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Current situation, trends and challenges for efficient and sustainable peach production

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ABSTRACT

In Spain, the total surface occupied by deciduous fruit species in 2019 was 190,414 ha. Peach is the second most important *Prunus* species with 77,464 ha and a production of 1,480,000 t per year. Labour is the main production cost, amounting to 45% of the total cost in 2020 and primarily involving pruning, thinning and harvesting. The common trend regarding agronomical orchard models, in deciduous fruit species, is planting intensification, combining mid to low vigour rootstocks and training systems based on small, bi-dimensional canopies. Size-controlling rootstocks such as Rootpac-40, Isthara or Adesoto-101, Among others, resulted in better yield efficiency and improved fruit quality compared with GF-677. In 7-year-old trees of 'Luciana' nectarine cultivar, the use of size-controlling rootstock Rootpac-40 and an intensive orchard trained in central leader allowed both earlier and higher yields, resulting in a difference of 102 tha^{-1} compared with the standard Spanish gobelet system on GF-677. With 'Noracila' and the same combinations, the difference was 109 tha^{-1}. The central leader/single row and central leader/double row training systems, despite requiring a greater orchard establishment cost, gave earlier and higher yields in 'Ambra' and 'Luciana' cultivars grafted on G-677, around 48% for double row and 30% for single row, compared to the Spanish gobelet system. Planar canopies allowed an efficient use of mechanical and manual pruning and flower thinning, which improved harvest efficiency (kg.h^{-1}) by 28%. As a result, a production cost reduction of around 15% was recorded in comparison to the Spanish gobelet system. Greater efficiency in total labour per season enabled a reduction of 39%, from 651 h.ha^{-1} for the Spanish gobelet system to 398 h.ha^{-1} for the central leader system. Additionally, an increase in fruit quality, particularly fruit size and SSC content, due to a more uniform light distribution was observed. In these planar intensive systems, including palmette, a reduction in light interception of 17% was recorded when compared to the open vase system. Yields obtained were more related to planting density and canopy architecture than the average of intercepted light. Currently, the central leader and bi-axis are the most important systems used in intensive orchards in Spain, with planting densities from 1,900 to 3,100 trees.ha^{-1}. All these results support the sustainable intensification concept and make peach tree production more economically sustainable for growers.

1. Introduction

Prunus species, in particular peach, cherry and almond, are amongst the most important tree crops in southern European countries such as Spain or Italy, the United States, Chile, and Australia. The European Union is the second largest producer of peach after China with an average annual production of 3612,000 t in the period 2018–2020 and a total harvested area of 206,660 ha in 2019. Spain is the first country in the ranking with 77,464 ha and 1480,000 tonnes per year, followed by Italy and Greece (Europech, 2021). Annual exports for the 2018–2020 period amounted to 55% of total production, corresponding to 826,100 tonnes. Nectarine represents 41% of total annual production, followed by peach (21% flat and 18% round) and clingstone (20%). Catalonia, Aragón and Murcia, all regions located in the Mediterranean basin, are the most important areas of production.

In other species, such as apple and pear, intensification started decades ago because of the availability of dwarfing rootstocks such as M9 in apple or different quince selections in pear, and because of the high cost of labour for pruning, fruit thinning and harvesting. The result has been smaller and more planar canopies compared to the gobelet system.

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With this particular tree architecture, mechanization is key to improving efficiency and productivity and represents the main guideline for modern fruit production. In peach, the gobelet or open vase training system has been the main techniques used in all countries, with complex 3D canopy architectures which vary depending on the country. In Spain, the Spanish gobelet system has been developed in the last two decades using vigorous rootstocks such as GF-677 or Garnem (Montserrat and Iglesias, 2011) and currently represents 92% of the total. In the last decade, new intensive orchards with planar canopies have been planted using size-controlling rootstocks to avoid the use of bio-regulators, a common practice in the traditional Spanish gobelet system (Iglesias and Echeverria, 2021). In all peach-producing countries there is a trend in orchard intensification from 3D canopy architectures, with multiple leaders per tree, to modern high-density, simple/planar designs with single, double or multiple leaders per tree. This shift to a modern orchard design is being facilitated by genetic advances (mainly dwarfing rootstocks) and horticultural techniques that control vigour (crop load management, green pruning or multiple leaders per tree). The final objective of modern orchards is to obtain early and constant yields with a high fruit quality and low production cost (Grossman and DeJong, 1998). Efficient canopies for optimum light interception and light distribution can be achieved by increasing planting density and adapting canopy architecture to the requirements of modern production technologies, including efficient mechanization and robotics. Previous results (Trentacoste et al., 2015) have shown that the lower light interception reported in planar canopies can be compensated by optimizing the inter-row planting distances. That is, optimal inter-row space is mainly dependant on the height of the canopy and the latitude. The most used inter-row distance/tree height ratio ranges from 1/1.0 to 1/1.2 in the main peach producing areas of Europe (Iglesias et al., 2021; Maldera et al., 2021).

Bi-dimensional planar canopies developed in the last two decades in Spain, Italy, France and Greece have increased the efficiency of inputs, in particular labour, reducing the cost of production through better machine and labour access to the canopy whilst at the same time improving fruit quality (Iglesias and Torrents, 2020). Indeed, improving the quality of the fruit is essential if the aim is to increase the low peach consumption of Spain and other European countries (Iglesias and Echeverría, 2021). This quality can only be developed and enhanced in the orchard through the optimization of preharvest factors, of which the most influential are cultivar and rootstock selection, crop load management, fruit position in the canopy, irrigation, fertilization, pruning and training systems (Minas et al., 2018). All of these factors need to be carefully considered by producers, researchers and breeders alike (Iglesias, 2022. *In press*). The present paper focuses on rootstocks, crop load management and training systems.

2. Material and methods

The results set out in this paper comprise a summary of several trails carried out at IRTA (rootstock and training system trials) and with private companies/growers (mechanization trials) in commercial orchards. All orchards were located in the area of Lleida (Ebro Valley, NE Spain). Trees were grown under a cold semiarid Mediterranean climate (Bsk in the Koppen-Geiger climate classification system) (Reig et al., 2020). The area has around 300–500 mm annual rainfall, and 32 °C mean summer daily temperature. Soils are calcareous with pH>8 and good fertility. Orchards were managed under the rules of integrated fruit production. Common technical operations carried out in different orchards, either by hand or mechanically, are summarized in Fig. 10. The Spanish gobelet (Montserrat and Iglesias, 2011) and central leader training systems were chosen to determine the rootstock × training system effect. The main aspects of green and winter pruning during the first 3 years and in adult trees are shown in Figs. 1 and 9. The support structure used with the central leader can be seen in Fig. 9, consisting of 3 wires and wooden poles situated 12–14 m apart, depending on the orchard. In both cases, annual green pruning (manual or mechanical) is essential to achieve the most adequate tree architecture in both unproductive and productive periods. In this training system, only the leader and some short scaffolds comprise the permanent canopy structure. The fruiting structure consists of 20–25 (second year) to 35–40 one-year-old shoots, each bearing 3–4 fruits and progressively renewed year by year. The study period ranged from 7 to 11 years depending on the trial. Common determinations in all the trials were yield, tree vigour (expressed as trunk cross sectional area (TCSA) at 20 cm of graft union), yield efficiency (yield/TCSA) and fruit quality parameters. The quality parameters (fruit

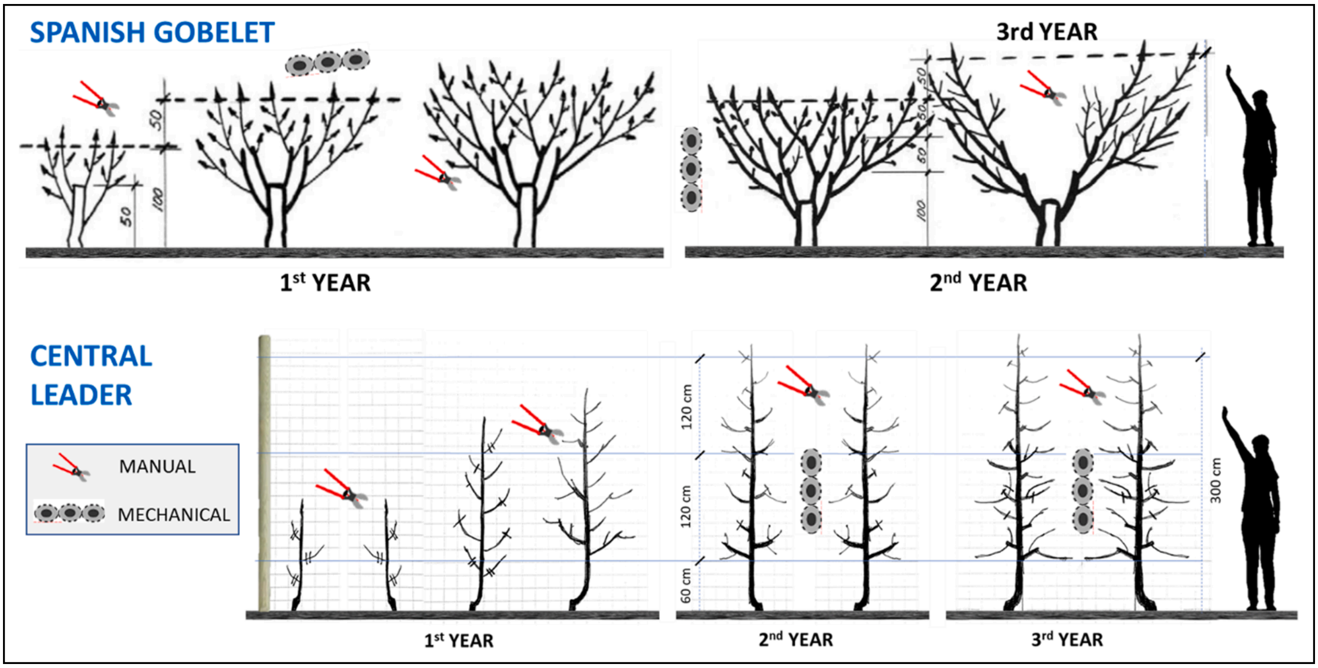


Fig. 1. The two training systems selected for the different trials: the Spanish gobelet (top) and central leader (below). The main green and winter pruning operations from planting to adult trees are indicated.

size, fruit firmness, soluble solids content and titratable acidity) were determined as described by Iglesias and Echeverria (2009). For the determination of tree vigour, yield and yield efficiency, 4 blocks or replications of 1 single tree per treatment and season were established, collecting a unique set of data as a mean of each block.

3. Results and discussion

3.1. Rootstocks, vigour, yield efficiency and fruit quality

Intensification in peach can be achieved using size-controlling rootstocks. Different peach seedlings, plums, and interspecific *Prunus* hybrids such as Nemaguard, Controller-5, Controller-6, Montclar, Adesoto-101, Montizo, Isthara or Penta, have been used as peach rootstocks in the US and different European countries, with some selected for vigour control (DeJong et al., 2005; Iglesias, 2018; Reig et al., 2020; Reighard et al. 2020). In the last two decades, additional vigour-controlling rootstocks have been introduced, both in experimental and commercial plots (Fig. 2). In Spain, numerous trials have been conducted that demonstrate the effect of rootstock on fruit size and yield efficiency (Iglesias and Carbó, 2006; Iglesias, 2018; Iglesias et al., 2020), in particular with the rootstocks Rootpac-40, Rootpac-20 and Isthara and some plum rootstocks such as Adesoto-101, MRS 2/5, Penta or Tetra.

The effect of the rootstock on the agronomical performance of 'Big Top' nectarine grafted on 20 rootstocks was evaluated in a long-term trial carried out at IRTA in the Ebro Valley (NE Spain) (Reig et al., 2020). Common planting distance for all rootstocks was 5.0 × 2.6 m. Trees were all Spanish gobelet-trained. The criteria established for the first pick were fruit size >65 mm Ø and fruit colour coverage >80%. Among the rootstocks, the highest vigour was recorded with Rootpac-70 and PADAC-0403, followed by PS, Garnem and GF-677. The lowest vigour was obtained with Poluce. The rest of the rootstocks were similar in terms of tree vigour. Since the vigour of the rootstocks is different and the spacing is the same, it is better to use yield efficiency to estimate their potential interest. Krymsk-1 provided the best yield efficiency and the lowest tree vigour, but showed clear symptoms of a lack of compatibility with 'Big Top' nectarine. Among others, Rootpac-40 provided one of the best yield efficiencies (Fig. 3), the best fruit size distribution (Fig. 4) and the best average yield harvested in the first pick (Fig. 5). Furthermore, based on firmness, Rootpac-40 anticipated fruit ripening by 7 days compared to GF-677. Similar positive results were obtained with Adesoto-101, Isthara, Penta and IRTA-1 in terms of yield efficiency, but not in relation to fruit size and in terms of advancing harvest date. Most of the plum rootstocks tested in this trial, namely AD-105, Krimsk-1, Adesoto-101, Pacer-01.36 and Padac-150, are sensitive to root sucker emission (Reig et al., 2020).

3.2. Training systems, cost of establishment and cost of production

The open vase training system, in combination with different 3D canopy architectures, continues to be the most used system in the main peach producing countries (the US, Spain, Italy, Greece and France). In the US, the main system is the traditional open vase with semi-vigorous rootstocks such as Nemaguard or Lowell (Fig. 2), with a progressive development of more intensive orchards with size-controlling rootstocks (Grossman and DeJong, 1998; Anthony and Minas, 2021). In Italy, axial systems such as the fusetto or palmette with the use of platforms have been employed for decades. Several plum rootstocks, such as Adesoto-101 as well as more vigorous rootstocks like GF-677, have also been widely used. These types of orchard are usually not pedestrian, and the use of platforms is common (Corelli-Grappadelli, 1998; Vittone et al., 2020). In Spain, the open vase adaptation is known as the Spanish gobolet, Spanish bush or Catalan vase, representing 92% of total production. The basis for efficient training of this system has been described by Montserrat and Iglesias (2011) and Iglesias and Echeverría (2021). The common spacing is 5 × 3 m with heights ranging from 2.3 to 3.0 m (667 trees ha^{-1}). The use of high vigour rootstocks like GF- 677, Garnem or Cadaman is common, and indeed required to rapidly occupy the space assigned to each tree and achieve maximum yield as soon as possible. In the fourth year, full yield is reached for most cultivars with yields ranging from 35 to 65 tha^{-1}. When the tree canopy has fully developed, use of the growth regulator (paclobutrazol) is necessary to properly manage tree vigour. The increasing restrictions imposed by EU regulations on the use of growth regulators, such as paclobutrazol, could restrict in the future the use of vigorous rootstocks associated with this training system.

Labour is one of the most important production costs in growing deciduous fruit trees, in particular in peach or cherry orchards, though of less importance in nuts (almond, walnut or hazelnut) (Iglesias, 2019; Iglesias et al., 2021). In recent decades, a significant increase in labour costs and a shortage of labour have become common in all countries. The cumulative increase in the cost of production has been much higher than the increase in the price received for the fruit by the growers in the

120-110%	110-100%	100-80%	80-60%	60-40%	<40%
Very vigorous	Standard	Standard-mid	Mid	Semi-dwarf	Dwarf
GF-677 Garnen Nemaguard Atlas	Montclar® GF-305 Cadaman Lovell, Kuban	Rootpac®R Tetra Penta	Adesoto-101 Isthara® Controller®6	Rootpac®40 MP-29 Controller®5	Rootpac®20

Fig. 2. Vigour conferred by different rootstocks in peach, from more (left) to less vigour (right).

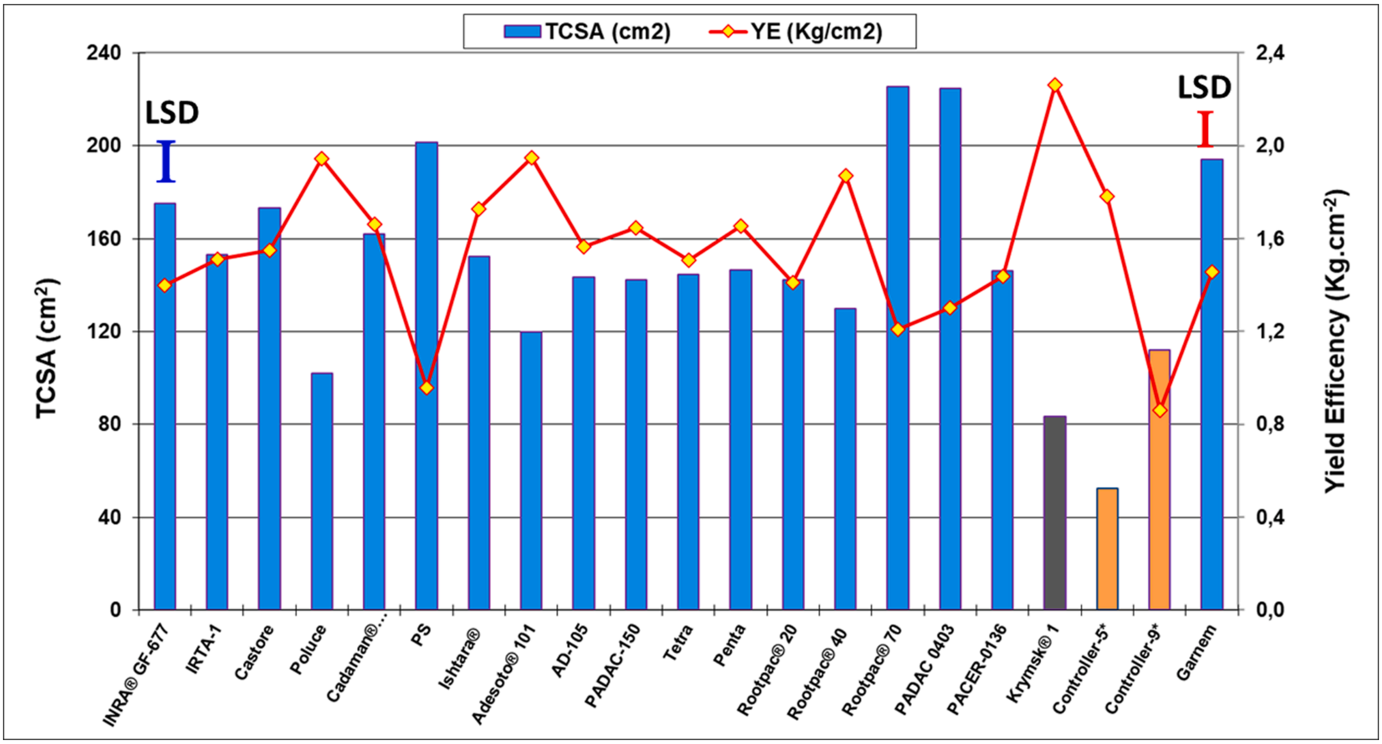


Fig. 3. Tree vigour (TCSA) and yield efficiency (YE) after 10th year of 'Big Top' nectarine grafted on 20 *Prunus* rootstocks (Reig et al., 2020). Vertical bars (blue for vigour, red for YE) represent the LSD at $P \leq 0.05$ (Reig et al., 2020).

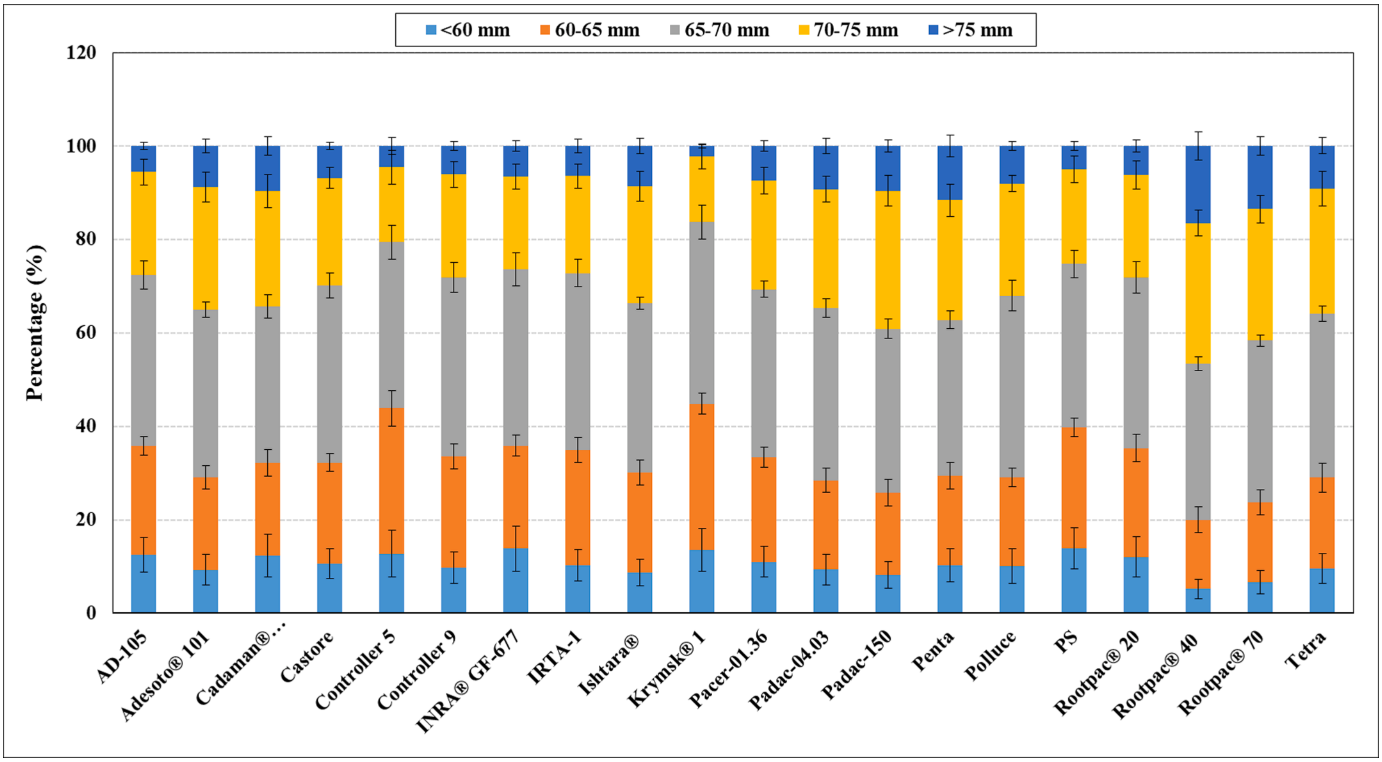


Fig. 4. Mean fruit size distribution percentage (%) from 3rd leaf to 11th year of 'Big Top' nectarine grafted on 20 *Prunus* rootstocks. Vertical bars indicate the standard error per fruit size (Reig et al., 2020).

most important production areas of Spain (Fig. 6). Total cost of production, varies from 0.45 to 0.28 cts €.kg^{-1} for an early (30 tha^{-1}) and a late harvest variety (55 tha^{-1}), respectively. It is mainly dependant on labour, which represents 45% of the total in the traditional Spanish gobelet system, followed by fertilizers, crop protection and soil management. Harvest, fruit thinning and pruning are the most important costs with a high labour demand (Fig. 7). While such costs can be partially reduced by replacing manual labour with mechanization

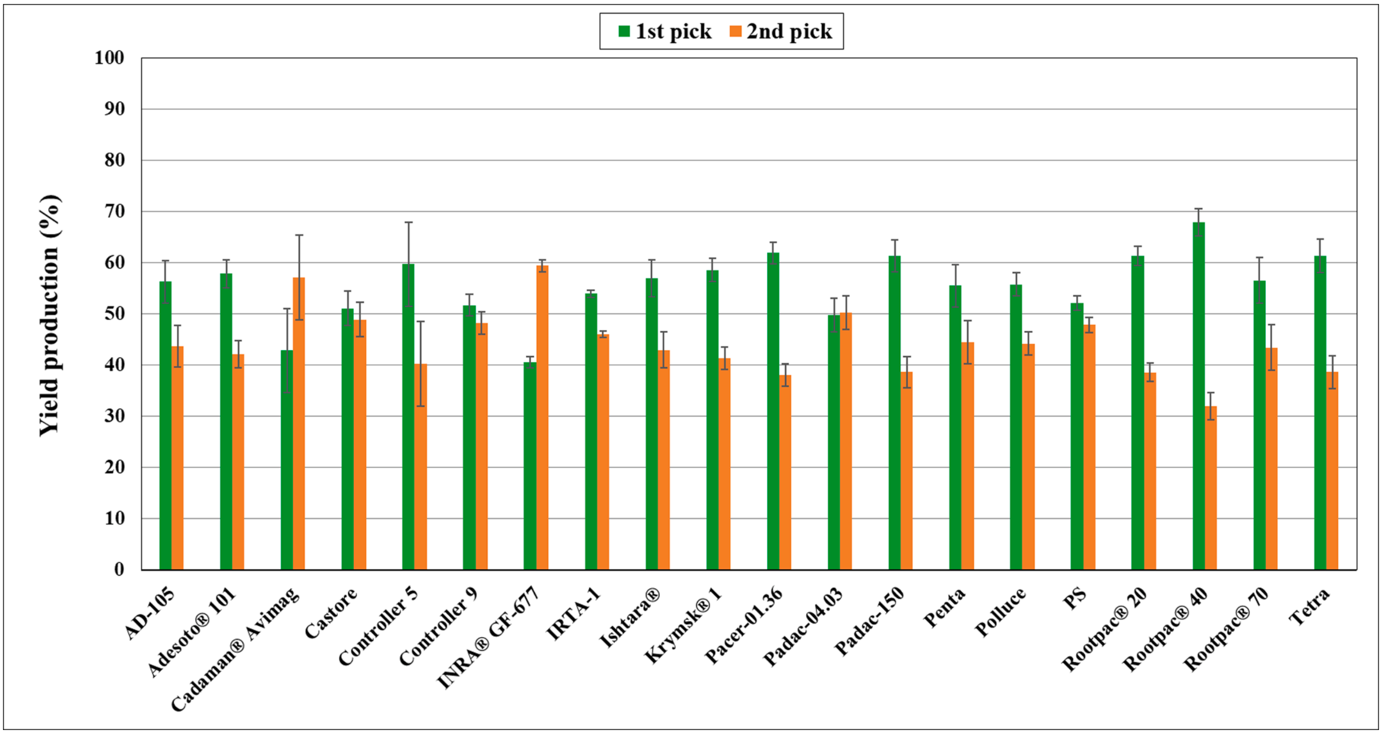


Fig. 5. Mean yield percentage values (%) for each harvest (1st and 2nd) from 3rd to 11th year, of 'Big Top' nectarine grafted on 20 *Prunus* rootstock. Vertical bars indicate the standard error per harvest (Reig et al., 2020).

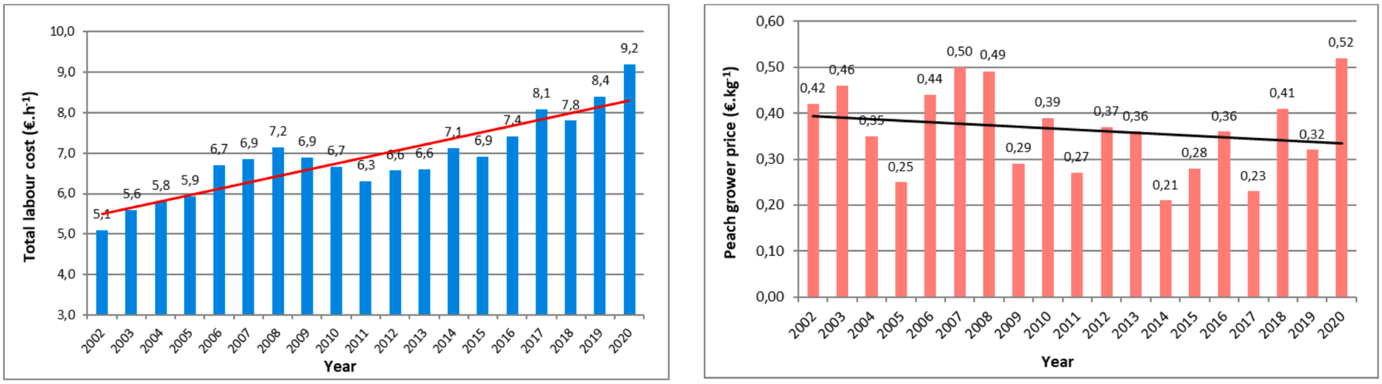


Fig. 6. Evolution of labour cost (€.h-1) and mean grower price (€.kg^{-1}) at constant prices for a mid-season nectarine variety in the Ebro Valley (NE Spain) across the period 2002–2020.

(Iglesias, 2019), this requires efficient planar canopies which are more accessible to both labour and machines (Iglesias, 2019; Iglesias, 2022. *In press*). In addition, bidimensional canopies in peach are more efficient in the use of pesticides and fungicides (Table 1), reducing drift and consequently the environmental impact and the cost of production (Iglesias, 2021).

One of the most important costs in peach production is harvesting (Fig. 7). In the same trail described below in Section 3.4., the harvest rate was determined with the aim of establishing the effect of intensification on yield and fruit quality. Adult trees of the midseason cultivar 'Luciana' had a harvest rate of 120 kg.h-person^{-1} for the Spanish gobelet system and 210 kg.hr-person^{-1} for the central leader, platform-assisted, system. Considering a mean labour price of 8.5 €.hr^{-1} (2020), the equivalent harvest cost.kg^{-1} was 7.0 cts €.kg^{-1} for the Spanish gobelet system and 4.0 cts €.kg^{-1} for the central leader system. By developing planar canopies with size-controlling rootstocks and using mechanization for pruning, thinning and harvest, including more efficient spraying, the total cost of production was reduced by 2647 €.ha^{-1} or 1933 €.ha^{-1} considering the annual amortization cost of 714 €.ha^{-1} (Table 1). The total labour requirements per season were reduced from 651 to 398 h.ha^{-1} when intensive planting orchards and planar canopies were used. This represents a 39% decrease in required labour due to greater efficiency. Despite this advantage, for intensive orchards the cost of planting is more than twice as high compared with the standard Spanish gobelet system. To calculate the current annual cost, we considered a total planting cost of 8000 €.ha^{-1} for the Spanish gobelet system and 18,000 €.ha^{-1} for the central leader system and a lifespan of 14 years, which resulted in an increased annual cost of amortization of 714 €.ha^{-1}, including interest costs, for the intensive system (Table 1).

To evaluate the effect of intensification, a second trial was initiated in 2011 to evaluate the agronomical and economic performance of 'Ambra' and 'Luciana' trained in double row and single row, both with the central leader system, compared with the Spanish gobelet system. The main characteristics and results of this trial corresponding to the

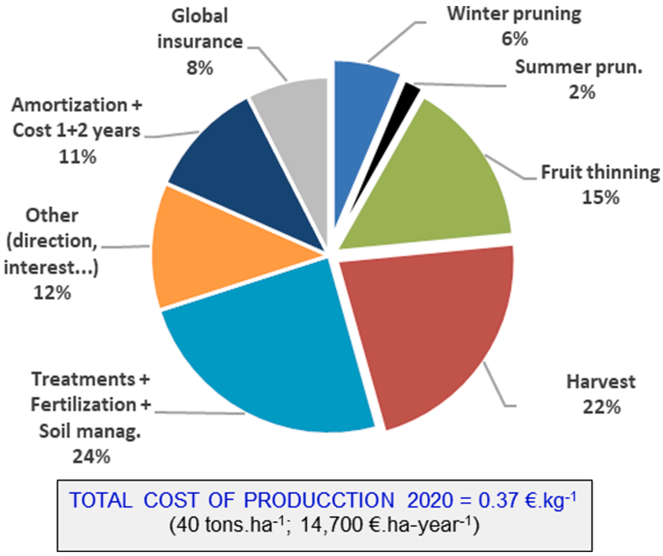


Fig. 7. Cost of production in 2020 for mid-season nectarine cultivar 'Luciana' (40 t/ha), trained in the Spanish goblet system in the Ebro Valley (NE Spain), with spacing 5 × 3 m and expected lifespan of 12 years.

period 2012–2017 are shown in Table 2 and Fig. 8. It can be observed that the two training systems with bidimensional canopies (central leader in single and double row), resulted in early yields and greater cumulative income for the grower, in particular with the double row. In contrast, the lowest cost of establishment and annual amortization was for the Spanish gobelet system, followed by the single row and double row. Even in a low-price scenario, as in the period 2012–2017, and considering the higher cost of establishment and amortization of both intensive systems, the additional income for the grower was positive and improved rapidly when the price rose in the case of 'Ambra' (Table 2).

In peach, the process of intensification towards smaller trees and 2D canopies, has not been as fast as in other crops such as pear, apple or cherry, mainly due to the lack of efficient size-controlling rootstocks (Iglesias, 2022. *In press*). The interest in developing bidimensional canopies and intensive training systems such as the central leader, bi-axis, or multileader (Fig. 9) is because of the potential for early and higher yields (Figs. 8 and 13) and the reduction of the cost of production, in particular labour. This is mainly due to the use of mechanical flower and/or fruit thinning, summer/winter pruning, and mechanical platforms for assisted harvesting (Table 1 and Fig. 10).

Different planar and intensive systems have been used in Spain for decades, but at a lower rate (about 8%) compared to the Spanish gobelet system. The triple axis and palmette systems are used in all areas with the same vigorous or semi-vigorous rootstocks as in the Spanish gobelet system. The use of growth regulator is common. Planting densities range from 3.5–4.0 × 1.5–2.5 m, achieving densities of 1000–1905-trees.ha^{-1}. Over the years the triple axis has gained in popularity compared to the palmette. Interest in the latter system has decreased because it requires more specialized labour during the first two years for the optimal occupation of space between trees compared to the central leader and Spanish gobelet systems (Figs. 1 and 9). Advantages of this system include the mid-planting density combined with a planar system, the benefits of canopy accessibility, mechanization and the good vigour control when semi-vigorous or vigorous rootstocks are used (Corelli--Grappadelli, 1998; Anthony and Minas, 2021).

An interesting option to reduce the cost of orchard establishment is to use the bi-axis system in a direction parallel to the row, thereby creating a homogenous, continuous fruiting wall. Planting densities range from 3.0–3.5 m × 1.0–1.5 m, achieving densities of 1905 to 3333 trees.ha^{-1}. This system achieves and/or increases the total number of leaders per hectare with fewer trees (Fig. 9). This is a major benefit for growers wishing to reduce upfront orchard establishment costs. This system is not as easy as the central leader to train during the first two years. Nevertheless, it achieves high light interception values, but also prioritizes uniform light distribution and high light penetration as these canopies are managed to be quite narrow (60–80 cm in depth) by

Table 1
Training system (Spanish gobelet and central leader) and rootstock effect on yield, production cost and labour efficiency for adult trees of the midseason cultivar 'Luciana' in the Ebro Valley (NE-Spain) in 2020.

TRAINING S./ ROOTSTOCK / SPACING	YIELD (kg/ha)	TOTAL COST (€.ha^{-1})$^{+}$	TOTAL COST (€.kg^{-1})	OTHER (€.ha^{-1})$^{+}$	PESTICIDES + FERTILIZERS (€.ha^{-1})*	WINTER PRUNING (€.ha^{-1})*	FLO. + FRU. THINNING (€.ha^{-1})*	HARVEST (€.ha^{-1})*	TOTAL VAR. COST (Σ*) (€.ha^{-1})	*Labour & efficiency (h.t^{-1})*
SPANISH GO. / GF-677 5 × 3 m	40,000	14,700	0.37	5634	3528 (2293 pest.) (1235 fert.)	920	1785	2833 333 h (120 kg.h^{-1})	9066	*(651 h/ha)* *16 h/t*
CENTRAL LEA. / RP-40 3.5 × 1.1 m	50,000	12,614	0.26	6195	2810 (1885 pest.) (1025 fert.)	750	836	2023 238 h (210 kg.h^{-1})	6419	*(398 h/ha)* *7.6 h/t*
DIFFE. CL-SG	+10,000	-2086	-0.11	+648	-718	-170	-949	-897	-2647	*+39%*

Labour cost considered: 8.5 €.h^{-1}.
(+): including annual amortization 714 €.year^{-1}; (*): variable cost.

Table 2
Characteristics of three training systems, prices and cumulative income for grower corresponding to the period 2012–2017 for varieties 'Ambra' (AM) and 'Luciana' (LU) grafted on GF-677 and planted in February 2011 in Lleida (Ebro Valley NE Spain).

Training System	Planting distance (m)	Planting density (Trees.ha^{-1})	Cost of planting (€.ha^{-1})	Amortiza-tion cost (€.ha^{-1})	Mean price grower (2012–17) (€.kg^{-1}) AM.	Mean price grower (2012–17) (€.kg^{-1}) LU.	Cum. income grower (2012–17) (€.ha^{-1}) AM.	Cum. income grower (2012–17) (€.ha^{-1}) LU.
Spanish Gobelet	5.0 × 3.0	667	6500	433	0.33	0.26	18,030	4151
Central leader/ Single row	3.5 × 1.0	2857	15,100	1007	0.33	0.26	18,980	7863
Central leader/ Double row	3.5 × 1.0 × 1.5	4000	21,400	1427	0.33	0.26	31,980	16,982

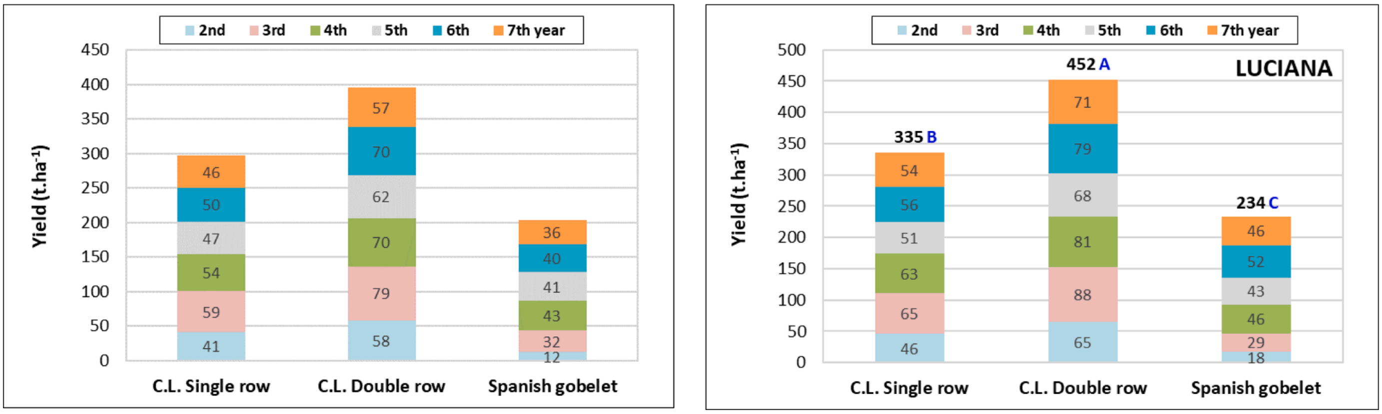


Fig. 8. Annual and cumulative yields of 7-year-old trees of nectarine cultivars 'Ambra' and 'Luciana' grafted on INRA GF-677 in central leader (C.L.; Single and Double row) and Spanish gobelet training systems in the Ebro Valley (NE Spain). Different letters, for the same variety, indicate significant differences according to Tukey HSD Test at $P \leq 0.05$.

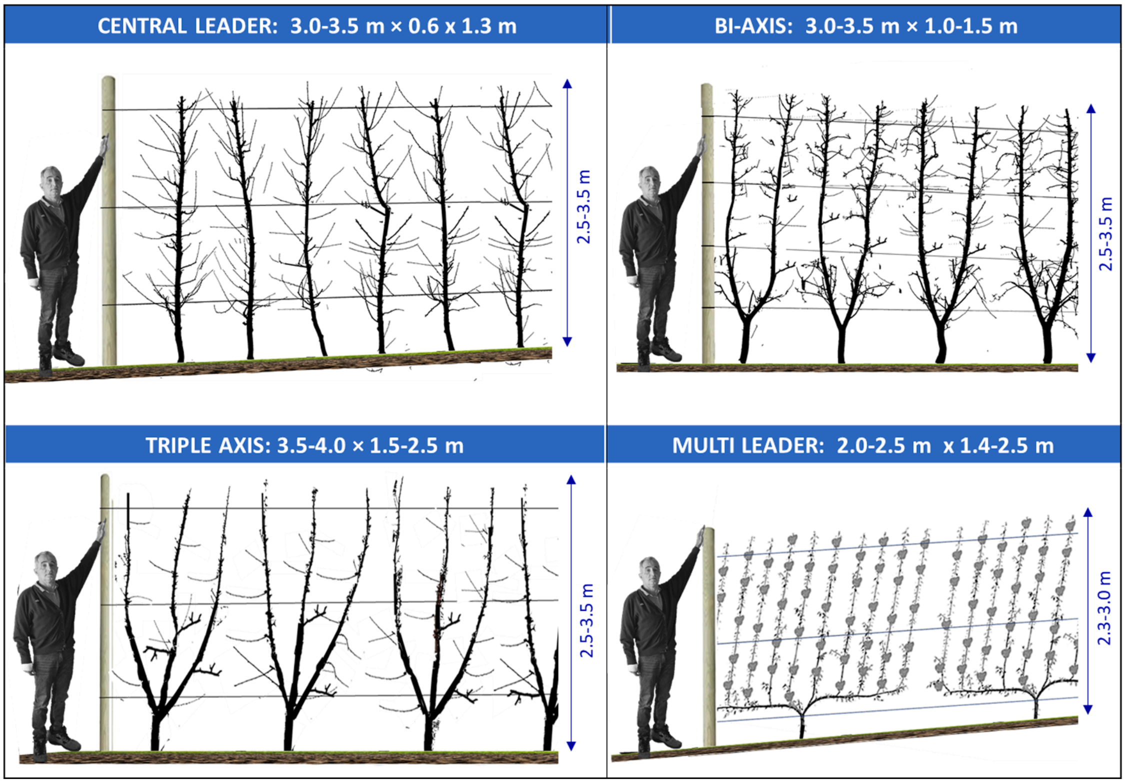


Fig. 9. Different options for planar orchards systems in peach: from central axis to the multi-leader system. Indicative planting distances are indicated for each system.

mechanical pruning (Fig. 10 and 11). In addition, the combination of intensification and two-fold leaders results in better control of vigour and a greater planar canopy compared with the central leader system. This is an interesting option for early and vigorous varieties grafted on semi-vigorous rootstocks such as Montclar, Cadaman or Rootpac-R (Fig. 2) and fertile soils.

The central leader system is increasingly used in Spain, mainly in combination with size-controlling rootstocks (Rootpac series, plums or other interspecific hybrids such as Isthara) (Fig. 2). Different options have been developed in different countries, including fusetto, tall spindle axe, slender spindle axe or free spindle (Loreti et al., 2002; Anthony and Minas, 2021). Planting densities range from 3.0–3.5 m × 0.6 × 1.3 m, achieving densities from 2198 to 5555 trees.ha^{-1}. With respect to the trials reported in this paper, the central leader characteristics are described in Section 2 (Material and methods). This is the simplest system to train trees during the first two years since it only requires, in comparison with the bi-axis, triple axis or multileader system, a relatively easy manual task of green pruning combined with mechanical pruning (Fig. 1 and 10). In this high-density planting system, the integration of optimum spacing, summer pruning and waterspout removal are key to ensure optimal light interception, penetration and distribution values. The objective of all these techniques is to achieve a "true" fruiting wall, capable of inducing early and constant yields, while integrating the use of machines for thinning and pruning as well as platforms for labour reduction. All these benefits can be also attained with pedestrian orchards by resizing the inter-row/tree height ration based on the latitude (Iglesias et al., 2021).

Multi-leader is a new training system based on several axes spaced

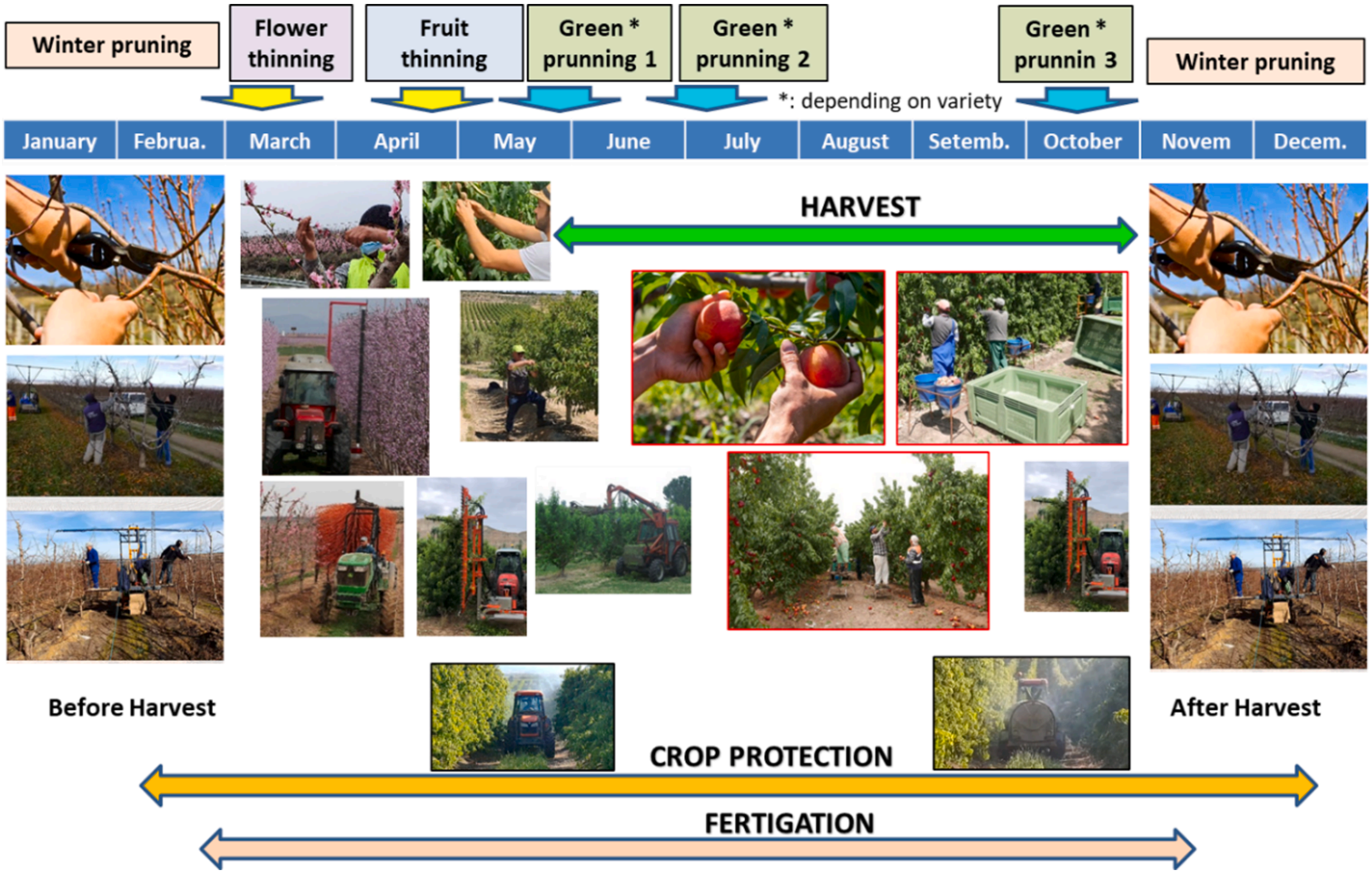


Fig. 10. Illustrative timeline representing different cultivation operations for peach, from pruning to harvest, fertigation, and crop protection in the Ebro Valley (NE Spain).

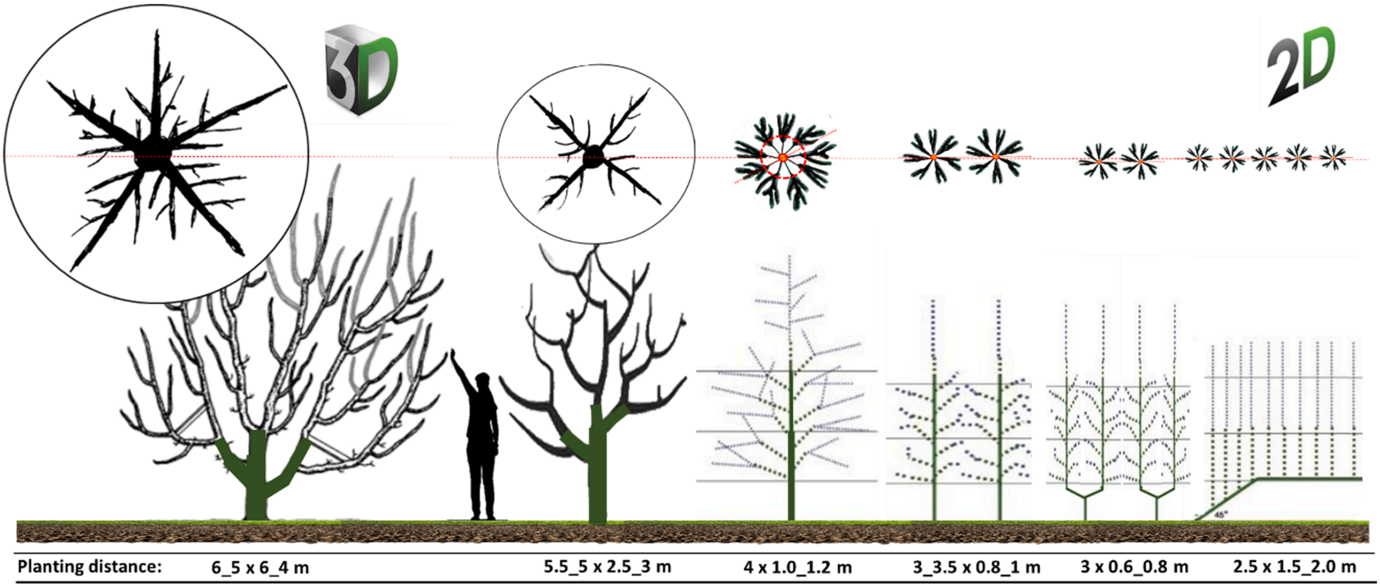


Fig. 11. Intensification of orchards and reduction of tree canopy towards planar canopies in deciduous fruit species. In the upper part of the figure, vertical projection of the canopy can be observed.

around 30 cm apart, inserted vertically in two (Fig. 9) or one (Fig. 11) horizontal permanent scaffolds/arms. The objective is to create a homogenous and continuous fruiting wall to manage as a pedestrian or non-pedestrian system, depending on rootstock vigour, with a tree height from 2.4 to 3.2 m. The main advantages of this system are the narrow canopy (30–40 cm in depth), resulting in optimum light exposure and accessibility to manual works and machines (Fig. 11), combined with medium density planting. The cost of the support structure and orchard establishment during the two first years is much higher than for the central leader, bi-axis or triple axis systems. Common planting densities range from 2.0–2.5 m (inter-rows) × 1.4–2.5 m (inter-trees), achieving densities from 1600 to 3571 trees.ha^{-1}. Different trials are ongoing to test its performance in Spain, Italy, Greece, and Australia. They have largely been undertaken in the last decade in both experimental and commercial orchards of apple and cherry UFOs (upright fruiting offshoots) in different countries.

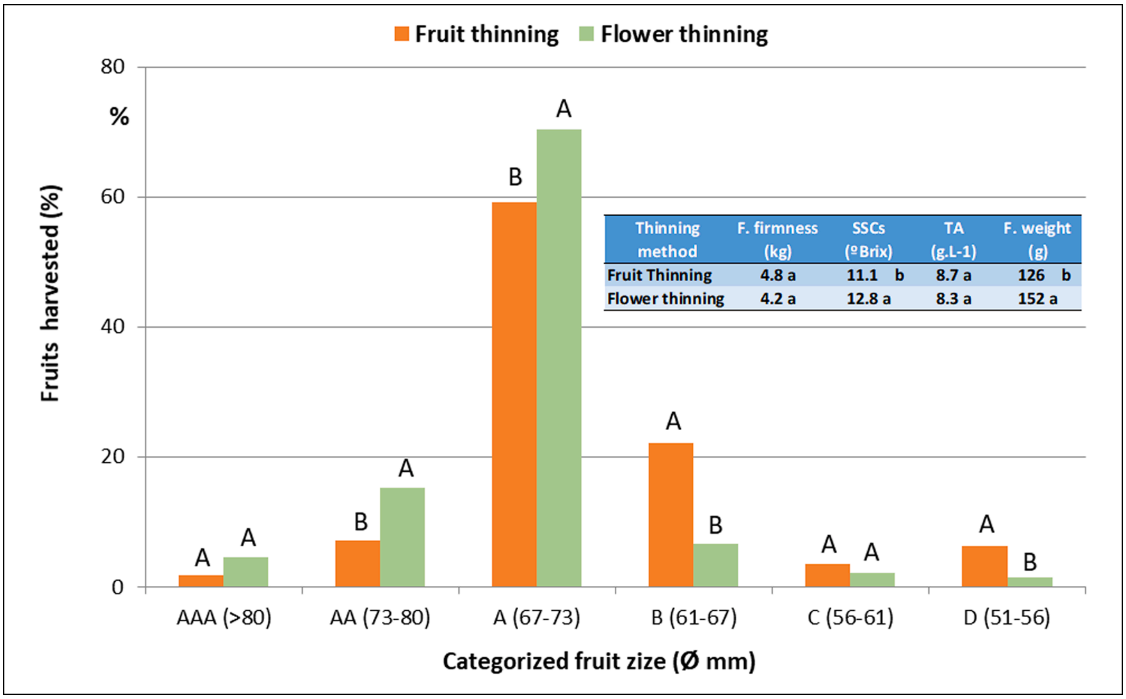
3.3. Training system flower/fruit thinning

Flower and fruit thinning represents 15% of the total production cost as shown in Fig. 7, in particular for high blooming intensity and early harvest varieties. Flower and fruit thinning has an effect on crop load management and, consequently, on peach quality (Sutton et al., 2020). In Spain and Italy, mechanical flower thinning is a common practice in intensive peach orchards of early and mid-season varieties with high or mid blooming intensity. It is applied at 10%-60% of bloom (Vittone et al., 2010; Iglesias and Echeverría, 2021). The results obtained on 8-year-old trees of cv 'Ambra' (early season) trained in Spanish gobelet and central leader systems, applying either standard manual fruit thinning or mechanical flower thinning with a Darwin machine (Fruit Tec) and complementary hand thinning of fruits are shown in Fig. 12. Flower thinning has a positive effect on fruit size distribution and some quality parameters, leading to an increase in SSC and fruit weight. Fruit quality (fruit size, colour, SSC) is directly related to the price received by growers, especially in early season cultivars (Iglesias and Echeverría, 2009). The total cost of thinning (hand fruit thinning *vs.* mechanical with Darwin plus complementary hand thinning) was reduced from 1785 €.ha^{-1} to 836 €.ha^{-1}, respectively (Table 1). With the Spanish gobelet system, use of the Ericius rotor machine adapted to the tractor and used for flower thinning resulted in a cost reduction from 1785 €.ha^{-1} to 1346 €.ha^{-1}.

3.4. Training systems and intensification with standard and size controlling rootstocks

In this section, we describe the results obtained from two trials. The first used the same rootstock GF-677 and two training systems: central leader and Spanish gobelet plus paclobutrazol as a growth regulator applied in both training systems. In the second, rootstock vigour was adapted to the training system: Rootpac-40 for the central leader system and GF-677 for the Spanish gobelet system. Both training systems had a similar crop load management.

The first trial was stablished in a commercial orchard in the area of Lleida (Ebro Valley, NE Spain). The aim of this trial was to assess how the training system (intensification) affects yield and fruit quality. The two cultivars used were 'Ambra' (early-season) and 'Luciana' (mid-season). Both cultivars were grafted on GF-677. Trees were planted in February 2011 as dormant bud with a spacing of 3.5 × 1.0 m (central leader single row), 3.5 × 1.0 × 1.5 m (central leader double row) and 5 × 3 m for the Spanish gobelet system. Planting densities and cost of planting are presented in Table 2. Paclobutrazol was applied, after the second year, through a drip irrigation system at a constant dosage of 0.60 lha^{-1} when one-year-old shots reached 20 cm long. At the end of the first year, the central leader trained trees (single row and double row) almost reached the entire volume assigned to them because of the high vigour conferred by the rootstock. This resulted in early yields compared to the Spanish gobelet system. In contrast, with the Spanish gobelet the space assigned to each tree was not fully covered until the end of the third year (Fig. 1). Cumulative yields obtained across the 2012 (2nd year) to 2017 (7th year) period are illustrated in Fig. 8. Increasing planting density with the central leader system (single and double row), together with a superior tree height, resulted in higher annual and cumulative yields compared with the Spanish gobelet system. In the case of the central leader system, the use of a small sledge was required to reach around 20% of the fruit, while in the Spanish gobelet system almost 90% of the fruit could be reached from the ground. Regarding fruit colour, fruit size and SSC content, no differences were recorded in 'Luciana', a high colour variety. However, fruit colour and SSC content were improved in 'Ambra', trained in both single and double row and compared with the Spanish gobelet system (data not shown). Tree vigour, determined as TCSA per each variety in November 2017, showed differences between the Spanish gobelet and central



Thinning method	F. firmness (kg)	SSCs (ºBrix)	TA (g.L-1)	F. weight (g)
Fruit Thinning	4.8 a	11.1 b	8.7 a	126 b
Flower thinning	4.2 a	12.8 a	8.3 a	152 a

Fig. 12. The effect of flower or fruit thinning on fruit size distribution and fruit quality parameters in 8-year-old trees of cultivar 'Ambra' (early season) grafted on GF-677 rootstock at Lleida (Ebro Valley-Spain) and trained in Spanish gobelet (hand fruit thinning) and central leader (flower thinning + hand fruit thinning) systems. Different letters, for the same categorized fruit size and quality parameter (table), indicate significant differences according to Tukey HSD Test at $P \leq 0.05$.

leader systems of -32% and -28% for ‘Ambra’ and ‘Luciana’, respectively. The results are aligned with the data shown in Fig. 13 with the same variety ‘Luciana’ grafted on GF-677. Considering the superior cost of establishment of intensive training systems (single row and double row), the additional profit for the grower improved rapidly when the fruit price was higher, as in the case of ‘Ambra’ (Table 2). In a scenario of good or very good fruit prices due to varietal innovation and a favourable market situation, the benefit of intensification is evident, either with single or double row central leader systems.

The above results show the interest of intensification with the use of paclobutrazol, currently registered in Spain, but of uncertain availability in the future. For this reason, a second trial using a size-controlling rootstock was conducted with ‘Noracila’ (early-season) and ‘Luciana’ (mid-season) cultivars, both grafted on Rootpac-40 and GF-677. Trees were planted as one-year-old trees (June graft) in December 2010 and trained with the central leader (spacing 3.5 × 1.1 m) and Spanish gobelet system (5 × 3 m), respectively. Paclobutrazol was applied for vigour control only in the trees grafted on GF-677. Tree height was established at 3.2 m for the central leader and 2.4 m for the Spanish gobelet systems. The annual and cumulative yields of 7-year-old trees are shown in Fig. 13. In both varieties, the use of size-controlling vigour rootstock Rootpac-40 resulted in early and higher annual and cumulative yields when compared with the Spanish gobelet system on GF-677. Fruit size was determined by grading 4 trees of each combination per season and cultivar. Mean fruit size values obtained for ‘Noracila’ were 71% and 88% of the fruits in the interval Ø 61–67 mm (Cat. B) for GF-677 and Rootpac-40, respectively. For ‘Luciana’ these values were 74% and 85% of the fruits in the interval Ø 67–73 mm (Cat. A).

3.5. *Training system effect on investment cost, agronomical performance, and light interception*

The effect of training systems on yield, fruit quality and profitability in peach have been previously reported (Corelli-Grappadelli and Marini, 2008; Sutton et al., 2020). Table 3 and Fig. 14 show the results obtained in a trial conducted by Nuñez et al. (2006) with the cultivar ’O’Henry’ grafted on Montclar and planted in 1995, in which six training systems (from flat canopy to 3D canopy) and one additional training system (narrow central leader), which was tested in the same trial but not included in this publication, were evaluated. These were evaluated for 10 years. Planting distance, planting density, cumulative yields, costs and NPVs (net present values) corresponding to all the systems are shown in Table 3. Cost of planting was directly related to planting density and support structure. In this case, both central leader systems were the most expensive, followed by Y-trellis. The highest cumulative yield was obtained with the narrow central leader, ypsilon, palmette and Y-trellis systems, and the lowest with the double Y system. Therefore, yield potential of angled canopies (T-trellis and Ypsilon) was similar to central leader but lower than narrow central leader. The highest variable cost, based on the traditional open vase system (not the Spanish gobelet), were recorded for the Y-trellis and the narrow central leader systems, both due to a higher cost of establishment. Considering economic profitability and taking into account mean grower average price for the period 1997–2005 (0.42 €.kg^{-1}), the most interesting systems were the narrow central leader and the transversal ypsilon (without support structure) and the least interesting were the double Y and the open vase due to their lower yields. This higher profitability of the narrow central leader system was due to the higher cumulative yields despite the higher cost of establishment, which was related to the higher planting density and the need for a support structure.

In the same trial, light interception was evaluated for different training systems for three consecutive years (2003–2005), measured on 5 sunny days in July of each year, using a Sun Scan SS1-UM-1.05 ceptometer within the PAR (photosynthetically active radiation) wavelength band of 400–700 nm. The results obtained were expressed as a percentage of total above canopy PAR and are shown in Fig. 14. Diurnal trend was nearly symmetric around solar noon. The maximum differences between treatments occurred at around noon. The largest inception values were obtained from 3D canopy systems like the Y-trellis, open vase, transversal ypsilon and double Y. The lowest values were registered with more or less 2D vertical canopies, namely the palmette followed by the central leader and narrow central leader systems. When the mean value (%) for the whole day was calculated, differences between systems were substantially reduced, as can be seen in Fig. 14, ranging from 70% to 89% for palmette and Y-trellis, respectively. The difference between the double Y (similar to the Spanish gobelet) and narrow central leader systems was only 6%. Intensification from the central leader towards the narrow central leader system resulted in a 3%

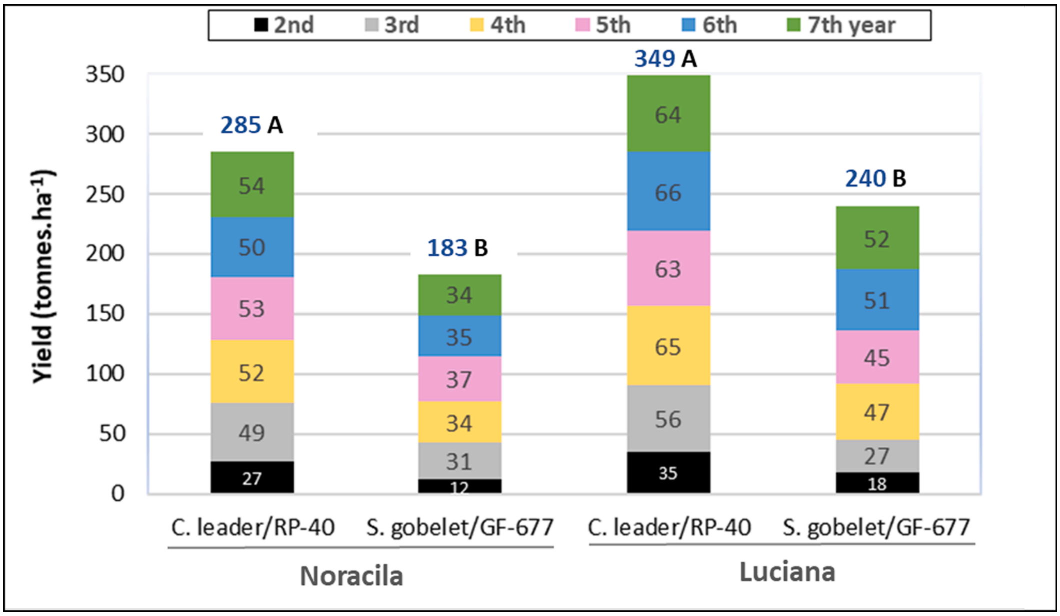


Fig. 13. Annual and cumulative yields of 7-year-old trees of nectarine cultivars ‘Noracila’ (early season) and ’Luciana’ (mid-season) grafted on Rootpac-40 (central leader) and GF-677 (Spanish gobelet) represented as mean values of different orchards in the Ebro Valley (Spain). Different letters, for the same variety, indicate significant differences according to Tukey HSD Test at $P \leq 0.05$.

Table 3
Performance of several training systems with cultivar ‘O.Henry’ grafted on Montclar rootstock in a 10-year trial (1995–2005) at the EE Lleida-IRTA (Ebro Valley, Spain) planted in 1995. Open vase was the reference. Adapted from Nuñez et al., 2006.

Training system	Planting distance (m)	Planting density (trees. ha^{-1})	Cost of planting (€. ha^{-1})	Cumulative yield 10 years (t.ha^{-1})	% Cumul. Yield referred Open vase = 100	Variable anual cost (€.ha^{-1})	% anual cost referred to Open vase	Net Present Value in % referred O.v.
Ypsilon (transversal)	5.5 × 1.75	1038	6800	295.3	113	8920	+7%	107
Central leader	4.5 × 1.75	1270	*9100*	286.1	109	8780	+6%	96
Narrow Central leader	*3.5 × 1.10*	*2597*	*16,800*	*480.0*	*183*	*8950*	*+9%*	*147*
Open vase (traditional)	5.5 × 3.5	519	5400	261.7	100 (referen.)	8100	0 (referen.)	100 (referen.)
Double Y	5.5 × 3.5	519	5300	225.6	86	7050	-17%	85
Palmette	4.5 × 3.5	635	6700	264.8	101	8150	0%	99
Y-Trellis	5.5 × 3.5	519	8400	285.1	109	9100	10%	98

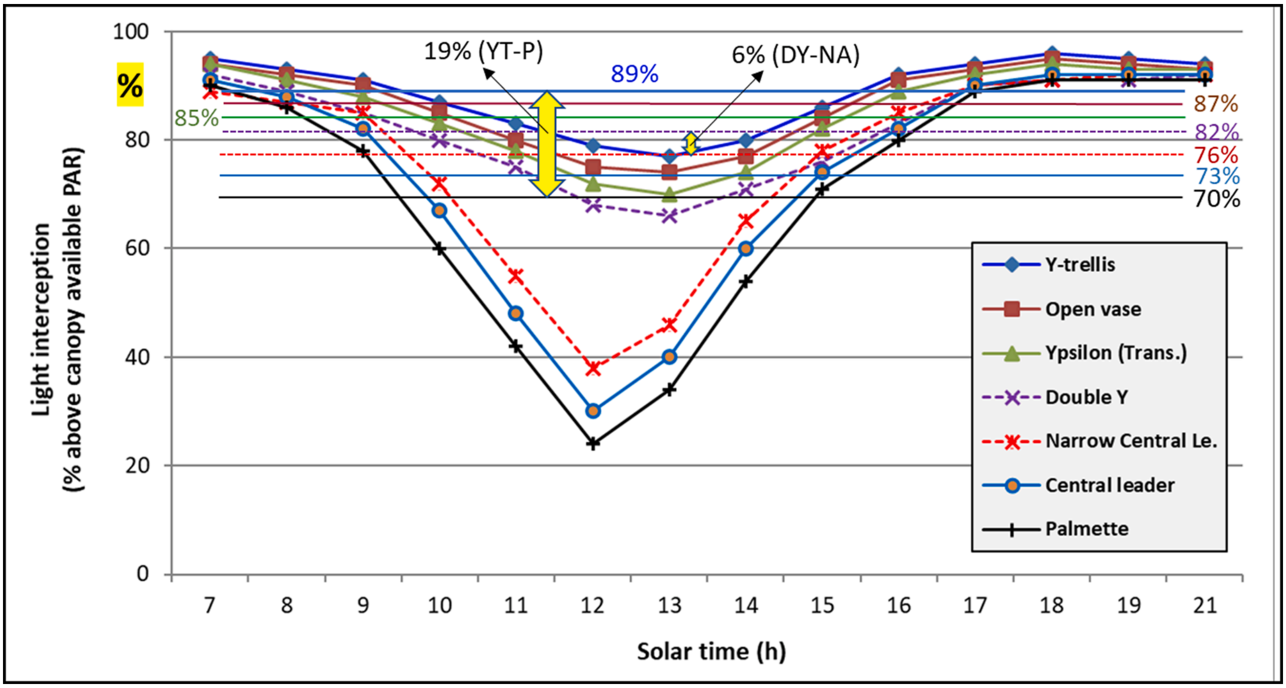


Fig. 14. Mean hourly values of light interception, expressed as % above canopy available PAR (μmol.m^{-2}.seg^{-1}), corresponding to different training systems for the period 2003–2005. Mean percentage (%) values along the day for each system are also shown.

increase in intercepted light. The reduction of light interception in planar canopies (palmette and central leaders), was compensated by a greater planting density and tree height.

Our results are in accordance with those reported by Whiting (2018) in cherry indicating similar values of light intercepted when Y-trellis and UFO (similar to palmette). However, yield potential of angled canopies was greater than planar canopy (UFO). Similar values of light intercepted have been also published by other authors in almond when comparing the open vase with the super high density (SHD) system (Casanova-Gascón et al., 2019; Iglesias et al., 2021). These data demonstrated, for a specific combination of variety/rootstock, that training system affects light interception and yield, as also reported by several authors in apple (Palmer, 1989), pear (Musacchi et al., 2021), peach (Corelli-Grappadelli and Marini, 2008; Iglesias, 2019), cherry (Long et al., 2015, Lugli et al., 2015), or almond (Iglesias et al., 2021). In this trial, no linear relationship between light intercepted and cumulative yield was found (Table 3 and Fig. 14). Therefore, yields were more related with planting density and canopy architecture than the daily average of light intercepted.

The data shown clearly demonstrate the benefits of intensification. Yields obtained with central leader systems have been always precocious and superior to those with the Spanish gobelet system. Small trees and bidimensional canopies result in better accessibility to the canopy for labour and machines. These benefits compensate the superior establishment cost of intensive orchards with reasonable fruit prices for the growers. In addition, this planar canopy architecture opens the door to the adoption of future advancements in precision production technology through the development of multispectral cameras, monitorization or robotic harvesting, providing useful data and tools for the optimization of inputs such as labour, water, fertilizers and pesticides.

4. Conclusions

Intensification combining size-controlling rootstocks and training systems based on small and bidimensional canopies result in more efficient use of inputs, in particular labour, reducing the cost of production and increasing the economic sustainability of orchards. Peach production involves high labour-intensive tasks such as pruning, thinning or harvesting. Planar canopies allow for easier access and higher efficiency of both workers and machines. In addition to labour cost reductions, bidimensional canopies combined with intensification lead to a reduction of labour in terms of training the trees during the initial years, as well as early and higher cumulative yields. As in other species such as apple, pear or cherry, providing technical data in peach about varieties × rootstocks, cost of orchard establishment and cost of production, training systems, pruning and mechanization options will be useful for growers in the transition towards more efficient and sustainable orchards. All these factors must be the main focus for producers, researchers and breeders alike.

CRediT authorship contribution statement

Ignasi Iglesias: Conceptualization, Methodology, Investigation, Writing – review & editing, Visualization, Formal analysis. **Gemma Echeverria:** Conceptualization, Investigation, Data curation, Writing – review & editing.

Declaration of competing interest

None.

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