm (Table 3). The climate of all locations is typically Mediterranean with an average reference evapotranspiration between 1209 (Torreperogil) and 1470 mm (Osuna).

For each orchard yield was recorded in a number of fixed trees ranging from 6 (farm La Loma) to 150 (farm Venta Cerro). Samples of 2 and 3 kg fresh fruit were processed for determining dry matter and oil contents.

The soils in the farms were of medium to heavy textures with depths from around 60 cm (farm Pompuda) to more than 200 cm (farm Casillas and Vaquería) and were classified as Calcixerollic Xerochrepts (seven orchards), Typic Chromoxererts (two orchards), Typic Xerofluvents (seven orchards) and Rendollic Arents (two orchards).

Oil yield and canopy dimension data from each orchard were averaged for 2-year periods to reduce the noise due to alternate bearing.

Table 2
Main characteristics of the olive orchards used for validation

Farm	Location	Cultivar	Density (tree/ha)	Pattern (m)	Planting date (year)	Years of data	n (trees)	Soil texture	Soil depth (cm)	Soil classification
Poco humo	Torreperogil	Picual	69.4	12 × 12	1935	1999–2003	24	Silty clay	<120	Calcixerollic Xerochrepts
Almindez	Torreperogil	Picual	69.4	12 × 12	1942	2000–2003	24	Silty clay	80	Typic Chromoxererts
Valdecastro	Linares	Picual	156	8 × 8	1975	2001–2002	14	Clay loam	>150	Calcixerollic Xerochrepts
Valdecastro	Linares	Picual	208	8 × 6	1978	2001–2002	36	Clay loam	>150	Calcixerollic Xerochrepts
Casillas	Córdoba	Picual	278	6 × 6	1976	2001–2002	100	Loam	>200	Typic Xerofluvents
Pompuda	Santisteban	Picual	80	12T	<1900	1999–2000	25	Clay	60	Typic Chromoxererts
La Loma	Jódar	Picual	65	13T	<1900	1996–2003	6	Clay	80	Rendollic Arents
Torralba 1	Torreperogil	Arbequina	250	8 × 5	1988	1997–2002	40	Clay	75	Rendollic Arents
Torralba 2	Torreperogil	Arbequina	250	8 × 5	1988	1997–2002	40	Silty clay	>100	Calcixerollic Xerochrepts
Robledos	Santisteban	Arbequina	238	7 × 6	1991	1997–1998	125	Clay	120	Calcixerollic Xerochrepts
Venta cerro	Villacarrillo	Arbequina	270	7 × 5.3	1991	1997–2002	150	Silty clay loam	140	Calcixerollic Xerochrepts
El villar	Osuna	Arbequina	300	7 × 4.75	1997	1999–2002	125	Clay loam	85	Calcixerollic Xerochrepts
Vaquería	Córdoba	Arbequina	200	6 × 8.33	1984	1988–1994	24	Loam	>200	Typic Xerofluvents
Vaquería	Córdoba	Arbequina	250	6 × 6.67	1984	1988–1994	24	Loam	>200	Typic Xerofluvents
Vaquería	Córdoba	Arbequina	300	6 × 5.56	1984	1988–1994	24	Loam	>200	Typic Xerofluvents
Vaquería	Córdoba	Arbequina	350	6 × 4.76	1984	1988–1994	24	Loam	>200	Typic Xerofluvents
Vaquería	Córdoba	Arbequina	400	6 × 4.17	1984	1988–1994	24	Loam	>200	Typic Xerofluvents
Vaquería	Córdoba	Arbequina	450	6 × 3.70	1984	1988–1994	24	Loam	>200	Typic Xerofluvents

In the planting pattern T stands for triangular arrangement of the trees. For the planting date <1900 indicates an undetermined planting date before 1900. The number of trees (n) refers to the total number of trees used for yield measurements.

Table 3
Geographic information of the locations of the validation experiments

	Latitude	Longitude	Altitude (m)	ET_0 (mm)	P (mm)
Torreperogil	38.03	3.28	328	1 209	510
Linares	38.08	4.17	423	1 422	541
Córdoba	37.85	4.80	110	1 382	597
Santisteban	38.25	3.20	675	1 150	575
Villacarrillo	38.12	3.08	794	1 169	505
Jódar	37.85	3.35	627	1 301	453
Osuna	37.23	5.10	328	1 470	478

Average values of annual reference evapotranspiration (ET_0) and annual rainfall (P) are also shown.

The annual intercepted PAR was calculated as the annual mean incoming PAR multiplied by the fraction of the PAR intercepted by the trees (Q_e). Considering an average daily solar radiation for this area of 17 MJ m^{-2} day^{-1} with a PAR proportion of 45% (Monteith, 1965; Meek et al., 1984), a value of 7.6 MJ PAR m^{-2} day^{-1} (2800 MJ PAR m^{-2} year^{-1}) is obtained. The Q_e was assumed to be equal to the fraction of diffuse radiation intercepted by the canopy (Fuchs et al., 1976; Villalobos, 1996), which may be calculated using the summary model proposed by Testi et al. (2005):

$$Q_{dif} = 1 - \exp(-k'v)$$

where v is the canopy volume per unit area (m^3 m^{-2}), $k' = 0.52 + 0.0007878d - 0.76\exp(-1.25\ \mathrm{LAD})$, and d is the planting density (olive trees/ha).

The value of LAD was taken as 1.5 which is within the values found by Villalobos et al. (1995) for olive trees of different sizes.

3. Results

3.1. Model calibration experiment

Olive dimensions increased throughout the experiment (Fig. 2) starting from trees of 1.4 m height and 0.6 m diameter and reaching at the end of 2001 a height of 3.5 m and a diameter between 3.25 and 3.5 m. The diameters in the x (nor-

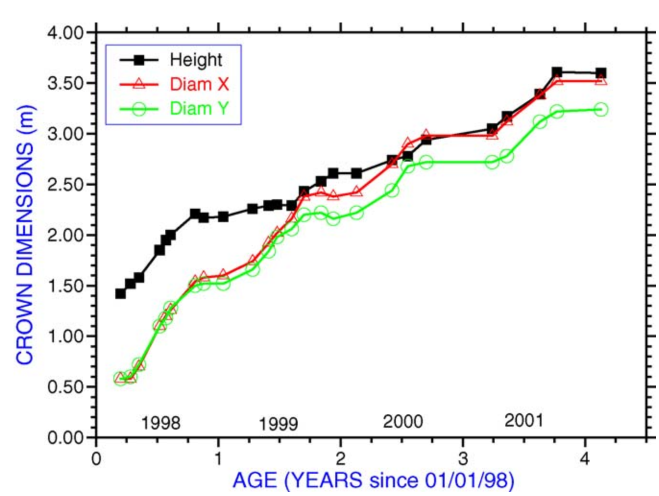

Fig. 2. Time course of dimensions of olive trees (cv. 'Arbequina'). Calibration experiment (Cordoba, 1998–2001).

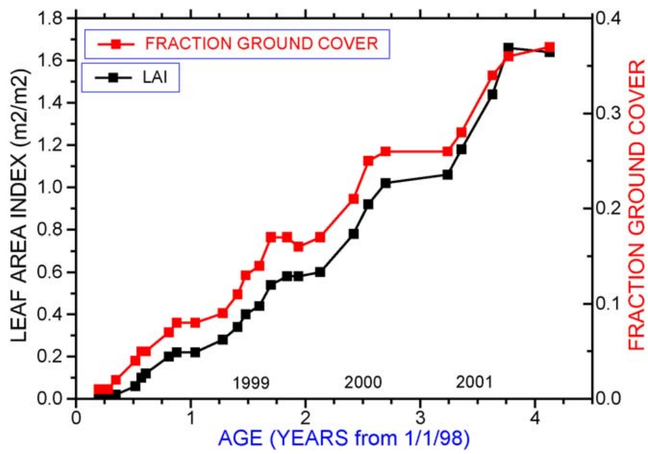

Fig. 3. Time course of LAI and ground cover of olive trees (cv. 'Arbequina'). Calibration experiment (Cordoba, 1998–2001).

mal to the row) and *y* (parallel to the row) directions started to differ during 1999 and the difference increased during 2000 and 2001 showing preferential growth in the *x*-axis. By the end of the experiment the trees had almost touched each other in the row direction (average diameter 3.25 m).

Non-destructive measurements of LAD yielded an average value of $2.0\,m^2\,m^{-3}$, which is very close to the value obtained in the destructive samples ($2.1 \pm 0.7\,m^2\,m^{-3}$). Average SLA was $42\,cm^2\,g^{-1}$.

Fraction of ground cover and LAI were very low at the start of the experiment and increased to 0.37 and 1.7, respectively, by the end of the experiment (Fig. 3).

Intercepted PAR increased during the experiment and showed a pattern associated to annual variations in incoming radiation (Fig. 4). The average fraction of PAR intercepted by the canopy increased from 0.05 during 1998 to 0.41 during 2001 (Table 4).

Fruit and oil yield were nil in 1998 and then increased for the three remaining years giving a total of $1134\,g\,m^{-2}$ of fruit dry matter ($426\,g$ oil m^{-2}). The fraction of oil in fruits was almost constant (0.37 and 0.38) (Table 4).

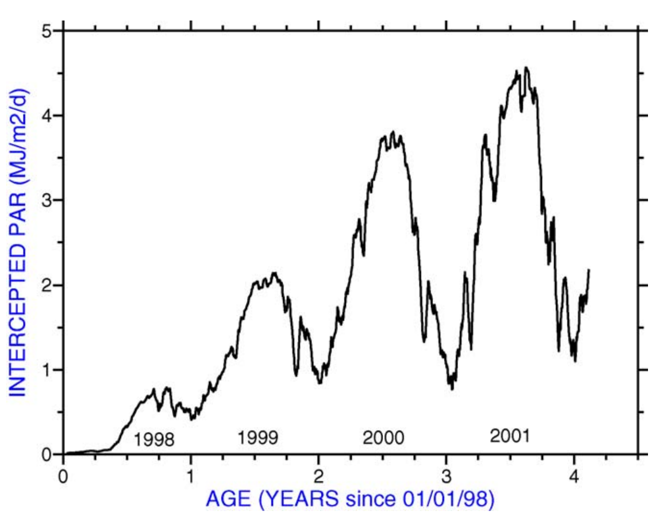

Fig. 4. Time course of intercepted PAR of olive trees (cv. 'Arbequina'). Calibration experiment (Cordoba, 1998–2001).

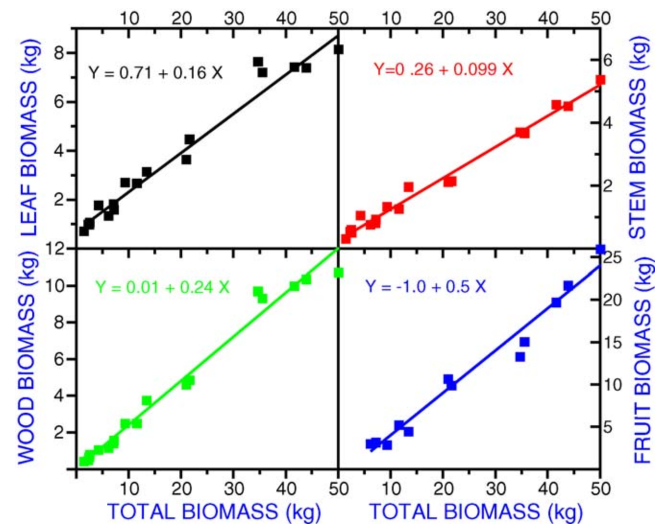

Fig. 5. Organ mass as a function of total above ground dry matter (including fruit yield). for leaves, stems, wood (branches + trunk) and fruits. Destructive samplings. Calibration experiment (Cordoba, 1999–2001).

Radiation-Use Efficiency for fruit and oil production decreased slightly during the experiment showing average values of $0.44\,g$ fruit MJ^{-1} and $0.16\,g$ oil MJ^{-1}. If the non-flowering period (1998) is excluded, the corresponding values of ε_f and ε_o are 0.46 and $0.17\,g\,MJ^{-1}$, respectively.

Above ground biomass increased from $160\,g\,m^{-2}$ at the end of 1998 to $986\,g\,m^{-2}$ at the end of the experiment (Table 5). Total above ground biomass production increased in parallel to above ground biomass giving a total of $2232\,g\,m^{-2}$ for the whole experiment ($4029\,g\,m^{-2}$ glucose). The HI was around 0.55 for the 1999–2001 period, while the value for the whole experiment was 0.51. There was a decrease in RUE for dry matter (or glucose) from 1998 to 2001, with average values of $0.86\,g\,MJ^{-1}$ for dry matter and $1.56\,g\,MJ^{-1}$ for glucose.

Average partitioning coefficients for leaves, stems, wood and fruits were 0.16, 0.10, 0.24 and 0.50, respectively (Fig. 5).

3.2. Model parameters

Oil yield may be calculated using:

$$Y = 0.17 R_{sp} Q_e \tag{4}$$

The coefficient 0.17 corresponds to the product of RUE, HI and F_o.

3.3. Model validation

Oil yields of the 2-year periods ranged from around 100 to $340\,g\,m^{-2}$ while annual intercepted PAR ranged from 200 to $2000\,MJ\,m^{-2}$ (Fig. 6). The minimum and maximum slopes of lines plotted from the origin for oil versus intercepted PAR were 0.14 and $0.25\,g\,MJ^{-1}$, while the slope of the linear regression for all data points was $0.17\,g\,MJ^{-1}$. Predictions of the simple model of oil yield (Eq. (4)) resulted in a RMSE = $55\,g\,m^{-2}$ and a relative RMSE of 0.26.

Table 4
Productivity of fruit dry matter and oil of olive (cv. 'Arbequina') in the calibration experiment (Cordoba)

Year	Q_e	$Q_e \times R_{sp}$ (MJ m^{-2})	Fruit yield (g m^{-2})	Oil yield (g m^{-2})	RUE$_f$ (g MJ^{-1})	RUE$_o$ (g MJ^{-1})	F_o
1998	0.05	122	0	0	0.00	0.00	0
1999	0.17	506	259	99	0.51	0.19	0.38
2000	0.30	901	412	157	0.46	0.17	0.38
2001	0.41	1055	463	171	0.44	0.16	0.37
Total		2584	1134	426	0.44	0.16	

Radiation-Use Efficiency of fruit (RUE$_f$) and oil (RUE$_o$) production are the ratios of yield and intercepted PAR. The fraction of intercepted PAR (Q_e), total intercepted PAR ($Q_e \times R_{sp}$) and fraction of oil in fruit dry matter (F_o) are also shown.

Table 5
Productivity of biomass and glucose equivalents of olive (cv. 'Arbequina') in the calibration experiment (Cordoba)

Year	Final biomass (g m^{-2})	Yield (g m^{-2})	Leaf loss (g m^{-2})	Total biomass accumulation (g m^{-2})	Glucose equivalent (g m^{-2})	HI	1/cvf (g g^{-1})	RUE dry matter (g MJ^{-1})	RUE glucose (g MJ^{-1})
1998	160	0		160	240	0.00	1.50	1.31	1.97
1999	373	259		472	864	0.55	1.83	0.93	1.71
2000	654	412	48	741	1359	0.56	1.83	0.82	1.51
2001	986	463	64	859	1566	0.54	1.82	0.81	1.48
Total		1134		2232	4029	0.51		0.86	1.56

The total biomass accumulation includes yield and estimated leaf loss. The production cost (1/cvf) is the amount of glucose required per unit of dry matter produced.

The efficiency of oil production (ratio oil/intercepted radiation) averaged for each orchard varied widely with a minimum of 0.14 g MJ^{-1} (Casillas, Córdoba, cv. Picual) and a maximum of 0.32 g MJ^{-1} (Villar Culebras, Osuna, cv. Arbequina). A large fraction of the variation was associated with intercepted radiation (Fig. 7) while other factors (planting density, orchard age, cultivar) did not contribute to the variation.

4. Discussion

4.1. Biomass accumulation and partitioning

Mariscal et al. (2000b) reported a RUE for biomass production of 1.3 g MJ^{-1} for young olive trees cv. 'Picual' before the onset of the reproductive period, which is similar to the value found herein for the first year of the calibration experiment (Table 5). During the following reproductive years RUE was only 62–71% of that of the first year. Part of this reduction is due to the higher cost of oil synthesis as the RUE in glucose equivalents of the reproductive period was between 79 and 87% of that of 1998. The remainder of the reduction should be caused by reduced photosynthetic capacity and/or increased maintenance respiration which deserves further research.

Both Mariscal et al. (2000b) and this study have shown the low RUE of olive trees when compared with annual crops (see the review by Sinclair and Muchow, 1999) although similar values have been found for other tree species. For example, Allen et al. (2005) have reported RUE of around 1 g MJ^{-1} for tree stands of sweetgum and sycamore while Kiniry (1998)

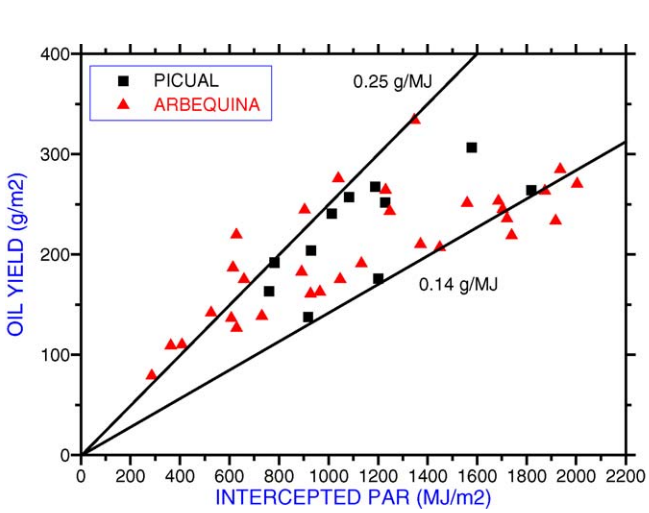

Fig. 6. Oil yield vs. annual intercepted PAR. Validation experiments.

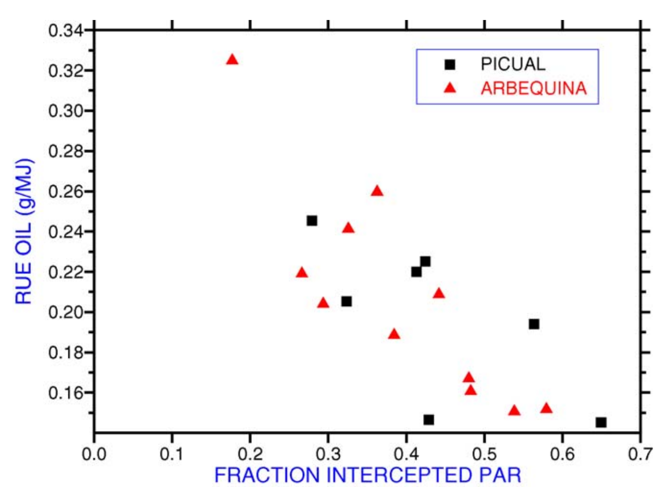

Fig. 7. Radiation-Use Efficiency for oil production vs. annual intercepted PAR. Validation experiments. Each value is the average for each orchard of Table 2.

has found larger values (around 1.6 g MJ^{-1}) for mesquite and juniper.

Despite the low RUE, olive oil productivity is high due to its Harvest Index (0.50), comparable to the maximum HI of cereals, and to the large annual fraction of intercepted radiation because of being perennial. Average oil yields in the validation experiments reached 3 t ha^{-1} in several orchards which may be compared with a potential oil yield for sunflower of 2.25 t ha^{-1} in the area (Villalobos et al., 1994).

Alternate bearing which is the tendency for alternating years of high and low yield has not been considered in this study despite its importance in determining flowering and yield on individual years (Cuevas et al., 1994). However, data from the calibration experiment suggests that young trees of cv. 'Arbequina' show little alternate bearing as HI was almost constant in 1999–2001. In any case the proposed oil yield model is aimed at long-term evaluations of productivity. Furthermore, the proposed concept of RUE for oil production (ε_o) could be useful for evaluating the degree of alternate bearing as a surrogate for HI instead of using yield directly. For instance the Alternate Bearing Index (ABI) (Pearce and Dobersek-Urbanc, 1967) which has values between 0 (no alternate bearing) and 1 (yield is zero in alternate years), is 0.13 for oil yield in our calibration experiment, while it is only 0.04 when the calculation is applied on data of ε_o. Therefore, the use of ε_o normalizes the data for changes in tree size which can be an important source of variability in oil yield.

The partitioning coefficients found in the calibration experiment indicate that roughly half of biomass production is directed to vegetative growth, which in turn is divided in 30% for leaves and 70% for supporting organs (stems, branches, trunk). As the leaves are renovated at 2- and 3-year intervals the capacity of olive trees for permanent carbon capture is limited to the supporting organs. Therefore, in areas of Southern Spain, with an average incoming PAR of around 2800 MJ m^{-2} $year^{-1}$, intensive irrigated orchards capturing 50% of incident PAR will be able to accumulate 421 g m^{-2} in supporting organs which is equivalent to 7 t ha^{-1} $year^{-1}$ of CO_2. This is close to the maximum value (6.2 t ha^{-1} $year^{-1}$ of CO_2 for grassland) reported by Smith (2004) for agricultural systems in Europe and much higher than values for permanent crops (2.2 t ha^{-1} $year^{-1}$ of CO_2). This high potential for C sequestration of olive orchards deserves further research to evaluate all components of carbon flux and its dependence on environmental factors (mainly drought) and management (e.g. use of prunning residues).

4.2. Model validation

The average slope of oil yield on intercepted PAR was 0.17 g MJ^{-1} for the validation data which is equal to the value found in the calibration experiment. However, the error was not negligible (relative RMSE = 0.26). Part of the error may be associated with alternate bearing despite the averaging of biennial periods. For instance, analysis of ε_o data from "La Loma" orchard, where four bienniums were available, yields an alternate bearing Index of 0.15, indicating that some alternate bearing still occurs for biennial data. In Fig. 7 this effect is almost removed as the average ε_o for each orchard is plotted against average intercepted PAR. The reduction in RUE for oil production with the increase in canopy size has to be related to a decrease in at least one of its three components (RUE, HI, F_o). A reduction in RUE with canopy size was observed in the calibration experiment from 1.71 g glucose MJ^{-1} in 1999 (start of productive period) to 1.48 g glucose MJ^{-1} in 2001. A reduction in HI in large canopies could occur as low irradiance could prevent flower development in shaded shoots which has been shown for other tree species (e.g. apple tree, Jackson and Palmer, 1977). Furthermore the fraction of oil in the fruit tends to decrease in denser canopies due to limitation of assimilates. For instance, comparison of the different density orchards in Vaqueria in 1999 shows that the lowest density had $F_o = 0.439$ while the highest had 0.405. An additional source of variation in oil concentration is the harvest date which may be advanced to improve quality of some cultivars. Future work should be directed at analyzing the causes for the reduction in RUE for large canopies and the effects of canopy size on HI and oil concentration. In the meantime the simple model could be improved by using the linear regression between ε_o and the fraction of intercepted radiation (Fig. 7):

$$\varepsilon_o = 0.33 - 0.30 Q_e, \quad r^2 = 0.63, \quad n = 18 \tag{5}$$

With this parameters, oil yield is a quadratic function of Q_e with the maximum at $Q_e = 0.55$. Although preliminary, this result indicates that intensive orchards with 50% of PAR interception are close to the maximum and that increasing interception beyond (e.g. super-intensive plantations) will not increase yields.

5. Conclusions

Olive orchards show a low RUE but compensate by a high Harvest Index and a large fraction of intercepted radiation due to being perennial, which results in high oil productivity (around 3 t ha^{-1} of oil) when compared to oilseed crops like sunflower. Olive RUE is lower after the onset of the productive period which is partly explained by the higher energy cost of oil accumulation as compared to vegetative growth. Accumulated biomass is allocated equally to fruits and vegetative growth, which in turn is divided into 30% for leaves and 70% for supporting organs.

Estimates of carbon sequestration by olive orchards show a much larger potential for C capture than that of other agricultural systems.

A simple model for predicting the average oil productivity of specific orchards has been calibrated and validated with partial success, although future work should be directed at studying possible changes in RUE, Harvest Index and oil concentration in response to canopy size. Possible applications of the model include not only the evaluation of productivity at different scales but also provide a framework for many aspects of crop management (nutrient requirements, effects of pests or diseases on yield, etc.). Additionally, the proposed concept of RUE for oil production may be very useful for evaluating alternate bearing by eliminating the effect of canopy size on yield.

Acknowledgments

The authors gratefully acknowledge the financial support of the Consejería de Agricultura y Pesca, Junta de Andalucía (Project CAO00-002) and Ministerio de Educación y Ciencia of Spain (Project OLI96-2212). Additional funding for the validation experiments was provided by Caja Rural de Jaén and Junta de Andalucía.

References

Allen, C.B., Will, R.E., McGarvey, R.C., Coyle, D.R., Coleman, M.D., 2005. Radiation-Use Efficiency and gas exchange responses to water and nutrient availability in irrigated and fertilized stands of sweetgum and sycamore. Tree Physiol. 25 (2), 191–200.

Bonachela, S., Orgaz, F., Villalobos, F.J., Fereres, E., 1999. Measurement and simulation of evaporation from soil in olive orchards. Irrigation Sci. 18, 205–211.

Bonachela, S., Orgaz, F., Villalobos, F.J., Fereres, E., 2001. Soil evaporation from drip-irrigated olive orchards. Irrigation Sci. 20 (2), 65–71.

Civantos, L., 2004. La olivicultura en el mundo y en españa. In: Barranco, D., Fernandez Escobar, R., Rallo, L. (Eds.), El Cultivo del Olivo, 5ª ed. Mundi-Prensa, Madrid, pp. 17–35.

Cuevas, J., Rallo, L., Rapoport, H.F., 1994. Crop load effects on floral quality in olive. Sci. Hortic. 59 (2), 123–130.

Fuchs, M., Stanhill, G., Moreshet, S., 1976. Effect of increasing foliage and soil reflectivity on the solar radiation balance of wide-row sorghum. Agron. J. 68, 865–871.

Grossman, Y.L., DeJong, T.M., 1994. PEACH: a model of reproductive and vegetative growth in peach trees. Tree Physiol. 14, 329–345.

Hunt Jr., E.R., Martin, F.C., Running, S.W., 1991. Simulating the effects of climatic variation on stem carbon accumulation of a ponderosa pine stand: comparison with annual growth increment data. Tree Physiol. 9, 161–171.

Jackson, J.E., Palmer, J.W., 1977. Effects of shade on the growth and cropping of apple trees. II. Effects on components of yield. J. Hortic. Sci. 52, 253–266.

Jones, C.A., Kiniry, J.R., 1986. CERES-Maize: A Simulation Model of Maize Growth and Development. Texas A&M University Press, College Station, Texas.

Kiniry, J.R., 1998. Biomass accumulation and radiation use efficiency of honey mesquite and eastern red cedar. Biomass Bioenergy 15 (6), 467–473.

Mariscal, M.J., Orgaz, F., Villalobos, F.J., 2000a. Modelling and measurements of radiation interception by olive canopies. Agric. For. Meteorol. 100, 183–197.

Mariscal, M.J., Orgaz, F., Villalobos, F.J., 2000b. Radiation-Use Efficiency and dry matter partitioning of a young olive (*Olea europaea*) orchard. Tree Physiol. 20, 65–72.

Meek, D.W., Hatfield, J.L., Howell, T.A., Idso, S.B., Reginato, R.J., 1984. A generalized relationship between photosynthetically active radiation and solar radiation. Agron. J. 76, 939–945.

Melo-Abreu, J.P., Barranco, D., Cordeiro, A.M., Tous, J., Rogado, B.M., Villalobos, F.J., 2004. Modelling olive flowering date using chilling for dormancy release and thermal time. Agric. For. Meteorol. 125, 117–127.

Monteith, J.L., 1965. Light distribution and photosynthesis in field crops. Ann. Bot. 29, 17–37.

Monteith, J.L., 1977. Climate and the efficiency of crop production in Britain. Philos. Trans. R. Soc. London Ser. B, 277–294.

Pearce, S.C., Dobersek-Urbanc, S., 1967. The measurements of irregularity in growth and cropping. J. Hortic. Sci. 42, 295–305.

Penning de Vries, F.W.T., Brunsting, A.H.M., van Laar, A.H., 1974. Products requirements and efficiency of biosynthesis, a quantitative approach. J. Theor. Biol. 45, 339–377.

Rapoport, H.F., 2004. Botánica y morfología. In: Barranco, D., Fernandez Escobar, R., Rallo, L. (Eds.), El Cultivo del Olivo, 5ª ed. Mundi-Prensa, Madrid, pp. 37–62.

Sinclair, T.R., Muchow, R.C., 1999. Radiation use efficiency. Adv. Agron. 65, 215–265.

Smith, P., 2004. Carbon sequestration in croplands: the potential in Europe and the global context. Eur. J. Agron. 20, 229–236.

Testi, L., Villalobos, F.J., Orgaz, F., 2004. Evapotranspiration of a young irrigated olive orchard in Southern Spain. Agric. For. Meteorol. 121, 1–18.

Testi, L., Orgaz, F., Villalobos, F.J., 2006. Variations in bulk canopy conductance of an irrigated olive (*Olea europaea* L.) orchard. Environ. Exp. Bot. 55, 15–28.

Testi, L., Villalobos, F.J., Orgaz, F., Fereres, E., 2006b. Water requirements of olive orchards I. Simulation of daily evapotranspiration for scenario analysis. Irrigation Sci. 24, 69–76.

Villalobos, F.J., 1996. Total daily PAR interception measurement using a Plant Canopy Analyzer. In: van Ittersum, M.K., Venner, G.E.G.T., van de Geijn, S.C., Jetten, T.H. (Eds.), Proceedings of the fourth Congress of the European Society for Agronomy. ESA, Colmar Cedex, France, pp. 210–211.

Villalobos, F.J., Mateos, L., Orgaz, F., 1995. Non-destructive measurement of leaf area in olive (*Olea europaea* L.) trees using a gap inversion method. Agric. For. Meteorol. 73, 29–42.

Villalobos, F.J., Orgaz, F., Testi, L., Fereres, E., 2000. Measurement and modelling of evapotranspiration of olive (*Olea europaea* L.) orchards. Eur. J. Agron. 13, 155–163.

Villalobos, F.J., Sadras, V.O., Soriano, A., Fereres, E., 1994. Planting density effects on dry matter partitioning and productivity of sunflower hybrids. Field Crop Res. 36, 1–11.