Performance of ‘Subirana’ flat peach cultivar budded on different *Prunus* rootstocks in a warm production area in North Africa

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Abstract

The agronomic performance and fruit quality traits were evaluated for ten *Prunus* rootstocks: Garnem, PADAC 150, PADAC 04-03, PADAC 04-01, Rootpac® 70, PM 105 AD, AGAF 0301-04, Krymsk® 1, Krymsk® 86 and PAC 847. These rootstocks were budded with ‘Subirana’ flat peach cultivar in September 2007 and planted in two adjacent plots in northern Tunisia (36°41’N, 10°15’E) on a heavy and calcareous soil typical of the Mediterranean area. Tree mortality, vegetative growth, rate of bud failure and fruit quality were assessed. Significant differences were found among rootstocks for the agronomic and fruit quality traits. Growing conditions generated varying levels of tree mortality, the highest with Krymsk® 1 rootstock. In contrast, all trees on PADAC 04-03 and PADAC 04-01 survived well. The lowest vigor was induced by Krymsk® 1 with a reduction of 90% in trunk cross-sectional area (TCSA) and canopy volume as compared to Garnem. PADAC 150 also expressed a low vigor. The highest canopy volume was found on Rootpac® 70 as similarly for Garnem. The remaining rootstocks induced a medium vigor level. Trees on vigorous rootstocks as Rootpac® 70 showed the lowest rate of bud failure, while dwarfing rootstocks induced the highest buds abscission. Yield was higher for AGAF 0301-04 in 2011 and 2012 as compared to the rest of rootstocks. The highest yield efficiency was recorded on PM 105 AD and AGAF 0301-04 rootstocks. Rootpac® 70 presented the highest fruit weight and fruit diameter. The highest level of soluble solids content (SSC) was recorded on Krymsk® 1, and the lowest on Garnem, although differences were not significant when compared to the other rootstocks. The less vigorous rootstocks seem to induce a better fruit quality of peach based on fruit sugar content. This study provides information that new *Prunus* rootstocks for peach can lead to a better agronomic performance than Garnem, mainly in vigor and in productive parameters. The peach-plum hybrid PADAC 04-03 induced good yield, with large fruit size and acceptable efficiency with significant smaller trees than Garnem.

45 **Keywords:** interspecific hybrids, vigor, yield, fruit quality

1. Introduction

Peach [*Prunus persica* (L.) Batsch] is considered the most important fruit species in the Mediterranean area. The prevailing climate in this area is highly suitable for peach growing. However, differences in temperature, humidity and cultural practices in various geographical areas affect blooming, fruit quality and disease susceptibility (Johnson and LaRue, 1989). Peach fruit quality is mainly determined by the genotype, but influenced by rootstock, horticultural practices and climatic conditions. The rootstock represents an important consideration for a productive peach orchard.

In commercial orchards, fruit trees are formed by a combination of two different genotypes, the scion and the rootstock, which could markedly affect tree vigor and water status of the scion (DeJong et al., 2005). Various species of *Prunus* can generate interspecific hybrids that can be used as rootstocks (Iglesias et al., 2001). The use of rootstocks is mainly oriented to overcome soil and disease problems (Zarrouk et al., 2005). Calcareous soils induce low iron availability. Iron chlorosis and replant disease can affect tree growth and peach production (Álvarez-Fernández et al., 2003; Reighard et al., 2008). The genetic approach to prevent iron chlorosis is based on the use of tolerant rootstocks (Jiménez et al., 2008; Rombolà and Tagliavini, 2006). The almond x peach hybrids, widely used in the Mediterranean area as rootstocks for stone fruit trees, need to be tolerant to lime, drought and graft-compatible with peach cultivars (Socias i Company et al., 1995; Moreno et al., 1994). These rootstocks are vigorous and appropriate for use in poor dry soils (Cambra, 1990; Zarrouk et al., 2005). However, they are susceptible to root asphyxia and/or associated root rot pathogens (Font i Forcada et al., 2012; Mestre et al., 2015).

The release of new rootstocks more resistant or tolerant to abiotic and biotic stresses represents the best solution to increase orchard productivity and efficiency (Reighard et al., 2008). New selections have been developed with resistance to biotic stresses such as root-

knot nematodes and tolerance to replant conditions (Calvet et al., 2000; Felipe, 2009; Pinochet, 2009; Pinochet, 2010; Jiménez et al., 2011). New rootstocks recently released or under selection may improve peach production with reduction of labor costs. Some of them are plum based or interspecific hybrids, which are more tolerant to compact soils, water logging conditions and provide greater tolerance to iron-chlorosis deficiency (Mestre et al., 2015). They also provide different levels of resistance to soil-borne pathogens (Moreno et al., 1995; Pinochet, 2010).

The selection of an appropriate rootstock can be an important decision because some traits such as yield, vigor or fruit quality depend on the selection of the right scion-rootstock combination. The influence of rootstocks of different genetic origin on the vigor, phenology, yield and fruit quality has been investigated by Massai and Loreti (2004), Zarrouk et al. (2005), Font i Forcada et al. (2014) and Mestre et al. (2015). The vigorous almond-peach rootstocks induced lower fruit quality (Font i Forcada et al., 2014), whereas dwarfing rootstocks were able to provide more nutrients to fructification due to a lower competition from vegetative parts (Chalmers et al., 1981; Mestre et al., 2015), a system that favors light penetration into the canopy, and consequently a more efficient photosynthesis. In contrast, excessive vegetation that causes canopy shading reduces the fruit qualitative parameters (Corelli Grappadelli and Sansavini, 1998), such as fruit size (Sansavini et al., 1984), color, and sugar content (Marini et al., 1991). However, trees grafted on the vigorous rootstock GF677 flowered earlier and mitigated negative effects of low chilling accumulation (Ghrab et al., 2014a). The significant effects of insufficient chilling accumulation on peach cultivars were somewhat attenuated by rootstock type under warm conditions.

A noticeable reduction in chilling accumulation has already been observed in recent years in different temperate areas (Luedeling et al., 2009). This reduction will be especially adverse in the coming decades in warm Mediterranean areas with unknown climate change

effects (Luedeling et al., 2011; Ghrab et al., 2014a). In peach production in warm climates, delayed and sporadic budburst occasionally occurs due to insufficient chilling, resulting in a significant reduction in yield (George and Erez, 2000; Ghrab et al., 2014a). Therefore, in these areas, peach cultivars with lower chilling requirements for bud break have been cultivated (Rouse and Sherman, 2002). In marginal regions, the use of low-chill rootstocks is empirically recommended for growing low-chill scion cultivars (George and Erez, 2000). The variability of chilling accumulation associated with yearly variation and the contrasting intensity of dormancy in different cultivars and rootstocks requires more investigation mainly in the southern part of the Mediterranean area.

Expanding peach adaptability to different growing conditions needs accurate evaluation of scions and rootstocks (Albás et al., 2004; DeJong et al., 2004; Giorgi et al., 2005; Mestre et al., 2015). The present study was carried out over seven years and aimed to evaluate the adaptability of ten *Prunus* rootstocks of different genetic origins to specific cultivation conditions in a heavy, calcareous soil, in a warm Mediterranean climate. This investigation focused on flowering and fruiting of the flat peach cultivar ‘Subirana’ budded onto rootstocks with different vigor under warm conditions.

2. Materials and methods

2.1. Experimental trial

This study was carried out in an experimental orchard situated in the region of Mornag (36° 41’N, 10° 15’E), the main fruit tree production area in northern Tunisia. Nine new *Prunus* rootstocks: PADAC 150, PADAC 04-03, PADAC 04-01, Rootpac® 70, PAC 847, Krymsk® 86, Krymsk® 1, AGAF 0301-04 and PM 105 AD were tested in reference to Garnem, the most widely used rootstock for peach in Tunisia (Table 1). Trees were planted at 2x6 m spacing and budded with the flat peach cultivar ‘Subirana’ in 2007. The production area is characterized by a warm Mediterranean climate with average annual rain-fall and

Penman-Monteith reference evapotranspiration (ET_o) of 450 and 1240 mm, respectively. Precipitation is characterized by a rainy fall-winter season with low evaporative demand and a prolonged dry-high evaporative demand season. Minimum and maximum winter temperatures fluctuate between 6 and 17°C. Trees were planted on a loamy-clay soil (18% sand, 52% silt and 29% clay). The orchard is under drip irrigation and was subjected to standard cultural practices for production.

Table 1

2.2. Measurements

The performance of the flat peach cultivar ‘Subirana’ on ten *Prunus* rootstocks was evaluated during seven years (2008-2014). Monitoring concerned the rate of buds abscission, vegetative growth, yield and traits of fruit quality. Ten replications (trees) were used for each rootstock in the first year. For the following years the number of replications varied depending on the rate of tree mortality. At the end of the experiment, the number of trees remained unchanged (10 trees) for PADAC 04-01 and PADAC 04-03. The experimental size decreased to 8 trees for Rootpac® 70, PM 105 AD and Garnem, 7 trees for Krymsk® 86, 6 trees for both PADAC 150 and AGAF0301-04, 5 trees for PAC 847 and 3 replications for Krymsk® 1.

2.2.1. Tree vigor

Tree vigor was estimated using trunk cross-sectional area (TCSA), canopy volume and root volume. The TCSA was measured during the dormant season at 15cm above the graft union. Tree size was evaluated by canopy volume in 2014, using Turrell’s formula (Turrell, 1946). Trees were uprooted in 2014 and root volume was also determined. It was estimated as a conical volume by measuring the length and the width of the main roots.

2.2.2. Flower buds abscission

Before bud break, six shoots per tree were chosen to analyze the phenological performance of ‘Subirana’ cultivar on each rootstock. Flower buds abscission was determined as the ratio of flower buds failure to total flower buds.

2.2.3. Yield efficiency

Yield and yield efficiency (kg of fresh yield per cm² of TCSA) were calculated. At harvest, all fruits from each tree were counted and weighed to determine total yield per tree (kg tree⁻¹) and mean fruit weight (FW).

2.2.4. Fruit quality traits

Ten mature fruits of each tree were randomly selected at harvest. Flesh firmness was measured on two paired sides of each fruit, by removing a 1mm thick disk of skin from each side of the fruit with a penetrometer. The point of measurements was the same on each tested fruit and data were expressed in kg cm⁻². Total soluble solids content (SSC) of fruit juice was measured with a digital refractometer with automatic temperature correction and was expressed as °Brix. The titratable acidity (TA) of samples was determined using a manual titrator. Ten mL of fresh fruit juice were diluted with 50 mL of distilled water, and micro-titrated with 0.1M NaOH, and was expressed as g L⁻¹. Ripening index was calculated based on the SSC/acidity ratio.

2.3. Statistical analysis

The statistical analysis was performed using Statgraphics software for Windows (version 4.1; Microsoft Corp., Redmond, WA, USA). An ANOVA was used to detect differences between rootstocks. When the F test was significant, means were separated by Duncan’s multiple range ($P \leq 0.05$). In addition, the analyses of bilateral Pearson correlation were carried out to conclude relationships between parameters. Principal components analysis (PCA) was used to study associations among traits.

3. Results

Table 2 shows factors affecting agronomical and fruit quality parameters of the ‘Subirana’ peach cultivar. Rootstock influenced the values of trunk-cross sectional area (TCSA), yield, yield efficiency, fruit weight (FW), fruit diameter, soluble solids content (SSC), flesh firmness (FF) and ripening index (RI). Similarly, the significant effect of year was found for all studied parameters. The year-to-year variation in fruit quality parameters may be explained by the differences in annual temperatures and crop load over the four years of the study. ANOVA results showed the absence of interaction between rootstock and year for all traits evaluated. This could indicate that rootstocks had consistent effects on ‘Subirana’ peaches and their fruit quality traits.

Table 2

3.1. Tree mortality

Seven years after budding, a variable tree mortality rate was observed depending on the rootstock. Trees budded on Krymsk® 1 showed the significantly highest mortality rate with 70% of dead trees (only 3 trees survived) (Figure 1). PAC847 showed 50% of tree mortality. Lower tree mortality rate was found on Garnem, Rootpac® 70 and PM 105 AD with 20% of dead trees. In contrast, all trees budded on PADAC 03-01 and PADAC 03-04 survived well during this period.

Fig. 1

3.2. Tree growth

Tree vigor, as measured by TCSA and canopy volume, was significantly affected by rootstocks by the end of the second year after budding. At the seventh year after budding (2014), the lowest TCSA was induced by Krymsk® 1 (Table 3). This rootstock showed a TCSA reduction of 89% as compared to Garnem. In contrast, Rootpac® 70 and PADAC 04-

03 presented higher TCSA values of ‘Subirana’, but 21% and 36% less vigorous than Garnem, respectively. The other rootstocks presented intermediate TCSA values.

Table 3

Figure 2 illustrates the canopy and root volumes determined at the end of the experiment for all combinations. The highest canopy volume was noted for trees budded on Rootpac® 70 with 25 m³. Krymsk® 86, PM 105 AD and PADAC 04-03 induced a similar canopy volume of ‘Subirana’ to that of Garnem. Trees budded on PADAC 04-01, AGAF 0301-04 and PAC847 showed an intermediate vigor. The lowest canopy volume of ‘Subirana’ was measured on PADAC 150 and Krymsk® 1 (Figure 2). When estimating root volume, three groups of contrasting root system vigor appeared. Garnem, Rootpac® 70 and PADAC 04-03 presented the most vigorous group with largest root volume exceeding 1 m³. In contrast, the least vigorous group included Krymsk® 1, PAC 847 and PADAC 150 with lower root volume (less than 0.3 m³). Krymsk® 86, PM 105 AD, PADAC 04-01 and AGAF 0301-04 formed the third group with intermediate root system vigor ranging between 0.5 and 0.9 m³ (Figure 2).

Fig. 2

3.3. Flower buds abscission

Peach trees performed contrasting differences in floral buds abscission among rootstocks over the 4-year monitoring period (Figure 3). Inter annual variation in flower buds abscission was observed. A substantial increase of bud failure occurred in 2010 reaching more than 25% for PADAC 150, PM 105 AD, AGAF 0301-04, Krymsk® 1, Krymsk® 86 and PAC 847. The most important commercial rootstock Garnem led to the lowest rate of bud fall in 2010. The increase in flower bud abscission in 2010 seemed to be related in part to lower chill accumulation, which occurred following the warmer winter of 2009-2010 [19 chilling portions (CP)]. Rootstock type seemed to affect the flower bud abscission. Less vigorous and

dwarfing rootstocks induced the highest values for bud failure, more evident during warmer years as observed in 2010 for AGAF 0301-04 and Krymsk® 1. Garnem and Rootpac® 70 appeared to be well adapted with the lowest rate of flower bud abscission.

Fig. 3

3.4. Yield and yield efficiency

During the early bearing years (2008-2010), very low yields were recorded with no significant rootstock effect (data not shown). However, after 2010, differences among rootstocks became evident. Throughout the two following years of the study (2011 and 2012), the highest average fruit yields were obtained by AGAF 0301-04 (Table 3). This rootstock yielded more than PADAC 150, both showing similar vigor. Yield of AGAF 0301-04 also differed significantly from Garnem. The lowest yield was recorded on the least vigorous rootstock Krymsk® 1. Yield efficiency was greatest on AGAF 0301-04 and PM 105 AD and differed from the rest of the rootstocks. The lowest yield efficiency was recorded on Garnem and PADAC 04-03.

3.5. Fruit quality

Fruit quality of the flat peach cultivar ‘Subirana’ was determined during four years (2010, 2011, 2012 and 2014). Rootstock influence seemed to have significant effects over these parameters. Rootpac® 70 induced the highest average values for fruit weight (FW) and diameter (FD), while trees budded on Krymsk® 1 performed the lowest FW and FD average values (Table 3). For soluble solids content (SSC) and RI, no consistent differences among rootstocks were found in the average values for the four years (Table 3). However, the highest values were recorded for trees budded on Krymsk® 1 and the lowest values seem to be induced by the most vigorous rootstock Garnem in several years of the study (data not shown). Regarding flesh firmness, rootstocks did not have significant effect on average

values. However, the highest values were recorded for trees budded on PADAC 04-03 and the lowest value was shown on PAC 847.

3.6. Phenotypic correlations

Significant correlations were found among agronomical parameters and fruit quality traits (Table 4). Fresh fruit weight was positively correlated with fruit diameter, TCSA, canopy volume and root volume, but negatively correlated with tree mortality. Similarly, positive correlations were obtained between fruit diameter, TCSA and canopy and roots volume. In contrast, a significant negative correlation was found between fruit diameter and tree mortality. Negative correlations were detected between cumulative yield and the fruit quality components and the ripening index (SSC/TA). Also, positive correlation was observed between cumulative yield and TCSA. On the other hand, roots volume was positively correlated with TCSA and canopy volume, and negatively correlated with tree mortality. TCSA was positively related to canopy volume, and negatively affected the ripening index.

Table 4

4. Discussion

In this field trial, the performance of the flat peach cultivar ‘Subirana’ showed noteworthy differences with *Prunus* rootstocks and over seven years. Under warm climate and on calcareous soil, *Prunus* rootstocks expressed differences in agronomic and fruit quality traits influencing TCSA, bud failure, yield, yield efficiency, and fruit quality. Moreover, significant yearly variations were observed for the monitored parameters related to climate variability.

The statistical analysis showed the significant effect of year for all quality traits in ‘Subirana’ cultivar. For the same rootstock, the year to year variation in fruit quality parameters may be explained by the differences in annual temperatures and crop load.

Tomás-Barberán et al. (2001) also showed that temperature had a marked effect on fruit quality in apples or plums. Therefore, the chemical composition of peach and nectarines fruits is significantly affected by rootstocks as well as by other factors, such as climate, harvest conditions and scion genotype. All these parameters may have significant roles in determining fruit quality. However, no interaction was found between rootstock and year.

Under our growing conditions, varying levels of tree mortality rate occurred depending on rootstocks. Trees budded on the less vigorous rootstock Krymsk® 1 had the highest mortality rate, while no dead trees were found on PADAC 04-03 and PADAC 04-01 at the end of the experiment. The widely used Garnem generated low tree mortality, less than 20%. Several factors could be related to tree mortality. It was reported that tree death on several rootstocks was due to problems of compatibility as the case of Krymsk® 1 (Zarrouk et al., 2006). This rootstock also showed the highest mortality rate in our conditions. Zarrouk et al. (2006) observed ‘translocated’ or ‘localized’ graft-incompatibilities when Krymsk® 1 was budded with 29 peach cultivars. Previous work has also reported a high tree mortality when budding peach cultivars on Garnem in Mediterranean conditions (Font i Forcada et al., 2012; Mestre et al., 2015), which could be explained by the sensitivity of almond-peach hybrid rootstocks to root asphyxia or susceptibility to various root rot pathogens (Felipe, 2009; Zarrouk et al., 2005; Mestre et al., 2015). Nevertheless, lack of chilling requirements could be another factor that causes tree death. Under our warm conditions, Krymsk® 86 induced a tree mortality rate of 30%. Legua et al. (2012) observed that poor performance of this rootstock was probably due to its bad adaptation to the growing Mediterranean conditions. This peach-plum hybrid is originally from Russia, where chill requirements are much higher than those found in a warm Mediterranean environment. Garnem and Rootpac® 70 have also similar genetic origin and tree death of Rootpac® 70 could also be attributed to sensitivity to root-asphyxia in compact soils. Although plum rootstocks (PM 105 AD and PADAC 150) are

considered more tolerant to root-asphyxia than peach-based rootstocks, it is also well known that they could partially lose their tolerance when budded with peaches.

Garnem, Rootpac® 70 and PADAC 04-03 were the most vigorous rootstocks with the highest values of TCSA, canopy and root volumes. These vigorous rootstocks exhibited lower flower bud failure and seemed to be suitable for peach production in poor and calcareous soils as previously suggested (Cambra, 1990; Moreno et al., 1994). Intermediate vigor was observed for the rest of rootstocks (PADAC 04-01, PAC 847, Krymsk® 86, AGAF 0301-04 and PM 105 AD). Krymsk® 1 and PADAC 150 induced less tree vigor with the lowest values for canopy and root volume. Krymsk® 1 was previously reported as one of the best size controlling rootstocks for apricot in California (Reighard, 2013). However, those two rootstocks induced the highest rate of flower bud failure more evident after warmer winters as previously reported (Ghrab et al., 2014a). Yearly variation of flower buds abscission was related in part to chill accumulation. An increase of bud abscission occurred a subsequent warm year with chill accumulation less than 50% of the average chilling units required for the region. Warmer climatic conditions affected flowering, fruit set and crop yield, and fruit quality of peach cultivars (Erez and Couvillon, 1987; Ghrab et al., 2014a). Consequently, rootstock effects on bud abscission and fruit set of peach cultivars could be explained by tree vigor level. Thus, the rate of bud growth may be related closely to the amount of starch accumulated in the bud tissues (Felker and Robitaille, 1985). Additionally, tree growth potential on different rootstocks was associated to starch reserves accumulated during dormancy (DeJong et al., 2005). The most vigorous rootstocks Rootpac® 70 and Garnem induced the lowest rate of flower buds abscission. Durner and Goffregna (1992) and Sorce et al. (2002) reported that vigorous rootstocks allowed a better supply of water, nutrients and hormones. In contrast, Legua et al. (2012) showed that the poor performance of Krymsk® 86 was probably due to its bad adaptation to the growing conditions. This peach-

plum hybrid originates from Russia, where chill requirements are much higher than those found in a warm Mediterranean environment.

The different vigor levels induced by *Prunus* rootstocks affected the yield performance of the peach cultivar. During the first bearing years, yields were very low, and there were no significant differences between rootstocks. However, differences among rootstocks became evident from the 4th year after budding. Thus, the highest yield was observed for AGAF 0301-04. The results obtained were not similar to previous findings, where the most vigorous rootstocks induced higher yields and higher number of fruits per tree (Iglesias et al., 2004; Loreti and Massai, 2002). The lowest yield was induced by the dwarfing rootstock Krymsk® 1 as shown by Reighard et al. (2008). Furthermore, trees grafted on AGAF 0301-04 and PM 105 AD had higher yield efficiency related to its intermediate vigor. Garnem and PADAC 04-03 performed lower yield efficiency due to their higher vigor (high TCSA), as previously reported by Zarrouk et al. (2005) in the case of Garnem. It appeared that vigor was negatively correlated with yield efficiency (Loreti and Massai, 2002; Forlani and Di Vaio, 1992). For trees budded on vigorous rootstocks, the vegetative growth is an important competitor of fruit development, generating lower carbohydrates availability for fruits and delayed harvest date (Guidoni et al., 1998).

This investigation revealed an important role of the different *Prunus* rootstocks on fruit quality as previously reported (Giorgi et al., 2005; Font i Forcada et al., 2012, 2014). A significant effect of different years for all quality traits was also observed. This may be explained by the differences in annual temperatures and crop load over the 4 years of monitoring (Jiménez et al., 2011; Font i Forcada et al., 2014). The invigorating rootstock Rootpac® 70 produced the largest fruit size and weight in average values, although differences were not significant from the rest of rootstocks with the exception of Krymsk® 1. Different studies have reported that the highest fruit weight was induced by the most

invigorating rootstocks (Albás et al., 2004; Legua et al., 2011; Font i Forcada et al., 2012), although Pinochet et al. (2012) showed that the less vigorous rootstock Krymsk® 1 could induce bigger fruit size. However, growing conditions and cultural practices could account for these differences.

Significant differences for flesh firmness, SSC and RI were found among rootstocks for all sampling years (data not shown), although differences become not statistically significant in the averaged values for the four years. Ghrab et al. (2014b) showed that peach trees budded on less vigorous rootstocks produced higher fruit quality. Less vigorous rootstocks were more capable to supply fruit with nutrients as a consequence of low competition from vegetative growth (Chalmers et al., 1981; Mestre et al., 2015). Excessive vegetation caused canopy shading and reduced the qualitative parameters, such as fruit size, color, and sugar content (Corelli Grappadelli and Sansavini, 1998; Sansavini et al., 1984; Marini et al., 1991). In our case, the three more vigorous rootstocks (Garnem>Rootpac® 70>PADAC 04-03) performed variable fruits quality during the studied four years period, although no significant differences among rootstocks were found in average values.

The higher ripening index is due to the ability of specific rootstocks to induce higher soluble solid content (Font i Forcada et al., 2012) in the absence of significant differences for acidity. Rootstock influence on fruit quality of a deciduous fruit tree was suggested via water relations (Olien and Lakso, 1986). Rootstock hydraulic limitation was directly involved in the vegetative growth control of peach trees (Solari and DeJong, 2006). In fact, the rootstock-related differences in tree water status had pronounced effects on dry matter distribution and the overall vegetative growth of the tree.

Significant correlations were found among agronomical parameters and fruit quality traits. Cumulative yield was positively correlated with TCSA but negatively correlated with ripening index as observed by Font i Forcada et al. (2014). The negative correlation between

cumulative yield and ripening index (SSC/TA) for ‘Subirana’ cultivar confirms the sink competition among fruits by the assimilate supply. Also, the positive correlation between fruit size and vigor characterized by TCSA, roots volume and canopy volume confirm that more vigorous rootstocks such as Rootpac® 70 have the possibility to induce bigger fruits. Significant negative relationships were observed between TCSA and ripening index. An increase in vigor results in a decrease in fruit quality. Indeed, less vigorous peach trees had the highest fruit SSC contents (Giorgi et al., 2005) probably because dwarfing rootstocks are generally capable to send more nutrients to the fruit because there is less competition from the vegetative parts (Morandi et al., 2008).

The correlations among agronomical and fruit quality parameters show the important relationships between the characteristics of yield, vigor, fruit weight and fruit quality traits. However, for each rootstock type, the most appropriate combination of plant training and cultivation system can help to increase the yield efficiency and fruit size, while retaining their adaptability and fruit quality. These results underline the important relationships between plant adaptability and development and the major factors of fruit quality.

The relative importance of the physiological parameters analyzed on the variability within *Prunus* rootstocks under warm Mediterranean conditions, and established on calcareous soil, was determined using principal component analysis (PCA). Data analysis using PCA revealed two main principal components (PCs). The sum of these PCs explained 72.6% of the variability observed (Table 5). PC1 (59.33%) was significantly related to roots volume, canopy volume, TCSA, fruit diameter, fruit weight and cumulative yield. PC2 (13.28%) mostly explained ripening index, buds falling and tree mortality. Two distinct groups were differentiated according to those parameters (Figure 4A). Trees on the positive side of F1 corresponded to the most invigorating rootstocks (Garnem, Rootpac® 70, PADAC 04-03 and PADAC 04-01) and formed the first group (Figure 4B). Nevertheless, two

subgroups were identified according to tree vigor and fruit quality traits. Indeed, the first two rootstocks were on the negative side of F2 while the other two were on the positive side. Garnem and Rootpac® 70 formed a subgroup of the most vigorous rootstocks. Garnem had poorest fruit quality (the lowest level of soluble solids content and the lowest ripening index) while Rootpac® 70 generated bigger fruits and much better fruit quality traits. The second subgroup included the two other medium to high vigorous rootstocks, PADAC 04-01 and PADAC 04-03, characterized by slightly smaller fruit size than Rootpac® 70 but better fruit quality in general (high SSC content, ripening index and firmness). For the second group, Krymsk® 1 was the most dwarfing rootstock with the highest rate of tree mortality. This rootstock induced the smallest fruit size and presented a separate subgroup. The results of the analysis of PCA show that rootstocks on the negative side of F1 had medium and low vigor (Krymsk® 86, AGAF 0301-04, PAC 847, PM 105 AD and PADAC 150) and formed the second subgroup with contrasting fruit quality traits (low to medium fruit size, medium to high SSC and ripening index). Krymsk® 1 was the only rootstock that showed leaf yellowing, a reduction of growth, and premature defoliation. Graft-incompatibility were predictable because of its parents (*P. cerasifera* and *P. tomentosa*) usually known to be incompatible with most peach and nectarine cultivars (Layne, 1987; Moreno et al., 1993). Zarrouk et al. (2006) also observed that the plum dwarfing rootstock Krymsk® 1 was incompatible with many peach cultivars. This may be the result of the differential response of this rootstock under our warm conditions. Thus, the use of the lowest vigorous rootstocks as Krymsk® 1 could be further limited in warm Mediterranean environments because of soil and climatic conditions (Loreti and Massai, 2006).

Conclusions

Under specific warm Mediterranean climate and soil conditions, a clear influence of different *Prunus* rootstocks on plant adaptability was confirmed. As a consequence, there was

an influence not only on the plant development and yield of the flat peach cultivar ‘Subirana’, but also on the qualitative characteristics of the fruit. In these growing conditions, Rootpac® 70 exhibited a similar field performance to Garnem with better fruit size and fruit quality traits. PADAC 04-01 and PADAC 04-03 showed superior adaptation by the absence of dead trees. Both are genetically similar (breeding lines with same parents) with 30% and 15% less vigor than Garnem, respectively, and good fruit quality. Krymsk® 1 presented an opposite response to Garnem due to its low vigor (90% less vigor than Garnem) and bad adaptation for Mediterranean conditions. It would not be recommended for peach plantings in North Africa. PAC 847, AGAF 0301-04 and PM 105 AD appear to control tree size due to their medium vigor. AGAF 0301-04 and PM 105 AD induced the highest yield efficiency. The results of our study demonstrate that the agronomic performance and fruit quality of flat peach fruits were affected by the rootstock. In a warm production area, Rootpac® 70, PADAC 04-01 and PADAC 04-03 seem to be the most suitable rootstocks. For PADAC 04-03 and PADAC 04-01, superior adaptation is obviated by the absence of dead trees. In addition, the PADAC 04-03 rootstock induced good yield and large fruit size, acceptable yield efficiency, and significant smaller trees especially when compared with Garnem.

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579 **Table captions**

580 Table 1. List of *Prunus* rootstocks, description and origin.

581 Table 2. ANOVA analysis of the effect of rootstock and year on agronomic and fruit quality
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583 Table 3. Effect of ten *Prunus* rootstocks on final trunk cross-sectional area (2014) and
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587 Table 4. Pearson’s correlations coefficients between agronomical and basic fruit quality traits
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Figures captions

Figure 1. Tree mortality rate (%) from the first (2008) to the seventh (2014) year after budding. Percentage values in the right side of the bars indicate accumulated mortality rate in 2014.

Figure 2. Canopy and roots volumes of ‘Subirana’ flat peach cultivar budded on ten *Prunus* rootstocks measured at the end of the experiment. Letters (a,b, ...) showed significant differences between rootstocks for each parameter according to Duncan’s Multiple Range Test at $p \leq 0.05$.

Figure 3. Flower buds abscission of the flat peach cultivar ‘Subirana’ budded on ten *Prunus* rootstocks.

Figure 4. Principal component analysis (PCA) representing the diversity of the ten *Prunus* rootstocks, plotted with the contribution of each parameter on the two PCA axes (A) and all the physiological parameters measured during 7 years (B).

Abbreviation: TCSEA, trunk cross sectional area.

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Table 1. List of *Prunus* rootstocks, description and origin.

Rootstock	Species	Origin
AGAF 0301-04	<i>P. cerasifera</i> x <i>P. persica</i>	AI-CEAF, Spain-Chile
Garnem	<i>P. persica</i> x <i>P. dulcis</i>	CITA, Spain
Krymsk® 1 ^a	<i>P. tomentosa</i> x <i>P. cerasifera</i>	KEBS, Russia
Krymsk® 86 ^b	<i>P. cerasifera</i> x <i>P. persica</i>	KEBS, Russia
PAC 847	<i>P. cerasifera</i> x <i>P. persica</i>	AI, Spain
PADAC 04-01	<i>P. cerasifera</i> x (<i>P. persica</i> x <i>P. dulcis</i>)	AI - CSIC, Spain
PADAC 04-03	<i>P. cerasifera</i> x (<i>P. persica</i> x <i>P. dulcis</i>)	AI - CSIC, Spain
PADAC 150	<i>P. insititia</i>	AI - CSIC, Spain
PM 105 AD	<i>P. insititia</i>	CSIC, Spain
Rootpac® 70 ^c	(<i>P. persica</i> x <i>P. davidiana</i>) x (<i>P. dulcis</i> x <i>P. persica</i>)	AI, Spain

Rootstocks: ^a Formerly known as VVA-1; ^b Formerly known as Kuban 86; ^c Formerly known as Purplepac.

Origin: AI: Agromillora Iberia. S.L. Private Nursery, Spain; CITA: Centro de Investigación y Tecnología Agroalimentaria de Aragón; CSIC: Consejo Superior de Investigaciones Científicas; KEBS: Krymsk Experimental Breeding Station; CEAF: Centro de Estudios Avanzados en Fruticultura.

Table 2. ANOVA analysis of the effect of rootstock and year on agronomic and fruit quality traits in “Subirana” cultivar for the average of the years of study.

Source of variation ¹	Rootstock	Year	Rootstock x Year
Trunk cross-sectional area (TCSA)	***	***	ns
Yield	***	***	ns
Yield efficiency	***	**	ns
Fruit weight (FW)	***	**	ns
Fruit Diameter (FD)	***	**	ns
Flesh firmness (FF)	***	***	ns
Soluble solids content (SSC)	***	*	ns
Ripening index (RI)	***	***	ns

¹ Data were evaluated by two-way variance (ANOVA); *** $p \leq 0.001$; ** $p \leq 0.01$; * $p \leq 0.05$; ns, not significant.

Table 3. Effect of ten *Prunus* rootstocks on final trunk cross-sectional area (2014) and average values of yield, yield efficiency (2011-2012) and mean values of fruit weight (FW), fruit diameter (FD), flesh firmness (FF), soluble solid content (SSC) and ripening index (RI) (from 2010 to 2014) of the flat peach cultivar ‘Subirana’.

Rootstock	Final TCSA (cm ²)	Yield (kg tree ⁻¹)	Yield efficiency (kg cm ⁻²)	FW (g)	FD (mm)	FF (Kg cm ²)	SSC (°Brix)	RI (SSC/TA)
Garnem	213.9 a	13.1 b	0.122 d	108.6 ab	66.1 ab	7.0 a	16.3 a	29.8 a
PADAC 150	106.8 de	10.4 d	0.142 c	87.7 ab	59.9 ab	7.5 a	19.3 a	32.9 a
PADAC 04-03	135.5 c	12.4 bc	0.127 d	103.0 ab	64.5 ab	7.6 a	19.0 a	40.0 a
PADAC 04-01	105.0 e	10.4 d	0.149 c	110.0 ab	65.7 ab	7.2 a	18.8 a	37.8 a
Rootpac® 70	167.4 b	11.3 c	0.145 c	116.0 a	66.8 a	7.2 a	17.4 a	35.9 a
PM 105 AD	76.4 gh	12.5 bc	0.230 a	92.4 ab	61.5 ab	7.2 a	18.8 a	38.1 a
AGAF 0301-04	114.1 d	14.3 a	0.227 a	94.3 ab	60.4 ab	7.3 a	19.3 a	38.3 a
Krymsk® 1	23.7 i	3.1 f	0.146 c	81.3 b	59.5 b	7.3 a	19.8 a	47.4 a
Krymsk® 86	90.0 fg	9.0 e	0.164 b	91.0 ab	61.0 ab	7.0 a	18.9 a	37.8 a
PAC 847	96.7 ef	9.7 de	0.167 b	99.3 ab	62.5 ab	6.7 a	18.5 a	35.0 a

Letters (a,b, ...) showed significant differences between rootstocks for each year according to Duncan's Multiple Range Test at $p \leq 0.05$.

Table 4. Pearson's correlations coefficients between agronomical and basic fruit quality traits on different *Prunus* rootstocks budded with 'Subirana' cultivar.

Variables	Cumulative Yield	Buds falling	Fresh weight	Fruit diameter	Fresh firmness	Ripening index	Tree mortality	TSCA	Canopy volume	Roots volume
Cumulative Yield	-	-0.197	0.517	0.403	0.073	-0.643*	-0.624	0.692*	0.526	0.558
Buds falling		-	-0.708*	-0.741*	0.041	0.547	0.426	-0.581	-0.329	-0.376
Fresh weight			-	0.968*	-0.174	-0.483	-0.699*	0.777	0.735*	0.708*
Fruit diameter				-	-0.142	-0.421	-0.719*	0.760*	0.704*	0.751*
Fresh firmness					-	0.317	-0.237	-0.076	-0.279	0.032
Ripening index						-	0.338	-0.768*	-0.440	-0.421
Tree mortality							-	-0.551	-0.631	-0.727*
TSCA								-	0.668*	0.801*
Canopy volume									-	0.874*
Roots volume										-

* represent statistical significance at $p \leq 0.05$. Abbreviations: TSCA, trunk cross-sectional area.

Table 5. Eigenvectors of the principal component analysis (PCA) axes of the agronomical and basic fruit quality traits evaluated on different *Prunus* rootstocks budded with ‘Subirana’ cultivar.

Traits	Component loading	
	F1 (59.33%)	F2 (13.28%)
Cumulative Yield	0.696	0.197
Buds falling	-0.667	0.184
Fruit weight (FW)	0.918	-0.063
Fruit diameter (FD)	0.902	-0.027
Fresh firmness (FF)	-0.115	0.909
Ripening index (RI)	-0.681	0.400
Tree mortality	-0.783	-0.458
Trunk cross-sectional area (TCSA)	0.907	-0.068
Canopy volume	0.828	-0.050
Roots volume	0.865	0.219