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Structure, management and productivity of hedgerow olive orchards: A review

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ABSTRACT

Olive was introduced into cultivation more than 3000 years ago, but only during the last two decades has cultivation shifted from low density to dense hedgerow orchards. This development responds to the need for mechanization to reduce production costs and achieve more timely management interventions. There is, however, little scientific or commercial knowledge available to support this new planting system in olive and to contribute to its development. This review focuses on what is known and what knowledge is required for design and management of hedgerow orchards for continuing productivity and economic viability. The review adopts a targeted approach based on consideration of the impact of orchard structure on microenvironment and production processes and oil quality. Particular emphasis is given to how orchard design and structure affect irradiance interception and how that determines productivity. The review also deals with establishment of orchards (cultivar selection, planting patterns, pruning for row formation) and maintenance of hedgerows for continuing productivity (irrigation, fertilization, pruning to maintain structure and productivity, control of pests and diseases, and regeneration of failed hedgerows). An important underlying consideration is the strong interaction between design and dimensions of both hedgerows and harvesting machines with examples taken from the two common, high density (HD) and super-high density (SHD) orchard designs. The search for new machine designs continues simultaneously with that for cultivars, orchard layouts, and pruning systems better suited to this new production system. Currently, only three cultivars ('Arbequina', 'Arbosana, 'Koroneiki') dominate SHD orchards. Over-row harvesters must match hedgerow dimensions while tree structure and fruiting behavior must suit the harvester. Context is provided by identifying reasons for major differences from traditional olive culture and attitudes from which most existing information on tree response and successful management practice has been accumulated. To account for these differences, terminology is proposed to define hedgerow structure that is required for effective management of oil production, oil quality, sanitary conditions, and profitability under various conditions. The review continues with discussions of requirements and current performance of mechanical harvesters and a comparative lifecycle economic analysis of alternative HD and SHD systems. The latter demonstrates the complexity of analysis and its importance to the choice of orchard design at the outset of each new project. The review concludes with recommendations for basic and applied research to determine optimal hedgerow structures and management for individual situations, development of new cultivars, and maintenance of hedgerow structure for continuing productivity.

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1. Introduction

Olive (*Olea europaea* L.) was introduced into cultivation over 3000 years ago and along with grape, date, and fig was one of the earliest tree-fruit additions to the previously grain-oriented agriculture of the Mediterranean Region (Zohary and Spiegel-Roy, 1975). Archeological remains and pollen cores provide evidence for cultivation 3500 BP in Turkey (Vermoere et al., 2003) and somewhat earlier in Crete (Riley, 2002). After early domestication in the eastern Mediterranean olive was spread west along trade routes on both sides of the Mediterranean Sea by the Phoenicians, Romans, and other human civilizations. However, some local selection from wild populations throughout Europe and North Africa likely occurred (Breton et al., 2006, 2009). Today, in the Mediterranean Basin, most orchards are rain-fed with tree densities in the range 100–300 trees ha^{-1}. To ensure survival through periods of drought (Connor, 2005), tree water requirement is reduced by pruning while losses to weed transpiration and soil evaporation are minimized by tillage. Well developed tolerance and avoidance mechanisms of olive trees (Connor and Fereres, 2005) greatly assist in resistance to drought, although under such conditions productivity is low and variable, as evident in a recent yield survey for Spain (Gómez-del-Campo and Barranco, 2009).

Hedgerow production systems are well established in many temperate fruit tree crops such as apple and peach (Robinson et al., 1991), but are relatively new in olive and currently occupy about 1% (80,000 ha) of the crop's global area of *ca* 10 Mha (Tous et al., 2010). They are, however, becoming the most common orchard design in new plantings, especially in non-traditional production zones away from the Mediterranean Region. Potential advantages relate to facilitating disease and pest control as well as irrigation and fertigation, but especially the rapidity and relatively small cost of mechanized harvesting and pruning (e.g., Tous et al., 2010). The major disadvantages are cost of establishment due to high plant density for SHD orchards and limited information on performance of optional orchard designs and cultivars in key locations. Early, high productivity offers compensation for initial investment, but longevity of hedgerow systems and management required to maintain it, are unknown.

Here, we consider hedgerows as rows of trees that present walls of foliage suited for continuous harvesting systems. Currently available machines comprise mostly straddle (over-row) canopy-contact harvesters of various sizes together with side-by-side trunk shakers (Tous et al., 2010) but other designs including lateral hedge harvesters are also being adapted. Harvesting is the key issue in olive production because without fast and efficient machinery it is too costly for economic viability and also it becomes too difficult to complete harvesting during sufficiently short periods to ensure high oil quality. Straddle harvesters are a fairly new application in olive production systems so there is a need to adjust orchard (structure, morphology and physiological responses) to machinery and in turn, machinery to orchard. This combination requires a new way of thinking about olive production systems that should open the way to a range of “optimum” solutions for individual growers, according to circumstance.

This review will focus on what is known and what knowledge is required for design and management of hedgerow orchards for high productivity and for how long that productivity can be sustained. The analysis draws on issues of olive physiology, cultivar selection, planting pattern, hedgerow structure and microclimate, pruning, nutrition, pest and disease control, and irrigation strategies. This in turn requires knowledge of many aspects of olive biology, but such information is available in other places (Lavee, 1996; Tattini et al., 1997; Connor and Fereres, 2005; Sibbett and Ferguson, 2005; Barranco et al., 2008; Conde et al., 2008). For this review, a more targeted approach is appropriate including the identification of ways in which modern hedgerow systems are likely to respond differently to traditional olive culture for which most existing information on tree response and successful management practice has been accumulated.

2. Hedgerows in context

Hedgerow orchards present geometrically consistent and simple structures with rows of evenly spaced trees grown to predetermined height and width and separated at equal distances from each other. Objectives of management are no longer individual widely spaced trees, as in traditional systems, but rather hedgerows, perhaps 100–200 m long, comprising many trees. Hedgerow dimensions are readily measured leading to straightforward calculations of vegetative cover, surface area, and interception of solar irradiance needed to estimate productivity and irrigation requirement.

In this section, we commence with the origins and critical importance of tree-machine interactions in hedgerow systems and then define hedgerow structure for further discussion of microclimate, management, and productivity.

2.1. Orchards adapted to machines and vice versa

The required fit between row dimensions and straddle harvesters is obvious. Less obvious, but also important, is impedance to forward progress of harvesters caused by density and stiffness of branches, and the relationship between structure and productivity, including fruit distribution. Straddle harvesters, and other emerging hedgerow contact designs, remove fruit most efficiently from or near canopy surfaces. Dense canopies encourage this distribution because olive fruit are produced on their periphery on 1-year-old shoots that have developed in high light environments. Side-by-side harvesters do not have the restrictions to row height and width of straddle harvesters and are more efficient when intra-row tree spacing requires fruit to be dislodged from fewer trees by shaking each main trunk rather than by “combing” the hedgerow walls, as in canopy-contact harvesters.

From a management perspective, the primary requirement of hedgerow design is that the distance between adjacent hedgerows (i.e. alley width) is sufficiently wide for entry of all equipment, and hedgerow dimensions and morphology are matched to the harvesting machinery. By comparison, machines for fertilization, spray application, and pruning are readily adapted to row geometry. Row dimensions refer to height, width and shape, while morphology refers to foliage density, porosity, and flexibility of branch structure, especially at the periphery of hedgerows. Two distinct olive hedgerow systems have evolved in recent decades.

In the first, high-density (HD) orchards which were planted during the 1980s and 90s at 250–400 trees ha^{-1} (in rows spaced 6–8 m apart) were intended for harvesting as individual trees using the then available mobile shaking equipment with umbrella-catch frames. Subsequently, side-by-side trunk and straddle harvesters were developed for HD plantations that formed tall, continuous hedgerows to 4–5 m height under high vigor conditions. There are now 100 large straddle machines (Colossus) in operation, mostly in Argentina and Australia, but also in Spain (Ravetti and Robb, 2010).

In the second system, commencing in 1995 in Spain (Rius and Lacarte, 2010), super high density (SHD) orchards were planted at 1500–2200 trees ha^{-1} in rows 3–4 m apart. These orchards were expressly intended for harvesting with small straddle harvesters that had been developed for harvesting grapes. Several models are now commercially available for different row heights from 2.5 to 3.5 m from such companies as New Holland, Gregoire, Maqtec and Pellenc. Lower cost favors smaller machines that now comprise the greater proportion of straddle harvesters in use in olive hedgerows in Australia, USA, Chile, Tunisia, Morocco, Portugal, and Spain (Tous et al., 2010). Further details of harvesters are presented in Section 6.

This dichotomy in development of two existing olive hedgerow systems exemplifies the importance of hedgerow-machine interaction. Harvesters were built for existing HD orchards in one case, while SHD orchards were planted to suit available commercial grape harvesters in the other. The future need not be a competition between the two extremes but rather a continuing and gradual adjustment of both harvesters and hedgerows. Developments in harvesting technology, cultivar characteristics, training, pruning, and orchard management must proceed together to improve performance for greater and more consistent productivity across a continuum of designs suited to individual growers. This also requires consideration of a range of economic and ecological factors including farm size, climate, topography and soil type, each of which can greatly influence the most suitable hedgerow-machine combination for each situation.

2.2. Defining canopy characteristics and hedgerow structure

Basic structural parameters of hedgerow orchards are row height, row spacing, row width (at base of canopy), canopy depth, row shape (e.g. rectangular or rhomboidal), and row orientation (Fig. 1). We will use the term canopy to refer to the entire system of leaves and shoots with accompanying fruits all of which are supported by the woody skeleton of the trees. Olive leaves are small (5–7 cm and 1–1.5 cm in length and width) (Barranco and Rallo, 2000) with high specific leaf mass (*ca* 230–260 g m^{-2}) and persist for two or more years in an evergreen canopy. Fruits are

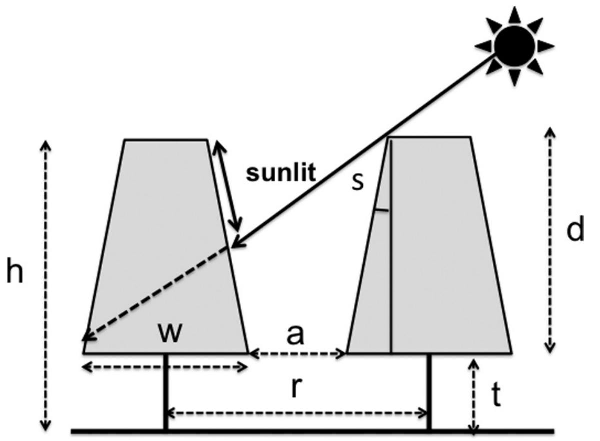

Fig. 1. Definition of structural parameters of hedgerow orchards. Canopies have depth (d), slope (s) to vertical ($s = 0$ for rectangular canopies) and width (w) at the base. Row height (h) is $d + t$, where t is the height above ground level maintained free of foliage for ease of management. Individual hedgerows are separated in planting lines, most commonly oriented N-–S, by distance (r) giving a free alley ($a = r–w$). In this case the solar beam is shown normal to row orientation.

small (mostly between 2 and 6 g fresh weight), develop during 6–8 months before harvesting, and while found throughout canopies they are concentrated in the periphery where leaves and fruits are displayed on flexible branches (Barranco and Rallo, 2000; Connor and Fereres, 2005).

Alley width is the difference between row spacing and canopy width, while canopy depth is row height less the height above ground maintained clear of foliage for management purposes. This geometry leads directly to important derived parameters that describe orchard structure on a hectare basis including row length and canopy surface area and volume. Geometry also determines fractional orchard cover (row width/row spacing) and, along with row height and orientation, canopy light interception that will be discussed more fully in Section 2.3.

Also important to canopy morphology are leaf area density (LAD, leaf area per unit volume, $m^2\,m^{-3}$), leaf spatial and angular distribution, and their visual result, porosity (ρ, %), the latter being the proportion of gap that varies with angle of sight through the hedgerow. Canopies can be described as open (narrow and/or low LAD) or closed (wide and/or high LAD). Various measurements of LAD are available. Rousseaux et al., 2009 consider open canopies to have LAD less than $2\,m^2\,m^{-3}$, and that this may be achieved by manual pruning and deficit irrigation. Values below $2\,m^{-2}\,m^{-3}$ were reported in several 'Arbequina' orchards by Villalobos et al., 2006 while Gómez-del-Campo et al., 2009 reported values of $2.5–2.7\,m^2\,m^{-3}$ in SHD hedgerows, which were also 'Arbequina'.

Porosity determines penetration of radiation into canopies for photosynthesis, air movement for ventilation to reduce pest and disease outbreaks, and also effectiveness of spray penetration for control when required. For these reasons, porosity should become a standard parameter for description of hedgerow structure, but few values have so far been published. Gómez-del-Campo et al., 2009 report horizontal porosity of 15% at mid canopy height (1–1.5 m) and an average of 37% in the newly growing upper parts of rectangular-shaped SHD hedgerows (2.0 m high and 0.8 m wide) in Spain.

2.3. Hedgerow structure and interception of solar radiation

Diurnal and seasonal variation in interception of direct beam solar radiation by hedgerow walls and alley floors, depicted in Fig. 1 in response to solar position, is the major driver of microclimate within hedgerow orchards. The literature on this subject in fruit tree orchards dates back several decades and is most recently concentrated in computer models (Cain, 1972; Jackson and Palmer, 1980; Gijzen and Goudriaan, 1989; Palmer, 1989; Annandale et al., 2004; Connor, 2006; Oyarzun et al., 2007). The diurnal progression of the Sun is accurately captured by few equations so that incidence patterns of direct beam solar irradiance, with added allowance for reflected and diffuse sky radiation, are readily determined depending on row dimensions and orientation, spacing, location

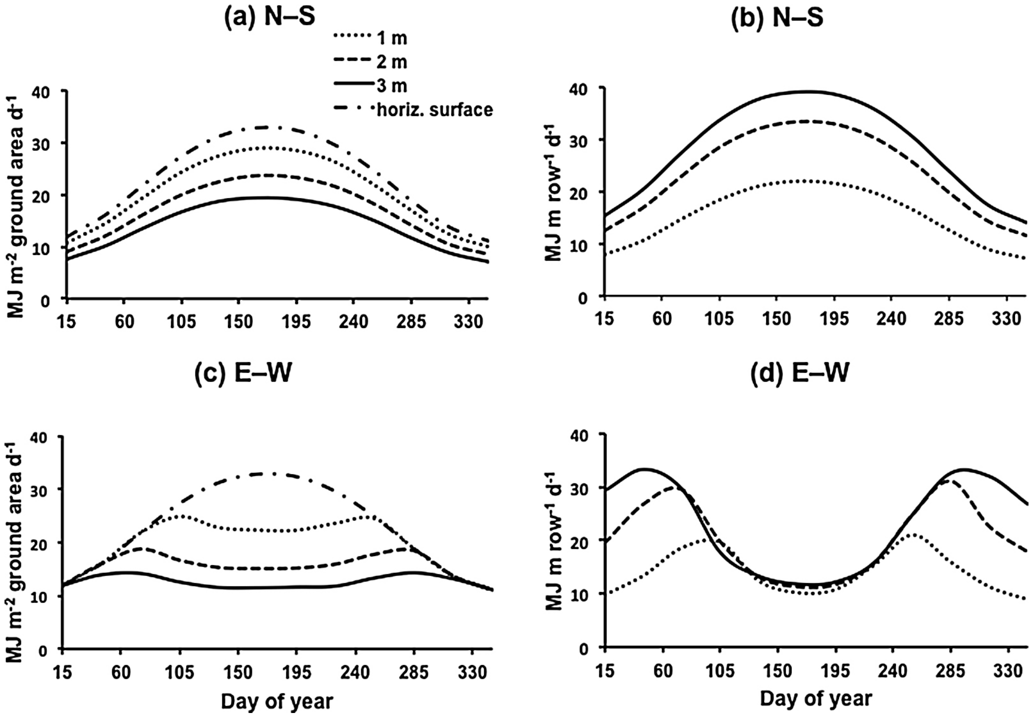

Fig. 2. Influence of row orientation (N–S and E–W) and alley width (1, 2 and 3 m) at 35°N on seasonal interception of direct beam radiation by rectangular hedgerow canopies 2 m deep and 1 m wide in (a and c) per unit orchard area and in (b and d) per unit row length on both walls of individual hedgerows.

(latitude), and day of year. Direct beam radiation is the key component because it comprises 90% of solar irradiance on clear-sky days.

Hedgerow orientation and the ratio of canopy depth to alley width determine the diurnal progression of sunlit length down canopy walls according to solar position. While hedgerow orientation is set at orchard establishment, solar altitude and azimuth vary diurnally and seasonally. Most orchards are planted N–S, but other orientations are used depending upon local circumstances.

Analyses identify important features of interception by crop and alley floor as follows:

- Latitude, orientation and day of year (doy) determine diurnal profiles of irradiance incident on hedgerow walls.
- Hedgerows with similar alley width and orientation have similar profiles of irradiance downwards from the top, irrespective of row height.
- Incidence patterns for N–S orchards are diurnally symmetrical on E- and W-facing walls. These walls receive strongest irradiance in mid-morning and mid-afternoon, respectively. Incidence is small at midday when solar azimuth coincides with row orientation.
- Incidence patterns for orchards of other orientations are asymmetrical. The greatest differences exist between N- and S-facing walls of E–W oriented hedgerows that also vary markedly during the year and between latitudes. S-facing (S hemisphere) and N-facing (N hemisphere) canopy walls only receive direct beam radiation for short periods during early morning and late afternoon from late Spring to early Autumn.
- Walls of E–W hedgerows receive less radiation in Summer and more in Winter, than those of N–S hedgerows.

To illustrate these points, Fig. 2 presents calculations using the model of Connor, 2006 of contrasting annual trends of direct beam irradiance on walls of non-porous ($\rho = 0\%$) hedgerows of rectangular shape (canopy depth = 2 m, width = 1 m) oriented both N–S and E–W and separated by alleys of 1, 2 and 3 m, respectively. In N–S hedgerows, the annual patterns of interception and wall irradiance follow that of horizontally incident solar irradiance according to alley width. Both increase to maxima during Summer and decrease through Autumn into Winter. The annual pattern in E–W hedgerows, is distinct. Interception and irradiance are both greater in Spring and Autumn and decline in Summer, again according to alley width. Irradiance is small during summer because the angle of incidence of direct radiation on canopy walls is small during much of the day and, with relatively high solar elevation, is unresponsive to the range of alley width included in Fig 2d.

More detail is provided in Fig. 3 in the form of irradiance profiles on contrasting orchard structures during the oil-filling period in Autumn (doy 285) at 35°N. Penetration to depth on canopy walls depends strongly on alley width, but again with differences between N–S and E–W oriented hedgerows, and in the latter case between N- and S-oriented walls. The low irradiance on N-facing walls suggests reliance for photosynthesis on radiation reflected from alley floor, adjacent sunlit walls and transmitted, depending on porosity, through the canopy from the sunlit S-facing wall. Neither effect is included in this analysis.

Measurements of porosity and interception are important to understanding the light relationships within hedgerow canopies, but so far little information is available for olive (Cherbiy-Hoffmann et al., 2012). Connor et al., 2009 used an exponential model (Saeki, 1963; Charles-Edwards, 1982) to estimate penetration of the solar beam from sunlit to shaded sides of E–W hedgerows but were unable to explain fruit growth there according to the simulated light environment.

The important point here is that research requirements for developing hedgerow systems are distinct to those that have dominated traditional orchards of open-spaced trees. For the latter, a management objective has been to maintain good light distribution throughout the canopy for greater fruit yield and higher quality oil (Tombesi and Standardi, 1977; Tombesi and Cartechini, 1986; Proietti et al., 2012). While pruning to open HD hedgerows may be advantageous, it is not, however, a suitable management objective for SHD hedgerows in which interception is best concentrated on high LAD at the periphery of narrow canopies where fruit are formed under high irradiance and are most accessible to straddle harvesting systems.

3. Microclimate and its impact on growth and production processes

Most studies on crop microclimate have been performed on full cover crops in which horizontal variation is small and so microclimate, as determined by the interaction of vegetation structure with processes of radiation balance, photosynthesis and transpiration, can be defined as vertical profiles of radiation, humidity, [CO_2], and wind speed (Rosenberg et al., 1983; Connor et al., 2011). The same processes apply within hedgerow orchards but the outcome is spatially more complicated resulting from the alternating structure of hedgerow and alley. As in full cover crops, however, microenvironment directly affects growth and physiological responses of vegetative (leaves and shoots) and reproductive (flowers, fruits) organs and indirectly affects these same responses through the depredations by pests and diseases favored by low light and high humidity.

Regretfully, to the best of our knowledge, there are no published reports of comprehensive micro-climatic studies of hedgerow olive orchards. The following discussion of microclimate and potential impact on physiological responses is developed from partial studies on olive and wider experience with other hedgerow crops.

3.1. Responses to irradiance

In traditional orchards planted at low density and highly pruned to maintain low leaf area, tree canopies are generally well-

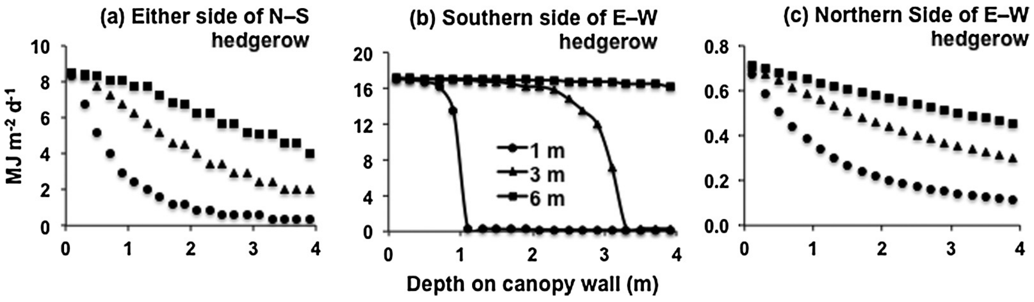

Fig. 3. Calculated profiles of daily shortwave irradiance on individual walls of 4 m deep rectangular hedgerow canopies in response to alley width (1, 3 and 6 m) on DOY 285 at 35°N. (a) Either side of N–S hedgerow, (b) Southern side of E–W hedgerow and (c) Northern side of E–W hedgerow.

illuminated and shading effects on fruit growth and oil content are relatively unimportant (Acebedo et al., 2002). Nevertheless, several past studies in such orchards have revealed that severe shading treatments in olive do affect many vegetative growth and fruit parameters (Tombesi and Standardi, 1977; Tombesi and Cartechini, 1986; Tombesi et al., 1999). More recent work in hedgerow systems is increasing the understanding of these relationships between vegetative and fruit growth and oil content and quality with irradiance.

3.1.1. *Light quality*

Solar radiation incident on hedgerow walls has a spectral range from 0.30–2.7 μm with most energy in the visible range, 0.40 μm (violet) to 0.70 μm (red) with a peak value around 0.51 μm (green). As radiation penetrates plant canopies it is subject to both differential absorption and reflection, dominantly by leaves, that also change the spectral distribution (light quality). Olive leaves are highly reflective to visible light (*ca.* 10–12%) and because of their high specific leaf mass (SLM, 180–220 g m^{-2}) have very low transmissivity (0.2%) (Mariscal et al., 2000a, 2000b). Green wavelengths are preferentially reflected (that is why leaves are green to the human eye) but there is also greater reflection of far-red light (FR, 0.70–0.85 μm) and preferential absorption by chlorophyll of red (R) and blue (0.48 μm) light.

The result is a gradual reduction within canopies of the R/FR ratio that results in morphological changes mediated by the chromophore phytochrome (Rousseaux et al., 1996). This effect is potentially enhanced in hedgerow systems because plants receive greater reflection of FR from neighboring rows without associated shading. Responses, recorded mostly in other species, include thinner leaves, faster leaf senescence, elongated shoots, and reduced flower induction (Ballaré et al., 1990, 1995; Botto and Smith, 2002; Franklin, 2008). Thus in olive hedgerows, effects of light quality may be enhanced height growth and modified flowering behavior as plant density increases. Both responses have practical consequences for the adaptability of olive cultivars to high-density hedgerow systems.

Selective shade cloth or reflective materials that increase R/FR within canopies are currently used in some horticultural crops (Bastías and Corelli-Grappadelli, 2012) and their use could be extended to olive production, if economically warranted, to improve flower induction, fruit quality, or modify plant architecture.

3.1.2. *Vegetative growth and development*

In terms of light quantity, detailed information on development and light relations within canopies have been reported from 5 m tall, N–S hedgerows of ‘Arbequina’ planted at 7 × 5 m, 286 trees ha^{-1} in Catamarca, Argentina (lat. 28.5°S) (Cherbiy-Hoffmann et al., 2012).

Key results are summarized in Fig 4 with irradiance measured as photosynthetically active radiation (PAR). The responses were generally bi-linear with low thresholds for maximum response. Threshold PAR values above which there was no further response were smallest for leaf production (4.9 mol m^{-2} day^{-1}), slightly greater for inflorescence density (6.3–7.2 mol m^{-2} day^{-1}) and greatest for fruit density (8.0 mol m^{-2} day^{-1}). Tombesi and Cartechini, 1986 have also reported higher sensitivity of floral initiation than vegetative growth to irradiance. These observations of greater requirement of illumination to maximize flowering compared to leaf production are consistent with observations that few fruit are found inside dense hedgerows. Illumination is greatest at and near the periphery of canopy walls depending on LAD, so experiments such as these provide a basis for establishing and managing optimum width of hedgerows for maximum production, i.e. to minimize unproductive volume per ha (Tombesi and Standardi, 1977).

No relationship between leaf production and PAR was found on the pruned side during the growing season following winter pruning because the head cuts generated by mechanical pruning resulted in strong regrowth across the entire exterior canopy independent of incident PAR. In contrast, inflorescence and fruit density were related to PAR on pruned sides when measured during the second growing season after pruning. These responses provide some insight into new pruning systems required to maintain productivity in hedgerow orchards (Section 5.3).

3.1.3. *Fruit density, size and oil content and quality*

Other experiments also reveal how fruit size, oil content and oil quality is related to incident irradiance on vertical walls of 12 N–S ‘Arbequina’ SHD hedgerows in Spain (lat. 37.5–39.9°N) (Connor et al., 2012). The data, presented in Fig. 5 demonstrate the importance of high illumination for large fruit size and high oil content. In these data, fruit density was well related to incident solar irradiance on the middle and lower parts of the canopy, but not towards the top. The explanation may be found in the response of new shoot growth after pruning to control hedgerow height. Using shade cloth to reduce PAR transmittance over 3the m tall ‘Arbequina’ trees during oil accumulation, Cherbiy-Hoffmann et al. (2013) similarly found that high irradiance is needed to maximize fruit size and oil yield.

Individual oil quality parameters also vary according to canopy position. Oils from fruit located in more exposed positions at tops of canopies in SHD orchards in Central Spain were more stable against oxidation, due to higher phenol content, along with higher contents of palmitic and linoleic but lower oleic acid (Gómez-del-Campo and García, 2012). Since these more exposed positions are subjected to higher temperatures, further work is warranted on individual and

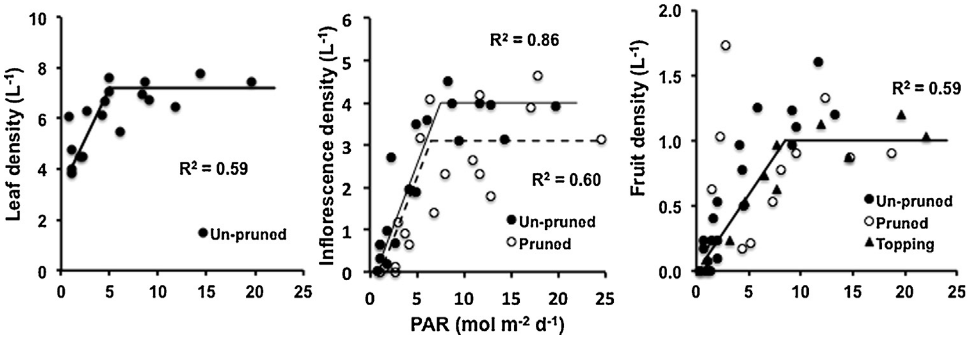

Fig. 4. Leaf, inflorescence and fruit density in relation to daily PAR irradiance within 5 m tall, N–S oriented ‘Arbequina’ hedgerows in Catamarca, Argentina (28.5°S). Bi-linear regressions, when appropriate, are indicated for unpruned and mechanically pruned sides as well as for the mechanically pruned hedgerow top. Leaf density is shown for the growing season following winter pruning, while inflorescence and fruit density are from the second growing season. The figure is adapted from Cherbiy-Hoffmann et al., 2012. 1.0 mol PAR = 0.48 MJ of shortwave radiation.

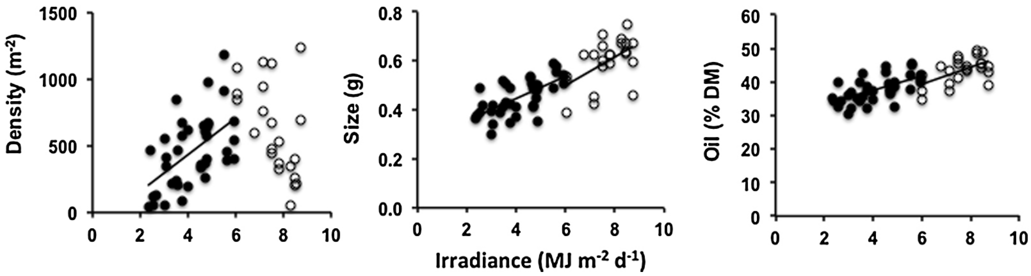

Fig. 5. Fruit density, size and oil content responses of 'Arbequina' hedgerows to daily shortwave irradiance on canopy walls during October (mid-oil filling) of 12 N–S oriented SHD orchards at 35°N in Spain (Connor et al., 2012). The empty symbols are for measurements made in the upper canopy where daily shortwave irradiance exceeded 6 MJ m^{-2} day^{-1}.

interactive effects of temperature and irradiance on maturity index and oil quality parameters.

3.1.4. *Orchard structure, canopy illumination and oil yield*

Simulations of oil yield of N–S oriented hedgerow orchards of rectangular shape presented in Fig. 6 combine simulations of irradiance on canopy walls (Fig. 3) with measured responses of fruit and oil yield to irradiance (Fig. 5). They provide guidelines for orchard design, revealing that orchard yield reaches a maximum when canopy depth equals alley width (row spacing–canopy width) and decreases at wider spacing, and/or with wider canopies, both of which reduce the length of hedgerows per ha. These responses are consistent with, and explain, some early experiences with olive hedgerow orchards. In Pastor et al., 2007, decreasing irradiance accompanied by inadequate control of vegetative growth, led to reduced fruit yield as the alleys narrowed and fruit distribution moved upwards with increasing canopy height. Severe pruning was needed to restore the possibility of mechanical harvesting.

Other simulations (Connor and Gómez-del-Campo, 2013) reveal that yield of wide canopies can be substantially increased by applying slopes to canopy walls, in part because sloping canopies improve light relations sufficiently to allow closer row spacing and hence provide more row length per unit orchard area. On a central issue to this review, other simulations suggest that high yields can be obtained within the wide range of high density (HD) to super-high density (SHD) orchards provided attention is paid to structure. For example, applying a 10° slope to a 4 m deep, 3 m wide HD canopy increases yield from 2060 to 2580 kg ha^{-1}, by a combination of greater irradiance and extra row length achieved by reducing row spacing from 7 to 6 m. Yield then is comparable to a 1 m wide, 2 m deep SHD canopy with row spacing of 3 m.

3.2. *Temperatures of leaves and fruit*

Ambient temperature, as measured above hedgerow orchards, results from the energy balance of surrounding areas and advection depending on wind speed and direction. This temperature is significantly modified within hedgerow canopies during daytime by interception of solar radiation (Section 2.3), ventilation due to wind, transpiration by leaves, and by heat exchange with exposed alleys that cool by evaporation when wetted or are heated when dry. During nighttime, dominant exchanges are loss of heat by long wave radiation emitted to clear skies and sensible heat gained from, or lost to, advected air.

Martínez-Cob and Faci, 2010 have presented the only study of energy balance of hedgerow olives. It was conducted in a commercial 57 ha 'Arbequina' orchard in north-east Spain, planted at 6×3 m with N–S row orientation and maintained at a canopy width of 2 m, row height of 3.5 m, and canopy depth of 2.5 m. The study concentrated on determining crop evapotranspiration from detailed measurements of radiation, humidity, and wind speed above the orchard using the eddy correlation method. The objective did not require measurements of environmental parameters within hedgerows. Energy balance principles and experience with other crops (Smart and Sinclair, 1976; Bergqvist et al., 2001; Saudreau et al., 2011) suggest, however, that heating and cooling of individual olive leaves, buds, flowers and fruit result in a range of temperatures that vary spatially, diurnally and seasonally above or below ambient temperature.

3.2.1. *Temperature patterns on opposing sides of hedgerows*

Olive hedgerows are commonly oriented N–S so that E- and W-facing walls receive the same daily irradiation before and after noon, but under different conditions of air temperature and vapor pressure deficit. The result, on clear sky days, is higher canopy temperature in the afternoon on W-facing walls than on E-facing walls in the morning. Additionally, there is less opportunity for transpiration to cool leaves after noon on W-facing walls, because stomatal closure is then very common in olive. Stomata of olive are sensitive to VPD with a feed-forward response evident in many observations of diurnal leaf conductance (Fernández et al., 1997; Moriana et al., 2002; Rousseaux et al., 2008). Similar results have also been seen

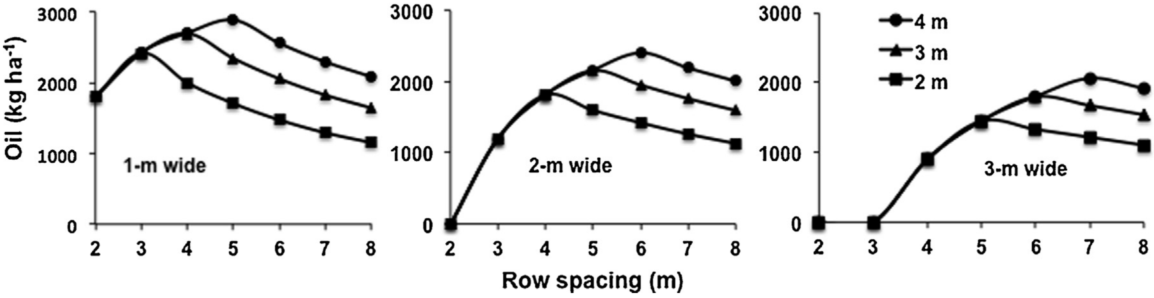

Fig. 6. Simulated responses of oil yield of rectangular hedgerow olive orchards to row spacing (2–8 m) for different hedgerow widths (1, 2 and 3 m) and heights (2, 3 and 4 m). The Figure is adapted from Connor and Gómez-del-Campo, 2013.

in a whole-tree study conducted in large transparent chambers (Villalobos et al., 2012).

Detailed measurements are needed to quantify and understand the importance of temperature differences on yield and oil quality between opposing sides of hedgerows. Overall, manipulations of hedgerow structure and orientation present opportunities to vary growing conditions, diurnally and seasonally, for photosynthesis and fruit metabolic activity in response to combined regimes of temperature and irradiance.

3.2.2. Fruit and leaf temperature

Olive fruit, unlike leaves, are not effectively cooled by transpiration because they have few and mostly inoperative stomata (Proietti et al., 1999). Thus, exposed fruit will experience higher temperature than leaves when sunlit, while shaded fruit within canopies may benefit from lower-than-ambient temperature caused by transpiration of surrounding leaves.

In a study of fruit pulp temperature, Orlandini et al., 2005 measured internal temperature of exposed fruit diurnally on N, S, E and W sides of widely-spaced olive trees in Tuscany, Italy. The data revealed how, on sunny days, fruit reached maximum temperature sequentially on E-, S-, and W-facing sides while fruit on the N side tended to follow ambient air temperature, as did fruit in all positions during cloudy days. On sunny days, fruit temperatures rose to 10 °C above air temperature with the greatest temperatures recorded on both S- and W-facing sides.

These data are consistent with some responses of exposed and shaded leaves and fruit in olive hedgerows on a calm sunny day in La Rioja, Argentina, that are presented in Table 1. In this case, leaves in the canopy periphery were at air temperature, while those within were 5 °C cooler. This reveals the impact of transpiration in lowering leaf temperature. In comparison, fruits were always warmer than leaves (2–6 °C). When transpiration is limited by water supply, temperature of leaves and fruits can increase substantially above air temperature. Canopy temperature has been studied as a water stress index in olive (Berni et al., 2009) while remote sensing of canopy temperature by thermal imaging now provides indirect estimates of water status that can be employed in irrigation management (Sepulcre-Cantó et al., 2006; Ben-Gal et al., 2009).

The differences in temperature recorded in both studies (Orlandini et al., 2005) and in La Rioja, Argentina, are sufficient to impact fruit growth and oil accumulation and quality. In olive, oleic acid content decreases with increasing temperature (Lombardo et al., 2008; Rondanini et al., 2011) and a positive relation has been shown, in cool areas, between total polyphenol content and temperature during the last three months before harvest (Tura et al., 2008).

The Tuscan study (Orlandini et al., 2005) also reveals an indirect impact of fruit temperature mediated by infestation by olive fly (*Bactrocera oleae*), which is a serious cause of premature fruit fall, yield reduction and decrease in oil quality due to changes in organoleptic properties and greater acidity. Infestations develop more quickly as temperature increases but survival is limited to temperatures below 36 °C. In that study, seasonal data on fruit temperature provided the opportunity to improve a simulation model of the development of olive fly infestations previously developed using ambient temperature.

Table 1
Temperatures of air, leaf, and fruit on canopy surfaces or within canopies of N–S oriented ‘Arbequina’ hedgerows at veraison on a sunny, calm day (April 11, 2012; 13–14 h solar time, lat. 28.55°S, long. 66.51°W). Air temperatures were measured in the alley with a shaded thermocouple sensor. For leaves, thermocouples were placed on the shaded abaxial surface. For fruit, they were inserted into the pulp of sunlit and shaded sides of individual fruits. Measurements are averages for 10 fruits and leaves (García Inza and Rousseaux, unpublished).

Position in canopy	Temperature (°C)			
	Air	Leaf	Fruit	
			Sunlit-side	Shaded-side
External	30.4	30.8	33.7	32.7
Internal	30.3	25.4	31.4	31.4

While there are relatively few temperature data for olive, the information available suggests the following generalizations.

- Leaf, but especially, fruit temperatures on sunlit sides will exceed those of shaded sides. In the case of fruit, the difference may rise to 10 °C at midday.
- Temperatures on sunlit canopy walls will decrease with depth from the top of canopies according to profiles of irradiance.
- Temperatures will be higher at the periphery than within canopies.
- During calm, clear-sky nights, temperatures may fall 1–3 °C below air temperature and hence be more susceptible to frost damage, especially in lower parts of hedgerows.
- In environments where low night temperatures are common, hedgerows should be oriented to allow cold air to move through orchards and not be trapped within them (see Section 4.3).

3.3. Humidity and air movement

Disease has been identified as a potentially serious problem of olive hedgerow orchards (Tous et al., 2010) due to high humidity and mild temperature conditions that often accompany high foliage density and narrow alleys. Special attention is required for orchard design and management in order to reduce this hazard (Lazzaro et al., 2008).

The level of humidity within hedgerow canopies is a balance between increase in water vapor due to evaporation of foliage wetted by rain, dew and frost, transpiration by leaves, and losses by diffusion and bulk air movement to alleys and from there onto ambient air outside the orchard. In micro-meteorological terms, the degree of ventilation is related to the amount of “coupling” between vegetation and atmosphere. With increasing plant density, there is less coupling and the vegetation becomes more isolated from the external air.

Hedgerow orientation, dimensions, and morphology play an important role here. For each location, row orientation determines the relative frequency that wind moves down or across hedgerows. Strong winds channeled down alleys increase coupling with the atmosphere leading to more thorough ventilation of hedgerows. Narrow and porous hedgerows allow air to move inside the canopy and reduce humidity that allows leaves and fruits to dry more quickly after wetting. There are, however, no published guidelines for orchard layout or management to minimize disease incidence in olive hedgerow orchards. This aspect of hedgerow microclimate deserves serious study.

3.4. Evapotranspiration and water requirement

Crops lose water to the atmosphere (evapotranspiration, ET) by transpiration from vegetation and evaporation from bare soil. Irrigation practice requires knowledge of water demand (ET_c) of individual orchards to maintain trees within the desired range of water status. This requires measurements of weather parameters and knowledge of soil water-holding characteristics that can be improved by measurement of soil and/or plant water status using a range of direct and indirect techniques (Jones, 2004; Naor, 2006).

The standard method to estimate crop water demand (ET_c) uses the equation $ET_c = ET_o \times K_c$ (Steduto et al., 2012). ET_o, the evapotranspiration of a well-watered reference crop, is an expression of atmospheric water demand that can be calculated accurately from environmental variables of solar radiation, temperature, humidity and wind speed that are best measured at sites of individual orchards (Allen et al., 1998). The crop coefficient (K_c) relates orchard evapotranspiration to that of the reference crop, accounting for morphological and physiological differences as well as crop cover. Steduto et al., 2012 have recently compiled values of K_c used for olive orchards in many growing regions. The range is quite wide (0.50–0.75) with average values around 0.55–0.65. The authors point out that K_c values are not constant throughout the year and also vary because tree transpiration responds to endogenous as well as environmental factors. They provide recommended K_c values for olive irrigation management for semi-arid and arid regions through the four seasons and for implementation of deficit irrigation, but potential differences between hedgerow and traditional orchards are not considered.

Recent developments to improve the estimation of water requirement for olive have decomposed K_c to account separately for tree transpiration (T) and soil evaporation (E_s) according to tree cover and have also included spatial patterns of soil wetting characteristic of drip irrigation in semi-arid climates (Bonachela et al., 1999, 2001; Orgaz et al., 2006, 2007; Rousseaux et al., 2009). An unexplored challenge for determining water demand of hedgerow orchards involves consideration of row orientation. Although vegetative cover for given combinations of row width and row spacing is independent of orientation, interception of solar radiation, an effectively linear determinant of ET_o, is not. Following this relationship, Fig. 7 compares interception of radiation by similar hedgerow structures, 2 m deep and 1 m wide with alley widths of 1, 2, and 3 m, oriented either N–S or E–W. The soil cover of these orchards according to alley width is 50, 33 and 25%, respectively. Fractional interception of solar radiation is, however, greater than fractional vegetative cover and orientation exerts a strong seasonal control over interception. E–W hedgerows intercept less radiation than N–S counterparts during the Summer irrigation period (69, 47, 36 *v.* 88, 72, 59%) leading to less water demand than when calculated against radiation intercepted rather than when estimated from cover. On the other hand, E–W hedgerows intercept more radiation in winter, respectively, 100 *vs.* 90, 77, 64%, for the three alley widths, respectively.

3.5. Concluding remarks

The increase in plant density that has characterized changes in olive orchard design over the last two decades, and the move towards hedgerows with dense canopies, has introduced an orchard microclimate distinct to that of traditional low-density orchards of isolated trees. Modifications include changes in total light interception and spectral composition, temperature, and also in air humidity and air movement. These micro-environmental changes can impact significantly on plant architecture, flower induction and water use, and oil production and quality. Most of these issues have been little considered in existing studies in olive and more attention is warranted to assist improvement in design and management of hedgerow orchards.

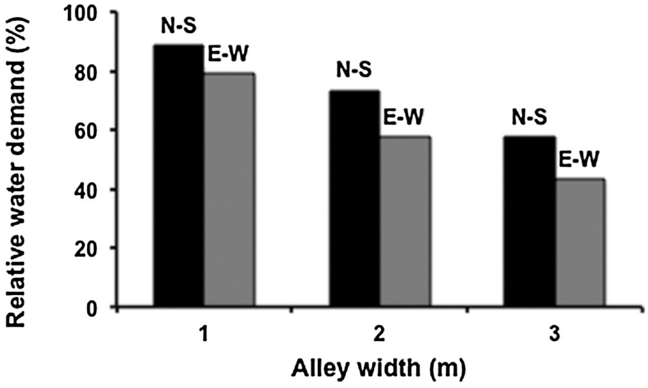

Fig. 7. Effect of alley width on relative water demand estimated from interception of shortwave radiation during the irrigation season in hedgerow orchards at 35°N. The hedgerows are 2 m deep, 1 m wide and oriented either north-south (N–S) or east-west (E–W).

4. Establishing hedgerows for high productivity and ease of management

Olive has been cultivated for many centuries in the Mediterranean Basin where climatic conditions combine mild, rainy winters and warm–hot, dry summers. Topography is quite variable, but soils are commonly alkaline. This long experience has identified the combinations of climate, soil, and topography most suited to olive production. The challenge now is to apply that experience to hedgerow production, including to other areas, often at lower latitude and with summer rainfall. This section also emphasizes guidelines that relate the importance of matching the desired hedgerow dimensions to those of the harvesting machinery. That combination must be established at the outset by considering, based on location and orchard size, the appropriate row spacing for the intended hedgerow width and height in order to later maintain the desired productivity (see Section 5).

4.1. Location

4.1.1. Temperature

Temperature is a key climatic factor in determining production and oil quality (see 3.2.2). Olive is sensitive to low temperatures in terms of frost damage, but requires winter chilling for breaking dormancy of floral buds formed in the previous growing season (Hartmann and Porlingis, 1958; Rallo and Martin, 1991; Orlandi et al., 2003; De Melo-Abreu et al., 2004). As a general rule, the geographical growing area for olive is found where temperatures are not less than −8 °C, although in some cases mature trees can survive −12 to −18 °C with adequate winter acclimation (Fiorino and Mancuso, 2000). Reproductive structures, buds, inflorescences, and fruit are very sensitive to frost (Graniti et al., 2011) and fruit can be damaged even at −1.7 °C (Sergeeva, 2010).

The northern margin of olive production (northern hemisphere) is well tested in Spain and Italy where the most cold tolerant cultivars have been developed and where experience has identified frost-prone areas in the topography. Even in such regions, large differences in frost resistance are common between cultivars. For example, studies have shown ‘Cornicabra’ and ‘Arbequina’ to be the most cold resistant of eight Spanish cultivars (Barranco et al., 2005) and ‘Bouteillan’ of 12 French and Italian cultivars evaluated by (Bartolozzi and Fontanazza, 1999).

Applying such knowledge of temperature responses to new growing regions raises an important issue of data availability and interpretation. Temperature records from meteorological stations in mountainous, or even hilly, areas do not have wide geographic application and so must be utilized with caution. This applies especially to estimates of chilling requirements and cold tolerance. Examples are seen in the recent experience in Argentina where hedgerow plantings have extended into pre-Andean valleys in La Rioja and Catamarca (latitudes 27–31°S, altitude 350–1400 m). There, frost damage, flowering intensity of some cultivars, and oleic acid content in the oils of others have shown great variability. While calculations based on meteorological data using chilling models such as that of De Melo-Abreu et al. (2004) have successfully predicted flowering in many instances, failures have also been recorded over short distances due to topography.

In the same way, estimates of likely frost damage based on data obtained from meteorological stations can be misleading. Again taking the example of pre-Andean valleys of Argentina, suitable thermal regimes for reproductive development are found around the periphery of high mountain valleys but with danger of frost where cold air drains through the orchards to the valley floor below. Small differences of elevation around this periphery result in large differences in minimum temperature and duration. On some winter days, minimum temperatures at the same altitude can vary from −5 to −10 °C for durations of 4–10 h within a distance of several km due to slope. The solution is to avoid valley locations where cold air accumulates and locate orchards higher in the foothills. Here, row orientation can also play an important role by ensuring that the cold air is not trapped in orchards (Section 4.2).

Temperatures during the growing season are also important to productivity and thus are relevant to site selection. For example, temperatures above 33 °C have been shown to reduce fruit set (Graniti et al., 2011), particularly when accompanied by low relative humidity that together reduce stigma receptivity and growth of pollen tubes (Vuletin Selak et al., 2013). After fruit set, the duration of fruit growth and oil accumulation seem to be shortened by high daily maximum temperatures (Trentacoste et al., 2012), and high temperatures appear also to reduce oil concentration (Rondanini et al., 2014).

4.1.2. *Common diseases*

When establishing hedgerow orchards, conditions that contribute to development of long-term disease problems must be considered. Soil diseases such as *Verticillium, Armillaria and Rossellinia* limit olive cultivation. Inoculum of the devastating vascular disease *Verticillium dahliae* has been detected in almost all regions where olive is cultivated. Potentially infected fields in close proximity to susceptible host crops (cotton, potato, tomato, alfalfa) should be avoided (López-Escudero et al., 2004).

Even in fairly young hedgerows, dense foliage increases humidity in canopies that encourages disease development and also often prevents penetration of sprays from current equipment. In olive, high humidity favors the development of *Spilocaea oleagina* (olive peacock spot), *Pseudocercospora cladosporioides* (olive cercosporiose), and *Colletotrichum spp.* (olive anthracnose). The most important impact of *Spilocaea oleagina* is defoliation of trees, with resultant weakening and loss of productivity. In some cases, infections cause fruit peduncles to fall with an additional direct effect on yield. *Pseudocercospora* affects all leaves and above all fruits, again causing severe defoliation, weakening trees and causing fruit loss that reduces oil yield and quality. *Colletotrichum* causes fruit decay, associated with a notable loss of weight and premature fruit fall, resulting in fruit with high acidity and low quality.

4.1.3. *Soils*

In contrast to many fruit-tree crops, olive can establish well in calcareous soils (Melgar et al., 2006, 2009; Tattini and Traversi, 2009) but can also thrive on moderately acidic soils. In practice, productive orchards are found on soils with pH in the range 5.5–8.5. Soil texture and depth are likely to affect tree growth due their effect on soil water holding capacity and yet olive trees can grow in both sand and clay soils of varying depth, with irrigation as required. Unlike soil texture and water holding capacity, inherent infertility can be corrected with fertilizer (Section 5.2) and in fact low, managed fertility is advantageous for control of vegetative growth that in turn increases porosity, reduces the need for pruning, and provides less competition with fruit and oil production.

In many regions, excess water (i.e., waterlogging) is the most important soil limitation to successful production. Olive roots are sensitive to oxygen supply such that young trees can survive waterlogged conditions for only 3–4 days, with susceptibility increasing during active growth periods (Navarro and Parra, 2008). Since even short periods of waterlogging can have disastrous results on orchard productivity and survival, susceptible locations usually found on poorly drained, light textured soils should be avoided as should also salinity and frost prone areas. In less severely affected locations, consideration can be given to installing drainage systems or planting trees on raised beds.

Heavy machinery cannot function properly when the soil is wet in orchards with fine-textured, clay soils. Given that rainfall is common during the autumn-harvesting period in many olive-growing regions, soil type can be restrictive to heavy machinery, in which cases orchard designs that require heavy machinery should rejected at the outset.

4.2. *Topography and orchard size*

Topography and intended orchard size must be considered in the design of hedgerow orchards. Microclimatic effects were discussed in Section 3 and the hazard of waterlogging in the previous section. In addition to these factors, aspect and slope are important considerations in site selection.

There are large differences in microclimate between south- and north-facing slopes resulting from exposure to solar radiation and consequent effects on temperature regime. For reasons of productivity, south facing slopes are generally favored in northern and avoided in southern latitudes. At low latitudes, high altitudes provide cooler locations, noting that mean temperature decreases by 0.5–0.6 °C for each 100 m increase in elevation.

Slope also determines row orientation. If it is too great to allow safe operation of machinery up-down slopes, or preserving soils intact from erosion, then contour planting is required. While modified grape harvesters can operate in orchards with slopes of 20%, larger harvesters (e.g. Colossus) are limited to 5% (Section 6). Although much remains to be learnt about the relationship between orientation and yield (Section 4.4), cross-slope rows do impede air drainage, and can cause frosting in orchards where cold air drainage is prevented (Section 4.1).

Unless contract services are available for harvesting, orchard size is a further determinant of machinery size because of high purchase cost (see Sections 6.3 and 7.2).

4.3. *Cultivars suited to hedgerow systems*

There are cultivar characteristics that are generally desirable for all hedgerow systems. They include: (1) flexible branches and central axes that are easily trained during early years; (2) early, followed by high and consistent production of oil with quality valued by consumers; and (3) low vegetative vigor and compact growth to facilitate continuous harvesting systems in SHD orchards by small harvesting machines. Early yield is essential for rapid recovery of high establishment costs (Section 7). Under appropriate meteorological and management conditions, consistent production can be largely achieved by planting cultivars with inherently little alternate bearing.

To date, only three cultivars of low vigour (‘Arbequina’, ‘Arbosana’ and ‘Koroneiki’) have been found widely suitable for SHD hedgerow orchards. Clones of these cultivars make up the vast majority of orchards planted in hedgerow systems in Spain (Tous et al., 2011), Italy (Godini et al., 2011) and Tunisia (Larbi et al., 2011). Of these cultivars ‘Arbequina’ is by far the most widely planted. Other proposed low-vigor selections and cultivars include ‘FS-17’ (Fontanazza et al., 1998), ‘Urano’ (Sonnoli, 2001) and ‘Tosca’ from Italy (Sonnoli, 2009) and ‘Askal’ from Israel (Lavee et al., 2003). So far in Spain, one new cultivar ‘Sikitita’ (Rallo et al., 2008), a cross between ‘Picual’ and ‘Arbequina’, has been bred specifically for hedgerow systems. In France, two promising possibilities, ‘Charmille’ and ‘AJ-17’, have been identified from a selection of new genotypes (Moutier et al., 2011). Some more traditional cultivars such as ‘Maurino’ from Tuscany (Italy) may also adapt well under SHD conditions (Tombesi et al., 2011).

In contrast, a wide range of cultivars has been planted in HD hedgerow systems. No special selections were made when these orchards were planted because the trees were intended to have discontinuous vase-shaped canopies. However, where climatic and soil conditions provoked, and orchard management allowed, rapid growth and development converted these plantings into continuous hedgerows. Such HD orchards can be found in Argentina where the main cultivars are ‘Arbequina’, ‘Arauco’, ‘Manzanilla de Sevilla’, ‘Coratina’, ‘Picual’, ‘Barnea’, ‘Frantoio’, and ‘Hojiblanca’ (Gómez-del-Campo et al., 2010) and in Australia are ‘Arbequina’, ‘Barnea’, ‘Coratina’, ‘Correggiola’, ‘Frantoio’, ‘Leccino’, ‘Nevadillo’, and ‘Picual’.

As hedgerow production systems develop, it is likely that cultivars will emerge that are better adapted to particular densities, planting patterns, and harvesting systems, but this will require a serious commitment to research in many aspects of hedgerow structure and function and exchange of information between researchers and industry.

4.4. Planting patterns

In hedgerows, trees are planted at closer distances within than between rows. The result is more rapid early growth to fill the hedgerow volume, more intense competition between trees within rows, earlier yield to repay the large investment in trees and their training, and provision of a tree form amenable to pruning to maintain the desired hedgerow structure and continuing productivity. Optimum tree density and row spacing is an economic question depending on costs of trees, their maintenance, cost of harvesting, and prices obtained for fruit. Economics of production are discussed in Section 7, here we discuss principles of plant response that underpin initial decisions on orchard design and continuing management with focus on hedgerow systems supplied with irrigation and nutrition as required.

4.4.1. Pollinizers

Olive is pollinated by wind and is partially self-incompatible so more than one cultivar should be planted to reduce production of shot berries and increase fruit set for higher yield. Cross-pollination has not been an important matter for traditional olive areas because many cultivars were planted in close proximity. However, for isolated and /or new orchards, production benefits from inclusion of pollinizers are evident, e.g., with cv. ‘Manzanilla’ in United States and Israel (Lavee and Datt, 1978). Some authors have proposed 30–40 m as the maximum distance from which pollinizers are effective (Griggs et al., 1975). In contrast, Cuevas et al., 2001 found effective cross-pollination at distances of 250–500 m and Morettini, 1972 at 12 km. Information about the most successful cross-compatible cultivar combinations is scarce and often contradictory (Morettini, 1972; Griggs et al., 1975; Cuevas et al., 2001). For ‘Arbequina’, the most important SHD cultivar, ‘Picual’ is considered a suitable pollen donor (Diaz et al., 2006).

Seasonal variation in pollen viability and flowering times identifies the importance of selecting donor cultivars and how they are most effectively deployed in individual orchards. The objective is to produce high and consistent yields that do not inhibit the flower induction process so, unless fruit are thinned chemically, this is best accomplished with a pollination deficit. The problem is to define and achieve such a level. Security suggests the advantage of using more than one donor cultivar, perhaps three or four, because a single best pollinizer is rarely identifiable. In small orchards, it is desirable to interplant a second cultivar with a proportion not lower than 10% of the main cultivar (Tombesi, 2003). In hedgerow systems, harvesting is simplified by planting of pollinizers in individual rows, although in large orchards, individual blocks may contain single cultivars. Nevertheless, it is important to indicate that pollination design for SHD orchards is still a largely unresolved question that must address not only the number and identity of pollinizers but also their proportion and distribution.

4.4.2. Density and early productivity

Along with growing conditions, intra-row density is the primary determinant of the duration required for individual plants to form mature hedgerow orchards. Two milestones include: (1) when the main stem exceeds the intended height for the hedgerow; and (2) when canopy width reduces alley width below that required for maximum yield or access by harvest machinery. When these milestones are reached, the orchard establishment phase is completed and the maintenance of hedgerows becomes important (see Section 5). For irrigated SHD orchards, the durations involved are relatively short. Softwood cuttings, 25–30 cm tall, can reach 2.5–3.0 m in 3 years after planting at intra-row spacing of 1.5 m and form canopies 0.8–1.0 m wide (Pastor et al., 2007; Camposeo and Godini, 2010; Godini et al., 2011).

In young plantings, there are strong positive relationships between yield and density that are gradually lost as hedgerows grow and trees compete for light. One potential production model is presented in Fig. 8 for hedgerows that are managed for canopy height and width. During establishment years, trees are small and differences in production per hectare are directly related to tree density. As time progresses, differences in production between tree densities become less important as individual trees occupy their allotted space and competition for light between trees begins to influence production. This theoretical evolution of orchard production as a function of density has been shown in olive trials with expected deviations due to impact of yearly climatic conditions (Tous et al., 1999; Leon et al., 2007). The advantage of high density is found in more rapid attainment of maximum yield. SHD orchards start producing in the second year and full production will be obtained from year 2–7. In HD orchards (300 olives/ha), full production will be achieved between years 7–10 (Tous et al., 2010).

Claims for high early productivity of SHD hedgerow orchards are substantiated by reports from Spain (Tous et al., 2011) and Italy (Godini et al., 2011). Reports from experimental orchards in two Spanish and one Italian location compare early productivity of three

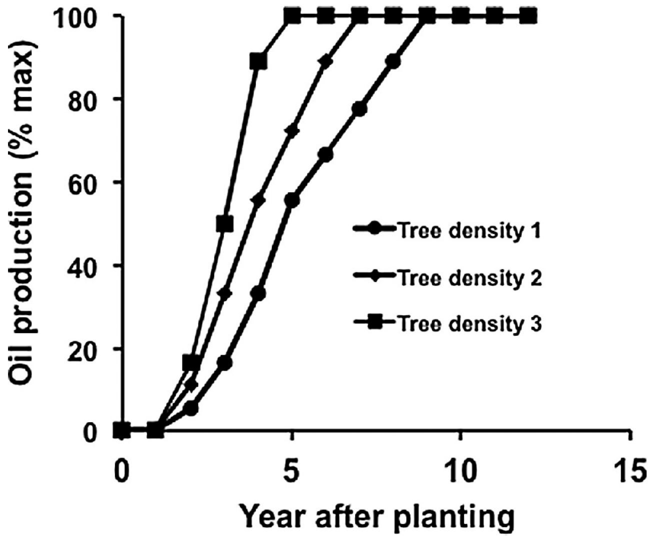

Fig. 8. Theoretical evolution of oil production in response to tree density. Densities 2 and 3 are, respectively, double and triple that of density 1.

cultivars, ‘Abequina’, ‘Arbosana’, and ‘Koroneiki’. Harvestable fresh weight fruit yields in the second year in Spain were 1.24 t ha^{-1} for ‘Arbequina’ and 0.90 t ha^{-1} for ‘Arbosana’ at Tarragona and 3.60 t ha^{-1} for ‘Koroneiki’ at Córdoba. Average yields for years 3–6 at Córdoba and Tarragona and for years 3–4 at Valenzano (Italy) reveal less difference in yield between cultivars than between sites. Córdoba was the most productive site in these studies with mean yield of 12.66 t ha^{-1} for the three cultivars, while Tarragona was the least with 7.39 t ha^{-1}. Overall yields of ‘Arbequina’ and ‘Arbosana’ at the Spanish and Italian sites were comparable (9.96 and 9.46 t ha^{-1}) and greater than ’Koroneiki’ (8.80 t ha^{-1}). Oil contents at Tarragona were 21.9, 19.8 and 22.9% of fresh weight for the three cultivars. The Italian study also included ‘Coratina’ and ‘Urano’ which yielded averages of 7.61 and 7.05 ha^{-1}, respectively, over years 3–4.

An important remaining issue is that, as yet, no convincing data are available for long-term yield trends in well-managed hedgerows of any configurations in the HD–SHD range. In other words how applicable is the model presented in Fig. 8 to long-term productivity, or the assumptions of longevity need for analyses of economic profitability in Section 7?

4.4.3. *Length and orientation of rows*

Length of rows is a matter for practical consideration during harvest. Some harvesters supply harvested fruit continuously to containers moving at the same speed in an adjacent alley. In this case there is no limit to row length and long rows are more efficiently harvested because less time is devoted to turning and entering adjacent rows. Also, less land is allocated for turning bays, considering that at least 8 m is required for small and 15 m for large harvesters. Considerations are distinct for harvesters that gradually fill their own bins. Bin capacity and hedgerow productivity determine the appropriate length. For example, a maximum length may be 200 m for small harvesters. The consequence is that large orchards are best planted in blocks that provide optimal row lengths for the intended harvester.

Potential effects of row orientation on crop performance were discussed in Section 3 in terms of oil yield and water demand. No differences in oil yield were detected between E- and W-facing walls in 12 N–S orchards in Central Spain (Connor et al., 2009; Gómez-del-Campo et al., 2009). These results may be a function of equal insolation and consequently similar photosynthetic assimilation on E- and W-facing walls, although considerations of leaf temperature, stomatal conductance and other factors might suggest a yield advantage on E-facing walls in some instances. In contrast, some tendencies in yield on opposing walls were observed in seven E–W oriented orchards in Spain and Argentina (Table 2). Fruit yield on sunny walls (N- or S-facing depending on hemisphere) was greater in three of the seven hedgerows examined, and the oil yield response was similar. In terms of yield profiles down individual hedgerow walls, it was possible, for the Spanish orchards, to relate fruit size and oil content to intercepted radiation for N–S but not for E–W orientations (Connor et al., 2009). Light transmission, which is greater for the same porosity in E–W than N–S oriented hedgerows may explain some of the response and deserves further analysis. However, the partition of assimilates produced by photosynthesis within unequally illuminated hedgerows is unknown, and translocation could play an important role in maintaining the productivity of shaded sides of E–W hedgerows.

There are, however, some other data available. Tous et al., 2012 report a comparison of productivity of N–S and E–W oriented orchards of ’Arbequina’ (4.0 × 1.5 m) at Tarragona, Spain (lat. 41 °N) during 2001–2009. No differences in yield were reported in the first three harvests (2003–2005) but in the following three years, yield of N–S hedgerows was always greater, with an average yield of 7.2 t ha^{-1}, compared with 4.2 t ha^{-1} from E–W hedgerows. Unfortunately, the study does not report differences in hedgerow structure other than orientation.

Optimization of oil production and oil quality based on row orientation is not sufficiently clear at present to allow for decision-making in orchard design. Rather, choice of orientation will depend on other aspects, including ease of machine movement and the conflicting requirements of erosion control and the need to facilitate drainage of water or cold air in wet or cold areas. For the former, hedgerows are best planted on the contour while for the latter up/down slope. In the newly planted areas in NW Argentina, other observations suggest that rows should be in the direction of the dominant wind to reduce branch breakage. E–W orientations should be avoided in cold areas where low solar radiation on the shaded-faces during the winter may lead to greater frost damage, high leaf humidity, and greater disease presence.

4.5. *Management for row formation and early productivity*

Irrigation of young trees is best directed towards maximizing growth in the first years after establishment without causing waterlogging. Some guidelines are presented by Testi et al., 2004 and Gómez-del-Campo, 2010. A practical consideration is that optimal soil water content should be maintained in the small root volume of young trees. One method to achieve this with drip irrigation is to include extra emitters that will not be needed once the orchard is established. Extending irrigation duration in young orchards wets much larger-than-needed areas and soil volumes and is inefficient because much water is lost to evaporation and drainage.

Proper plant nutrient status is also required to maximize early growth with requirements generally being determined by foliar analysis (Freeman et al., 2005; Fernández-Escobar et al., 2008). Nitrogen is often applied starting in Spring once soil temperatures have risen and is more efficient by foliar application in the first years to avoid loss with excess water. Later, when root volume and nutrient demand is greater, nutrients are more efficiently applied with irrigation water.

Pruning during early years should be focused on developing the tree skeleton. Trunk length and positions of main stem and

Table 2

Yield and contribution (%) by the predominantly sunny sides of E–W oriented rows in various olive hedgerow orchards in Spain (39°N) and Argentina (28°S). Width and height refer to the hedgerow dimensions. Inter-row distances were 4 and 8 m in Spain and Argentina, respectively. Horizontal porosity was 5–18%. The Spanish data are adapted from Gómez-del-Campo et al., 2009, while the Argentine data are unpublished.

Lat. (deg)	Cultivar	Year	Width (m)	Height (m)	FW Yield (t ha^{-1})	(% sun)	Oil yield (t ha^{-1})	(% sun)
39.9°N	‘Arbequina’	2006	1.0	2.2	13.3	44	2.3	45
39.9°N	‘Arbequina’	2007	1.1	2.5	7.5	62[a]	1.8	61[a]
39.5°N	‘Arbequina’	2008	1.1	2.8	12.8	45	2.4	45
39.5°N	‘Arbequina’	2009	1.2	3.0	10.8	66[a]	2.0	65[a]
28.4°S	‘Hojiblanca’	2009	4.7	4.8	10.6	59	1.14	62
28.4°S	‘Criolla’	2009	5.1	4.4	11.3	41	1.19	41
28.4°S	‘Hojiblanca’	2010	3.7	4.3	19.4	56[a]	2.30	56

[a] Indicates statistically significant greater yield ($P < 0.05$) on the sunny than shaded sides for orchards individually.

branches should be decided before pruning. If a high vertical main stem is desirable, it should be held upright by binding to a suitable post. Growth and early yield depend on leaf area so light pruning is recommended. It is advisable to eliminate branches when the center of the canopy is shaded in HD, or in SHD when branches are damaged by narrow harvesters.

In addition to light pruning, leaf area development can also be encouraged by other means. For example, fruit removal in the first year of fruiting eliminates competition for assimilates between stems and fruits, with resultant increased vegetative growth. Sanitary problems that reduce leaf number or damage shoot tips (as does Glyphodes) should be controlled by spraying to promote foliage development.

4.6. Concluding remarks

The accurate selection of orchard location, cultivars, and planting design before establishment is crucial for long-term hedgerow productivity. In terms of location, particular attention should be paid to: (1) temperature regime in order to avoid potential frost damage and ensure flowering; (2) soil type to avoid waterlogging; and (3) soil history to avoid fungal diseases such as *Verticillium*. Such factors cannot be easily overcome by crop management and can largely determine the success of the orchard. Special care is needed in new growing regions where experience and data are often limited. Many cultivars are well suited for HD orchards, but few low vigor cultivars with compact tree form are available for SHD orchards. Cultivars that serve as pollinizers should be included to reduce the influence of self-incompatibility and increase fruit set, particularly in regions with small areas of existing olive orchards. For orchard design, row length and spacing need to consider the proposed harvester, while row orientation should pay special attention to soil erosion and air drainage. Lastly, the goal of management during the establishment phase is to maximize tree growth for high yields in the short-term.

5. Maintaining hedgerow structure and productivity

Hedgerows are planted and managed to achieve a structure, height, width and row spacing, suited to long-term productivity and mechanical harvesting. When either row height or width exceeds the intended dimensions, they must be reduced in size. This implies a needed equilibrium between vegetative and reproductive growth. Sufficient new stem growth is required per unit hedgerow surface area during the spring and summer months to provide adequate reproductive floral buds for the following season without generating either an excessively low or high fruit load that could promote alternate bearing or shading by excessive vegetative growth. In practical terms, this is best accomplished by appropriate irrigation and fertilization together with a well-designed, often mechanical, pruning strategy. Control of pests and diseases is also required.

5.1. Irrigation

The response of olive production to irrigation is a second order function in which small increments of irrigation increase production linearly when total water applied is small, while the response gradually decreases as water applied approaches maximum demand (Moriana et al., 2003). Thus, irrigation somewhat below full ETc (100%) may be economically sound in some regions on a cost-benefit basis when considering water costs versus yield production, (Grattan et al., 2006; Naor, 2006), especially because there is also an opportunity to use irrigation management to control vegetative growth. Once hedgerows have completely formed, deficit irrigation strategies including sustained deficit irrigation (Goldhamer et al., 1993; Correa-Tedesco et al., 2010), regulated deficit irrigation (Goldhamer et al., 1999; Tognetti et al., 2006), low-frequency irrigation (Lavee et al., 1990; García et al., 2013) and partial root zone drying (Wahbi et al., 2005; Ghrab et al., 2013) are recommended to contain hedgerow size within harvester dimensions. When properly applied, deficit irrigation strategies can control excessive shoot growth while allowing for high and consistent production. This management strategy contrasts with that employed during hedgerow establishment when freely available water is preferred to favor rapid leaf area development and generation of early, high yield (Section 4.5).

Differences in amount and timing of rainfall and evaporation between regions require precise knowledge of water demand for each phenological stage of development in order that deficit irrigation can be accurately applied (Rapoport and Rallo, 1990; Rousseaux et al., 2008; Iniesta et al., 2009; Gómez-del-Campo, 2013b). Deficit irrigation has traditionally been used in olive during summer months once fruit set is finalized and greatest water savings can be obtained under the most evaporative conditions. Water stress after this time can reduce oil synthesis (Tognetti et al., 2007) but stem elongation rates are typically low and so irrigation does not greatly affect vigor. Given that most stem growth occurs in the first two months following flowering under many growing conditions (Rallo and Suarez, 1989; Gómez-del-Campo, 2013a), further investigation is needed to determine how best to control vegetative growth in hedgerows without severely affecting flowering and initial fruit set, which overlap to some degree with stem growth. Early summer water deficit can be an option because shoots are still growing and fruit set has finished (Gómez-del-Campo, 2013a).

Accumulation of salinity in the soil from low quality irrigation water is a major concern, especially in areas of scarce water supply. Olive can be irrigated with water containing from 3–6 $\mathrm{dS\,m^{-1}}$ (Aragues et al., 2005) provided that salt is not allowed to accumulate in soils. If rainfall amount and distribution does not provide adequate leaching, irrigation above the water demand or complementary irrigation from a low salinity water source is required. Thus, Melgar et al., 2009 observed that production was not affected when olive was irrigated with water of 10 $\mathrm{dS\,m^{-1}}$ for nine years because annual rainfall at the site was 700 mm and the leaching fraction (water additional to crop demand) was controlled to move salt to depth below the root zone.

Lastly, there is a potential trade-off to be considered between olive oil quantity and quality in response to irrigation. Grattan et al., 2006 established that while fruit production in 'Arbequina' reached a maximum with irrigation equivalent to 75% of ETc over the course of the growing season, oil extractability was reduced at high irrigation levels while intermediate levels (30–40% of ETc) produced oils with superior sensorial attributes (i.e. balance and complexity). Reductions in oil production are less prevalent with short-term regulated deficit irrigation (RDI) than sustained deficit irrigation, and RDI can also improve oil quality in 'Arbequina' and other hedgerow cultivars such as 'Koroneiki' with increases in total phenols and slightly higher oleic acid percentages, which may be important in some regions (Stefanoudaki et al., 2001; Tovar et al., 2001; Vita Serman et al., 2011).

5.2. Fertilization

To maintain productivity of olive hedgerow orchards, fertilization from the fourth year onwards is directed to replace nutrient losses (i.e. harvest, pruning, nitrate leaching, etc.) and generate adequate new vegetative and reproductive growth (Rius and Lacarte, 2010). Fertilization, principally with nitrogen, phosphorus and potassium, is typically done in hedgerow systems according to leaf tissue analysis (Fernández-Escobar, 2008) in small doses over most of the growing season via the drip irrigation system. Potassium is particularly important during fruit growth and oil synthesis, but vegetative growth does not respond greatly to foliar K content.

Several recent studies have found that vegetative growth is not consistently affected over a wide range of foliar nitrogen content (Erel et al., 2008; Morales-Sillero et al., 2008; Fernández-Escobar et al., 2009), although very low or high values should be avoided. High N may cause excessive growth, although this was not found recently in 'Arbequina' in a SHD orchard under water deficit conditions (Centeno and Gómez-del-Campo, 2011). On the other hand, fruit load, which is a function of both flowering and fruit set, has been shown to increase with foliar N content from 0.8 to 1.7% and then decrease, while fruit load increased with P content from 0.1 to 0.2% (Erel et al., 2013). Although N fertilization may enhance oil yield, excessive nitrogen can be detrimental to oil quality (Fernández-Escobar et al., 2006; Morales-Sillero et al., 2007). The reduction in total polyphenols is a common response to excessive N that decreases both oxidative stability of oil and its bitterness. Mono-unsaturated fatty acids such as oleic acid, which provide human health benefits, may also decrease relative to polyunsaturated fatty acids.

5.3. Pruning

The olive industry is quickly adopting mechanical pruning practices including topping and lateral hedging with rotating disks, elevating the tree "skirt" using mechanized trimmers, and eliminating individual branches with pneumatic cutters (Gucci and Cantini, 2000; Rius and Lacarte, 2010; Dias et al., 2012). Such practices reduce cost and time required compared to manual pruning, although some practical management issues such as when and how to mechanically prune need to be resolved to ensure consistent yields. Pruning machines for olive hedgerows can be readily adapted from those used in other fruit orchards.

Once hedgerows have been established, by about year 4 in SHD orchards, the objectives of pruning are to maintain a well-illuminated foliar surface area, keep a proper balance between vegetative and reproductive growth, facilitate air circulation through the hedgerow, and allow for a successful mechanical harvest. Branch renovation for fruit location near the trunk is necessary in SHD orchards for constant production. Mechanical pruning is more practical in large SHD orchards due to high tree number and in HD orchards due to tree size. Nevertheless, some manual pruning of internal, dead branches will likely be necessary in most mechanically pruned orchards.

The vegetative response to mechanical pruning depends on other factors including irrigation, fertilization, and crop load. For example, if fruit load is low, mechanical pruning may over stimulate stem growth, especially in regions with warm climates (Cherbiy-Hoffmann et al., 2012). Severe pruning should also be avoided to reduce yield losses in the current year and avoid excessive regrowth. To optimize production, both sides of the hedgerow should not be pruned simultaneously. Mechanical pruning is best alternated between sides of hedgerows at multi-year intervals (Ferguson et al., 2012). Light yearly pruning is recommended in small orchards where manual pruning is predominantly used.

5.4. Control of pests and diseases

Control of pests and diseases in hedgerow orchards is more critical than in low density traditional orchards (Hall, 2011; López-Escudero and Mercado-Blanco, 2011) where freer air movement prevents build-up of high humidity. Problems arise with air-borne fungi (Section 4.1.2) such as *Spilocaea oleagina* (olive peacock spot), *Pseudocercospora cladosporioides* (olive cercosporiose) and *Colletotrichum* spp. (olive anthracnose) (López-Escudero and Mercado-Blanco, 2011). Narrow and porous hedgerows obtained by a combination of planting design, pruning and controlled irrigation and fertilization will reduce humidity and increase the efficiency of spraying by allowing applied materials to penetrate inside the canopy. Deficit irrigation, discussed above for control vegetative vigor, will likely also reduce hedgerow humidity and mitigate potential disease outbreaks, but no data are currently available.

Many olive cultivars are sensitive to the soil-borne fungus *Verticillium dahliae* Kleb that damages the vascular system of trees and causes leaf wilt. In a sampling survey of 873 olive orchards in Spain, Rodríguez et al., 2008 reported that incidence of *V. dahliae* peaked in trees 8–12 years-old but it is not influenced by tree density (López-Escudero and Mercado-Blanco, 2011). This may, however, be associated more with excessive irrigation doses and N fertilization than plant density *per se* because other experience suggests that management can contribute to controlling outbreaks.

Some risk of disease spread exists in hedgerow systems due to transfer during mechanical harvesting because wounds caused by the harvester facilitate entry of disease organisms. An example is olive knot, a disease caused by the bacterium *Pseudomonas savastanoi pv. savastanoi*. Copper spray just after harvest is desirable to reduce this problem.

Currently, there is growing consumer demand to reduce pesticide and other residues in food and the environment. Integrated approaches to pest and disease management that combine knowledge from many disciplines will be needed to maintain hedgerow systems that meet such requirements. In this sense, hedgerows have proven very effective in intercepting pesticide sprays and so reduce opportunities for drift to surrounding fields and residential areas compared to traditional orchard designs (Lazzaro et al., 2008).

5.5. Longevity and productivity

The longevity of hedgerow systems depends on cultivar, climate, soil conditions, planting density, and many of the cultural practices mentioned above (irrigation, fertilization, disease control, pruning, etc.). Although individual olive trees can survive for centuries, longevity of hedgerow orchards is much shorter due to economic issues. Nevertheless, considering the number of factors involved and variation from place to place, there is likely to be large variation for both productivity and longevity. Current estimates of average yield and longevity of HD and SHD orchards are included in the economic analysis of hedgerow systems presented in Section 7. Given the newness of olive hedgerow systems, more time is required for these issues to be clarified.

5.6. Hedgerow renewal

Renewal of olive trees is a traditional practice even in low density orchards in most regions (García-Ortiz et al., 2008) because old wood maintains its sprouting capacity. Many reasons may justify hedgerow renewal in hedgerow orchards, including removal of:

- excessive growth to return hedgerow dimensions to those of the harvesting machinery.
- alternate trees or complete rows to modify the original orchard design to increase yield and/or facilitate management.
- excessively thick and rigid branches that do not vibrate sufficiently during harvesting to allow fruit removal.
- major parts of the canopy for recovery from frost or to control disease. The latter perhaps caused by mechanical harvesting that has gradually weakened trees over time due to disease entry.

Successful examples of these interventions can be found in commercial orchards. In addition, orchards can be replaced entirely by removing existing trees and replanting. This is expensive and there is no production for several years. In SHD orchards, removal of the entire tree canopy by pruning has been shown to allow rapid recovery, including of commercial yields within three years. In Córdoba (Spain), Hidalgo et al., 2012 evaluated responses to various cutting heights in a SHD orchard in which excessive vegetative growth resulted in the need for renewal (Pastor et al., 2007). Eliminating tree crowns above 1.5 or 2 m was unsuccessful because regrowth was high and the trees became too tall for mechanical harvesting after one year. Cutting tree trunks at 0.1 or 0.5 m and reforming a single, central axis after thinning the new shoots gave better results. Shoots can be selected from those oriented in the direction of the rows to reduce the probability of subsequent damage by mechanical harvesters.

5.7. *Concluding remarks*

Maintaining hedgerow orchards requires appropriate irrigation and fertilization strategies to ensure consistently high yields without excessive vegetative growth. Sustained or regulated deficit irrigation are potentially useful strategies. Pruning should focus on low intensity interventions to avoid significant regrowth that decreases yield. If hedgerow renewal becomes necessary, there are several options including removing the entire canopy.

6. Harvesters and harvesting

Short, narrow hedgerows can reduce the cost of manual harvesting relative to that of traditional plantings, and such hedgerows may be harvested mechanically for table olive production (Ferguson et al., 1999, 2010). However, the main interest in hedgerow designs is to lower cost, increase speed, and improve the timeliness of fruit retrieval by mechanical harvesters for oil extraction. Costs are discussed further in Section 7. Here, we concentrate on features of olive biology and hedgerow systems that determine the principles, current practice, and performance of continuous mechanical harvesting for production of high quality oil.

6.1. *Fruit and tree biology*

Olive fruit are small and formed on 1-year-old shoots. While fruit are potentially distributed throughout the canopy, they are mainly located at the periphery due to the positive response of fruit set, fruit growth, and oil accumulation to increasing irradiance (Section 3.1). The fruit removal force depends on cultivar and stage of maturity (Barranco et al., 2002) but is fairly high ($2–12\,\mathrm{N\,g^{-1}}$) (Camposeo et al., 2013). Such force increases the risk of trunk, branch, and fruit damage that may also reduce oil quality. Fortunately, the characteristic flexibility of olive branches alleviates some of the potential damage. Early harvesting, which is common for table olives, requires much greater force (up to $10\,\mathrm{N\,g^{-1}}$) than later harvesting for oil cultivars and increases damage. In contrast, very late harvest runs the risk of fruit fall and the impossibility of timely harvest by completely mechanical methods. In practice, the force required to remove fruit can be applied by shaking entire trees or just the canopies. The two methods have different impacts on tree and fruit.

6.2. *Harvester designs*

Tree shakers apply a detachment force by vibrating trunks for several seconds and rely on the woody structure of trees to transmit the force to fruit-bearing shoots. Considerable experience with low-density orchards has revealed that success requires predominately vertical branches with narrow insertion angles, and that dense canopies should be avoided because they mute the transmission of the detachment force from trunk to fruit. The required frequency of the shaker head (>42 Hz; >2500 cycles per minute) at the trunk is substantial (Ferguson et al., 2010) and has disadvantages of stripping bark and/or dislodging of roots, both of which may reduce tree longevity.

Few options exist for harvesting hedgerows with tree shakers. One shaker suitable for HD hedgerows consists of two sections that are driven in tandem down opposing sides of individual hedgerows. One side grips and shakes each trunk, while both sides join under the canopy to collect harvested fruit that is then be discharged into a following bin. Machines of this design are suitable for HD, but not for SHD hedgerows because of the many closely spaced trees that are insufficiently robust for the shaker head, and alleys between rows are frequently too narrow for passage of the harvester. For HD hedgerows, harvest efficiency of tree shakers is likely less in comparison to isolated trees because the interlacing of branches between adjacent trees dampens transmission of vibration.

Over-row olive canopy contact harvesters have been adapted from grape harvester technology, and to some extent simulate the traditional method of beating olive canopies with wooden sticks. Contact rods radiate from a vertical cylinder and extend into the canopy, rotating from side to side to generate the shaking of shoots and smaller branches in order to remove fruits. There are various types of rods and frequency and rhythm of operation, each seeking a compromise between high efficiency of fruit removal and minimum damage to canopy and harvested fruit. Again, fruit is collected at the base of the harvester from where it can be discharged, often over an adjacent row, into collecting bins. Hedgerows are trimmed to around 0.5 m height above the ground to facilitate the closing of collection plates, which if not well set may damage trunks. This design is suitable for both SHD and HD hedgerows, and the harvester chosen will depend on hedgerow size and its flexibility to adjust to individual hedgerow shapes. Each machine can only operate to a maximum row height, some are made for a single width of hedgerow, some work best on rectangular hedgerows, while others can be adjusted for width and/or canopy slope.

This design is well suited to hedgerows where canopy surface area is high and fruit are located at the periphery where the rods are most effective. But fruit can be damaged by direct contact with the rods, with the degree of damage depending on skin thickness and flesh firmness. Damage increases as firmness decreases during maturation (Camposeo et al., 2013) and is also affected by temperature and turgor. Once the skin is broken, hydrolytic and oxidative processes are accelerated and secondary pathogens can colonize the damaged zone (Sanzani et al., 2012) increasing free acidity and peroxide values that affect oil chemical composition and sensory characteristics. Defects in oil quality are more likely to occur if processing is delayed after harvest (García et al., 1996). In other crops, such as grapes, mechanical harvesting at night is becoming popular because temperatures are then lower and fruit are firmer with higher turgor. In olive, harvesting is conducted during 24 h each day in some areas so that harvesting large commercial farms can be completed in a reasonable time period.

Mechanical harvesting also affects olive tree health. Damage to trunks, roots, shoots, stems, and leaves allows the entrance of diseases. Preventive application of Cu products is recommended immediately after harvest, as is the removal of infected trees from which mechanical harvesters can spread infection more widely. On the other hand, mechanical harvesting facilitates early harvesting, which can reduce the risk of disease and insect damage. For example, if olive fruit fly infection (*Bactrocera oleae*) is reduced, oil quality will be improved with less free acidity and peroxidation and greater oxidative stability (Gucci et al., 2012).

6.3. *Performance characteristics*

Harvester performance can be measured in various ways including harvest speed (ha/h), harvest rate (t/ha), percentage of fruit harvested or damaged, and percentage of damage to the canopy (i.e., to shoots and branches). The percentage of fruit harvested to that produced is the proper estimate of harvest efficiency. In addition to amount harvested, this calculation requires measurements of how much fruit remains on the trees and is found on the ground after harvest.

Ravetti, 2008 reported a performance comparison of three over-row harvesters on 3-year-old ‘Barnea’ and ‘Picual’ trees planted at 6 × 4 m (HD), which were yet to form complete hedgerows. These commercially-available harvesters differed in speed of operation in the following sequence: Braud > Gregoire > Colossus. Average tree yield was 19 kg (7197 kg ha^{-1}). Harvest efficiency was assessed as the percentage of yield collected and damage as the percentage of shoots or trunks damaged. Results of the comparison are summarized in Table 3.

Differences are not unexpected for the trees harvested because the Braud is a fairly small modified grape harvester, while the Gregoire and Colossus are larger and heavier and more suited to bigger trees or hedgerows. Harvest efficiency was high (>93%) in all cases except when Braud or Gregoire were used to harvest ‘Picual’. Canopy and trunk damage were small and less with Colossus than using the other two machines. Given the same operation costs, the greater harvest speed of Braud contributed to a significant economic advantage over the other machines. On average, for the two cultivars, return per unit spent on harvest was 2.6, 1.3, and 1.0 for Braud, Gregoire, and Colossus, respectively. These results represent the functioning of these machines on given cultivars at a certain age and density, and different harvesters are likely to be better for other combinations.

The high harvest efficiency reported for the Braud harvester in Table 3 was not always achieved by observations in SHD orchards made in Israel (Zion et al., 2011). In that case, observations were made on ‘Arbequina’, ‘Barnea’ and ’Coratina’ orchards (3.0 × 2.5 m) in three farms with a wide range of harvest efficiency (50–93%). Unharvested, rather than fallen fruit, was the major contributor to this variability.

A comprehensive performance analysis of Colossus on HD hedgerows of full grown ‘Barnea’ and ‘Frantoio’ trees (8 years-old; >4 m tall) planted at 7 × 4 m was provided by Ravetti and Robb, 2010. Harvests were made 7 and 30 days after fruit achieved maximum oil content on trees with either heavy or light fruit load. Harvest efficiency compares well with the data presented above, with overall values of 92 and 90% for ‘Barnea’ and ‘Frantoio’, respectively, and 89 and 93% for early and late harvests. Harvest rate was about 110 trees per hour, which is about one-half of that reported in Ravetti, 2008 and is likely a reflection of the larger trees. Damages were again slight, with a mean of 2.5% for canopy and none to trunks. Costs, based on charges by contractors, were presented in two ways; per kg of fruit harvested (0.07 €/kg, Aus\$ = 0.57 €cents) and including the value of fruit lost (0.11 €/kg) in the harvesting process. These costs can be compared with a commercial scale analysis of the performance of eight Colossus harvesters working on 1968 ha in Northern Victoria, Australia (Ravetti and Robb, 2010). Cost of harvest based on purchase, maintenance, and operation of harvesters was 0.03 €/kg. This was achieved by an average 91% harvesting efficiency with fruit losses being divided between unharvested fruit (5.1%) and fallen fruit (3.9%).

6.4. *Concluding remarks*

Analyses reveal that over-row contact harvesters are efficient and economical, and cause little damage to trees, which was always a concern for mechanical harvesting systems. For hedgerow orchards, over-row harvesters are also the cheapest option for commercial olive oil production (Ravetti, 2008; Ravetti and Robb, 2010). In the future, combinations of hedgerow design and harvesters will be chosen on the basis of the imputed financial return. Orchards planned for shallow canopies (i.e., short trees) will be planted in narrow rows that can be harvested from the outset with a single small machine. Orchards planned for deep canopies will be planted in wide rows and will need access to small harvesters in the first two or three seasons and larger harvesters thereafter. Use of large machines will be restricted to flat land and by cost to large areas if owned by individual growers.

7. Economic issues

Mechanization is the major management change contributing to survival of traditional orchards in developed countries of the Mediterranean. In Spain, harvesting with tree trunk shakers maintains the economic viability of the widespread, now 300-year-old, investment in traditional olive orchards in the Andalusian heartland. Without efficient mechanical harvesting there would be no expansion of olive production in the Mediterranean or the New World. Australia, for example, is in the second phase of olive production development. The first phase included major investment in research and development following settlement in the 19th century in an effort to enter world export markets (Hill, 2000), but failed principally for lack of manual labor. In South American countries such as Argentina and Chile, manual harvesting is also no longer a viable option due to cost and increasing labor regulations. Thus, continuous mechanical harvesting is the key to profitability of new orchards everywhere. Here, we concentrate on issues that determine the relative profitability of hedgerow orchards and will discuss the direction in which hedgerow designs will likely develop in the future.

7.1. *Economic analysis*

In principle, the data required for comparative analyses of profitability of individual ventures combine, in addition to cost of land:

- cost of orchard establishment that is obviously much greater for SHD than HD orchards, although not just in proportion to tree density because much more effort is required to train trees in SHD systems in the early years.

Table 3

Comparison of harvest speed, cost, efficiency and damage to canopy and trunk by three over-row harvesters on 3-year-old HD orchards of ‘Barnea’ and ‘Picual’ at Boort, Australia (adapted from Ravetti, 2008).

Parameter	Braud		Gregoire		Colossus	
	Barnea	Picual	Barnea	Picual	Barnea	Picual
Harvest rate (trees h^{-1})	450	650	380	450	250	180
Harvest efficiency (%)	97	89	94	86	94	97
Canopy damage (%)	3.0	4.9	3.1	5.5	1.25	0.5
Trunk damage (%)	0.35	0.40	0.25	0.3	0.3	0.15
Cost (\$Aus h^{-1} in 2008)	220	220	220	220	205	205

Braud = a small, modified grape harvester; Gregoire (133 V) = a larger olive harvester (3.5 m head room); Colossus = a large olive harvester (4.0 m head room).

- annual maintenance of irrigation, pruning, weed, disease and pest control that is variable from place to place, changing as the orchard develops, and not related simply to tree density.
- annual rent or amortized purchase of harvesting machinery and, in the latter case, machinery maintenance over its lifetime.

with returns from:

- annual returns based on production and price when both climatic and economic environments are variable and the longevity of these new production systems is as yet unknown.

Given the large uncertainty in critical assumptions of productivity and longevity, a major objective is to evaluate the opposing major expenses of the greater initial investment required to establish SHD orchards with the much greater cost of harvesters required for HD orchards.

7.2. Comparison of HD and SHD orchards

The following analysis, summarized in Table 4 (from Freixa et al., 2011) presents a comparison of the profitability of HD and SHD orchards based on published reports and surveys of Spanish growers. Given the assumptions made, it is presented here to identify the range of issues involved and not as a widely applicable financial analysis. Cost analyses of establishing HD and SHD orchards in California (Vossen et al., 2007, 2011) provide further useful comparative data.

In Table 4, SHD and HD orchards develop maximum production in years 3 and 6; respectively, and maintain that production until year 10 in SHD and year 20 in HD. Maximum productive life is set at 15 years in SHD and 25 in HD. The cost of orchard establishment is 50% greater for SHD than HD and annual maintenance is also slightly greater (10%), while harvester purchase is 40% that of HD. The more rapid development of production in SHD offers only slightly more rapid recovery (9 *vs.* 10 years) of initial investment, while the shorter productive life is a major disadvantage compared to HD orchards.

Cost of contract harvesting per hectare is determined by harvester rental price and rate of harvest (ha per day). Usefully, this study identifies minimum areas required to justify purchase and how the cost of harvesting then decreases markedly as orchard area increases up to the maximum that the machine can harvest during a season, here of three months duration. In this analysis, minimum areas required to justify purchase of harvesters suited to SHD and HD orchards are 60 and 79 ha, respectively. The corresponding maximum seasonal harvest areas per harvester are 200 and 300 ha. The lowest cost of harvesting, achieved at maximum area, is much less for SHD than for HD (200 *vs.* 320 € ha^{-1}). The economic analysis then compares orchard types in terms of time to recover initial investment (payback time), net present value (NPV, €) and internal rate of return (IRR, %). Analyses are also presented for various orchard areas including the areas that give the most economic usage of the harvesters in Table 4.

The analysis concludes that while both production systems are economically viable, HD has a slightly better economic perspective. Pastor et al., 2007 arrive at a similar conclusion. In their comparison of SHD (3.5 × 1.5 m) and HD (7 × 7 m) orchards over the first 7 years in southern Spain, SHD yielded twice the oil of HD and while harvest costs were less (0.04–0.08 *vs.* 0.07–0.10 €/kg) high establishment costs in SHD resulted in a similar final economic balance.

In contrast, a recent economic analysis of a 1 ha SHD hedgerow system for Bari, Italy (De Gennaro et al., 2012) concludes that even with a higher oil price (€ 3.5/kg), return on SHD orchards is negative. This study compared SHD with an ‘intensive’ open tree system (400 trees ha^{-1}) over 50 years, and included re-plantings of the SHD orchard at 17 and 33 years and removal and sale of the wood. Because there are many differences in costings between the various studies, comparison is difficult. For example, costs of establishment, maintenance, and harvesting were much greater in the Italian than in the Spanish study.

Taken together these studies do, however, identify the range of production and management issues that determine economic viability of hedgerow orchards and how analyses of profitability depend on assumptions that must apply over many years. They present evidence that with present cultivars and technology open tree ‘intensive’ systems harvested by tree shakers equipped with umbrella catchers appear to have at least as a good an economic return as SHD hedgerow systems with continuous canopies. But

Table 4
Economic comparison of HD and SHD orchards combining costs of establishment, management and mechanized harvesting with appropriately sized continuous over-row harvesters[a,b] (adapted from Freixa et al., 2011).

	High density (HD)	Super high density (SHD)
Density (trees ha^{-1})	476	1667
Height × width (m)	4.5 × 4	3 × 1
Economic life (year)	25–30	15
Full production (FP, year)	6–25	3–10
Average yield at FP (kg ha^{-1})	9500	9000
Establishment cost (€ ha^{-1})	5909	8701
Maintenance cost (€ ha^{-1} year^{-1})	1430	1600
Harvester purchase price (€)	370,000[a]	154,800[b]
Harvester rental price (€ h^{-1})	177	175
Harvest rate (ha day^{-1})	2–3	3–4
Efficiency (%)	90	95
Minimum area for purchase (ha)	79	60
Harvest cost at purchase area (€ ha^{-1})	750	413
Harvest cost at max. seasonal area (€ ha^{-1})	320	200
Payback time (year)	10[c]	9[d]
Economic life (year)	25[c]	15[d]
NPV at maximum seasonal area (€)	17,669[c]	6,133[d]
IRR at maximum seasonal area (%)	17.64[c]	12.88[d]

[a] Colossus.
[b] Gregoire 133 v.
[c] seasonal campaign area of 300 ha.
[d] seasonal campaign area of 200 ha.

that comparison is over a long period of 50+ years when economic assumptions are unlikely to be maintained and technology will likely advance.

7.3. *Considerations for the future*

The future of hedgerow systems will depend on success in finding optimum combinations of hedgerow structure and management to maintain productivity for longer periods as well as cheap and rapid mechanized harvesting. This effort will be long-term and is only just beginning. Hedgerow height and width and canopy management adapted to individual cultivars are critical to this effort. In Spain, some hedgerow orchards are now more than 15-year-old and remain productive. SHD will not be profitable under conditions that promote vigorous growth in some cultivars, but orchard longevity in SHD can likely be extended (Section 8.1) once appropriate maintenance and pruning techniques are developed. Even if SHD orchards become unproductive, regeneration does not require removal and replanting because experience has already shown the potential for regrowth and rapid establishment of productive canopies after coppicing (Section 5.6).

8. Recommendations for future research

Commercial olive production moved ahead of scientific and technical knowledge of crop response in recent decades when olive production was greatly intensified (e.g., orchards with greater tree density) and expanded into non-Mediterranean environments. Now, the economic need to harvest mechanically is contributing further to change by promoting the adoption of olive hedgerow systems as an economically viable production option. This is again pushing commercial olive practices faster than the ability of research to answer many questions posed by producers and extension specialists. These include:

a How does olive tree biology limit or support success of hedgerow systems?
b What hedgerow structures are the most productive and profitable for specific locations?
c What cultivars are best suited to given locations and structure of hedgerows?
d What pruning techniques and schedules are suited to which hedgerow types and where?
e How does hedgerow structure determine specific management practices for pest control, irrigation, and fertilization to maximize return on investment in various environments?

This review has contained two persistent themes. First, that olive hedgerow systems must develop such that machinery, essentially harvesters, are increasingly better adapted to hedgerows and that hedgerows, and the cultivars and management that form and maintain them, are better adapted to harvesters. Second, that hedgerow systems are high input, high technology systems requiring high and consistent yields for economic survival. In consequence, management of these new systems should restrict the natural tendency of olive for biennial bearing and establishment should avoid locations of saline soils and those prone to waterlogging, low and variable water supply, and transient frosts that olive can tolerate, albeit at the expense of low productivity. Hedgerow systems require new understanding of the biology of olive crop response because the microclimate is drastically different from that of individual tree systems. Also, soil and climatic conditions suitable for traditional olive orchards are likely not applicable to small hedgerows. Shallow, low fertility soils and lower temperatures will find use to limit vegetative vigor.

For hedgerow olive, the goal should be one of high production in individual orchards for a sufficient period to obtain return on capital with acceptable profitability rather than the long-lived, low-yielding, low-density orchards of marginal environments for which the past has accumulated much cultural and scientific knowledge. While this review drew as much as possible on existing information collected from hedgerow systems, it became evident how much extrapolation was required from traditional olive production systems and from other horticultural crops because detailed information on olive hedgerows is surprisingly scarce. These many extrapolations provide the basis for recommendations for future research by identifying the issues that must be resolved to improve productivity and efficiency before other, currently unforeseen issues arise and demand attention.

8.1. *What hedgerow structures?*

An important issue that will determine the demands of future research can be found in the range of hedgerow structures that researchers could address. Clearly, if research is to cover the entire HD–SHD range, then the scope for selection of adapted cultivars and interactions with their management will be correspondingly wide. Equipment manufacturers are currently developing intermediate size harvesters suggesting confidence for mid-sized hedgerows in commercial production (Section 7). Simulation studies reported in Section 3.1 also predict the possibility of high yield over a range of hedgerow sizes provided adapted cultivars and proper management are identified. A question is where best to apply the increasingly limited resources that are available for public research and how to link that with production and technological advances in the private sector? The latter point is important because it advises that current commercial activity, or intention, will point the direction for research in individual regions.

It is our view that, while HD hedgerow orchards will coexist with SHD because some desirable cultivars can only be cultivated in large hedgerows, the major emphasis in expansion of olive hedgerow production systems will be away from HD. This will be so despite the economic advantage that some analyses give to HD orchards. Reasons for this include: (1) the rapid rate of recovery of investment more attuned to modern commercial investment; (2) the small physical size of hedgerows that is more attuned to human operators and mechanical interventions; (3) emerging evidence that improved management can increase the productive lifespan of SHD orchards, while providing opportunity for rapid regeneration into a second cycle; and (4) large machines for HD require flat large orchards, which are not common in many olive areas. This view will determine our own research efforts in the future, both in Spain where most new orchards are already in SHD, but also in Argentina and Australia where HD hedgerow orchards are quite common. Our recommendations for future research are not, however, limited by this view.

8.2. *Underpinning research*

Our review has identified that microclimate of olive hedgerow orchards is distinct to that of traditional orchards and a major unknown that determines the growth and yield responses of olive trees and the water demand of orchards. It has also identified that no single comprehensive analysis has been made; just one energy balance study (Martínez-Cob and Faci, 2010). To correct this omission, research should establish terminology and parameters to define hedgerow structure so comparisons can be made to assist interpretation of responses and behavior observed in various situations. The simple repetitive structure provides a basis for careful analysis and transfer of information about hedgerows from site to site provided they are fully described. Here, the review has shown how basic parameters of canopy depth, width, slope, row spacing, and orientation can lead to new functional descriptors of orchard structure, such as row length per hectare and canopy surface area rather than the traditional canopy volume per hectare. Adequately illuminated canopy surface area leads directly to an estimate of potential productivity of N–S hedgerows and thus provides a benchmark for comparison of alternative production strategies. This review also offers hedgerow porosity as a significant parameter for describing hedgerow microclimate. Examples are seen in relation to the penetration and distribution of light for photosynthesis, that needs further investigation to resolve the basis of productivity in E–W hedgerows, and also for ventilation of hedgerows of any orientation. When porosity is high, disease control is improved due to lower humidity and greater spray penetration. However, high porosity can be disadvantageous in terms of greater water demand due to closer coupling with the atmosphere.

For hedgerow orchards, that are well defined structurally, information on overall radiation and energy balances and of water and carbon dioxide exchanges, together with detailed microclimatic parameters within hedgerows will assist understanding of responses and guide design of appropriate structures and their management. The range of application is wide ranging from overall productivity and water demand to control of fruit distribution. Fruit position determines accessibility for harvesting machines and microclimate (e.g., light interception and fruit temperature), which in turn determine oil quality and susceptibility to disease (e.g., depredations of olive fly) (Section 5). Pruning will be a major factor in maintenance of hedgerow structure (see below) and a determinant of hedgerow longevity. It will be increasingly mechanized and infrequent and so dramatic enough to cause major changes to hedgerow microclimate. The balance between vegetative regrowth and fruit production will depend in large measure on the new microclimate, including the possibility of responses to such subtle changes as light quality as well as quantity.

8.3. *Cultivars for hedgerows*

Critical cultivar yield characteristics for SHD orchards are a high degree of self-fertility, early yielding, high oil yield and quality, and low biennial bearing (Rius and Lacarte, 2010). These features derive directly from economic considerations and are also appropriate for HD hedgerows. Regardless of hedgerow size, canopy contact harvesters require cultivars that form compact canopies and bear fruit on their periphery. However, some differences between HD and SHD hedgerows do arise that affect cultivar choice and the intended mechanical harvester. For example, cultivars with flexible stems and low vigor are very important for harvesting SHD systems in order to avoid damage to both trees and harvester. For HD systems, somewhat more vigorous cultivars are feasible. In contrast, trunk shakers are only appropriate for HD hedgerows (Section 6.2), and rely more on a combination of strength, flexibility, and angle structure of the tree skeleton to dislodge fruit. Trunk shaking harvesters are also able to dislodge fruit from inside more open canopies than are suited to contact harvesters. The result is a potential strong dichotomy in structural characteristics of cultivars suited for orchards depending upon harvesting method and these characteristics are in early stages of development.

Some studies have focused on how genetic differences in plant architecture between cultivars are important in determining cultivar suitability to hedgerows (Moutier et al., 2004; Moutier, 2006; Rosati et al., 2013). Rosati et al., 2013 specifically found that 'Arbequina' and 'Arbosana' have greater branching with smaller shoot diameters than other cultivars, which provides more fruiting sites (shoots) per canopy volume or per row length and presumably greater branch flexibility for mechanical harvesting. Unfortunately, 'Koroneiki', another commonly used cultivar in SHD orchards, was not evaluated. The results of such architectural studies should contribute greatly towards better selection and breeding for SHD.

The breeding program carried out over the last 20 years by the University of Córdoba (Spain) and the neighbouring Instituto de Investigación y Formación Agraria y Pesquera (IFAPA) has obtained a cross between 'Picual' and 'Arbequina' called 'Sikitita' that has less vigour than 'Arbequina', a compact drooping growth form, and early yield (Rallo et al., 2008). Such success reveals the possibility to obtain new cultivars via breeding, but the process is long and demanding. New cultivars needed for HD also include architectural characteristics appropriate for effective harvesting by trunk shakers. From a practical perspective, close interaction between breeders and harvester manufacturers will be important to develop a strong synergy between plant growth form and harvester.

8.4. *Maintaining hedgerow structure*

Experience with other crops and simulation studies with olive (Connor and Gómez-del-Campo, 2013) identify how to maximize well-illuminated productive canopy area with various combinations of hedgerow height, width, slope and spacing. The challenge is to establish hedgerows quickly and then maintain them with the necessary balance of vegetative growth and reproductive productivity. Along these lines, it is possible to identify three critical areas for research across the range of hedgerow structures.

First, is how to define and measure hedgerow and tree structure in order to work with specific cultivar-management combinations and consider how structure responds differently to management practices depending on cultivar. With this in mind, planting density and early tree training are likely to affect subsequent hedgerow structure and harvest efficiency. While various studies have explored effects of irrigation on simple growth parameters such as branch elongation and on yield in SHD 'Arbequina' hedgerows (Fernández et al., 2013; Gómez-del-Campo, 2013a, 2013b), specific irrigation programs for maintaining and harvesting different planting densities have not been evaluated. More basic irrigation studies for many other hedgerow cultivars are also lacking.

Second, is to establish how hedgerows of different cultivars respond to mechanical pruning and its severity and frequency. Preliminary findings of mechanical pruning experiments with 'Arbequina' in Argentina indicate that shoot regrowth can be controlled and future yields only slightly reduced after two years if crop load is moderate to high when pruning is applied (Albarracin and Rousseaux, unpublished data). Additionally, Ferguson et al., 2012 have suggested that the efficiency of canopy contact harvesters is improved, i.e. a greater proportion of fruit is recovered, after mechanical pruning, likely because it provides a uniform canopy periphery. Nevertheless, little is known about the effects of repeated pruning and how the progressive diameter increase of the central leader and branches will affect harvesting efficiency. Branches will likely be less flexible and harvesting more difficult as trees age.

Third, is how to predict the outcome of two or more management practices that are applied concurrently. In this regard, factorial experiments could contribute greatly to a better understanding of potential interactions between variables. For example, the response of vegetative regrowth after pruning is certainly affected by other management practices such as irrigation or fertilization. Sufficient irrigation is needed to foster reasonable growth on pruned sides to regain lost yield the following year, but irrigation should be controlled so that the pruned volume is not restored in the first year. Obtaining the proper balance between high yield and the need to maintain canopy size within harvester dimensions is a challenge that must be met under many climatic conditions. Multi-factor experiments are common in the eco-physiological literature of annual crops, but are uncommon for fruit trees, in part due to plant size and the required extension of experimental plots.

9. Conclusions

Olive is one of the most recent crops to benefit from the cost reduction associated with mechanization in hedgerow systems. The crop has been under commercial production for centuries but the transition towards mechanically harvested hedgerow systems has been underway for just two decades. The change is dramatic and so the design and management of new production systems, and their adaptation to new regions with different climates, require a reassessment of knowledge of the response of the tree to environment and management.

In this review, we have assembled information currently available on those physiological and agronomic aspects of olive crop response that can be affected by differences in location, topography, soil type, orchard design, plant density and management (pruning, fertilization and irrigation). In doing so, the lack of published studies on the physiological responses of olive trees in hedgerows systems became quickly evident. Consequently, it was necessary to extrapolate knowledge from responses observed on hedgerows of other crops and also from the substantial body of literature from low-density olive orchards. Comparison with these traditional olive production systems is valuable because it emphasizes how olive responds differently in usually fertigated hedgerows relative to open-grown, usually rain-fed orchards and that those differences should become the foci of research for new management systems.

Much of the analysis concentrated on the two existing and contrasting hedgerow designs, high density (HD) and super-high density (SHD). This approach is consistent with a major theme of the review, *viz.* that improvement of hedgerow production in olive will require joint development of hedgerows and their management together with that of suitably sized, increasingly efficient, continuous, over-row harvesters. Intermediate plant densities and structures are possible and will develop, along with a greater range of cultivars, as the offer of harvester designs and sizes widens.

We conclude that critical objectives for research into hedgerow systems are: (1) study of biological responses to tree density (e.g., branching habit, flowering, fruit set) and the variation of these characters between genotypes; (2) hedgerow structures best suited to different cultivars and environments; and (3) responses to pruning and how these responses interact with techniques and schedules best suited to different hedgerow structures and environmental conditions. To underpin these objectives, more information is required in micro-environment within hedgerows (e.g., irradiance, temperature, air movement and humidity) in response to variations in hedgerow structure and how these variations affect yield, oil quality and crop management (e.g. irrigation, fertilization, pest control and pruning).

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