Simulation of oil productivity and quality of N–S oriented olive hedgerow orchards in response to structure and interception of radiation

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ABSTRACT
Simulations of oil yield and quality are presented for N–S oriented, hedgerow olive orchards of a range of structures (viz. canopy depth, canopy width, canopy slope and row spacing) using responses of yield and quality parameters to solar irradiance on canopy walls measured in a range of orchards, cv. Arbequina, in Spain. Results reveal that orchard yield of hedgerows of rectangular shape reaches a maximum when canopy depth equals alley width (row spacing−canopy width) and decreases at wider spacing, and/or with wider canopies, as the length of productive row decreases per unit area. Maximum yields for 4-m deep canopies were 2885 kg ha−1 at 1-m width and 5-m row spacing, 2400 kg ha−1 at 2-m width and 6-m spacing, and 2050 kg ha−1 at 3-m width and 7-m spacing. Illumination of canopies can be increased by applying slopes to form rhomboidal hedgerows. Substantial yield advantage can be achieved, especially for wide hedgerows, partly by closer row spacing that increases row length per unit area. By comparison, responses to latitude in the range 30–40◦ are small and do not warrant different row spacing. Oil quality parameters also respond to orchard structure. Responses are presented for oleic and palmitic acid, stability, and maturity index. Oleic acid content declines as alley spacing increases and is smaller, shallow than in wide, deep canopies. Palmitic acid content, stability, and maturity index increase with row alley spacing and are greater in narrow, shallow than in wide, deep canopies.

1. Introduction

Mechanized hedgerows are a new production method for olive and currently exist in two forms resulting from commercial innovation. First, in some vigorous high density (HD) orchards, first planted in 1980s at densities of 250–500 ha−1 in rows 6–8 m apart, where rows formed continuous hedgerows. Large overhead continuous harvesters were built to improve harvesting efficiency. Second, starting in 1995, super-high density orchards (SHD) were planted at densities of 1500–2000 ha−1 in rows 3–4 m apart to take advantage of availability and relative cheapness of smaller modified grape harvesters. Trees were trained to vase structures in HD orchards but are trained to central leader in SHD. Large harvesters can harvest rows to 4.5 m high and 4 m wide, while small harvesters are suited to hedgerows to 2.5 m high and 2 m wide.

Advantages of hedgerow designs are early yield and economy of mechanized management, especially harvesting, but also pruning. Disadvantages are high cost of establishing high-density plantations and associated training requirements of young trees, few suitable cultivars, vigour control in some conditions, and cost of mechanized harvesters. Freixa et al. (2011) present a recent comparative economic analysis of oil production by mechanized HD and SHD orchards in Spain.

In traditional olive production (10 m × 10 m), with trees trained to vase structure and heavily pruned to reduce water use, light distribution in tree canopies was not a limitation to growth or reproductive development (Mariscal et al., 2000; Villalobos et al., 2006). Consequently it was little studied (Tombesi and Cartechini, 1986; Tombesi and Standardi, 1977) until dense systems, mostly in hedgerow form, were introduced. Now there is quantitative information on the role of light in determination of fruit density, size and oil content in hedgerow orchards (Cherbiy-Hoffmann et al., 2012; Connor et al., 2012) and more recently on oil quality (Gómez-del- Campo and García, 2012). High light intensity promotes dense, large fruits with high oil percentage. Oil is also more stable against oxidation by virtue of high concentrations of polyphenols. Palmitic acid content is also higher, while oleic acid content is smaller than in fruits that develop in shade (Gómez-del-Campo and García, 2012). For individual producers of hedgerow olives, the choice of a mechanized production system must be an appropriate combination of harvester and orchard design suited to location and resources. At present that places choice at either end of the HD-SD range, but mid-sized harvesters are becoming available so a wider range of orchard design will soon be possible. To date, most experiments on orchard design have been made at commercial scales and are slow and expensive, so other methods are required to investigate the performance of alternative designs across the range of feasible hedgerow structures.

This paper presents a simulation study of impact of canopy depth, width, and shape and row spacing on productivity of N–S hedgerow orchards. It uses a model of illumination of hedgerow orchards (Connor, 2006) and associated data on yield (Connor et al., 2012) and oil quality (Gómez-del-Campo and García, 2012) collected from a range of SHD orchards of cv. Arbequina in Spain. The analysis combines these components to simulate yield and oil quality across a wide range of structures, including many not yet tested experimentally or commercially. The approach provides guidance on hedgerow design, identifies issues that require resolution, and provides a framework for future research and development.

2. Methods

2.1. Terminology

Hedgerow orchards comprise rows of given spacing (r), height (h), canopy width at base (w), and slope to vertical (s) as depicted in Fig. 1. Alley width (a), for access and illumination, is the difference between row spacing and canopy width (r−w). Canopy depth (d) is less than row height (h) because bases of rows (t) are maintained free of vegetation to facilitate passage of harvesting and pruning machinery and, as needed, application of pesticides to trees and herbicides to inter-row vegetation. In this analysis, illumination and productivity are made relative to canopy depth (d) that is less than row height (h) by 0.5−1.0 m (=t in Fig. 1), being greater for tall hedgerows that require more space for large harvesters. It is convenient to use the term "depth" to emphasize that illumination of canopies is a top-down process. Analyses are made for rectangular shaped canopies (s = 0) and rhomboidal shaped canopies (s > 0).

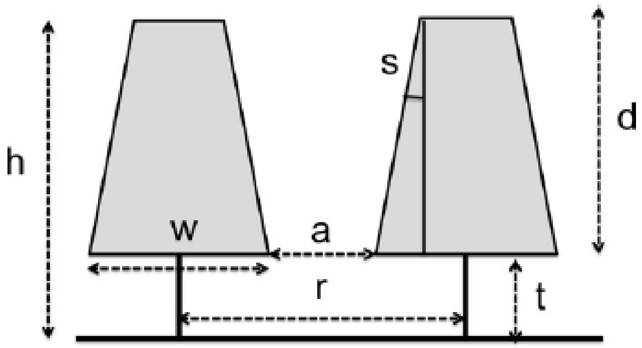

Fig. 1. Structural parameters of hedgerow orchards. Canopies have depth (*d*), slope (*s*) to vertical (*s* = 0 for rectangular canopies) and width (*w*) at the base. Row height (*h*) is *d* + *t*, where *t* is the height above ground level maintained free of canopy for ease of management. Individual hedgerows are separated in planting lines by distance (*r*) giving a free alley width (*a* = *r* − *w*).

2.2. Simulations of productivity in relation to hedgerow structure

2.2.1. This combines two approaches

First is a simulation study that establishes profiles of shortwave irradiance on canopy walls in response to orchard structure, location (latitude), and time of year (Connor, 2006). The model was previously verified during an annual cycle on hedgerows 2.0–2.5 m deep, 0.7–1.0 m wide at 4-m row spacing (Connor et al., 2009). Simulation of profiles of incident radiation on canopy walls is a straightforward geometrical problem that provides accurate predictions, as shown by comparison with measured data, in this and other studies on hedgerow crops (Jackson and Palmer, 1980; Oyarzun et al., 2007; Palmer, 1989).

In its simplest form, the model treats canopies as solid objects, i.e. all incident radiation is intercepted by canopy walls of the hedgerow. This is a reasonable assumption for N–S canopies of 0.7-m width or more, even those with a horizontal porosity of 15–20%. This arises because the trajectory of sunlight through the hedgerows is sufficiently long for almost complete interception diurnally (Connor et al., 2009). Further, since N–S hedgerows are illuminated equally on each side during the day, radiation passing through to the other side of the hedgerow before noon is compensated,
on a daily basis, by complementary interception afterwards.

Second, is an analysis of relationships with depth on canopy walls of cv. Arbequina orchards, between components of yield, viz. fruit density, fruit size and fruit oil content, with incident radiation. Data were collected in 11 orchards of varied structures (height 2.0–3.6 m, canopy width 0.7–1.3 m, row spacing 3.0–4.0 m, alley width 2.1–3.3 m), over a narrow latitudinal range (37.5–39.9°) in Spain. The orchards were adequately watered and fertilized for yield and not adversely affected by heavy pruning, disease, lack of winter release, or frost. They were used to establish the following responses of yield components to daily direct plus diffuse shortwave irradiance (x, MJ m^{-2}) on canopy walls during October (Connor et al., 2012):

Density (fruits m^{-2}) $= 206x - 86.94$ $(2.0 < x < 6.0)$
$= 1000$ $(6.0 < x < 10.0)$ ($R^2 = 0.44$)
Size (g) $= 0.31 + 0.034x$ ($R^2 = 0.78$)
Oil content (%) $= 32.0 + 1.55x$ ($R^2 = 0.52$)

The combined relationships, canopy irradiance profiles in response to canopy structure and oil yield in response to irradiance, were used to investigate the following issues.

• Effect of canopy depth, width and row spacing on productivity of rectangular canopies.
• Effect of slope on productivity of rhomboidal canopies, and
• Effect of latitude on productivity.

2.3. Simulations of oil quality and fruit maturity in response to hedgerow structure

These analyses were made by extending the yield simulations described above with response profiles of oil quality and maturity to irradiance (Gómez-del-Campo and García, 2012) measured on some of the cv. Arbequina orchards from which yield profile data were collected. Three parameters that describe quality and one for maturity are related to daily incident radiation on canopy walls, direct and diffuse components, during October (x, MJ m^{-2}) as follows:
Oleic acid=−0.339x+75.14 (R^2 =0.83)
Palmitic acid=0.114x+12.96 (R^2 =0.69)
Stability=2.360x+17.86 (R^2 =0.83)
Maturity index=0.192x+0.453 (R^2 =0.62)

The effect of hedgerow structure on these parameters was evaluated and is expressed, for each parameter, as the weighted average for total hedgerow oil production.

3. Results

3.1. Row yield as a function of canopy depth and row spacing Analysis of yield per unit row length of 1-m wide rectangular hedgerows in response to canopy depth (2–5 m) and row spacing (2–10 m) at 35◦N is presented in Fig. 2.

The responses reveal how yield per unit row length increases rapidly with row spacing until alley width (row spacing−row width) equals canopy depth. Yield per unit row then increases more slowly with benefit from additional diffuse radiation entering alleys, not by more direct radiation. An important corollary is that at fixed row spacing, yield increases little with canopy depth once it exceeds optimum alley width. Then, fruit simply moves higher towards the top of the canopy, where the same vertical distribution of illumination occurs (results not shown). These responses assist explanation of distinct responses in orchards of various structures, as canopy width also changes.

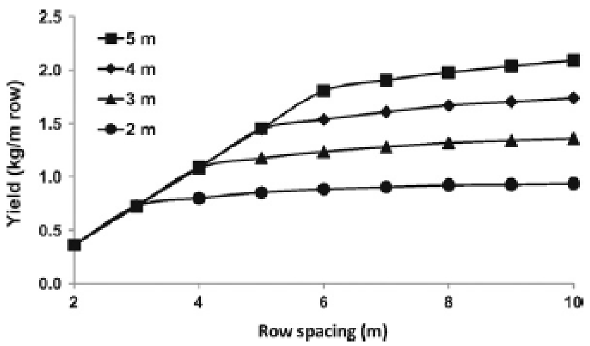

Fig. 2. Simulated effect of row spacing and canopy depth on oil production per m row length of 1 m wide canopies.

3.2. Yield of orchards with rectangular canopies

Three panels of Fig. 3 display simulated yield responses of orchards of rectangular hedgerow canopies, 1-, 2- and 3-m wide, to row spacing (2–8 m) over a range of canopy depths (2, 3 and 4 m) at 35◦N. While the abscissa is labelled “row spacing”, it can also be interpreted as “alley width” by subtracting the corresponding canopy width.

In Fig 3a, 1-m wide canopies of 2–3 m depth are characteristic of intended structures of many new plantings of SHD hedgerows. The response of yield to row spacing is instructive. Canopies of all depths have the same yield at row spacing of 2–3 m. At 3 m spacing (2-m alley), the orchard with a shallow, 2-m canopy, reaches its maximum production, around 2400 kg ha^{-1}. The same pattern is evident for canopies of greater depth. Again, for 3- and 4-m deep canopies, yield increases with row spacing until alley width is approximately equal to canopy depth, and then falls as fewer rows contribute to productivity. Maximum yield of 2850 kg ha^{-1} is simulated for 4-m deep canopies spaced at 5 m (4-m alley).

Responses in Figs. 3b and c provide insight into productivity of wide canopies typical of HD orchards. The same pattern of yield response to row spacing is evident. Maximum yield occurs when canopy depth equals alley width but maximum yield for all canopy depths decreases as row width increases. In this example, maximum yield of 4-m deep canopies falls from 2800 to 2300 to 2000 kg ha−1 as row width increases from 1 to 2 to 3 m.

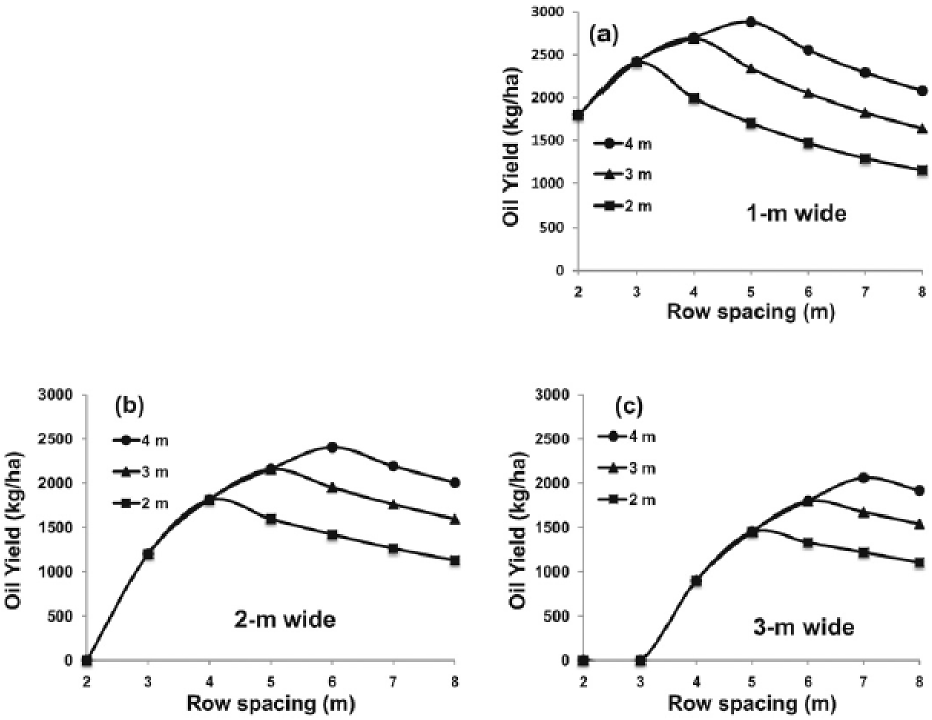

Fig. 3. Simulated response of oil yield of rectangular canopies to spacing, width, and canopy depth.

3.3. Orchards with sloping canopies

Sloping canopies increase angles of incidence of direct radiation onto canopy walls, increase entry of diffuse radiation into alleys, and also increase (slightly) length of canopy walls. The combination of effects serves to increase yield. Results are shown in Fig. 4a–c for canopies of selected width and depth. Narrow canopies can take little slope so Fig. 4a shows the small effect of imposing a slope of 5◦ on a 2-m deep, 1-m wide rectangular canopy (0.7 m at the top). The yield benefit is negligible at the optimum row spacing of 3 m. But as canopies widen, the benefit increases, and more so for deep canopies. In Fig. 4b, yield of a 2-m wide, 3-m deep canopy is increased from 2150 to 2800 kg ha−1 by adding a slope of 10º (0.9 m at top) and reducing row spacing from 5 to 4 m. In Fig 4c, the benefit of a slope of 15º is substantial on a 3-m wide, 4-m deep rectangular canopy (0.9 m at top). Yield is greatly increased relative to a rectangular canopy (2900 *v* 2050 kg ha−1) as optimum row spacing for maximum yield is reduced from 7 to 5 m.

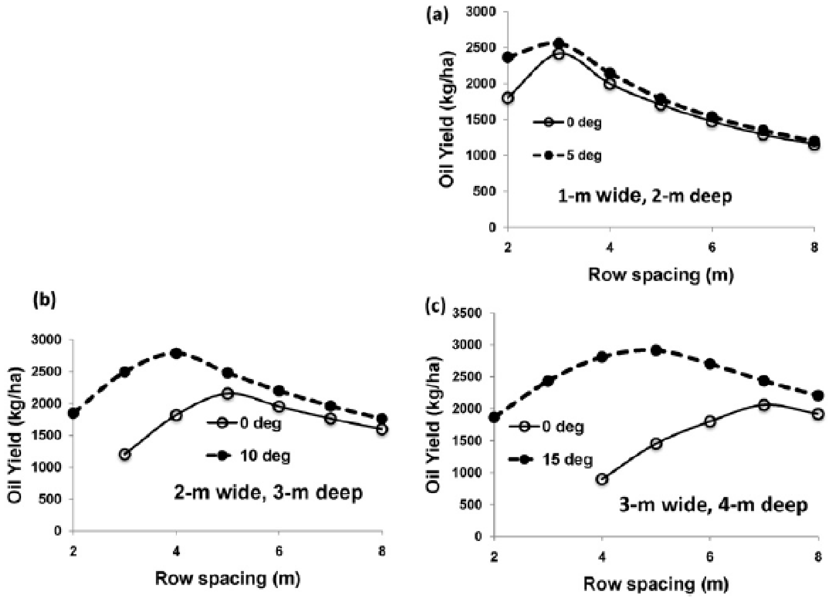

Fig. 4. Simulated response of oil yield to row spacing and canopy slope for various hedgerow structures.

3.4. Comparison of HD and SHD orchards

The relative yield performance that appears to exist across the HD–SHD range of orchard structures is presented in Fig. 5. This figure compares a typical HD orchard, 4 m deep and 3 m wide, with and without a 10◦ canopy slope, with a SHD counterpart, 2 m deep and 1 m wide. Yield relationships are plotted against row spacing and alley width. The simulations reveal that fairly comparable yields can be obtained with a range of orchard structures, provided that attention is paid to depth, width and row spacing. The results again emphasize the benefit from applying slope to wide hedgerows and that the yield benefit is partly achieved by reducing row spacing (alley width).

3.5. Effect of latitude on orchard yield

The effect of latitude on yield is presented in Fig. 6 over the range 30–40◦N chosen to cover major olive growing regions. Simulated oil yield of various hedgerow structures to latitude are presented, including a comparison of slope for a 2-m wide, 3-m deep canopy. Greater yield is obtained at lower latitude, with a yield advantage of ca. 500 kg ha−1 at 30◦N compared with that at 40◦ latitude. In these comparisons, the effect is small compared to the addition of slope and is insufficient to change the optimum row spacing for productivity.

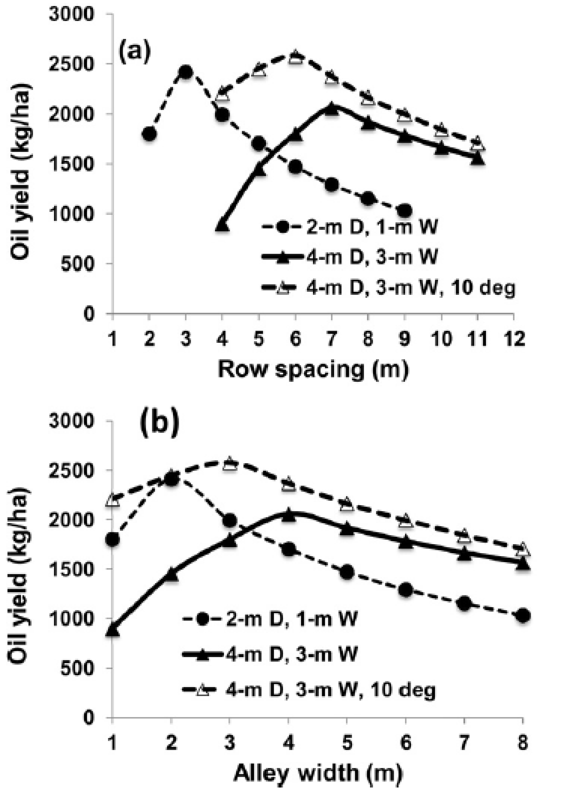

Fig. 5. Simulated effect of (a) row spacing and (b) alley width on oil production of three canopies contrasting in canopy depth, width, and slope.

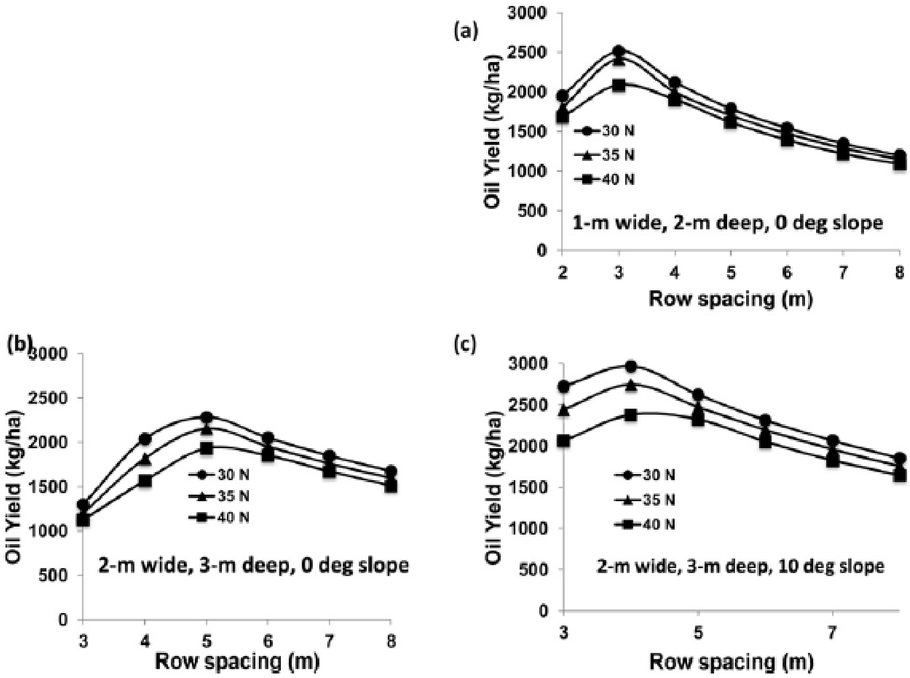

Fig. 6. Simulated response of oil yield of various orchard structures to latitude.

3.6. Orchard structure and oil quality and fruit maturity

Relationships between canopy structure and oil quality are compared in Fig. 7 for two canopy types, viz. 2-m deep and 1-m wide (SHD, short) vs. 4-m deep and 3-m wide (HD, tall) over a range of alley spacing from 1-m width. The parameters are presented as weighted mean values for profiles of oil yield and oil quality on the canopy walls. The relationship of yield to row spacing for these orchard types was shown previously in Fig. 5.

Simulations reveal different responses for individual quality parameters and also between canopy types as exposure to solar radiation increases with alley width. Oleic acid responds negatively while responses of the other parameters (palmitic, stability and maturity index) are positive. Oleic acid content is smaller in SHD than HD canopies but other parameters are greater. The major shift in response in either canopy type is for oleic acid, palmitic acid and maturity index that occurs as increasing row spacing approaches optimum alley width for maximum yield, i.e. 2 and 4 m for 2-m and 4-m deep canopies, respectively. For stability, the major shift in response occurs as row spacing exceeds optimum alley width for maximum yields. In all cases, responses continue as row spacing increases further.

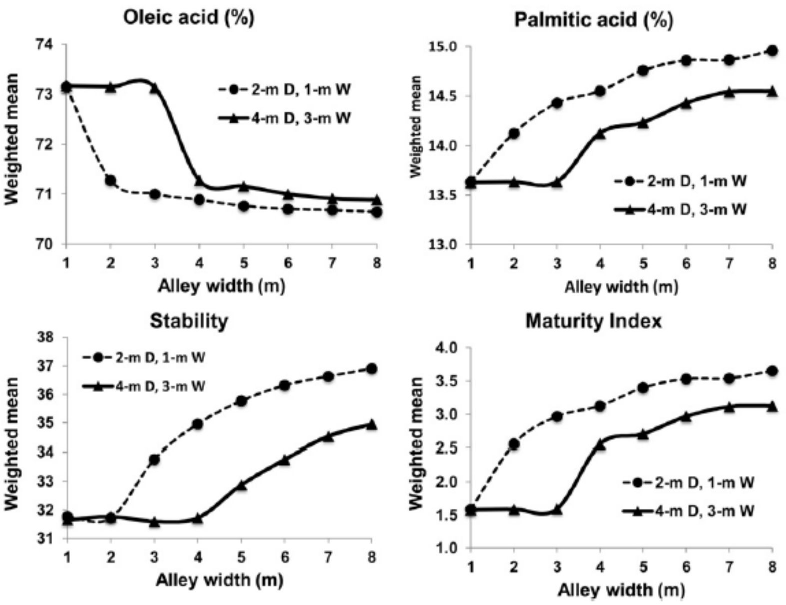

Fig. 7. Simulated effect of alley spacing on three oil quality parameters and maturity index, weighted by amount and distribution of fruit, for two canopy types, viz. 2 m deep and 1 m wide and 4 m deep and 3 m wide.

4. Discussion

The conclusion that productivity of hedgerows depends upon row structure such that it establishes a strong relationship with the ratio of canopy depth to alley spacing is not new. Cain (1972) introduced the concept with his analysis of productivity of apple orchards and Smart and Robinson (1991) have used the same conclusion to propose optimal structures for vineyards. Many other studies have reported analyses of irradiance profiles in hedgerow orchards of various crops (Annandale et al., 2004; Friday and Fownes, 2001; Jackson, 1980; Olesen et al., 2007; Oyarzun et al., 2007; Palmer, 1989; Palmer and Jackson, 1977) but, in the absence of yield responses to incident radiation, none have proceeded to simulations of orchard fruit yield.

This paper is a first attempt to correct this deficiency for olive, cv. Arbequina, by incorporating measured responses of yield components (fruit density, mass, and oil %) to patterns of daily irradiance on canopy walls in October (Connor et al., 2012), the period of major oil formation, into a hedgerow canopy illumination model (Connor, 2006). A small amount of biology is added to well-established geometrical relations of radiation incidence. Simulation then allows extrapolation to a wider range of structures and locations with the following assumptions:

• Orchards are on flat land and are well irrigated and optimally supplied with nutrients.
• Orchards are oriented N–S, because previous work has shown that the relationships are not applicable to asymmetrically illuminated E–W orchards (Connor et al., 2009).
• Yield component and oil quality responses to irradiance are appropriate to the range of orchard structures evaluated.
• Poorly illuminated low parts of tall canopies do not detract from productivity of well illuminated upper canopies.
• Relationships between productivity and October irradiance, established between 37.5 and 39.9◦N, can be extended to the range 30–40◦N.
• No other physiological responses, e.g. to temperature for growth or oil quality are considered.

Within those assumptions, analyses presented here provide defensible guidelines for identification and maintenance of olive hedgerow structures because they are based on field-established production functions and established methods to calculate irradiance patterns on hedgerow orchards. Importantly, they also provide guidelines for research required to improve management and increase yield of hedgerow olives.

4.1. Canopy structure and oil yield

A range of simulations reveal the nature of interactions between canopy depth, canopy width, and row spacing on yield, first of rectangular canopies and then how these relationships are modified in canopies of rhomboidal shape. The results emphasize the importance of alley width, i.e. row spacing − canopy width, in discussions of orchard structure and performance. Simulations for rectangular canopies of given depth (Fig. 3) demonstrate how orchard oil yield reaches a maximum when alley width equals canopy depth. Yield declines as row spacing widens further because the slight positive response to greater diffuse radiation (Fig. 2) is offset by decreasing row length per orchard area. Yield also decreases if canopies widen, because that reduces alley width and hence the needed balance with canopy depth. Unless alleys widen, yield of deepening canopies does not increase, fruit just move towards the top of the canopy where the same favourable illumination pattern is established. That response was recorded by Pastor et al. (2007) in an early experiment with a SHD cv. Arbequina orchard planted at 3.5-m row spacing in Córdoba, Spain. When the unpruned trees reached 5 m height, and the alleys narrowed considerably, fruit was too high to be harvested and production was delayed for another year until recovery after severe "topping".

Simulations are extended to rhomboidal canopies and provide results that warrant serious consideration (Fig. 4). Wide canopies can be managed with sloping walls with a slight increase of surface area per orchard area but with a greater impact on incidence of both direct and diffuse radiation. Simulations of rhomboidal shaped canopies illustrate two important features of yield response. Narrow canopies (Fig. 4a) show little response because they can accept little slope. On the other hand, deep (4 m), wide canopies (2+ m), that can best accept sloping walls, respond significantly in yield, in part because improved illumination allows maximum yield at narrower alley (and row spacing) and hence greater row length per hectare.

Applying slopes to HD orchards changes the yield comparison with SHD orchards. This was shown in Fig. 5 as a direct comparison of typical SHD and HD orchards, the latter with and without a slope of 10◦. The features of yield response to structure noted previously are evident. First that rectangular SHD canopies are more productive (2400 kg ha−1) than rectangular HD canopies (2050 kg ha−1). Second that applying slope to a wide canopy increases yield in part by reducing optimum row spacing. In this case, greater yield of the rhomboidal canopy (2580 kg ha−1) at 5-m row spacing exceeds that of the SHD orchard. Pastor and Humanes (1996) have reported experiments with mechanical pruning that increased yield in traditional and hedgerow orchards with sloping canopies.

The important conclusion is that search for high yield of wide canopies must pay attention to slope as well as canopy depth and alley width and that there appear to be options for orchards of intermediate structure between the current SHD and HD versions. 4.2. Effect of latitude on productivity Yield decreased at higher latitude (40º vs. 30º) by 430 and 350 kg ha−1 for two rectangular canopies (Fig. 6a and b) and by 575 kg ha−1 for a canopy 2-m wide, 3-m deep canopy with 10% slope (Fig. 6c), otherwise comparable to the canopy in Fig. 6b. The latter comparison reveals that slope was more advantageous at lower latitude where optimum spacing decreased with 10º canopy slope. There is no evidence here that without consideration of slope there is any advantage to vary row spacing for SHD orchards as suggested recently by Rius and Lacarte (2010). The analysis is, however, limited because no other physiological responses to low latitude, e.g. cold requirement for flowering, are included in the simulation.

4.3. Orchard structure and oil quality

The study also offers some preliminary information concerning impact of hedgerow structure on oil quality and the possibility to design and manage hedgerows to control it. It is well known that radiation intensity plays a major role with factors that control development of "quality" in maturing olive fruit (Proietti et al., 2012). Quality here refers to factors that improve odour and taste of extracted oil and prolong storage life. Analyses presented here demonstrate that clear relationships exist between quality and irradiance, and also identify opportunities to include considerations of quality in design and management of orchards.

Oleic and palmitic acid contents are important because they define well studied health characteristics of olive oil. High content of mono-unsaturated oleic acid contributes to reduction of blood pressure, while high concentration of saturated palmitic acid increases risk of cardiovascular disease. Stability against oxidation (time to become rancid) is important in commerce and is generally low in cv. Arbequina oil (Barranco et al., 2005). Polyphenols provide part of taste factors, and also antioxidant properties that increase stability to further differentiate oil between cultivars. Ideal combinations are high stability together with high oleic and low palmitic acid contents. Oil of high oil quality (extra virgin) must have oleic acid content above 55% and palmitic acid content between 7.5 and 20.0% (European Community Regulation CE 2568/91). The simulation data presented here reveal that changes in oleic acid content from 71 to 73% are small and that responses in palmitic oil content (13.5–15.0%) remain within the required range.

Fruit maturity also has high impact on oil content (Lavee and Wodner, 2004) and quality (Yousfi et al., 2006). Cultivar Arbequina is characterized by rapid development of oil quality with harvest date, such that differences in the range 1.5–3.5 suggested by the simulations can be significant. Class 1 refers to olives with yellowish-green skin and Class 3 to reddish or purple skin over more than half of each fruit. Stability decreases with maturity due to increase in poly-unsaturated fatty acids (Yousfi et al., 2006) and decrease in polyphenol content (Ayton et al., 2007). The impact of hedgerow design on maturity index (Fig. 7) could offer guidelines for designs of large orchards where progressive harvesting is needed to make effective use of machinery.

Canopy temperature, not included in the present analysis, except as a covariate with exposure to direct radiation is also an important environmental determinant of oil quality in olive, and particularly so in cv. Arbequina (Lombardo et al., 2008). The results presented here point to the need to evaluate effects of illumination and temperature separately but also the possible value, in areas of high environmental temperature, of hedgerows that are spaced closer than required for maximum yield.

4.4. Designing and maintaining hedgerows

There is of course much importance about hedgerow structure that this simulation analysis does not include. The focus here on the radiation-limited yield of various N–S-oriented hedgerow structures begs the question about how such structures can be formed and maintained in productive condition. For N–S orientations, what cultivars are appropriate for the various structures and what method, frequency, and timing of pruning is required to maintain or recover optimum structure of mature hedgerows for high productivity and quality? In what way can hedgerow structure facilitate control of pests and diseases? Further, how does the response to structure depend on row orientation? These are all questions that lay outside the scope of the model in its present form. That is not, however, a criticism of the model; it is simply a limitation of the current objective. The model and analyses presented here offer a framework to aid current discussion of design of optional hedgerow structures and also to guide further research and analysis of hedgerow orchard yield data as it becomes available.

The productivity of alternative designs is only one part of the search for optimum designs that must also include suitability to site and economic analyses for individual growers. Climate, soils, topography, size of orchard, and costs of establishment, maintenance and harvest are important to these analyses. What the analyses do show, however, is that there is scope for many orchard designs of high productivity for new, or recovered, orchards across a range of tree densities and canopy dimensions and separations. There is, it seems, much scope for hedgerow designs within the current range defined by the present more common HD and SHD orchards.

5. Conclusions

Oil yield and quality respond, via responses to incident radiation, to structure in N–S oriented hedgerow olive orchards. Optimum row spacing for rectangular hedgerows occurs when canopy depth equals alley width, the difference between row spacing and canopy width. Narrow hedgerows provide greatest yields because at optimum spacing they allow most row length per hectare. Rhomboidal canopies, respond to improved irradiance patterns with greater yields mainly in wider canopies, in part achieved by reduction in optimum row spacing. There is much scope to devise structures between the current SHD and HD designs and manage them for high yield with attention to patterns of incident radiation. Preliminary analysis reveals how hedgerow design might also be used to manipulate oil quality, mainly stability and maturity index, aspects that determine preferences for cv. Arbequina oils.

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