Combining new rootstocks and training systems for sustainable production in deciduous tree crops

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Abstract

The common trend for orchard design with all these crops is intensification, combining mid- to low-vigour rootstocks with training systems based on bidimensional canopies. In deciduous species as apple, peach and cherry, the use of size-controlling rootstocks, such as M9 and low vigour Geneva® selections in apple, "Rootpac®" series in peach or Gisela® and Adara rootstocks in cherry, combined with intensive training systems has produced earlier and higher cumulative yields than using the traditional open vase. Combining intensification, size controlling rootstocks and planar canopies resulted in greater efficiency in the use of labour and mechanization as mechanical flower thinning and mechanical pruning. It also helps improve the harvest rate efficiency reduces production costs and increases fruit quality. However, an increase in skilled labour requirements was recorded when the number of axes increased from a central axis to bi-, tri- and multi-axes. In almond, super high density (SHD) developments with the size-controlling rootstocks Rootpac®20 and Rootpac®R, allowed the full mechanization of pruning and harvesting, resulting in very early yields and a reduction in production costs compared with the traditional open vase, in particular crop protection. Furthermore, all these planar canopies were better adapted to the application of precision technologies based on artificial vision (AV) and artificial intelligence (IA) for fruit counting, yield forecasting and robotic harvesting.

Keywords: deciduous crops, rootstocks, high-density, planar canopies, production cost, efficiency, sustainability

INTRODUCTION

Prunus fruit species are among the most important crops grown in countries such as Spain the USA, Italy, Poland, Chile and Australia in terms of fruit production. Europe is the second largest producer of peach after China, with an average annual production of 3,710,029 t in the period 2019-2021 and a total harvested area of 226,607 ha. Spain is the second country in this ranking after China with a surface area occupied by deciduous fruits in 2021 of 184,500 and 721,100 ha for almond crop. Annual world cherry production was 2,665,313 t in 2021 and led by China, Turkey, the USA, and Chile. Almond has been the most widely planted species in the last decade in countries such as the USA, Spain and Australia, accounting for a total harvested surface area of more than 2 million ha. Apple is the most important pip fruit species. The main production area is Asia, with China in the first place, followed by the USA, Turkey, and Poland.

In peach, different interspecific hybrids and seedling rootstocks providing mid to high vigour (GF-677, Garnem, Guardian, Nemaguard, Atlas, and Lowell, among others), are commonly used. In the last decade, the interest in size-controlling rootstocks has increased, with the aim of developing more intensive and efficient orchards (Iglesias and Echeverría, 2022; Iglesias et al., 2023a). Among others "Rootpac®" series, Isthara® and MP-29 (Beckman et al., 2012), are well now. In the last decade new rootstock selections as Intensia (Lordan et al., 2019) and Pilowred (Bielsa et al., 2023) are in process of testing and development in different countries. In cherry there is a wide range of rootstocks that is used. In southern

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Europe, different selections of *P. mahaleb* and Adara are commonly combined with MaxMa®14 (Iglesias et al., 2023b). In the USA, Chile and many other countries, Colt, Mazzard, Mahaleb and Krymsk are used, and also different selections of GiSelA® (Long et al., 2019). In almond most of the production is from low to mid-density orchards, using mid to high-vigour rootstocks as Nemaguard, Lowell, Krymsk or Atlas in USA. In southern Europe various peach × almond hybrids such as GF-677 and Garnem are commonly used. In both species, peach and almond, different size-controlling rootstocks, such as some of the "Rootpac®" series from Agromillora, and new peach × almond hybrids (Pilowred® and Intensia®) have started to be used at the commercial scale during the last decade (Iglesias and Torrents, 2022). In apple, M.9 selections are widely used in the main producing areas of Europe, the USA, Brazil, Chile, and New Zealand. Innovation has led to different Geneva® rootstocks being used in the USA (Cornell-Geneva breeding programme) (Robinson, 2019, pers. commun.).

Labour is one of the most critical production costs in deciduous fruit production, and particularly for peach, cherry, and apple, but it is less important in nuts (almond, walnut or hazelnut) production (Iglesias et al., 2022a, 2023b). In this scenario, an efficient way to gain competitivity is by partially replacing labour by efficient mechanization (pruning, thinning, harvest) by developing planar canopies (Day et al., 2005; Neri et al., 2022). These bidimensional canopies are more accessible to workers and machines (Long et al., 2019). Combining intensification with planar canopies results in early yields and in a reduction in the cost of production (Iglesias et al., 2023a). Developing intensive orchards with planar canopies better adapted to mechanization and thereby achieving greater efficiency in the use of inputs, particularly labour, increasing fruit quality and yield (Lugli et al., 2015; Musacchi et al., 2015; Iglesias et al., 2023b), providing also better accessibility to the canopy for both workers and machines (Iglesias et al., 2023a). Thanks to that, many bi-dimensional training systems are being used worldwide to optimize production and fruit quality (Reig et al., 2019; Tustin et al., 2022).

In *Prunus* species, the open vase or goblet system, is the standard training system for most peach, cherry and apricot orchards, system traditionally associated with mid- to high-vigour rootstocks and important canopy volumes. In Spain, new, intensive peach orchards have been planted in the last decade, using size-controlling rootstocks from the "Rootpac®" series and other interspecific hybrids to avoid the need for bio-regulators, a common practice with the traditional Spanish open gobelet system (Iglesias and Echeverría, 2022). Bi-dimensional planar canopies trained on single and bi-axes have been developed in all deciduous species with aiming to increase the efficiency of inputs, reducing production costs by providing better accessibility to the canopy for both workers and machines (Iglesias et al., 2023a). In almond, the traditional almond cropping system is based on low-medium density orchards of medium-large trees, and using vigorous, or semi-vigorous, rootstocks (Miarnau et al., 2019; Iglesias et al., 2022b). The mechanization of pruning and harvesting, with the use of over-the-row harvesters, has led to more efficient use of inputs and produced higher yields in mid- to high-density or SHD orchards (Maldera et al., 2023). In apple, intensification has been progressive over the last five decades, thanks to the availability of size-controlling rootstocks such as M.9 selections and Geneva® rootstocks (Fazio and Robinson, 2021). Thanks to that, bi-dimensional training systems are being used worldwide to optimize production and fruit quality (Reig et al., 2019; Tustin et al., 2022).

RESULTS AND DISCUSSION

In this section, we illustrate, using different *Prunus* species (peach, cherry and almond) and apple as examples, the effect of combining size-controlling rootstocks and intensive training systems on yield, yield efficiency and fruit quality. The data were collected from either experimental or commercial orchards in different countries, such as the USA, Spain, and Italy. The aim was to show the benefits of an optimal combination of cultivar/rootstock/training systems and how this could be used to achieve the best orchard performance. In the case of rootstocks, the most commonly mentioned species are shown in Figure 1, which is based on vigour conferred to the cultivar.

SPECIES	120-110%	110-100%	100-80%	80-60%	60-40%	<40%
	Very vigorous	Standard	Standard-mid	Mid	Semi-dwarf	Dwarf
PEACH	Garnen (GN.15) Guardian® Nemaguard Atlas, Viking	GF.677, GF.305 Montclar® Cadaman® Krysmk®86	Tetra Penta Controller®7 Controller®8	Adesoto.101 Isthara® Controller®6 Rootpac®R	Rootpac®40 MP.29 Controller®5 Intensia®	Rootpac®20 Pilowred®
CHERRY	INRA®SL.64 Mazzard Mahaleb	Adara MaxMa®14 GiSelA®17	GiSelA®13 GiSelA®12 Piku®1	GiSelA®6 Weiroot.158 Krymsk.6	Weigi.2 GiSelA®5 Clinton	GiSelA®3 Lake, Cass Crawford,Clare
ALMOND	Garnen, Krimsk-86 Nemaguard Hansen-536	GF.677, GF.305 Montclar® Krysmk®86	Barrier Myran	Adesoto.101 Montizo Rootpac®R	Isthara® Pilowred®	Rootpac®20 Intensia®
APPLE	Seedling	MI.793 MM.111 M.4	M.7, MM.106 G.969, G.210 CG.5257, CG.6001	M.9 Pajam®2 G.41 G.213	M.9 T337 NAKB M.9 EMLA G.11	M.27 M.65

Figure 1. Comparative vigour (%) conferred by different rootstocks used for different stone fruit, apple and almond species (Source: own research, based on different sources).

Peach

After cherry, peach is the crop with the greatest demand for labour, with this representing around 50% of the total cost of production, based on € 0.43 kg^{-1} in the Ebro Valley (Spain), for a mid-season cultivar in 2022 (Iglesias et al., 2023b). The main components of labour costs are harvesting, fruit thinning and pruning. A full set of data reported by Iglesias and Echeverría (2022), showed the benefits for growers of combining intensification using size-controlling rootstock (Rootpac®40) and planar canopies (axis and bi-axis). A recent experiment was started in 2020 and conducted involving the nectarine cultivar 'Boreal®', grafted onto different size-controlling rootstocks from the Rootpac® series and GF-677, as a reference rootstock (Figure 2).

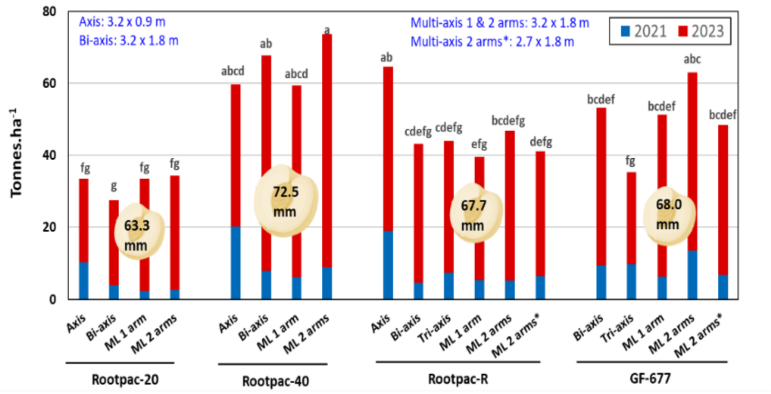


Figure 2. Annual, cumulative yields and fruit size (2021 and 2023) of 'Boreal' nectarine grafted onto different rootstocks and subjected to different training systems. The trees were planted in February 2020 at Soses (Ebro Valley, Spain), as dormant buds.

Trees were planted in February 2020 as dormant buds. The interrow spacing was 3.2 m and all the training systems were bidimensional and almost fully pedestrian orchard. Spring frosts annulled the yields in 2022. The cumulative yields and mean fruit size for each rootstock are shown in Figure 2 and again highlight the gain in yield obtained with intensification and controlled fruit size, particularly with Rootpac®40. This rootstock also produced the greatest yield efficiency, being followed by Rootpac®R (data not shown). Despite the different multi-axes restricting the yield in the first year, the cumulative yields (2021+2023) achieved with single and bi-axes were greater for some rootstocks (Rootpac®40 and GF-677).

The greatest effect of intensification is a reduction in the amount of labour required for manual training of the trees to fill the spaces between two consecutive trees within each row in the case of bi-axis, tri-axis or multi-axis (Figure 3, blue bars). This space was, instead, occupied by additional trees. The collateral effect of intensification and planar canopies use was therefore an increase in the cost of plantation plus the extra cost of the support structure that was required to keep the canopies as vertical as possible for and efficient mechanization (Iglesias and Echeverría, 2022). Annual and cumulative years from the 2nd to 5th year after planting show that early yields were obtained from more intensive training system as the central axis, followed by multi-axes, bi-axis and tri-axis, as illustrated in Figure 3 (yellow bars). It also shows the cost of the trees associated to each system, highest for central axis and lowest for multi-axis (green numbers). As in apple (Tustin et al., 2022; Iglesias et al., 2022a), multi-axis system combines high cumulative yield with the lowest cost of planting but requires more labour during first two years. So, the selection of one specific option will be depending on the labour availability/cost and scion cost in each situation.

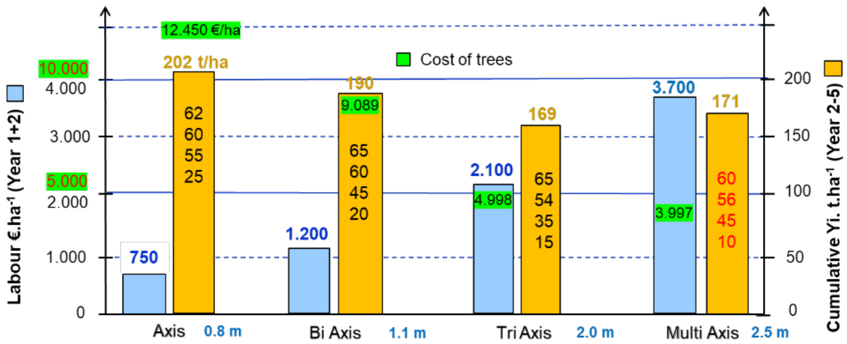


Figure 3. Labour cost, corresponding to the first two years, required to train 1 ha of mid-season nectarine cultivar ‘Luciana’ grafted on Rootpac®40 in the Ebro Valley (Spain), including the cost of the trees, and the annual/cumulative yield (2nd to 5th year). Interrow distance 3.0 m. The distance between trees for each system is indicated on the *x*-axis. Costs of labour: 9.5 € h^{-1}, cost of tree 3.5 € $tree^{-1}$, corresponding to 2021.

Cherry

As previously shown for apple and peach, in cherry production, intensification again requires size-controlling rootstocks (Dallabetta et al., 2019). Some of those currently available have come from the “Corette®” series (Michigan State University, USA), while others are from the “GiSelA®” series (CDB, Germany). Results of their agronomical performance in different states of the USA have shown their potential interest regarding early yields and fruit quality (Iezzoni, 2013, pers. commun.; Lang, 2000; Long et al., 2019). In various countries in Europe, a set of trials sponsored by Agromillora and CDB began in 2022. These were conducted in collaboration with EUFRIN and other companies with the objective of discovering their potential interest (Iglesias et al., 2023b). The results obtained by applying this concept in commercial orchards in the Emilia Region of Italy, combining different “Sweet series” cultivars with dwarfing rootstocks, such as GiSelA®5, are shown in Table 1. Their efficiency in terms of reducing the unproductive period, increasing yield and improving fruit quality, especially in terms of fruit size, was very clear.

Other rootstocks, named Corette®, have been released by Michigan State University (MSU) in the USA. They have the following names: Corette®1 Cass, Corette®2 Clare, Corette®3 Clinton, Corette®4 Crawford, and Corette®5 Lake. Three of these MSU rootstocks: Cass, Clare and Lake, produce particularly small trees, which are equivalent to, or smaller than, trees grown on GiSelA®3. Clinton and Clare also exhibited significantly greater yield efficiencies than Lake, GiSelA®5 (Gi5) and Krimsk®6. They have been tested at different locations in the USA, providing interesting results.

Table 1. Annual and cumulative yields, mean fruit size and fruit weight of 7-year-old 'Sweet Valina', 'Sweet Sareta' and 'Kordia' trees grafted onto GiSelA®5 at Ferrara (Emilia Romagna, Italy). Source: Iglesias and Torrents (2022).

Cultivar	Spacing distances (m)	Yield (t ha^{-1}) 2nd year	3rd year	4th year	5th year	6th year	C.Y. (t)	Fruit size % (Ø mm)	mm	Fruit weight (g)
S. Valina®	3.50×0.50	3.3	6.5	15.1	18.4	16.3[a]	59.6	100% (28+)	28-30	7.7
S. Saretta®	3.50×0.50	3.8	7.7	18.3	22.8	20.7[a]	73.3	100% (30+)	30-32	8.2
Kordia	3.50×0.50	3.0	6.5	12.6	13.1	5.2[a]	40.4	90% (28+)	28-30	7.4

[a]Affected by spring frost during bloom: 9 days at 0°C and 2 days at -4.5°C.

For example, Corette® selections combined with 'Bing' provided a significant reduction in tree canopy size with a high yield efficiency and a similar fruit size to GiSelA® selections. The yield efficiency and fruit weight of the 'Bing' cultivar were shown to be improved by the Cass and Clare rootstocks, but the trial was limited, and more testing is required (Long et al., 2019). For 'Regina', grown at The Dalles (OR), in 2019, and trained to a steep leader, Cass and Clare, followed by Clinton, produced significantly greater annual projected yields ha^{-1} than Krymsk®6 (K6) and GiSelA®6 (Gi6) (Table 2).

Table 2. Tree yields, projected per hectare yields and fruit size for 'Regina' grown on four Corette® and GiSelA® rootstock selections, for trees planted in 2015 at The Dalles (Oregon). The tree numbers ha^{-1} and spacings (m) used for the projected yields were 1,282 (1.8×4.3) for Krimsk®6 and G6; 1,537 (1.5×4.3) for G5, Clinton and Lake; and 1,922 (1.2×4.3) for Clare and Cass. Data for three years are presented with yield efficiencies (Y.E.) for 2019.

Rootstock selection	Tree yield (kg) 2017	2018	2019	Y.E. (kg cm^{-2}) 2019	Yield ha^{-1} (t ha^{-1}) 2017	2018	2019	Fruit size (mm) 2017	2018	2019
GiSelA®5	2.9 a	10.8 ab	5.9 bc	0.13 bc	0.8 a	3.0 ab	1.6 bc	28 a	28 ab	29 a
GiSelA®6	2.4 a	13.7 a	7.5 abc	0.23 ab	0.5 a	3.2 ab	1.7 c	28 a	27 ab	28 ab
Krismk®6	1.4 a	10.1 ab	2.9 c	0.06 c	0.3 a	2.3 b	0.7 d	28 a	28 ab	28 ab
Cass	1.8 a	10.7 ab	12.5 a	0.39 abc	0.6 a	3.7 a	4.3 a	28 a	28 ab	28 ab
Clare	6.1 a	6.2 b	7.8 ab	0.33 a	1.0 a	2.1 b	2.7 b	28 a	29 a	29 a
Clinton	2.0 a	10.3 ab	8.8 ab	0.39 a	0.5 a	2.8 ab	2.5 ab	28 a	27 b	27 b
Lake	1.4 a	6.8 b	4.5 bc	0.14 b	0.4 a	1.9 b	1.3 c	28 a	28 a	28 ab

Significantly different means (P<0.05) are denoted by different letters.

Almond

Spain has developed important innovations in growing almonds, creating new self-fertile and/or late blooming cultivars, new rootstocks and new intensive or SHD training systems (Miarnau et al., 2019; Iglesias et al., 2022b; Batlle et al., 2023). Thus, plantation densities from 500 to 800 trees ha^{-1} are commonly used in new orchards, mainly based on the use of medium-high-vigour rootstocks as GF-677, Garnem, Hansen-536 and Krymsk-86 (Lordan et al., 2019; Miarnau et al., 2019) (Figure 1). The most innovative change in the last decade has been the introduction of SHD, as a new training system. Its development in Spain started on a commercial scale around 8 years ago, with the total surface that it occupied being 14,634 ha in December 2022, mainly located in Spain and Portugal. This SHD is based on an edge which allows almost full mechanization of pruning and harvesting, as reported by Maldera et al. (2023) and Iglesias et al. (2022b). This efficient mechanization, together with the most efficient pesticide application, has produced a reduction of around 25% in the cost of production (Iglesias et al., 2022b). Size-controlling rootstocks are required for these SHD orchards, with Rootpac®20 and Rootpac®R being the most used. Other new rootstocks, such as Intensia® and Pilowred® (Figure 1), are also giving promising results in either intensive or

SHD orchards. The primary consequence of using SHD is obtaining earlier yields compared with the intensive system, as shown in Figure 4. These are mainly related to the interrow spacing and have progressively reduced from the first version (V1), in which 4.0 m spacings were used, to the third version (V3), in which distances between rows ranged from 3.0 to 3.2 m (Casanova-Gascón et al., 2019; Iglesias et al., 2022a, b; Maldera et al., 2023). The height of the hedge is limited by the dimensions of the over-the-row harvester, which usually stands at less than 3 m above the ground. Between trees, the most common distances used range from 1.0 to 1.2 m.

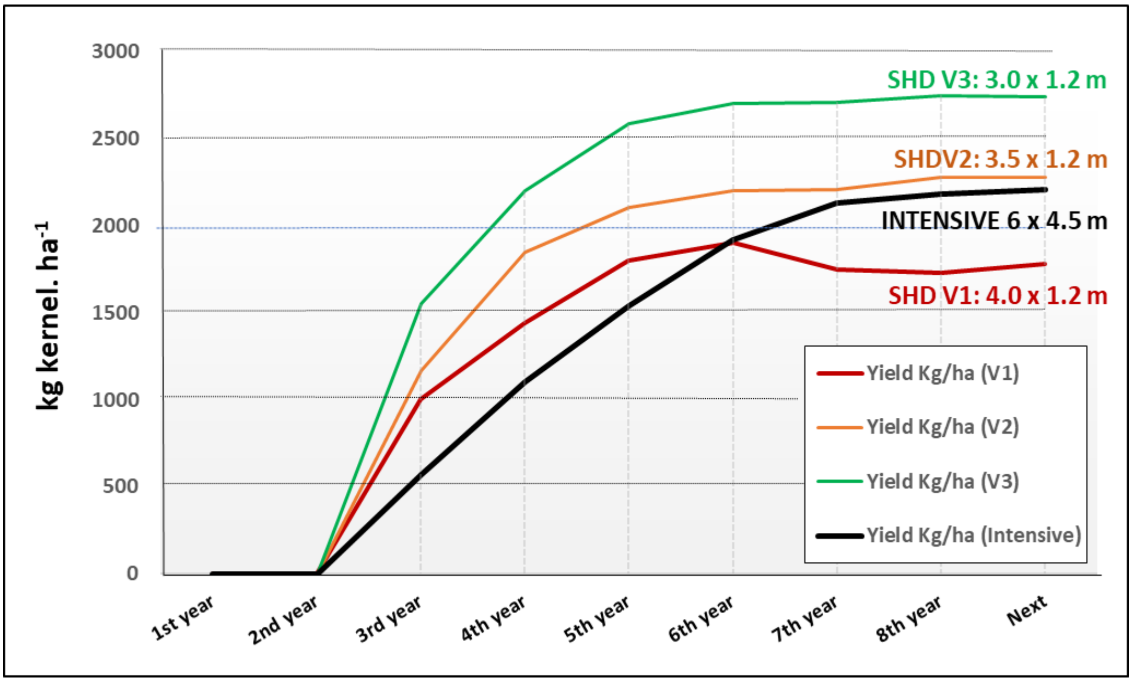
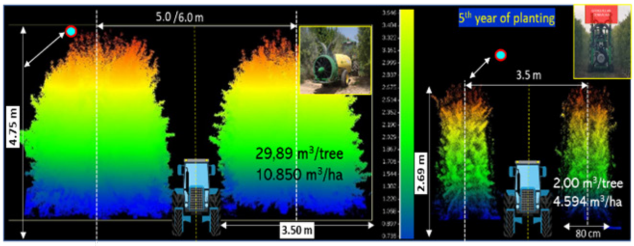


Figure 4. Yields obtained from the 3rd to 8th year corresponding to 'Lauranne' grafted onto GF-677 (intensive system), compared with those from 3 versions of SHD (V1, V2 and V3) with Rootpac-20 rootstock. The data for each point are the mean values for 6 orchards located in the Ebro Valley and in Extremadura (Spain).

Regarding the impact of inputs on the total cost of production, the cost of pesticides for plant protection ranks second (Iglesias et al., 2022b). For this reason, it is interesting to know the effect that the training system has on plant protection efficiency. The results for 2021, corresponding to a multi-year trial carried out by GRAP-Universitat de Lleida, which compared the intensive open vase system with SHD, both with very different tree architecture and volume canopy, are presented in Figure 5. The most significant effects were on the volume of water applied, leaf deposition, drift, and the cost of the treatment. With SHD, the water volume applied was reduced significantly, as were the drift and the total cost ha^{-1}-season of plant protection. In addition, leaf deposition increased.

Apple

Among the deciduous fruit species, apple is the reference crop for the development of intensive orchards. This was largely thanks to the massive development of M.9 selections in the main producing areas of the world. This exceptional dwarfing rootstock provided a very significant increase in yield efficiency and fruit quality compared with conventional ones such as seedlings, MM-111 or MM-106 Work conducted within the Cornell-Geneva USDA-ARS breeding programme, over more than five decades, allowed the selection of a new generation of rootstocks. Some of them (G.11, G.41, etc.) improved the yield efficiency of M.9, while also adding greater tolerance to biotic and abiotic factors (Robinson, 2019, pers. commun.; Fazio and Robinson, 2021). Figure 6 shows the increase in yield efficiency when these two rootstocks were used. In the same trial, the results presented in Figure 6 show how the increase in fruit quality and yield efficiency resulted in an increase in net profit for the grower, particularly when B9, M.9 337T and G.41 TC were compared. In the USA, several long-term studies have been done combining Geneva® rootstocks along with B.9, M.9 and others with different training systems on different top ten apple produced (Reig et al., 2019, 2020; Fazio and Robinson, 2021), proving their better yield efficiency in different training systems. In Europe, some ongoing trials are still testing these new improved rootstocks with different training systems under quite diverse European climatic conditions (Spain, Italy) (Iglesias et al., 2022a).



FACTOR	Intensive (JD R-130)	SHD (HD Fede)
Spacing (m) & planting density (trees ha^{-1})	5.5 x 5.0 (363)	3.5 x 1.25 (2,285)
Canopy volume (m^3 ha^{-1})	10,850	4,770
Applied volume (L ha^{-1})	1,130	745
Applied volume per canopy (mL m^{-3} canopy)	104	131
Leaf deposition (%)	69 %	76 %
Drift (%)	29.3 %	16.6%
Treatment cost (€ ha^{-1} year^{-1})	1,014	716

Figure 5. Tree architecture, canopy volume as scanned by LiDAR and equipment used corresponding to the Intensive Open Vase system (spacing of 6.0×5.5 m) with GF-677 rootstock and SHD (spacing of 3.5×1.2 m) with Rootpac®20, (left). Planting distances and results, in the 4th year after planting (2021) on a commercial plot located in Lleida (right). Source: Grau and Iglesias (2023).

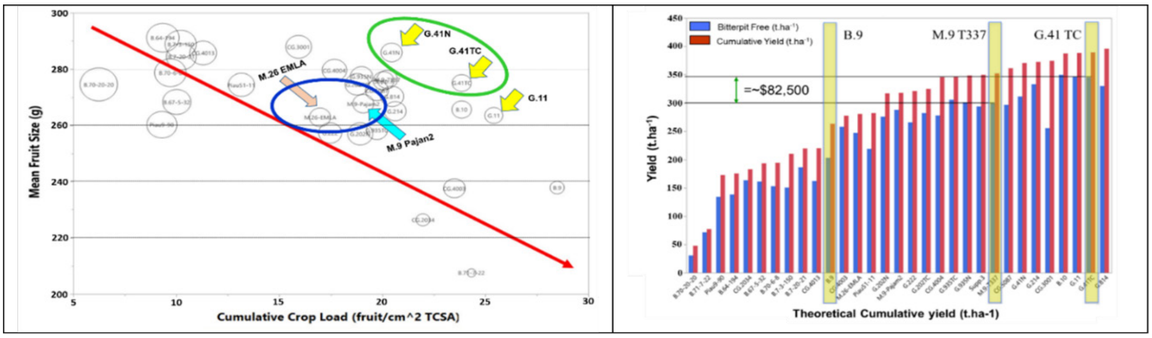


Figure 6. Bubble plot of 8-year yields of 'Honeycrisp', showing mean fruit size by cumulative crop load, sized by the trunk cross-sectional areas of trunks for 31 rootstocks (Fazio and Robinson, 2021) (left). Theoretical cumulative and bitter pit-free yields (t ha^{-1}) for 8-year yields of 'Honeycrisp' grafted onto 31 rootstocks (Robinson, 2019, pers. commun.).

CONCLUSIONS

Selecting the best combination cultivar/rootstock and joining it with the right training system, adapted to each specific situation, is the key for future orchards. Generally, size controlling rootstocks, combined with bidimensional canopies, are required for an efficient accessibility to canopy of labour and machines. In addition, small trees resulted in a better efficiency of inputs as labour, pesticides, or irrigation water, among others.

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