This document is a postprint version of an article published in Scientia Horticulturae © Elsevier after peer review. To access the final edited and published work see https://doi.org/10.1016/j.scienta.2019.108558

Document downloaded from:

Horticultural Performance of ‘Marinada’ and ‘Vairo’ Almond Cultivars Grown on a Genetically Diverse Set of Rootstocks

Abstract

Evolution of almond planted area and production has been mainly due to the arrival of new cultivars and rootstocks that have contributed to improve agronomic characters such as yield, precocity and efficiency. In recent years, are becoming available new cultivars that have contributed to provide late blooming time and self-fertility, and with ease to adapt for mechanical harvest and high-density. However, there is scarcity of studies where the interaction of these new cultivars with hybrid rootstocks has been tested. The aim of this study was to assess the performance of Cadaman®, Garnem®, INRA GF-677, IRTA-1, IRTA-2, Ishtara®, Adesoto, Rootpac® 20, Rootpac® 40, and Rootpac® R rootstocks with two promising almond cultivars such as ‘Marinada’ and ‘Vairo’. Bloom and nut ripening dates were affected by rootstock genotype. Both ‘Marinada’ and ‘Vairo’ cultivars showed low biennial bearing, with some differences among rootstocks, with IRTA-2 and Adesoto inducing the lowest values. On the other hand, Adesoto had higher number of suckers than the rest of the rootstocks. Garnem® provided the biggest trees, followed by Cadaman®, and then a third group which comprised IRTA-2 and INRA GF-677. Rootpac® 20 was the most dwarfing rootstock, followed by IRTA-1, Adesoto, Ishtara®, Rootpac® R, and Rootpac® 40. In terms of yield efficiency and partitioning index, IRTA-1, INRA GF-677, and Rootpac® R were the ones with higher values. Differences in tree volume and vigor for these rootstocks suggested that INRA GF-677 would be a suitable rootstock for low-medium planting densities with wide spacings; whereas Rootpac® R and IRTA-1 would be suitable rootstocks for medium- and high-density

plantings. Findings of this study showed dramatic differences in tree vigor, yield, kernel weight, yield efficiency, and partitioning index, which provide a wide range of options to deem for each cultivar in a particular climate and management.

***Keywords**: Biennial bearing; bloom; kernel yield; partitioning index; tree vigor; tree volume; yield efficiency*

Introduction

Almond (*Prunus dulcis* (Mill.) D. A. Webb. syn. *Prunus amygdalus* Batsch) planted area and production have been increased over the last years mainly due to the arrival of new cultivars that have contributed to provide late blooming time and self-fertility, and improved agronomic characters such as yield, precocity and efficiency (Batlle et al., 2017; Gradziel et al., 2017; Socias I Company et al., 2009). However, the good performance of an almond tree relies to the cultivar × rootstock interaction. Therefore, it is key to make the right election of rootstock and cultivar for each particular situation of production models and agro-climatic conditions.

The almond seedling has been the most common rootstock used in the Mediterranean basin for the last decades (Rubio Cabetas, 2016). This rootstock has a powerful root system, resistant to drought and limestone, and is very suitable for the survival of almond trees in dry, poor, and marginal soils (Felipe, 1989). Arrival of almond × peach hybrids in the 1970s implied a great change (Bernhard and Grasselly, 1981). Initially, these were used for peach trees (*Prunus persica* (L.) Batsch), but because of their good behavior, they have also been widely used in almond (Felipe, 2009; Mestre et al., 2015; Reig et al., 2019; Yahmed et al., 2016b). In recent years, the almond × peach hybrid INRA GF-677 rootstock is the most used in both dry and irrigated lands (Rubio-Cabetas et al., 2017). In particular, in the early 2000s, the hybrid rootstocks obtained by the CITA Saragossa, Garnem®, Monegro®, and Felinem® were released to the market with good success (Felipe, 2009;

Socias I Company et al., 2009). These CITA rootstocks (Garfi × Nemared series), with similar characteristics to INRA GF-677, provide nematode tolerance, and in addition their red-colored-leaves makes them very easy to handle in the nursery (Rubio Cabetas, 2016).

Concurrently, various hybrid rootstocks (almond × peach and other interspecific *Prunus* hybrids) as Barrier and Cadaman® appeared in the market searching root-knot nematode resistance and waterlogging resistance as new characteristics (Edin and Garcin, 1994; Iglesias and Carbó, 2006; Iglesias et al., 2004; Roselli, 1998; Rubio Cabetas, 2016). Some of them have begun to replace INRA GF-677 in peach orchards, and to a lesser extent, in almond (Font Forcada et al., 2012; Remorini et al., 2015; Rubio-Cabetas et al., 2017).

Use of seedling plum rootstocks (diploid plum clones) with the aim to reduce the tree vigor and adapt almond tree to soils with root asphyxia problems has also been studied. However, these rootstocks have been barely used due to their low vigor and their suckering habit (Felipe, 1989; Moreno et al., 1995).

In California, the use of peach seedlings (Lovell, Nemared and Nemaguard) has been common in almond orchards for sandy, deep, and fertile areas and with certain nematode problems (Duncan and Edstrom, 2008; Kester and Grasselly, 1987). In Australia, they have also used peach seedlings, but in recent years the inclusion of almond × peach hybrids has begun. These rootstocks can be better adapted to the poorest and shallow soils, with high concentration of calcium carbonates, which predominate in the new production areas of Australia (Sedgley and Collins, 2002; Wirthensohn and Iannamico, 2017).

Nowadays, in Mediterranean areas, most of the new almond orchards are being planted in fertile and irrigated lands (Miarnau et al., 2016). This implies a change in agronomic requirements with regard to rootstocks. In addition, root asphyxia tolerance is a new characteristic seek in new rootstocks. Currently, with the introduction of high-density systems, dwarfing rootstocks to help with tree vigor control are becoming more requested, for instance new hybrid rootstocks such as the Rootpac® series are becoming available (Gasic and Preece, 2014; Pinochet, 2010).

Other than rootstocks, successful almond production requires cultivars well adapted to the environment, with high yields, easy training, and good fruit quality (Vargas et al., 2008). New late-blooming and self-fertile almond cultivars such as ‘Vairo’, ‘Marinada’, ‘Constanti’, and ‘Tarraco’ have been recently released by IRTA (Vargas et al., 2008; Vargas et al., 2011), whereas cultivars such as ‘Belona’, ‘Guara’, ‘Mardía’ and ‘Soleta’ have been released by CITA (Felipe, 2000; Felipe, 2006; Felipe and Socias I Company, 1987; Socias I Company and Felipe, 1992) and ‘Antoñeta’, ‘Marta’, ‘Penta’ and ‘Tardona’ by CEBAS-CSIC (Dicenta et al., 2015).These new cultivars show promise and are starting to have a great impact on almond production, with consistent high yields (Lovera et al., 2015; Malagón et al., 2017; Miarnau et al., 2018; Puebla, 2016). However, there is scarcity of studies where the interaction of these new cultivars with hybrid rootstocks have been tested (Rubio Cabetas, 2016).

The aim of this study was to assess the agronomic and productive performance of different rootstocks grafted onto two promising almond cultivars ‘Marinada’ and ‘Vairo’. Interaction among tree growth variables and how rootstocks may modify the vigor, yield, efficiency, biennial bearing and even bloom and nut ripening phenology was examined.

Materials and methods

Plant material and experimental design

Two rootstock trials were planted in 2010 at the experimental station of IRTA (Institute of Research and Technology, Food and Agriculture) in Les Borges Blanques, Spain (41°30'31.89"N; 0°51'10.70"E), using ‘Marinada’ and ‘Vairo’ as the scion cultivars

(Vargas et al., 2008; Vargas et al., 2011). Both cultivars were selected due to their late-flowering and self-fertile characteristics, with different vegetative and productive habits; being ‘Marinada’ a medium-low vigor cultivar, and ‘Vairo’ a high vigor cultivar. For the ‘Marinada’ trial, trees were planted in a randomized complete block design, with 12 single-tree replications. Rootstocks included Cadaman® (Edin and Garcin, 1994), Garnem® (Felipe, 2009), INRA GF-677 (Bernhard and Grasselly, 1981), IRTA-1 and IRTA-2 (Felipe et al., 1997), Ishtara®, Adesoto (Moreno et al., 1995), Rootpac® 20 and Rootpac® 40 (Gasic and Preece, 2014), and Rootpac® R (Pinochet, 2010) (Table 1). Selection of these rootstocks was made to seek for alternatives tolerant to limestone soils, nematodes and replant issues, and more dwarfing stocks suitable for irrigated high-density orchards. Therefore, almond and peach seedlings were discarded, which have been reported to have poor adaptability to root asphyxia (almond), and to limestone soils (peach) (Felipe, 1989; Rubio-Cabetas et al., 2017). For the ‘Vairo’ trial, trees were planted in a randomized complete block design, with 6 single-tree replications. Rootstocks included INRA GF-677, IRTA-1, IRTA-2, Ishtara®, Adesoto, Rootpac® 20, Rootpac® 40, and Rootpac® R (Table 1). For both trials, trees were trained to an open vase system, with a tree spacing of 5 m × 4.5 m. The soil was a loam clay, with good water holding capacity, well drained and fertile with about 2% organic matter content. Trees were drip-irrigated (climate is semi-arid Mediterranean, with a mean annual rainfall of 350 mm). Plots were managed within IPM management according to industry standards.

Horticultural assessments

Phenological stage was recorded every year from bud break (B) to fruit growth (I) (Felipe, 1977). Assessments were visually made twice a week for each tree, recording the previous, actual, and subsequent stages. Each actual stage was defined when >50% of the tree organs were on that stated stage. Hull split was assessed for each tree twice a week during four weeks. Nut ripening was considered when >75% of the hulls had a visible opening in suture more than 1 cm in width, right before the initial drying.

Trunk circumference (20 cm above the graft union) and number of suckers were assessed every year. Tree height and tree width in the row and in the alley were measured from 2014 onwards. Trunk-cross-sectional area (TCSA) and tree volume ($4/3\pi r^3$) were then calculated.

Every year at harvest, trees were shaken mechanically by commercial equipment. The in-shell nuts were then collected with a reversed-umbrella and a self-moving production huller. Once the in-shell nuts were dehulled, their fresh weight was measured and the gross yield calculated. A 1 kg in-shell nut sample was collected from each replicate and naturally dried for about three weeks (until reaching 6% of kernel moisture). Dry weight was determined, and then one sample of 100 in-shell nuts per 1 kg sample was collected to determine shell and kernel dry weights, and shelling percentage (kernel weight/in-shell weight *100). Kernels were separated by a sieve into four different categories according to their caliper (<12 mm, 12 mm - <14 mm, 14 mm - <16 mm, and ≥16 mm). From this data we calculated a simulated packout (economic value). Packout returns were taken from statewide averages of typical almond industry. Number of double and dried kernels (not marketable) per 100 nuts-sample were also assessed. In-shell nut drop was calculated counting the number of nuts per tree on the ground, before the mechanical harvest was performed. Kernel yield was calculated by multiplying in-shell nut yield (kg/tree) for shelling percentage (kernel weight/in-shell weight). Kernel number counts were determined by dividing the kernel yield by the kernel weight. We calculated a theoretical kernel yield and economic value per hectare by multiplying kernel yields per tree by a theoretical optimal tree density (trees/ha) coefficient based on tree size (TCSA) and tree volume (278 trees/ha for seedling size rootstocks to 1,000 trees/ha for sub-dwarfing rootstocks: Cadaman®, Garnem® and INRA GF-677 278 trees/ha; IRTA-2, Rootpac® 40, and Rootpac® R 417 trees/ha; IRTA-1, Ishtara® and Adesoto 667 trees/ha; and Rootpac® 20 1000 trees/ha). Biennial bearing index (BBI) was calculated as follow:

$$\mathrm{BBI} = \frac{\text{year 1 kernel yield} - \text{year 2 kernel yield}}{\text{year 1 kernel yield} + \text{year 2 kernel yield}}$$

where 0 indicates no alternate bearing and 1 complete alternate bearing.

Yield efficiency (kernel kg/TCSA cm^2), volume yield efficiency (kernel kg/volume m^3), and crop load (kernel number/TCSA cm^2) were calculated. Cumulative kernel yield (kg/tree) and TCSA increase (cm^2) were used to calculate the partitioning index (calculated as the kg of fruit per square centimeter increase in TCSA) 2012-2018 (Lordan et al., 2018). Partitioning index was obtained by applying the following formula:

$$\mathrm{PI} = \frac{\text{Cumulative kernel yield}}{\text{TCSA increase}}$$

where

Cumulative kernel yield = Cumulative kg/tree from 2012-2018.

TCSA increase = Trunk cross-sectional area increase (cm^2) from 2012 to 2018.

Data analysis

Response variables were modeled using linear mixed effect models. Mixed models including rootstock as fixed factor and year as a random factor were built to separate treatment effects for the bloom and nut ripening dates (Julian days) and lengths (number of days). Data was square root transformed to normalize data distribution. Mixed models including rootstock as fixed factor and block as a random factor were built to separate treatment effects for the TCSA, number of suckers, tree volume, kernel yield, economic value, shelling percentage, kernel number, biennial bearing, yield efficiency, volume yield efficiency, crop load, and partitioning index. Mixed models including rootstock as fixed factor and block nested to year as a random factor were built to separate treatment effects for kernel dry weight, double kernels, dried kernels, and nut drop. For all the models, when the main effect (rootstock) was significant, comparisons among treatments were made by Tukey's HSD test at P values ≤ 0.05.

Two two-way hierarchical cluster using the Ward method were built in order to classify the rootstocks based on all the variables analyzed. All the data were standardized before analysis. Data were analyzed using the JMP statistical software package (Version 12; SAS Institute Inc., Cary, North Carolina).

Results

Phenology

Over the 5 years of the study, bloom was at ~80 Julian day for 'Marinada' and ~73 Julian day for 'Vairo' (March 21st and March 14th, respectively) (Table 2 and Figure 1). For 'Marinada', there were significant differences among rootstocks. The earliest bloom dates were when grafted on Garnem®, IRTA-2, and INRA GF-677, whereas the latest bloom date was on Rootpac® 20. Bloom lasted about 15 days for 'Marinada' and 17 days for 'Vairo', with no significant differences among rootstocks.

For both cultivars there were significant differences among rootstocks regarding nut ripening, which was considered when >75% of the hulls had a visible opening in suture more than 1 cm in width and right before the initial drying (Table 2 and Figure 2). For 'Marinada' nut ripening occurred at 263 Julian day on average (September 20th), whereas for 'Vairo' it occurred at 247 Julian day (September 4th) on average. For 'Marinada', the earliest ripening dates were on Rootpac® 20, Ishtara®, Rootpac® R, and Adesoto. Then there was a second group comprised by Rootpac® 40, followed by a third group which comprised IRTA-2, IRTA-1, and the latest ripening dates on Cadaman®, INRA GF-677, and Garnem®. For 'Vairo', the earliest ripening date was on Rootpac® 20, followed by

Rootpac® R, Adesoto, Ishtara®, Rootpac® 40, IRTA-2, IRTA-1, and the latest date on INRA GF-677.

Tree vigor and suckers

For 'Marinada', tree size measured by the size of the trunk-cross-sectional area (TCSA) in the fall of 2018 was strongly influenced by rootstock genotype (Figure 3). Rootpac® 20 was the most dwarfing rootstock of the trial, followed by IRTA-1, Adesoto, Ishtara®, Rootpac® R, Rootpac® 40, INRA GF-677, IRTA-2, Cadaman® and Garnem® as the largest stock of the trial. For 'Vairo', Adesoto and IRTA-1 were the smallest stocks of the trial, whereas Rootpac® R and INRA GF 6-77 were the largest; however, there were no significant differences among them.

In terms of tree volume, the largest canopies for 'Marinada' were when grafted on Garnem®, Cadaman®, and INRA GF-677, whereas the smallest were on Rootpac® 20, Adesoto, and Rootpac® R (Figure 3). For 'Vairo', the largest canopies were on INRA GF-677, followed by IRTA-2, and Rootpac® 40. On the other hand, the smallest tree volumes were on Rootpac® 20, Rootpac® R, Adesoto, and Ishtara®.

For both 'Marinada' and 'Vairo' cultivars, Adesoto had significantly more suckers than the rest of the rootstocks (Figure 3).

Yield, kernel dry weight, caliper distribution, and economic value

For 'Marinada', cumulative yield over the first 3 years (2013-2015) was greatest for Garnem® (14 kg/tree) and INRA GF-677 (10 kg/tree); the lowest yields were on Rootpac® 20 (3 kg/tree) and Ishtara® (4 kg/tree) (Table 3). Once at full production (2016-2018), the highest yields for 'Marinada' were on Garnem® (27 kg/tree), Cadaman® (25 kg/tree), and INRA GF-677 (23 kg/tree). A second group comprised IRTA-2 (16 kg/tree), Rootpac® 40 (14 kg/tree), and IRTA-1 (13 kg/tree), followed by a third group comprised by Ishtara® and Rootpac® R, both with 11 kg/tree. Adesoto (9 kg/tree) and Rootpac® 20 (7 kg/tree) had the lowest yields. In terms of cumulative kernel yield over immature plus mature stages (2013-2018), the highest values were on Garnem® (~18 t/ha), INRA GF-677 (~14 t/ha), and Cadaman® (~13 t/ha), followed by IRTA-2 (~10 t/ha), Rootpac® R (~9 t/ha), Rootpac® 40 (8 t/ha), IRTA-1 (7 t/ha), Adesoto and Ishtara® (6 t/ha), and Rootpac® 20 (4 t/ha) (Table 3 and Figure 4). When looking at the theoretical kernel yield, there were no significant differences among rootstocks for immature stages (2013-2015) or total cumulative values (2013-2018) (Table 3). For mature stages (2016-2018), the highest yields were for IRTA-1 and Ishtara® (~8 t/ha), followed by Cadaman®, Garnem®, and Rootpac® 20 (~7 t/ha). A third group comprised IRTA-2, INRA GF-677, Adesoto, Rootpac® R and Rootpac® 40 (~6 t/ha).

For ‘Marinada’, Cadaman® had the largest kernel dry weight (1.33 g), followed by INRA GF-677 (1.29 g), Garnem® (1.26 g), IRTA-1 (1.25 g), IRTA-2 (1.24 g), Rootpac® 40 (1.21 g), Ishtara® (1.18 g), Rootpac® R (1.17 g), and Rootpac® 20 (1.15 g) (Table 3). Caliper distribution varied at mature stages (2016-2018) depending on the year. In 2016 Cadaman®, Garnem®, INRA GF-677, IRTA-2, Adesoto, and Rootpac® 40 had more than 80% of the kernels larger than 14 mm, whereas in 2018 only Cadaman® had more than 50% above 14 mm (Figure 5). Rootpac® 20 was the rootstock that tended to have higher percentage of smaller calipers. There were no significant differences among rootstocks for number of double kernels and dried kernels (data not shown).

In terms of economic value, Garnem®, Cadaman®, and INRA GF-677 had the highest values for ‘Marinada’ (~42,000-49,350 €/ha), followed by IRTA-2 (~28,000 €/ha), Rootpac® 40 (~26,000 €/ha), IRTA-1 (~23,000 €/ha), and Ishtara® (~21,000 €/ha) (Table 3). Rootpac® R, Adesoto, and Rootpac® 20 had the lowest values (~12,000-19,000 €/ha). There were less differences among rootstocks when looking at the theoretical economic value, in this case the highest values were for IRTA-1 (~35,000€/ha), Ishtara® and

Garnem® (~31,000 €/ha), and Cadaman® (~29,000 €/ha) (Table 3). The lowest value was for Rootpac® 40 (24,000 €/ha).

For 'Vairo', the highest cumulative yields at immature stages (2013-2015) were on INRA GF-677 (17 kg/tree), followed by IRTA-2, Rootpac® 40 and Rootpac® R, all with 11 kg/tree (Table 3). At mature stages (2016-2018), INRA GF-677 had the highest cumulative yield (31 kg/tree), followed by IRTA-2 and Rootpac® 40 (25 kg/tree), and IRTA-1 (21 kg/tree). Regarding cumulative yield over the whole study (2013-2018), INRA GF-677 had the highest values (~22 t/ha), then there was another group that comprised IRTA-2 and Rootpac® 40 (~16 t/ha), followed by IRTA-1 (~13 t/ha), Rootpac® R and Ishtara® (~12 t/ha), Adesoto (~11 t/ha), and Rootpac® 20 with the lowest cumulative yield (~8 t/ha) (Table 3 and Figure 4). There were no significant differences among rootstocks when comparing the theoretical cumulative yield for the early stages (2013-2015) (Table 3). At full production (2016-2018), IRTA-1 and Ishtara® had the highest values (~14 t/ha), followed by Rootpac® 20 (13 t/ha), Adesoto (~12 t/ha), Rootpac® R (~11 t/ha), Rootpac® 40, and IRTA-2 (~10 t/ha). There were significant differences for the whole cumulative period (2013-2018), however these differences were not enough to be significant according to Tukey's HSD test.

For 'Vairo', the largest kernel dry weight was on INRA GF-677 (1.18 g), followed by IRTA-1 (1.15 g), IRTA-2 (1.11 g), Adesoto and Rootpac® 40 (1.09 g), Ishtara® and Rootpac® R (1.05 g), and Rootpac® 20 (1 g). There were differences among years at mature stages (2016-2018) for caliper distribution (Figure 5). Larger calipers were observed in 2016 and 2018. In 2016, INRA GF-677, IRTA-1, IRTA-2, Adesoto, and Rootpac® R had more than 90% of the kernels with calipers larger than 14 mm. In 2017, INRA GF-677, IRTA-2, and Adesoto had the higher percentage of larger calipers. In 2018, INRA GF-677 and IRTA-1 had the higher values, with ~90% of the kernels >14 mm. There were no significant differences among rootstocks for number of double kernels and dried kernels (data not shown).

In terms of economic value, INRA GF-677 had the highest (~57,000 €/ha), followed by Rootpac® 40 (~47,000 €/ha), and IRTA-2 (~46,000 €/ha) (Table 3). When looking at the theoretical economic value, IRTA-1 and Ishtara® had the highest (~58,000 €/ha), followed by Rootpac® 20 (~54,000 €/ha), Adesoto (~50,000 €/ha), Rootpac® R (~45,000 €/ha), Rootpac® 40 and IRTA-2 (~41,000 €/ha), and INRA GF-677 (~34,000 €/ha).

Rootstock genotype significantly affected shelling percentage, but differences were more apparent at full production (2016-2018) rather that at young stages (2013-2015) (Table 4). Overall (2013-2018), for ‘Marinada’, Cadaman® had the highest values, followed by INRA GF-677, Garnem®, IRTA-1, Rootpac® R, Rootpac® 40, Rootpac® 20, Ishtara, IRTA-2, and Adesoto. For ‘Vairo’, IRTA-1, INRA GF-677, and IRTA-2 had the highest values, followed by Rootpac® R, Ishtara, Rootpac® 40, Rootpac® 20, and Adesoto with the lowest shelling percentage.

Biennial bearing, yield efficiency, crop load, and partitioning index

In general terms, biennial bearing was not important, with low values (<<1) for both ‘Marinada’ and ‘Vairo’ cultivars (Table 5). There were slightly higher values for ‘Marinada’ than ‘Vairo’ (0.22 vs 0.19 on average, respectively). For ‘Marinada’, the lower values (less biennial bearing) were observed for IRTA-2 and Adesoto, whereas the higher values were on Rootpac® 20 and Ishtara®. For Ishtara® however, there were high values in 2014-2015 and 2015-2016, and low values in 2016-2017. There were no significant differences among rootstocks for ‘Vairo’, but the general trend (2013-2018) was that Rootpac® R and INRA GF-677 induced lower biennial bearing.

Yield efficiency for ‘Marinada’ ranged from the lowest efficiencies on Rootpac® 20 and Ishtara® (0.07-0.08) to the highest yield efficiency of both IRTA-1 and INRA GF-677

(0.13) (Table 5). There were no significant differences among rootstocks regarding volume yield efficiency and crop load for 'Marinada'. In terms of partitioning index, Rootpac® R had the highest value (0.21), followed by IRTA-1 (0.19), INRA GF-677 (0.18), and Garnem® (0.17). The lowest values were for Ishtara® and Rootpac® 20 (0.09 and 0.1, respectively).

For 'Vairo', the highest yield efficiencies were for INRA GF-677 (0.15) and IRTA-1 (0.14) (Table 5). The lowest yield efficiency was for Rootpac® 20 (0.09). In terms of volume yield efficiency, Rootpac® R had significantly higher efficiency than the rest of the rootstocks. There were no significant differences among rootstocks regarding crop load. INRA GF-677 had the highest partitioning index (0.23), followed by Rootpac® R (0.22), IRTA-1 and Rootpac® 40 (0.19), Ishtara® and Adesoto (0.17), IRTA-2 (0.16), and Rootpac® 20 (0.14).

Overall agronomic performance

Considering all the studied variables, rootstocks were clustered within four different groups (Figure 6 and Figure 7). In addition, clustering the variable values revealed which variables are connected. When clustering rootstocks for 'Marinada', variables were grouped within three main groups (Figure 6). The first group included kernel yield, economic value, TCSA, tree volume, kernel dry weight, nut ripening date, and shelling percentage. The second group included theoretical yield, theoretical economic value, yield efficiency, crop load, and partitioning index. The third group included sucker number, bloom length, volume yield efficiency, bloom date and biennial bearing index. Variables were similarly grouped for 'Vairo'; however, in this case variables were grouped within four groups to cluster rootstocks (Figure 7). The first group included: kernel yield, economic value, tree volume, nut ripening date, kernel dry weight, and TCSA. A second group included yield efficiency, partitioning index, crop load and shelling percentage. A third group included theoretical kernel yield, theoretical economic value, biennial bearing index, and bloom length. A fourth group included sucker number, volume yield efficiency, and bloom date.

For ‘Marinada’, Cadaman®, Garnem®, and INRA GF-677 were clustered together (Figure 6). These rootstocks were the ones with higher values for the variables that were within the first group (yield, TCSA, tree volume, etc). IRTA-1 and Rootpac® R were clustered together, and were the rootstocks with higher values regarding yield efficiency, and theoretical yield and economic value, especially IRTA-1. A third group comprised IRTA-2, Rootpac® 40, Ishtara®, and Adesoto. This third group of rootstocks was characterized for having medium-low values for the variables representing yield and vigor, comprised within the first group of variables. Rootpac® 20 was clustered alone. This rootstock had the lowest values for almost all the variables comprised within the first, second, and third group of variables, and with the highest volume yield efficiency and the latest bloom date.

For ‘Vairo’, INRA GF-677 was clustered alone (Figure 7). This rootstock was the one with the highest values for the variables that were within the first group, which comprised yield, vigor and efficiency. IRTA-1, Ishtara, IRTA-2, and Rootpac® 40 were clustered together in a second group. These were the rootstocks with higher yield and vigor after INRA GF-677, but had higher theoretical yield and economic value than INRA GF-677, especially IRTA-1. A third group of rootstocks comprised Adesoto and Rootpac® 20. This group was characterized for having the lowest values for the variables comprising yield, vigor and efficiency indexes. A fourth group clustered alone Rootpac® R, which had among the highest partitioning index and crop load values (together with INRA GF-677), the highest volume yield efficiency, and a lately bloom date.

Discussion

Bloom and nut ripening dates were affected by rootstock genotype in our study. Both ‘Vairo’ and ‘Marinada’ have been described as late to extra-late flowering cultivars (Vargas et al., 2008; Vargas et al., 2011), and use of Rootpac® 20 instead of Garnem® delayed bloom up to 3 days for the case of ‘Marinada’, which it is very important to avoid frost events in Spring. Rootstocks affect the hormone profile of the scion (Lordan et al., 2017; Sorce et al., 2002; Tworkoski and Miller, 2007). Therefore, concentration of hormones that are responsible for bud break and other phenological processes such as bloom would be affected as well. In regards to that, previous studies on apple have reported such variations (Lordan et al., 2017). In our case, nut ripening for ‘Marinada’ ranged from 255 Julian day on Rootpac® 20 to up to 270 Julian day when grafted on Garnem®, a 15-day time lapse that can really affect not only the harvest logistics but even hinder a proper nut ripening, especially in certain cold areas. For ‘Vairo’ differences were tinier, but still 9 days between Rootpac® 20 and INRA GF-677 were observed. Hence, use of some specific rootstocks may also play a role in terms of managing bloom and harvest seasons, which could be key in singular cold areas to delay bloom and advance nut ripening.

Effect of rootstocks on tree vigor has been widely reported (Atkinson and Else, 2001; Felipe, 1989; Mestre et al., 2015; Reighard et al., 2018; Sepahvand et al., 2015; Yahmed et al., 2016a). However, to our knowledge, this is the first time that two new cultivars such as ‘Vairo’ and ‘Marinada’ are being evaluated on this set of rootstocks. For ‘Marinada’, a medium-vigor cultivar (Vargas et al., 2008), Garnem® provided the largest trees, followed by Cadaman®, and then a third group which comprised IRTA-2 and INRA GF-677. With the exception of IRTA-2, these three rootstocks (Garnem®, Cadaman®, and INRA GF-677) were also the ones which conferred the greatest tree volume, with no significant differences among them. On the other hand, IRTA-2 (being the third largest rootstock) provided similar tree volume than IRTA-1, the second most dwarfing rootstock of the trial after Rootpac® 20. A similar trend was observed for the case of 'Vairo', where Adesoto, IRTA-1, and Rootpac® R were the smallest stocks of the trial, and INRA GF-677 the largest. However, there were no significant differences among rootstocks regarding the TCSA, suggesting that vigor conferred by the rootstock might be disguised in situations of high-vigorous cultivars, like 'Vairo'. In a similar study with peach, Mestre et al. (2015) did not report significant differences between Cadaman® and INRA GF-677, whereas Remorini et al. (2015) did see differences on 'Flavorcrest' peach. Despite there were no significant differences among rootstocks regarding TCSA for 'Vairo', canopy tree volume was significantly affected by rootstock in our trial, with the largest tree volumes on INRA GF-677, IRTA-2, Rootpac® 40, and IRTA-1. In addition, we observed that in rootstocks with similar vigor (TCSA) such as IRTA-1 and Rootpac® 20, and Rootpac® 40 and Rootpac® R, tree volume was lower for both cases when *Prunus cerasifera* was one of the parents (Rootpac® 20 and Rootpac® R). This may be due to low compatibility between rootstock and cultivar. Furthermore, in situations with high vigor cultivars, such as 'Vairo', this effect is disguised like for instance with IRTA-2. Such incompatibility between cultivar and *Prunus cerasifera* rootstock has been reported by Felipe (1989), as both translocated and localized incompatibility.

Kernel yield was highly affected by the rootstock genotype. Overall, the more vigorous rootstocks (Garnem®, Cadaman®, and INRA GF-677 for 'Marinada'; and INRA GF-677, IRTA-2 and Rootpac® 40 for 'Vairo') provided the highest kernel yields, either at immature stages, full production, or cumulative over the whole period of the study (2013-2018). However, these differences disappeared when calculating the theoretical kernel yield. Theoretical kernel yield is a useful variable in terms of optimizing tree spacing according to tree vigor and canopy volume. Therefore, lower yields that were attained by some rootstocks when using the trial spacing might be corrected by using the ideal tree spacing that they should be planted at according to their vigor and volume. Theoretical values (kg/ha) were calculated by multiplying kernel yields per tree by a theoretical optimal tree density based on tree size (TCSA) and tree volume. The estimated tree spacing for vigorous rootstocks such as Cadaman®, Garnem®, and INRA GF-677 was 278 trees/ha, instead of the initial 444 trees/ha of the trial, and explains why the theoretical kernel yield calculated for these rootstocks is lower than the yield obtained in the trial. This reduction in number of trees per hectare was thought in terms of light interception and light energy conversion. Yield is a function of intercepted light converted to dry matter (Jackson and Palmer, 1972; Jackson and Palmer, 1980; Jackson, 1980; Palmer, 1999; Palmer et al., 1992; Robinson and Lakso, 1991). However, in some situations greater vigor requires more pruning to contain trees to their allotted space, which would have lower yield per unit of light interception and lower light conversion efficiency (Lakso and Robinson, 2014; Lordan et al., 2018). On the other side, the optimum tree spacing for dwarfing rootstocks such as Ishtara®, Adesoto, and IRTA-1 was 667 trees/ha, and 1000 trees/ha for Rootpac® 20, the most dwarfing rootstock of the trial. Hence, the theoretical kernel yield increased substantially, since the optimum tree spacing implied greater number of trees per hectare. Conversely to what happened with the theoretical kernel yield, there were significant differences among rootstocks for the theoretical economic value. Other than yield and optimum tree spacing, this variable also accounts for kernel caliper and their price in the market. Rootstock genotype did affect kernel size, and the most dwarfing rootstocks such as the Rootpac® 20 and R series were more severely affected, which kept the theoretical economic value low, despite of increasing yield by rising the number of trees per hectare.

It is important to not only consider yield, kernel size and economic value, but also the interaction with vigor of the rootstock, which must be sufficient to fill the allotted space rapidly. In terms of yield efficiency and partitioning index, IRTA-1, INRA GF-677, and Rootpac® R were the ones with higher values. Therefore, these three rootstocks were the ones that invested more resources to fruit rather than vegetative. However, differences in vigor within rootstocks imply that different tree spacings should be used in order to optimize rootstock × scion interaction to enhance yield and economic return. For instance, there were significant differences among rootstocks regarding yield per hectare when all the rootstocks were planted at the same (trial) spacing (444 trees/ha). These differences disappeared when estimating the theoretical yield per hectare according to the rootstock vigor and volume.

Differences in tree volume and vigor for these rootstocks suggested that INRA GF-677 would be a suitable rootstock for low-medium planting densities with wide spacings, (7 m × 6 m, 5 m × 4.5 m; 238-444 trees/ha, respectively), especially in absence of root asphyxia and nematode situations. On the other hand, Rootpac® R and IRTA-1 would be suitable rootstocks for medium- and high-density plantings (5 m × 3 m, 5 m × 2 m; 667-1,000 trees/ha, respectively). In addition, further economic studies should address net present value and internal rate of return to ponder the extra cost of planting more trees per hectare. It is hard to contrast our results with other studies, since this set of rootstocks has not yet been tested with 'Marinada' and 'Vairo' cultivars. Furthermore, this experiment showed dramatic differences in tree vigor, yield, kernel weight, yield efficiency, and partitioning index, which provide a wide range of options to deem. One important factor is that when scion cultivar vigor is high the best rootstock may not be the same as for a more moderate vigor scion cultivar or even a weak scion cultivar which need more enhancing power from the rootstock compared to vigorous scion cultivars. This leads to the need for “designer rootstocks” which combine the rootstock characteristics needed to maximize the potential of each scion cultivar in a particular climate. For both cultivars ‘Marinada’ and ‘Vairo’, rootstocks were clustered within four different groups. Therefore, decisions can be made according to priority in regard to yield, vigor, kernel size, efficiency to optimize planting density, and even phenology to match season management when different cultivars are grown together in the same orchard.

Acknowledgements

We thank Ramon Girabet, Guillem Martínez, and Anna Geli for field and laboratory support.

Literature Cited

Atkinson, C. and M. Else. 2001. Understanding how rootstocks dwarf fruit trees. Compact Fruit Tree 34(2), 46-49.

Batlle, I., F. Dicenta, R. Socias i Company, T.M. Gradziel, M. Wirthensohn, H. Duval, and F.J. Vargas. 2017. Classical genetics and breeding, p. 111-148. In: Socias i Company, R. and Gradziel, T. M. (eds.), Almonds: Botany, Production and Uses. CABI.

Bernhard, R. and C. Grasselly. 1981. Les pêchers x amandiers. Arboric. Fruit 328(6), 37-42.

Dicenta, F., R. Sánchez-Pérez, M. Rubio, J. Egea, I. Batlle, X. Miarnau, M. Palasciano, E. Lipari, C. Confolent, and P. Martínez-Gómez. 2015. The origin of the self-compatible almond ‘Guara’. Scientia Horticulturae 197, 1-4.

Duncan, R.C. and J. Edstrom. 2008. Field evaluation of almond rootstocks. Annual Almond Industry Conference Modesto, California.

Edin, M. and A. Garcin. 1994. Un nouveau porte-greffe du pêcher Cadaman® Avimag. L'Arboriculture fruitière 475, 20-23.

Felipe, A. 1977. Estados fenológicos del almendro. Inf Tec Econ Agrar 8, 8-9.

Felipe, A. 1989. Rootstocks for almond. Present situation. Options mediterraneennes. Serie A. Séminaires Méditerranéens 5, 13-18.

Felipe, A. 2000. El Almendro. I El material vegetal. Integrum, Lleida, Spain.

Felipe, A. 2006. 'Belona' and 'Soleta', two new almond cultivars. ITEA 102(4), 398-408.

Felipe, A., J. Gomez-Aparisi, F. Vargas, M. Romero, F. Monastra, E. Caboni, A. Simeone, and A. Isaakidis. 1997. Obtention et selection de porte-greffe pour l'amandier multiplies par voie vegetative. Options Mediterraneennes N 16, 73.

Felipe, A.J. 2009. 'Felinem','Garnem', and 'Monegro' almond × peach hybrid rootstocks. HortScience 44(1), 196-197.

Felipe, A.J. and R. Socias i Company. 1987. 'Ayles', 'Guara', and 'Moncayo' almonds. HortScience 22, 961-962.

Font Forcada, C., Y. Gogorcena Aoiz, and M.Á. Moreno Sánchez. 2012. Agronomical and fruit quality traits of two peach cultivars on peach-almond hybrid rootstocks growing on Mediterranean conditions. Scientia Horticulturae 140, 157-163.

Gasic, K. and J.E. Preece. 2014. Register of new fruit and nut cultivars list 47. HortScience 49(4), 396-421.

Gradziel, T.M., R. Curtis, and R. Socias i Company. 2017. Production and growing regions, p. 70-86, Almonds: Botany, Production and Uses. CABI.

Iglesias, I. and J. Carbó. 2006. Situació actual, característiques i comportament agronòmic dels portaempelts de presseguer. Dossier tècnic 17, 3-18.

Iglesias, I., R. Montserrat, J. Carbó, J. Bonany, and M. Casals. 2004. Evaluation of agronomical performance of several peach rootstocks in Lleida and Girona (Catalonia, NE-Spain). Acta Horticulturae 658(1), 341-348.

Jackson, J. and J. Palmer. 1972. Interception of light by model hedgerow orchards in relation to latitude, time of year and hedgerow configuration and orientation. J. Appl. Ecol., 341-357.

Jackson, J. and J. Palmer. 1980. A computer model study of light interception by orchards in relation to mechanised harvesting and management. Scientia Horticulturae 13(1), 1-7.

Jackson, J.E. 1980. Light interception and utilization by orchard systems. Horticultural Reviews, Volume 2, 208-267.

Kester, D.E. and C. Grasselly. 1987. Almond rootstocks, p. 265-293. In: Rom, R. C. and Carlson, R. F. (eds.), Rootstocks for fruit crops. Wiley, New York.

Lakso, A.N. and T.L. Robinson. 2014. Sunlight, yield, and productivity of apples. New York Fruit Quarterly 22(2), 5-7.

Lordan, J., G. Fazio, P. Francescatto, and T.L. Robinson. 2017. Effects of apple (*Malus* × d*omestica*) rootstocks on scion performance and hormone concentration. Scientia Horticulturae 225, 96-105.

Lordan, J., P. Francescatto, L. Dominguez, and T.L. Robinson. 2018. Long-term effects of tree density and tree shape on apple orchard performance, a 20 year study - Part 1, agronomic analysis. Scientia Horticulturae 238, 303-317.

Lovera, M., N.S. Castillo, B.C. Caro, J.L. Fernández, A. Mesa, M.V. Martín, and O.A. Quilez. 2015. Comportamiento de las principales variedades de almendro de floración tardía. Vida rural(404), 58-68.

Malagón, J., L. Velázquez, M. Carot, and C. Felipe. 2017. Comportamiento de las variedades de almendro en zonas frías. Revista de Fruticultura 53, 6-23.

Mestre, L., G. Reig, J.A. Betrán, J. Pinochet, and M.Á. Moreno. 2015. Influence of peach–almond hybrids and plum-based rootstocks on mineral nutrition and yield characteristics of 'Big Top'nectarine in replant and heavy-calcareous soil conditions. Scientia Horticulturae 192, 475-481.

Miarnau, X., L. Torguet, I. Batlle, and S. Alegre. 2016. El cultivo del almendro en alta densidad. Revista de Fruticultura 49, 68-87.

Miarnau, X., L. Torguet, L. Zazurca, L. Maldonado, R. Girabet, I. Batlle, and M. Rovira. 2018. El futuro del almendro en España: ¿Será posible producir 4.000 kg de grano/ha? Horticultura 337, 16-26.

Moreno, M., M. Tabuenca, and R. Cambra. 1995. Adesoto 101, a plum rootstock for peaches and other stone fruit. HortScience 30(6), 1314-1315.

Palmer, J.W. 1999. Light, canopies, fruit and dollars. 42nd Annual IDFTA Conference, Ontario, Canada.

Palmer, J.W., D.J. Avery, and S.J. Wertheim. 1992. Effect of apple tree spacing and summer pruning on leaf area distribution and light interception. Scientia Horticulturae 52(4), 303-312.

Pinochet, J. 2010. 'Replantpac'(Rootpac® R), a plum–almond hybrid rootstock for replant situations. HortScience 45(2), 299-301.

Puebla, M. 2016. Estudio del comportamiento de variedades de almendro en las Vegas Bajas del Guadiana. Revista de Fruticultura 52, 38-51.

Reig, G., A. Salazar, O. Zarrouk, C. Font i Forcada, J. Val, and M.Á. Moreno. 2019. Long-term graft compatibility study of peach-almond hybrid and plum based rootstocks budded with European and Japanese plums. Scientia Horticulturae 243, 392-400.

Reighard, G., W. Bridges, D. Archbold, A. Atucha, W. Autio, T. Beckman, B. Black, D. Chavez, E. Coneva, J. Lordan, I. Minas, D. Ouelette, R. Pokharel, T. Lindstrom, M. Parker, T. Robinson, J. Schupp, M. Warmund, and D. Wolfe. 2018. Rootstock performance in the 2009 NC-140 peach trial across 11 states. Acta Horticulturae 1228, 181-186.

Remorini, D., C. Fei, F. Loreti, and R. Massai. 2015. Observations on nine peach rootstocks grown in a replant soil. Acta Horticulturae 1084, 131-137.

Robinson, T.L. and A.N. Lakso. 1991. Bases of yield and production efficiency in apple orchard systems. J. Am. Soc. Hort. Sci. 116(2), 188-194.

Roselli, G. 1998. Miglioramento genetico dei portinnesti presso il CNR di Firenze. Frutticoltura 4, 20-22.

Rubio Cabetas, M.J. 2016. Almond Rootstocks: Overview. Options Mediterraneennes A 119, 133-143.

Rubio-Cabetas, M.J., A.J. Felipe, and G. Reighard. 2017. Rootstock development, p. 209-227. In: Socias i Company, R. and Gradziel, T. M. (eds.), Almonds: Botany, Production and Uses. CABI.

Sedgley, M. and G. Collins. 2002. Almond improvement in Australia. Fruits 57(2), 129-134.

Sepahvand, E., A. Khadivi-Khub, A. Momenpour, and E. Fallahi. 2015. Evaluation of an almond collection using morphological variables to choose superior trees. Fruits 70(1), 53-59.

Socias i Company, R. and A. Felipe. 1992. Self-compatibility and autogamy in ‘Guara’ almond. J. Hortic. Sci. 67(3), 313-317.

Socias i Company, R., J. Gomez Aparisi, J. Alonso, M. Rubio-Cabetas, and O. Kodad. 2009. Retos y perspectivas de los nuevos cultivares y patrones de almendro para un cultivo sostenible. Información Técnica Económica Agraria 105, 99-116.

Sorce, C., R. Massai, P. Picciarelli, and R. Lorenzi. 2002. Hormonal relationships in xylem sap of grafted and ungrafted Prunus rootstocks. Scientia Horticulturae 93(3-4), 333-342.

Tworkoski, T. and S. Miller. 2007. Endogenous hormone concentrations and bud-break response to exogenous benzyl adenine in shoots of apple trees with two growth habits grown on three rootstocks. J. Horticult. Sci. Biotechnol. 82(6), 960-966.

Vargas, F.J., M. Romero, J. Clavé, J. Vergés, J. Santos, and I. Batlle. 2008. 'Vairo', 'Marinada', 'Constantí', and 'Tarraco' almonds. HortScience 43(2), 535-537.

Vargas, F.J., M.A. Romero, J. Clavé, I. Batlle, X. Miarnau, and S. Alegre. 2011. Important traits in IRTA's new almond cultivars. Acta Horticulturae 912, 359-365.

Wirthensohn, M. and L. Iannamico. 2017. Almond in the southern hemisphere, p. 87-110. In: Socias i Company, R. and Gradziel, T. M. (eds.), Almonds: Botany, Production and Uses. CABI.

Yahmed, J.B., M. Ghrab, and M.B. Mimoun. 2016a. Eco-physiological evaluation of different scion-rootstock combinations of almond grown in Mediterranean conditions. Fruits 71(3), 185-193.

Yahmed, J.B., M. Ghrab, M.Á. Moreno, J. Pinochet, and M.B. Mimoun. 2016b. Performance of 'Subirana' flat peach cultivar budded on different Prunus rootstocks in a warm production area in North Africa. Scientia horticulturae 206, 24-32.

Tables

Table 1. Evaluated rootstocks, their parentage, origin and cultivar in which they have been tested on.

Rootstock	Parentage	Origin	Tested cultivar
CADAMAN®	*Prunus persica* × *Prunus davidiana*	IFGO (Hungary) & INRA	‘Marinada’
GARNEM®	*Prunus dulcis* × *Prunus persica*	CITA (Spain)	‘Marinada’
INRA GF-677	*Prunus dulcis* × *Prunus persica*	INRA (France)	‘Marinada’ & ‘Vairo’
IRTA-1	*Prunus dulcis* × *Prunus persica*	IRTA (Spain)	‘Marinada’ & ‘Vairo’
IRTA-2	*Prunus cerasifera* × *Prunus dulcis*	IRTA	‘Marinada’ & ‘Vairo’
ISHTARA®	*(Prunus cerasifera* × *Prunus salicina)* × *(Prunus cerasifera* × *Prunus persica)*	INRA	‘Marinada’ & ‘Vairo’
ADESOTO	Clonal selection of *Prunus insititia*	CSIC-Aula Dei (Spain)	‘Marinada’ & ‘Vairo’
ROOTPAC® 20	*Prunus besseyi* × *Prunus cerasifera*	Agromillora Iberia (Spain)	‘Marinada’ & ‘Vairo’
ROOTPAC® 40	(*Prunus dulcis* × *Prunus persica*) × (*Prunus dulcis* × *Prunus persica*)	Agromillora Iberia	‘Marinada’ & ‘Vairo’
ROOTPAC® R	*Prunus cerasifera* × *Prunus dulcis*	Agromillora Iberia	‘Marinada’ & ‘Vairo’

Table 2. Bloom date (Julian day), bloom length (days), and nut ripening date (Julian day) for ‘Marinada’ and ‘Vairo’ almond cultivars grafted on Cadaman®, Garnem®, INRA GF-677, IRTA-1, IRTA-2, Ishtara®, Adesoto, Rootpac® 20, Rootpac® 40, and Rootpac® R rootstocks. Data represents values averaged over 5 years (2014-2018) at Les Borges Blanques, Spain. Bloom was considered when >50% of the flowers were at F stage (Felipe, 1977). Nut ripening was considered when >75% of the hulls had a visible opening in suture more than 1 cm in width, right before the initial drying. Means within a column followed by different letters denotes significant differences among rootstocks (Tukey's honestly significant difference, $P \leq 0.05$). ^{NS}Non significant at $P \leq 0.05$.

Cultivar	Rootstock	Bloom date (Julian day)	Bloom length (days)	Nut ripening date (Julian day)
Marinada	Cadaman	80.0 ab	13.3	269.3 ab
	Garnem	78.3 b	14.5	270.2 a
	INRA GF-677	79.0 b	14.7	269.8 a
	IRTA 1	80.5 ab	14.0	267.2 ab
	IRTA 2	78.5 b	15.2	267.0 ab
	Ishtara	80.2 ab	15.3	257.4 c
	Adesoto	79.7 ab	15.3	258.0 c
	Rootpac 20	81.5 a	13.7	255.4 c
	Rootpac 40	80.5 ab	14.7	261.4 bc
	Rootpac R	80.5 ab	14.8	257.6 c
	P	0.0003	NS	<0.0001
Vairo	INRA GF-677	72.0	17.0	251.8 a
	IRTA 1	72.8	17.3	247.8 ab
	IRTA 2	72.0	17.5	248.4 ab
	Ishtara	73.7	17.7	247.8 ab
	Adesoto	73.3	16.7	245.8 ab
	Rootpac 20	73.0	17.7	242.2 b
	Rootpac 40	72.7	17.2	248.4 ab
	Rootpac R	73.7	17.3	244.2 b
	P	NS	NS	0.0013

Table 3. Kernel yield (kg/tree & kg/ha), theoretical kernel yield (kg/ha), average kernel dry weight (g), economic value (€/ha), and theoretical economic value (€/ha) for 'Marinada' and 'Vairo' almond cultivars grafted on Cadaman®, Garnem®, INRA GF-677, IRTA-1, IRTA-2, Ishtara®, Adesoto, Rootpac® 20, Rootpac® 40, and Rootpac® R rootstocks at Les Borges Blanques, Spain. Economic values were calculated using packout returns from statewide averages for the different kernel caliper categories and yields. Theoretical values were calculated by multiplying kernel yields per tree by a theoretical optimal tree density (trees/ha) coefficient based on tree size (TCSA) and tree volume (278 trees/ha for seedling size rootstocks to 1,000 trees/ha for sub-dwarfing rootstocks: Cadaman®, Garnem® and INRA GF-677 278 trees/ha; IRTA-2, Rootpac® 40, and Rootpac® R 417 trees/ha; IRTA-1, Ishtara® and Adesoto 667 trees/ha; and Rootpac® 20 1000 trees/ha). Data was separated for young stage (2013-2018), mature stage (2016-2018), and cumulative stage (2013-2018). Means within a column followed by different letters denotes significant differences among rootstocks (Tukey's honestly significant difference, $P \leq 0.05$). [NS]Non significant at $P \leq 0.05$.

Cultivar	Rootstock	Kernel yield (kg/tree) cum. 2013-2015	Kernel yield (kg/tree) cum. 2016-2018	Kernel yield (kg/tree) cum. 2013-2018	Kernel yield (kg/ha) cum. 2013-2015	Kernel yield (kg/ha) cum. 2016-2018	Kernel yield (kg/ha) cum. 2013-2018	Theoretical kernel yield (kg/ha) cum. 2013-2015	Theoretical kernel yield (kg/ha) cum. 2016-2018	Theoretical kernel yield (kg/ha) cum. 2013-2018	Kernel dry weight (g)	Economic value (€/ha) 2016-2018	Theoretical economic value (€/ha) 2016-2018
Marinada	Cadaman	7 bcd	25 ab	28 bc	3,724 ab	11,268 ab	13,147 abc	3,438	7,042 abc	9,328	1.33 a	46,951 ab	29,344 abc
	Garnem	14 a	27 a	41 a	6,433 a	11,855 a	18,060 a	6,427	7,402 ab	13,665	1.26 bc	49,350 a	30,815 ab
	INRA GF-677	10 bcd	23 b	32 ab	4,360 b	10,102 b	14,062 ab	4,595	6,314 bc	10,658	1.29 ab	42,060 b	26,287 bc
	IRTA 1	5 cd	13 cde	16 cde	2,061 cde	5,598 cde	7,215 de	4,869	8,396 a	12,600	1.25 bcd	23,189 cde	34,784 a
	IRTA 2	7 bcd	16 c	23 bcd	3,262 bcd	6,783 c	9,955 bcd	5,680	6,359 bc	11,954	1.24 cde	28,181 c	26,419 bc
	Ishtara	4 d	11 def	14 de	1,684 de	5,060 def	6,358 de	4,146	7,590 ab	11,158	1.19 efg	20,983 def	31,475 ab
	Adesoto	5 cd	9 fg	15 de	2,272 cde	4,070 fg	6,438 de	5,887	6,104 bc	12,135	1.18 fg	16,883 fg	25,324 bc
	Rootpac 20	3 d	7 g	10 e	1,508 e	2,952 g	4,299 e	5,105	6,594 bc	11,385	1.15 g	12,161 g	27,163 bc
	Rootpac 40	6 bcd	14 cd	19 cde	2,777 bcde	6,209 cd	8,154 cde	4,438	5,821 c	9,480	1.21 def	25,727 cd	24,119 c
	Rootpac R	8 bc	11 ef	20 cde	3,712 bc	4,679 ef	8,779 cde	6,110	6,277 bc	12,961	1.17 fg	19,365 ef	25,977 bc
	P	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	NS	<0.0001	NS	<0.0001	<0.0001	<0.0001
Vairo	INRA GF-677	17 a	31 a	50 a	7,365 a	13,610 a	21,830 a	9,384	8,098 d	18,567	1.18 a	56,874 a	33,830 d
	IRTA 1	9 bcd	21 bc	30 c	3,347 cd	9,263 bc	12,806 c	10,013	13,995 a	24,422	1.15 ab	38,444 bc	58,099 a
	IRTA 2	11 bc	25 b	37 b	4,823 bc	11,048 b	16,251 b	9,864	9,817 cd	20,712	1.11 bc	45,900 b	40,758 cd
	Ishtara	8 cd	19 c	28 c	3,601 bcd	8,452 c	12,255 c	11,323	13,975 a	24,422	1.05 cd	35,031 c	57,969 a
	Adesoto	7 d	19 c	26 c	3,240 d	8,564 c	11,249 c	9,542	11,949 abc	21,673	1.09 bc	35,717 c	49,781 abc
	Rootpac 20	6 d	12 d	18 d	2,788 d	5,448 d	8,071 d	11,468	13,186 ab	23,453	1.00 d	22,405 d	54,239 ab
	Rootpac 40	11 b	25 b	37 b	5,092 b	11,210 b	16,482 b	9,736	9,966 cd	20,548	1.09 bc	46,599 b	41,411 cd
	Rootpac R	11 bc	16 cd	28 c	4,994 b	7,136 cd	12,335 c	8,876	10,993 bc	19,853	1.05 cd	29,511 cd	45,161 bc
	P	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	NS	<0.0001	0.0452	<0.0001	<0.0001	<0.0001

Table 4. Shelling percentage (kernel weight/in-shell weight *100) for 'Marinada' and 'Vairo' almond cultivars grafted on Cadaman®, Garnem®, INRA GF-677, IRTA-1, IRTA-2, Ishtara®, Adesoto, Rootpac® 20, Rootpac® 40, and Rootpac® R rootstocks at Les Borges Blanques, Spain. Means within a column followed by different letters denotes significant differences among rootstocks (Tukey's honestly significant difference, $P \leq 0.05$). [NS]Non significant at $P \leq 0.05$.

Cultivar	Rootstock	Shelling % 2013	Shelling % 2014	Shelling % 2015	Shelling % 2016	Shelling % 2017	Shelling % 2018	Average shelling % 2013-2015	Average shelling % 2016-2018	Average shelling % 2013-2018
Marinada	Cadaman	33	33 ab	35 a	37 a	35 a	35 a	34 a	36 a	35 a
	Garnem	33	32 bc	32 abc	35 abc	35 a	33 ab	32 a	35 ab	34 bc
	INRA GF-677	35	33 a	32 bc	36 ab	34 ab	34 a	34 a	35 a	34 ab
	IRTA 1	32	32 bc	32 bc	35 abc	34 abc	34 a	32 a	35 ab	34 bc
	IRTA 2	33	31 cd	30 c	32 de	33 bcd	32 bc	31 a	32 cde	32 ef
	Ishtara	34	30 d	31 c	34 bcd	32 de	30 c	31 a	32 def	32 def
	Adesoto	32	31 cd	30 c	31 e	31 e	31 c	31 a	31 f	31 f
	Rootpac 20	30	32 bcd	34 ab	32 e	33 cde	30 c	32 a	31 ef	32 def
	Rootpac 40	33	31 cd	31 c	34 cd	34 abc	32 bc	31 a	33 cd	32 de
	Rootpac R	34	32 bc	31 c	34 cd	33 bcd	33 ab	32 a	33 bc	33 cd
	P	NS	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	0.0354	<0.0001	<0.0001
Vairo	INRA GF-677	28 ab	27	26	29 a	32 ab	27 a	28	29 a	28 a
	IRTA 1	28 a	27	25	29 a	34 a	26 ab	27	30 a	28 a
	IRTA 2	27 abc	28	27	29 a	31 bc	27 a	27	29 ab	28 a
	Ishtara	27 abc	27	27	28 ab	29 cd	26 b	26	28 cde	27 bc
	Adesoto	26 c	27	27	28 ab	28 d	25 b	26	27 e	27 c
	Rootpac 20	26 bc	29	26	27 b	29 cd	26 b	27	27 de	27 bc
	Rootpac 40	27 abc	27	26	29 a	30 cd	25 b	26	28 cd	27 bc
	Rootpac R	28 ab	28	26	27 b	32 ab	27 ab	27	28 bc	28 ab
	P	0.0049	NS	NS	0.0001	<0.0001	0.0001	NS	<0.0001	<0.0001

Table 5. Biennial bearing index (BBI), yield efficiency (kernel yield/trunk-cross-sectional area), volume yield efficiency (kernel yield/tree volume), crop load (kernel number/trunk-cross-sectional area), and partitioning index (kg of cumulated yield/trunk-cross-sectional area increase) for ‘Marinada’ and ‘Vairo’ almond cultivars grafted on Cadaman®, Garnem®, INRA GF-677, IRTA-1, IRTA-2, Ishtara®, Adesoto, Rootpac® 20, Rootpac® 40, and Rootpac® R rootstocks at Les Borges Blanques, Spain. Means within a column followed by different letters denotes significant differences among rootstocks (Tukey's honestly significant difference, $P \leq 0.05$). [NS]Non significant at $P \leq 0.05$.

Cultivar	Rootstock	BBI 2013-2014	BBI 2014-2015	BBI 2015-2016	BBI 2016-2017	BBI 2017-2018	BBI 2013-2018	Yield efficiency (Yield kg/TCSA cm^2)	Volume yield efficiency (Yield kg/Volume m^3)	Crop load (kernel $\#/cm^2$)	Partitioning index (cumulated yield /TCSA increase)
Marinada	Cadaman	0.39	0.33 ab	0.47 ab	0.07 b	0.18	0.32	0.10 ab	0.65	82.46	0.13 abcd
	Garnem	0.33	0.23 abcd	0.34 cd	0.06 b	0.15	0.22	0.11 ab	0.76	92.52	0.17 abcd
	INRA GF-677	0.25	0.18 bcd	0.34 cd	0.08 b	0.15	0.19	0.13 ab	0.73	100.15	0.18 abc
	IRTA 1	0.16	0.22 abcd	0.40 bc	0.10 ab	0.13	0.20	0.13 a	0.76	110.55	0.19 ab
	IRTA 2	0.24	0.14 d	0.28 d	0.11 ab	0.19	0.19	0.10 ab	0.86	78.21	0.13 abcd
	Ishtara	0.18	0.32 abc	0.58 a	0.06 b	0.14	0.27	0.08 b	0.65	75.42	0.09 d
	Adesoto	0.19	0.15 cd	0.29 cd	0.12 ab	0.13	0.22	0.10 ab	0.83	81.63	0.14 abcd
	Rootpac 20	0.25	0.36 a	0.41 bc	0.18 a	0.18	0.25	0.07 b	1.32	73.59	0.10 cd
	Rootpac 40	0.14	0.29 abcd	0.37 bcd	0.14 ab	0.19	0.16	0.09 ab	0.79	78.29	0.12 bcd
	Rootpac R	0.28	0.23 abcd	0.33 cd	0.08 b	0.11	0.16	0.11 ab	0.94	96.04	0.21 a
	P	NS	0.0002	<0.0001	0.0017	NS	NS	0.0096	NS	NS	0.0012
Vairo	INRA GF-677	0.09	0.09	0.18	0.29	0.19 a	0.14	0.15 a	0.62 b	126.82	0.23 a
	IRTA 1	0.22	0.11	0.32	0.29	0.30 a	0.26	0.14 ab	0.57 b	111.73	0.19 ab
	IRTA 2	0.24	0.10	0.16	0.32	0.10 a	0.17	0.11 ab	0.54 b	100.93	0.16 ab
	Ishtara	0.28	0.05	0.22	0.25	0.14 a	0.19	0.12 ab	0.59 b	116.76	0.17 ab
	Adesoto	0.29	0.14	0.32	0.20	0.14 a	0.22	0.11 ab	0.64 b	106.37	0.17 ab
	Rootpac 20	0.18	0.16	0.19	0.32	0.14 a	0.19	0.09 b	0.62 b	94.92	0.14 b
	Rootpac 40	0.25	0.08	0.30	0.20	0.25 a	0.20	0.12 ab	0.59 b	117.60	0.19 ab
	Rootpac R	0.05	0.09	0.12	0.23	0.12 a	0.13	0.12 ab	0.92 a	124.70	0.22 a
	P	NS	NS	NS	NS	0.0499	NS	0.0393	0.0061	NS	0.0198

Figures

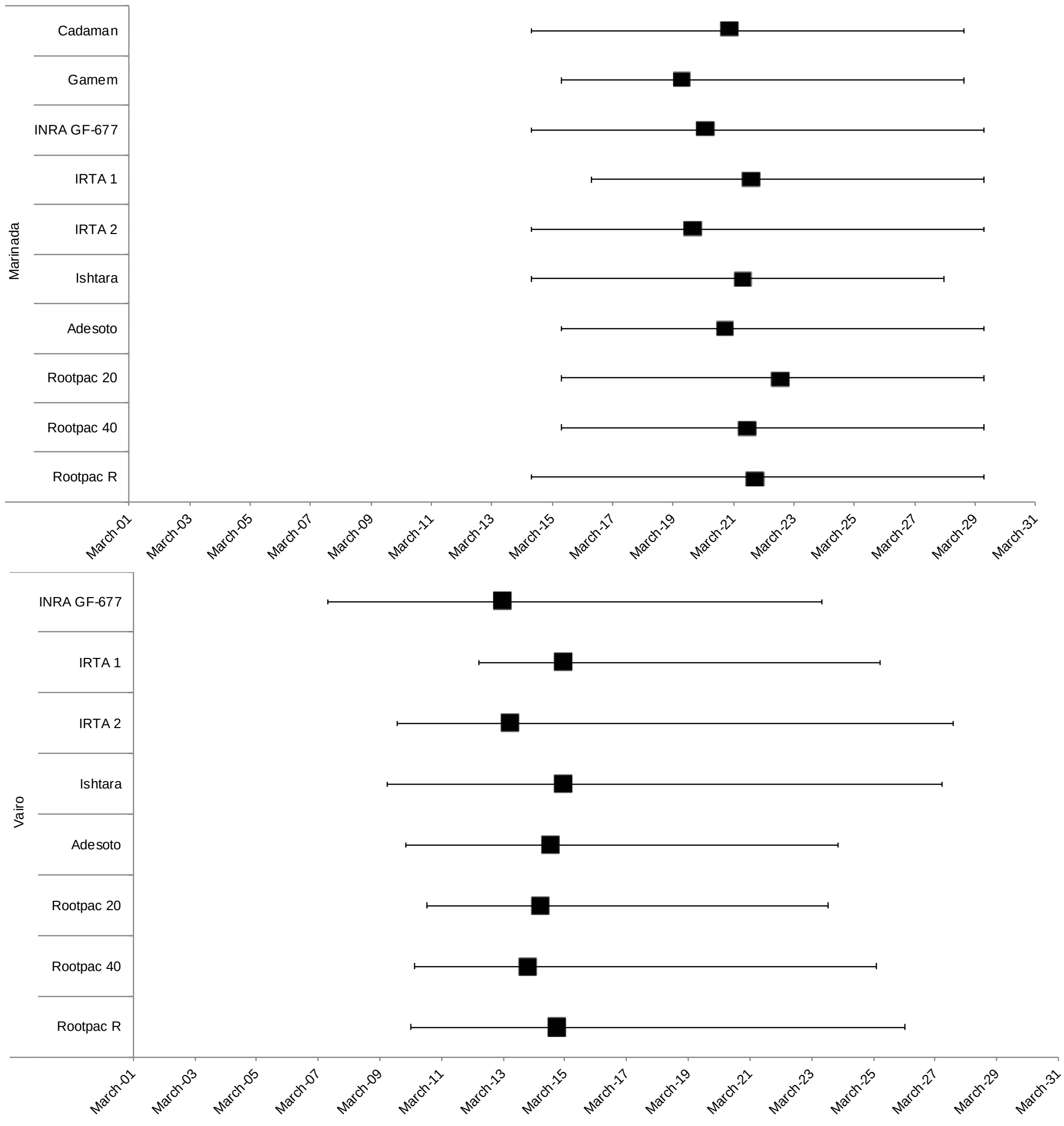

Figure 1. Bloom dates for 'Marinada' and 'Vairo' almond cultivars grafted on Cadaman®, Garnem®, INRA GF-677, IRTA-1, IRTA-2, Ishtara®, Adesoto, Rootpac® 20, Rootpac® 40, and Rootpac® R rootstocks. Figure represents beginning bloom, full bloom (black square), and end of bloom averaged over 5 years (2014-2018) at Les Borges Blanques, Spain. Bloom was considered when >50% of the flowers were at F stage (Felipe, 1977).

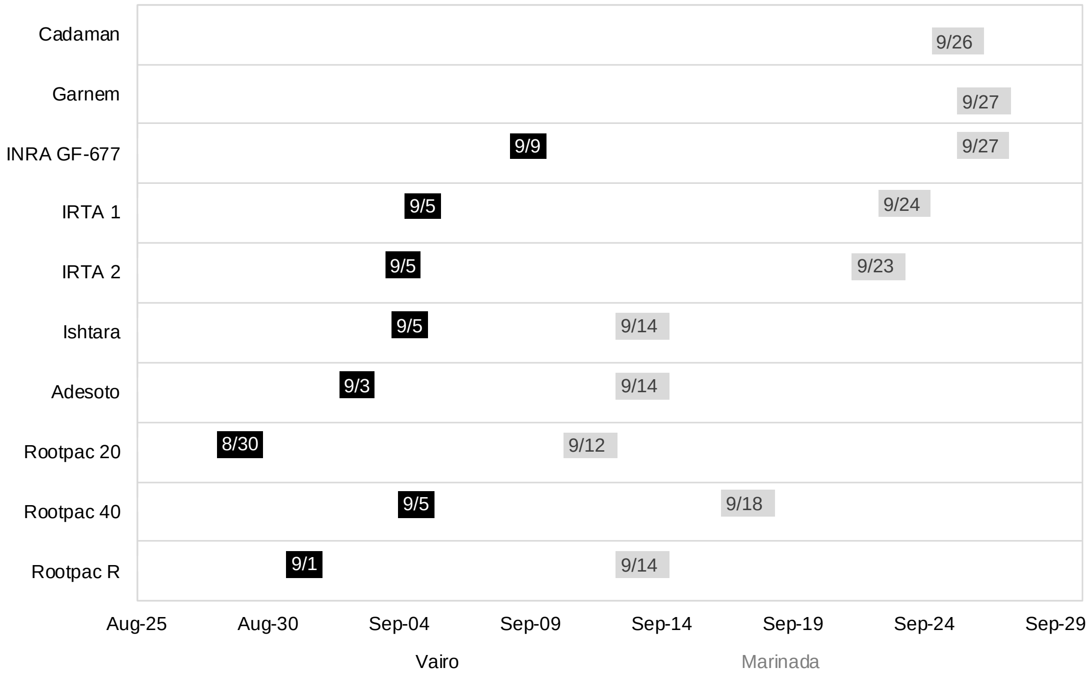

Figure 2. Nut ripening dates for ‘Marinada’ and ‘Vairo’ almond cultivars grafted on Cadaman®, Garnem®, INRA GF-677, IRTA-1, IRTA-2, Ishtara®, Adesoto, Rootpac® 20, Rootpac® 40, and Rootpac® R rootstocks. Figure represents values averaged over 5 years (2014-2018) at Les Borges Blanques, Spain. Nut ripening was considered when >75% of the hulls had a visible opening in suture more than 1 cm in width, right before the initial drying.

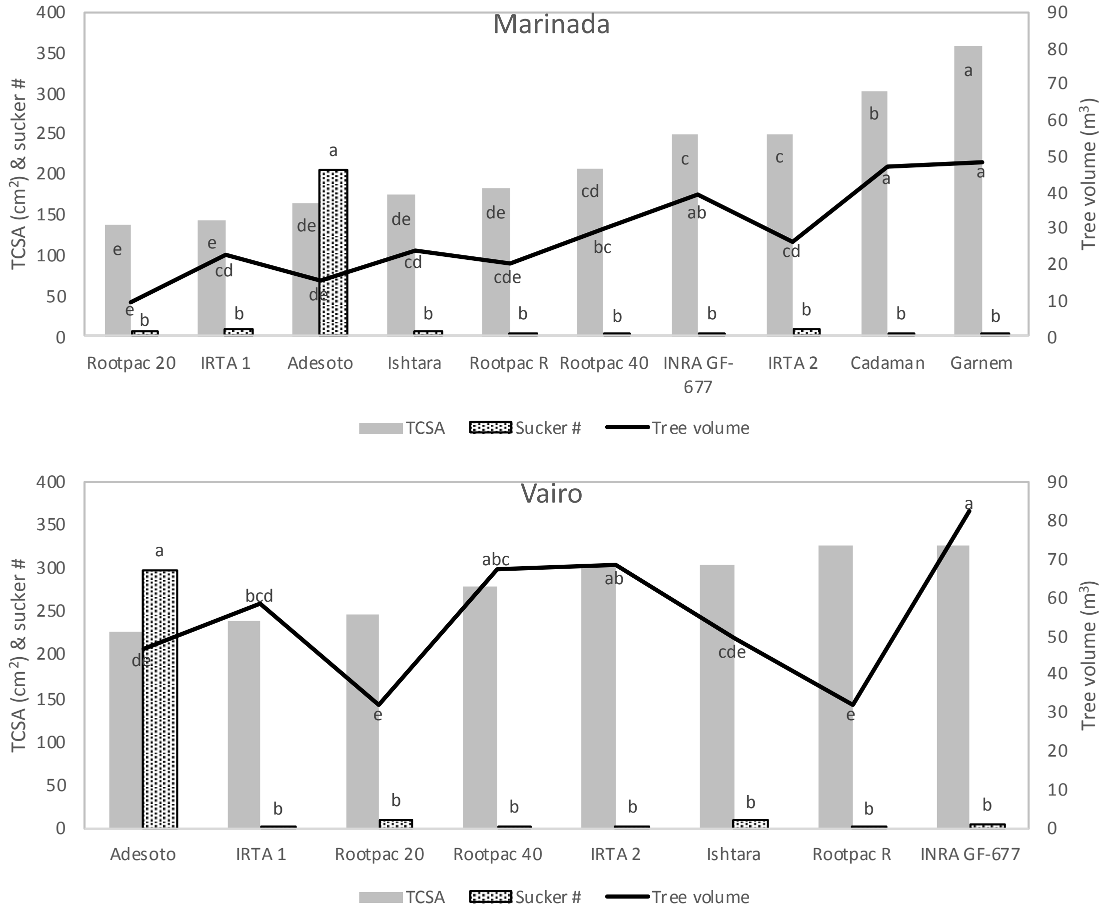

Figure 3. Trunk cross sectional area (TCSA), sucker number, and tree volume for ‘Marinada’ and ‘Vairo’ almond cultivars grafted on Cadaman®, Garnem®, INRA GF-677, IRTA-1, IRTA-2, Ishtara®, Adesoto, Rootpac® 20, Rootpac® 40, and Rootpac® R rootstocks at Les Borges Blanques, Spain. Data represent cumulated values for sucker number (2012-2018), and 2018 values for TCSA and tree volume. Bars or lines with different letters denotes significant differences among rootstocks (Tukey's honestly significant difference, $P \leq 0.05$). Rootstocks are ranked by TCSA.

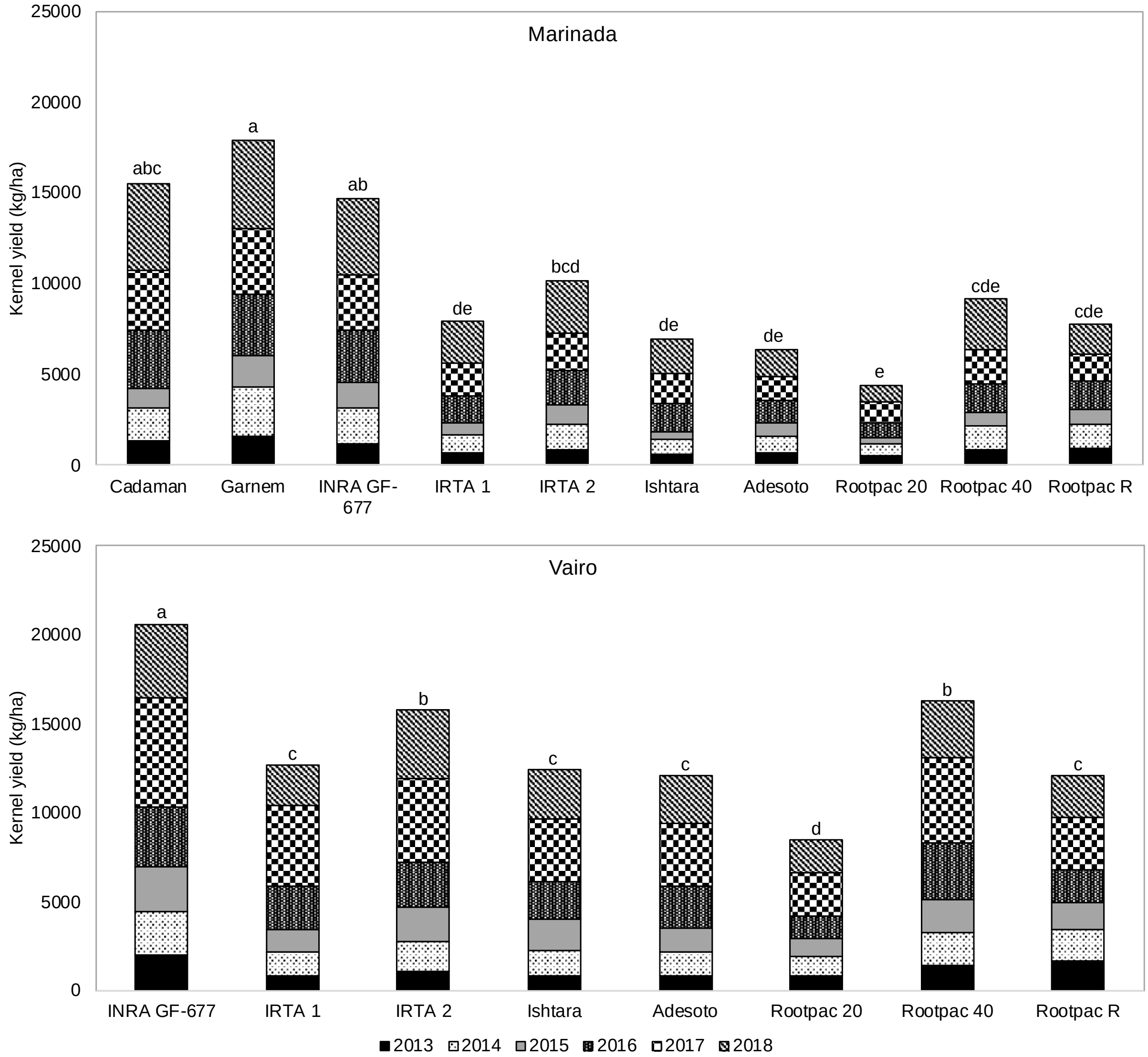

Figure 4. Cumulative yield (2013-2018) for 'Marinada' and 'Vairo' almond cultivars grafted on Cadaman®, Garnem®, INRA GF-677, IRTA-1, IRTA-2, Ishtara®, Adesoto, Rootpac® 20, Rootpac® 40, and Rootpac® R rootstocks at Les Borges Blanques, Spain. Different letters denotes significant differences among rootstocks for the cumulative value (Tukey's honestly significant difference, $P \leq 0.05$).

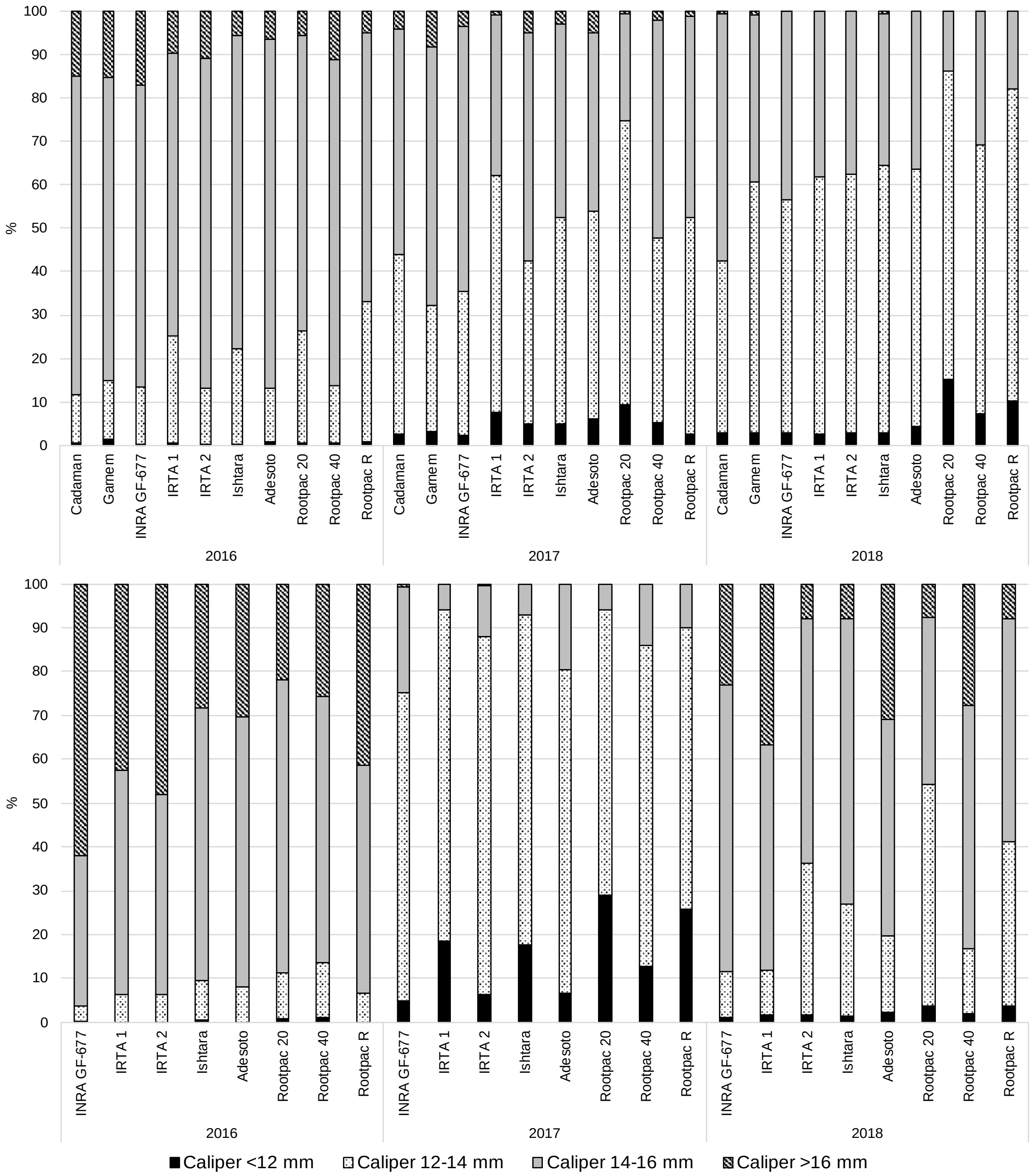

Figure 5. Caliper distribution at mature stages (2016-2018) for 'Marinada' (top) and 'Vairo' (bottom) almond cultivars grafted on Cadaman®, Garnem®, INRA GF-677, IRTA-1, IRTA-2, Ishtara®, Adesoto, Rootpac® 20, Rootpac® 40, and Rootpac® R rootstocks at Les Borges Blanques, Spain.

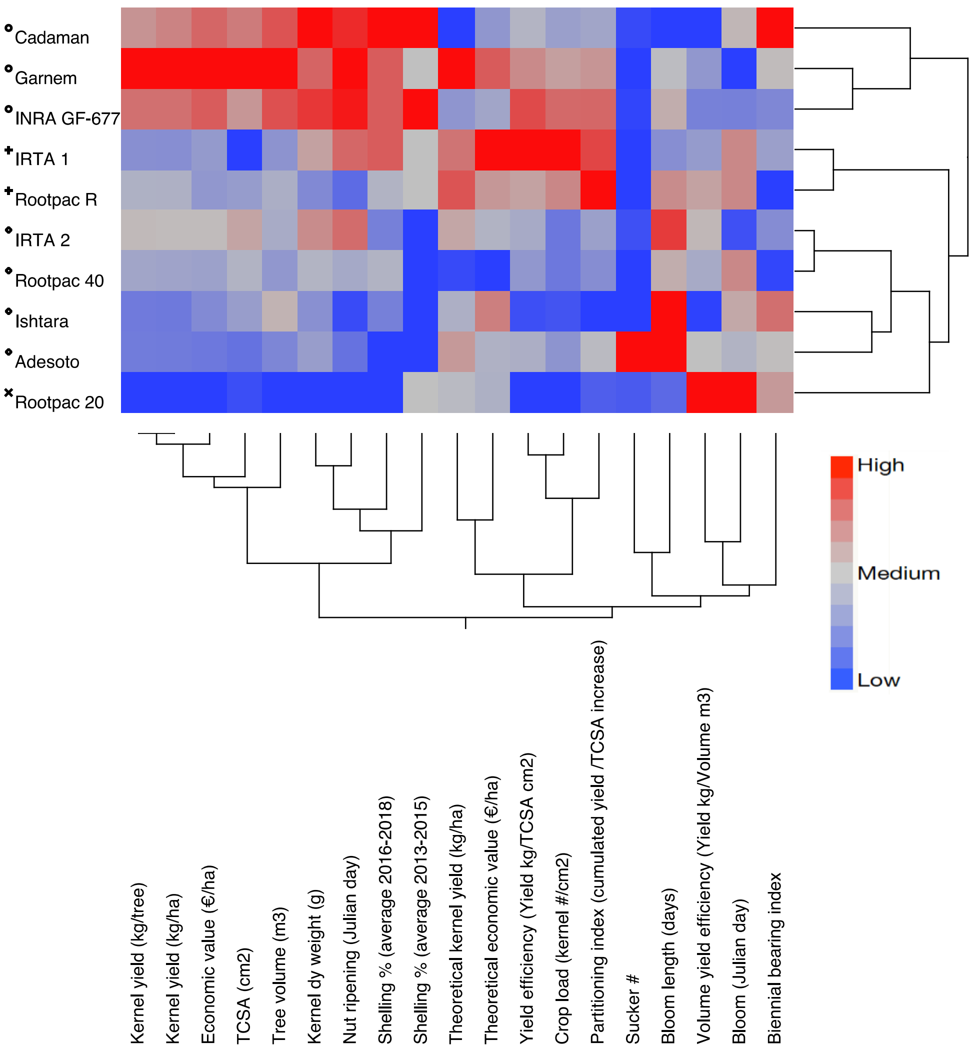

Figure 6. Clustering of 'Marinada' almond cultivar grafted on Cadaman®, Garnem®, INRA GF-677, IRTA-1, IRTA-2, Ishtara®, Adesoto, Rootpac® 20, Rootpac® 40, and Rootpac® R rootstocks based on their kernel yield (kg/tree & kg/ha), economic value (€/ha), kernel dry weight (g), shelling percentage (kernel weight/in-shell weight *100), tree volume (m^3), trunk-cross-sectional area (TCSA) (cm^2), number of suckers, yield efficiency (kg/cm^2 TCSA), volume yield efficiency (kg/m^3 tree volume), crop load (kernel number/cm^2 TCSA), average biennial bearing index, partitioning index (kg of cumulated yield/TCSA increase cm^2), bloom length (days), and bloom and nut ripening dates (Julian day) at Les Borges Blanques, Spain. Economic values were calculated using packout returns from statewide averages for the different kernel caliper categories and yields. Theoretical values were calculated by multiplying kernel yields per tree by a theoretical optimal tree density (trees/ha) coefficient based on tree size (TCSA) and tree volume (278 trees/ha for seedling size rootstocks to 1,000 trees/ha for sub-dwarfing rootstocks). Bloom was considered when >50% of the flowers were at F stage (Felipe, 1977). Nut ripening was considered when >75% of the hulls had a visible opening in suture more than 1 cm in width, right before the initial drying. Note that for bloom and nut ripening dates, red color (high value) indicates later date (higher Julian day).

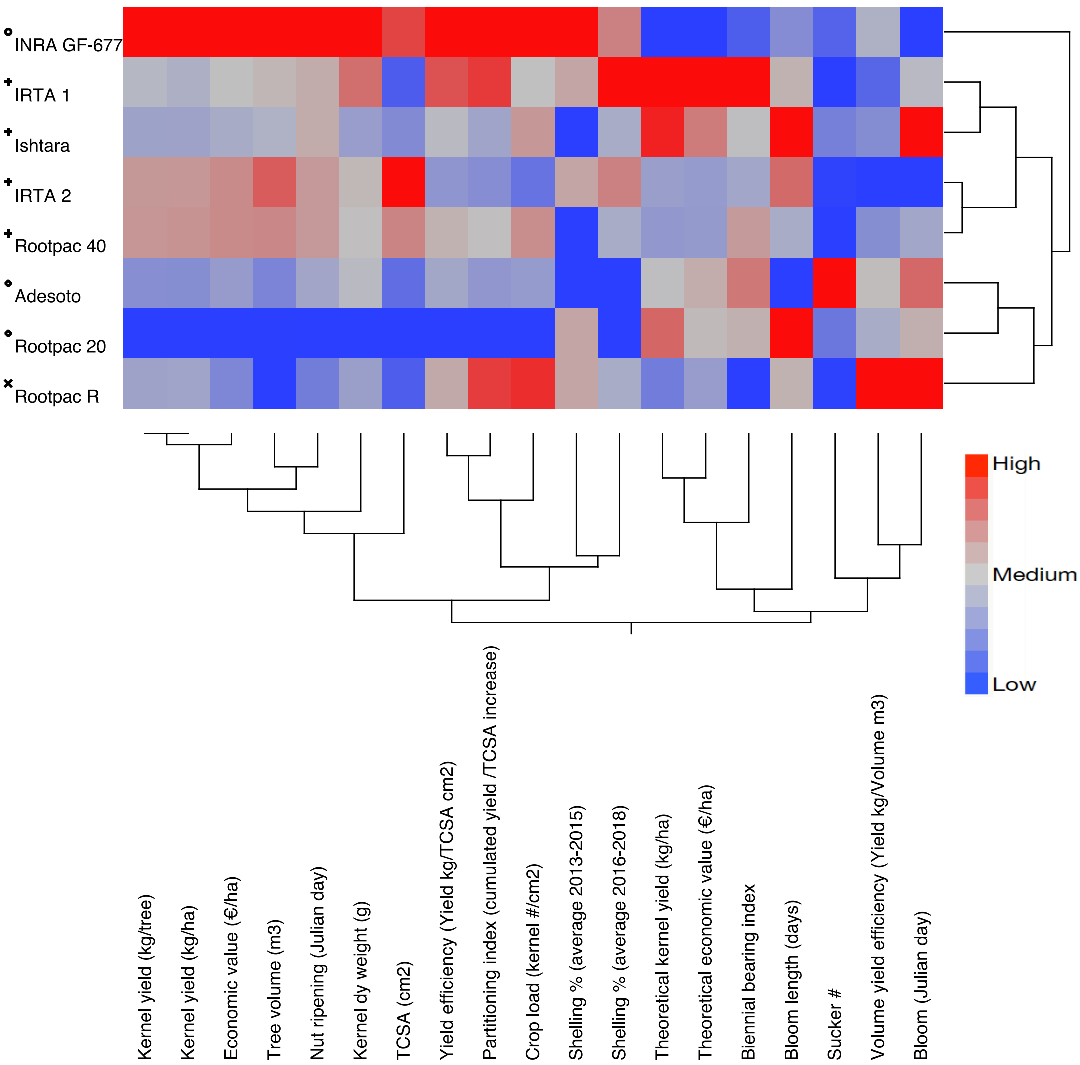

Figure 7. Clustering of 'Vairo' almond cultivar grafted on INRA GF-677, IRTA-1, IRTA-2, Ishtara®, Adesoto, Rootpac® 20, Rootpac® 40, and Rootpac® R rootstocks based on their kernel yield (kg/tree & kg/ha), economic value (€/ha), kernel dry weight (g), shelling percentage (kernel weight/in-shell weight *100), tree volume (m^3), trunk-cross-sectional area (TCSA) (cm^2), number of suckers, yield efficiency (kg/cm^2 TCSA), volume yield efficiency (kg/m^3 tree volume), crop load (kernel number/cm^2 TCSA), average biennial bearing index, partitioning index (kg of cumulated yield/TCSA increase cm^2), bloom length (days), and bloom and nut ripening dates (Julian day) at Les Borges Blanques, Spain. Economic values were calculated using packout returns from statewide averages for the different kernel caliper categories and yields. Theoretical values were calculated by multiplying kernel yields per tree by a theoretical optimal tree density (trees/ha) coefficient based on tree size (TCSA) and tree volume (278 trees/ha for seedling size rootstocks to 1,000 trees/ha for sub-dwarfing rootstocks). Bloom was considered when >50% of the flowers were at F stage (Felipe, 1977). Nut ripening was considered when >75% of the hulls had a visible opening in suture more than 1 cm in width, right before the initial drying. Note that for bloom and nut ripening dates, red color (high value) indicates later date (higher Julian day).