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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

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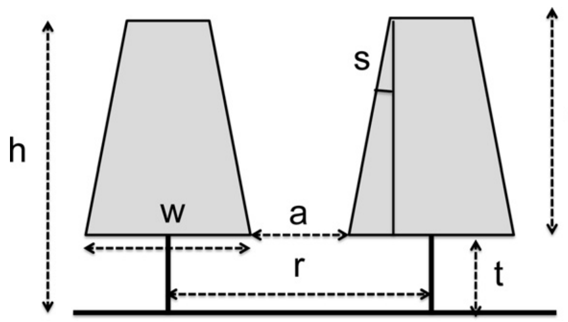

Fig. 1. Structural parameters of hedgerow orchards. Canopies have depth (d), slope (s) to vertical ($s = 0$ for rectangular canopies) and width (w) at the base. Row height (h) is $d + t$, where t is the height above ground level maintained free of canopy for ease of management. Individual hedgerows are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

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 ($s > 0$).

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):

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

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:

$$\text{Oleic acid} = -0.339x + 75.14 \quad (R^2 = 0.83)$$

$$\text{Palmitic acid} = 0.114x + 12.96 \quad (R^2 = 0.69)$$

$$\text{Stability} = 2.360x + 17.86 \quad (R^2 = 0.83)$$

$$\text{Maturity index} = 0.192x + 0.453 \quad (R^2 = 0.62)$$

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.