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

Lucía Mestre[1], Gemma Reig[2], Jesús A. Betrán[1], Jorge Pinochet[3] and María Ángeles Moreno[2]*

[1]Dpto. de Suelos y Aguas de Riego, Laboratorio Agroambiental. Gobierno de Aragón, Apdo. 727, 50080 Zaragoza, Spain

[2]Dpto. de Pomología, Estación Experimental de Aula Dei (CSIC), Apdo. 13034, 50080 Zaragoza, Spain

[3]Agromillora Iberia S.L., C/El Rebato s/n, 08739 Subirats, Barcelona, Spain

***Corresponding author. Tel: +34 976 71 61 36. Fax: +34 976 71 61 45; E-mail address: mmoreno@eead.csic.es

Abstract

The agronomic performance and leaf mineral nutrition for 'Big Top' nectarine budded onto twelve *Prunus* rootstocks were evaluated. Seven *Prunus amygdalus* × *Prunus persica* hybrids (Adafuel, Adarcias, Felinem, Garnem, Monegro, GF 677, and Mayor), two *Prunus davidiana* × *P. persica* hybrids (Barrier, Cadaman), a *Prunus insititia* plum (Adesoto), a *Prunus domestica* plum (Tetra), and another selection considered to be an hybrid of *Prunus cerasifera* × *P. amygdalus* parentage (Replantpac). Rootstocks were budded during the summer of 1999, and trees were established in a replant site in March 2001. The trial was located in the Ebro Valley (Northeastern, Spain) on a heavy-textured and calcareous soil typical of the Mediterranean area which supported a previous peach orchard until 2000. At the thirteenth year after budding, growing conditions generated varying levels of tree mortality, the highest with peach-almond hybrids: Adafuel, Garnem and Monegro. In contrast, all Replantpac trees survived well and the mortality rate was low on the other rootstocks. Adesoto, Tetra, and Adarcias proved to be the most dwarfing rootstocks, while Cadaman and Replantpac were the most invigorating and generated greater cumulative yields. However, the highest yield efficiency was recorded on GF 677, although it did not differ significantly from other peach-almond (Adarcias, Felinem) and plum (Adesoto, Tetra) rootstocks. The highest fruit weight was observed on Barrier and the lowest on Felinem and Mayor, but they did not differ significantly from the rest of rootstocks. Leaf mineral analysis of trees showed all rootstocks induced N and Fe deficiency and P optimum value according to reference values. Nevertheless, the tendency of plum Adesoto to induce higher Fe leaf concentration could indicate higher tolerance to iron-chlorosis in calcareous soils. The most invigorating rootstock Replantpac seems to induce higher SPAD values and adequate K, Mg and Mn values according to reference values. Tetra induced the best balanced nutritional values (ΣDOP), especially when compared with Barrier and Cadaman, although it did not differ significantly from GF 677 and Mayor.

Keywords: Interspecific hybrids, chlorosis, vigour, foliar mineral analysis

1.Introduction

Peach [*Prunus persica* (L.) Batsch] is the most important temperate and deciduous fruit tree grown in the world, after apples. Spain is the third leading peach producer in the world, only surpassed by China and Italy, and the second larger producer in the EU, after Italy (FAOSTAT, 2014). The main peach producing area is the Ebro Valley, which includes regions of Aragon and Catalonia, and it accounts for 63% of the total Spanish peach production (MAGRAMA, 2014).

Different studies with *Prunus* spp. (Font i Forcada et al., 2012, 2014; Giorgi et al., 2005; Jiménez et al., 2007, 2011; Loreti and Massai, 2006; Moreno et al., 1994, 2001; Remorini et al., 2008; Zarrouk et al., 2005) revealed that the rootstock influences the agronomic performance (tree vigour, yield efficiency, water relations, leaf gas exchange, mineral nutrients uptake, plant size, bloom and harvest dates, and fruit bud survival). The rootstock choice represents one of the most important considerations for a productive peach orchard, particularly in a replant situation (Jiménez et al., 2011; Orazem et al., 2011; Reighard et al., 1997). The use of rootstocks is mainly directed to overcome soil and disease problems to which scions have limited or no resistance. Peach-almond hybrids (*Prunus amygdalus* × *P. persica*) are largely used as rootstocks for peach trees in the Mediterranean countries. They are tolerant to lime induced iron-chlorosis and alkaline soil conditions, and they are graft-compatible with peach and almond cultivars (Moreno and Cambra, 1994; Moreno et al., 1994; Zarrouk et al., 2005). They are also vigorous and appropriate for use in poor dry soils (Cambra, 1990) and in fruit tree replanting situations (Jiménez et al., 2011; Orazem et al., 2011). In recent years, new selections of peach-almond hybrids have also been developed with resistance to biotic stresses, such as root-knot nematodes (*Meloidogyne* spp.) (Felipe, 2009; Pinochet, 1997, 2009), and tolerance to replant conditions (Jiménez et al., 2011). Similarly, several plum rootstocks used for different stone fruit species have also been released. They adapt well to highly calcareous and heavy-textured soils, being tolerant to root asphyxia and Fe chlorosis and resistant to root-knot nematodes (Moreno et al., 1995a, 1995b).

The present research was carried out over thirteen years of study with 'Big Top' nectarine cultivar budded onto different peach-based diploid rootstocks (almond × peach, peach × *Prunus davidiana*), hexaploid plums and an almond-myrobalan diploid hybrid of different vigour and grown on a heavy and calcareous soil typical of the Mediterranean area, in a replant site. The objective was to evaluate the performance of the rootstocks in these conditions, through tree survival, leaf mineral status, vegetative growth, and yield characteristics.

2.Materials and methods

2.1.Plant material and trial characteristics

Twelve *Prunus* rootstocks, including seven *Prunus amygdalus* × *Prunus persica* hybrids: Adafuel, Adarcias, Felinem, Garnem, Monegro, GF 677 and Mayor; two *Prunus davidiana* × *P. persica* hybrids: Barrier and Cadaman; one *Prunus insititia* plum: Adesoto; one *Prunus domestica* plum: Tetra; and one *Prunus cerasifera* × *P. amygdalus* hybrid: Replantpac, were evaluated since the third (2003) to the thirteenth (2013) year after planting at the Experimental Station of Aula Dei-CSIC (Zaragoza, Spain) (Table 1). Adafuel (Cambra, 1990), Adarcias (Moreno and Cambra, 1994) and Mayor (Cos et al., 2004) were selected due to their tolerance to iron chlorosis. The hexaploid plum Adesoto was selected due to its resistance to root-knot nematodes and good graft-compatibility with peach (Moreno et al., 1995a). Replantpac (Rootpac® R) shows resistance to root-knot nematodes and exhibits a high tolerance to root asphyxia caused by waterlogging (Pinochet, 2010). Felinem, Garnem and Monegro were selected due to their tolerance to iron chlorosis and resistance to root-knot nematodes (Fernández et al., 1994; Felipe, 2009). GF 677 is the most commonly used peach × almond hybrid rootstock in Mediterranean countries due to its tolerance to lime induced iron-chlorosis and good agronomical performance (Moreno et al., 1994).

These rootstocks were budded with 'Big Top' nectarine cultivar during the summer of 1999, and trees were established in an experimental plot on March 2001. 'Big Top' nectarine is an American cultivar (Zaiger breeding program, USA) highly valued and widespread in the European Union in the last decade (Iglesias, 2010). This nectarine is a mid-season reference cultivar, known for its early coloration resulting in highly colored fruit, sweet taste and optimum fruit size (Della Strada and Fideghelli, 2003; Bellini et al., 2004).

The trial was located in the Ebro Valley (North-Eastern of Spain), on a heavy and calcareous soil, with 28% total calcium carbonate, 8% active lime, water pH 8.4, and a clay-loam texture. Trial was established on a non-fumigated replant site, one year after uprooting an 8-year-old peach ('Summergrand' nectarine cv.) orchard that was budded on plums (*P. insititia*, *P. domestica*) and peach-almond rootstocks. The experiment was established in a randomized block design with five single-tree replications for each scion-rootstock combination. Guard rows were used to preclude edge effects. Trees were planted at 5.5 m × 5.5 m and trained to a low density open-vase system. Cultural management practices, such as fertilization, winter pruning, and spring thinning, were conducted as in a commercial orchard. Open vase trees were pruned to strengthen existing scaffold branches and eliminate vigorous shoots, inside and outside the vase, that would compete with selected scaffolds or shade fruiting wood. Moderate-sized fruiting wood (0.3-0.6 m long) was selected. All trees were hand-thinned at 45-50 days after full bloom (DAFB) leaving approximately 20 cm between fruits. The plot was level-basin irrigated every 12 days during the summer.

2.2.Tree survival and suckering

Tree health and survival were monitored throughout the trial. Dead trees were recorded each year at time when growth measurements were taken. The incidence of rootstock suckering (root and collar suckers) was also recorded during this study.

2.3.Growth measurements and yield characteristics

For all the cropping years, starting in 2003, trunk girth, yield and number of fruits per tree were recorded. Trunk girth was measured each dormant season at 20 cm above the graft union, and the trunk cross-sectional area (TCSA) was then calculated. At harvest, all fruits from each tree were counted and weighted to determine total yield per tree (kg/tree). Fruit weight (FW) was calculated considering the total number of fruits and total yield per tree. Average fruit weight (AFW) from 2009 to 2013 was also calculated. Cumulative yield (CY) per tree and yield efficiency (YE) of each scion-stock combination were computed from the harvest data. YE was calculated as the ratio between the cumulative yields in kilograms per tree (from 2003 to 2013) per final TCSA (cm^2) determined in the winter of 2013-2014.

2.4.Chlorophyll analysis

The chlorophyll (Chl) concentration per unit leaf area was estimated in the field, using a SPAD 502 meter (Minolta Co., Osaka, Japan). After calibration, SPAD measurements were converted into Chl concentration per unit of leaf area (nmol Chl cm^{-2}). Thirty leaves per tree, selected from the middle of bearing shoots located all around the crown, were measured with the SPAD to obtain an average leaf Chl concentration representative of the leaves belonging to the outer part of the tree canopy. Measurements were carried out 120 days after full bloom (DAFB) in 2012, as performed during the previous years (Pinochet, 2010).

2.5.Mineral analysis

Leaf mineral element concentrations were determined in 2012, i.e. in year 12 after budding, for ‘Big Top’ trees with no asphyxia symptoms and/or associated diseases. Leaf sampling was carried out at 120 DAFB. Leaf samples (40 leaves per tree) were collected from shoots around the crown of the trees. The mineral element composition of the dried tissue was determined using the methods of C.I.I (1969) and C.I.I et al. (1975), as previously reported by Jiménez et al. (2007). Total N was determined by Kjeldahl analysis (Gerhardt Vapodest); P was analyzed spectrophotometrically by the phospho-vanadate colorimetric method (Hewlett-Packard 8452A); K, Ca, Mg and Na by atomic emission spectroscopy (ICP, Horiba-Jobin Yvon, Activa-M); and Fe, Mn, Cu and Zn by atomic absorption spectroscopy (PerkinElmer 1100).

The DOP index (deviation from optimum percentage) was estimated for the diagnosis of the nutritive status of the trees (Montañés et al., 1993). This index provides similar information to the Diagnosis and Recommendation Integrated System (DRIS) (Sanz, 1999). The DOP index was calculated from the leaf analysis by the following mathematical expression:

$$DOP = \frac{C \times 100}{C_{ref}} - 100$$

where C is the nutrient concentration in the sample to be studied and C_{ref} is the nutrient concentration considered as optimum, both values given on a dry matter basis. The C_{ref} has been taken from optimum values proposed by Leece (1975). The ΣDOP is obtained by adding the values of DOP indices irrespective of sign. The larger was the ΣDOP the greater was the intensity of imbalances among nutrients.

2.6.Data analysis

Data were evaluated by two-way variance (ANOVA) analysis with the program SPSS 21.0 (SPSS, Inc, Chicago, USA). When the F test was significant, means were separated by Duncan's multiple range test ($P \leq 0.05$). A principal component analysis (PCA) was performed to understand how agronomic and leaf traits contribute to variability among the different rootstocks budded with 'Big Top' nectarine cultivar, using Unscrambler X 10.3 software (CamoAsa, 2001).

3.Results and discussion

3.1.Tree mortality

At the thirteenth year after budding, replant and heavy soil conditions generated varying levels of tree mortality (Fig. 1). Adafuel, Garnem and Monegro rootstocks experienced the highest tree mortality with 80%, 60% and 80% of dead trees, respectively. Therefore, they were excluded of the study. Poor adaptation of Garnem and Felinem to heavy soil conditions was already mentioned by Zarrouk et al. (2005). However, better adaptation of Adafuel budded with different peach and nectarine cultivars was reported in other studies (Font i Forcada et al., 2012; Zarrouk et al., 2005). For Adarcias, Adesoto, Barrier, Cadaman, GF 677 and Mayor, only one tree per rootstock was lost. Some authors considered Adesoto (Massai and Loreti, 2004) and GF 677 tolerant rootstocks to replant conditions. Indeed, Adesoto was released because it adapts well to highly calcareous and heavy soils, being tolerant to root asphyxia and Fe chlorosis (Moreno et al., 1995a). However, in this study both Adesoto and GF 677 experienced a 20% mortality rate, in agreement with results obtained by Jiménez et al. (2011). In contrast, all trees budded on 'Replantpac' survived and seem to tolerate better replant and heavy soil conditions.

In the growing conditions, tree mortality could be attributed to the sensitivity of some almond × peach hybrid rootstocks to root asphyxia caused by waterlogging (Felipe, 2009) or susceptibility to various root rot pathogens such as *Phytophtora* spp. (Zarrouk et al., 2005). Soil conditions and flooding irrigation are prone to waterlogging. The soilborne fungi *Rosellinia necatrix* Prill and *Armillaria mellea* Vahl. P. are associated with a high mortality rate in replant sites where peach-almond hybrids are used as rootstocks in Spain (Jiménez et al., 2011; Pinochet, 2010). However, the presence of both pathogens has not been detected in the present work.

3.2.Tree growth and yield characteristics

The vegetative growth of trees, expressed as TCSA, showed a considerable influence attributable to the rootstock as early as the fourth year of growth (Fig. 2). At the thirteenth year of scion growth, 'Big Top' showed higher TCSA values on Cadaman and Replantpac (356.7 cm^2 and 342.2 cm^2, respectively), compared with the plums Adesoto and Tetra, and the peach-almond Adarcias (173.6 cm^2, 204.7 cm^2 and 207.1 cm^2, respectively). On Adarcias, Adesoto and Tetra, the reduction in TCSA was 42%, 52% and 43% compared to Cadaman, and 40%, 50% and 41% compared to Replantpac. Tree growth was intermediate on the other rootstocks (Table 2 and Fig. 2). The low-medium vigour of Adarcias and Tetra and the high vigour of Cadaman have already been mentioned (Font i Forcada et al., 2012; Hudina et al., 2006; Moreno et al., 1994). In a different replanting soil, Adesoto and Tetra resulted in a medium vigour (Jiménez et al., 2011). Mayor, Barrier, GF 677 and Felinem showed an intermediate TCSA and around 20% and 23% reduction in trunk size compared to Replantpac and Cadaman, respectivelly. However, Zarrouk et al. (2005) and Font i Forcada et al. (2012) reported Felinem as one of the most vigorous rootstocks in similar soil conditions, but not under replant conditions.

In the first bearing years (2003 and 2004), yields were insignificant, and there were no statistically significant differences among rootstocks. However, in the following cropping years differences among rootstocks became evident (Mestre, 2012). In 2013, Cadaman showed the greatest cumulative yield although it did not differ from Barrier and Replantpac. The highest yield and cumulative yield efficiency of Cadaman were already mentioned (Massai and Loreti; 2004; Zarrouk et al., 2005). The lowest cumulative yield was recorded on the less vigorous rootstocks (Adarcias, Adesoto and Tetra) but did not differ from Felinem, GF 677 and Mayor.

'Big Top' budded on GF 677 showed the highest yield efficiency, although differences were not significant when compared with Adarcias, Adesoto, Barrier, Felinem and Tetra. The lowest yield efficiency was recorded on Mayor, although not significantly different from Adesoto, Cadaman, Felinem, Replantpac and Tetra (Table 2). Thus, less vigorous rootstocks (Adarcias, Adesoto and Tetra) induced yield efficiency similar to that on more invigorating rootstocks as Cadaman, GF 677 and Replantpac.

The average of fruit weight for the last five years of study was significantly affected by rootstocks, as observed during the previous years (Mestre, 2012). The peach × *P. davidiana* Barrier, with an intermediate level of vigour, tended to show higher fruit weight, especially when compared with the peach-almond hybrids Felinem and Mayor (Table 2). The tendency of Barrier to induce higher fruit weight has been previously reported (Loreti and Massai, 2006; Orazem et al., 2011).

Yield was generally proportional to growth or tree size. Thus, positive correlations were found between rootstock vigour and cumulative yield (r=0.84; $P\leq0.05$) in 2013, and between annual yield and vigour, except in the period 2003-2006 (Mestre, 2012). However, the greater vigour on fertile and well-irrigated soils may become excessive for good orchard practice unless some irrigation and other cultural practices are modified (Font i Forcada et al., 2012). Vigorous rootstocks appear suitable for peach production under harsh replant conditions or in poor and calcareous soils that might otherwise be unfavorable for growing peach (Cambra, 1990; Moreno et al., 1994; 1996). Replantpac and Cadaman were the most vigorous rootstocks and seem to induce a higher cumulative yield, demonstrating a good adaptation to the growing conditions. In contrast, Adarcias, Adesoto and Tetra with lower vigour and medium to high yield efficiency may be suitable for reducing excessive growth of peach cultivars or to increase planting density (Moreno and Cambra, 1994) allowing the possibility of establishing pedestrian orchards with the benefits of reducing labour costs, especially at pruning and harvest (Jiménez et al., 2011).

3.4.Root suckering

The number of suckers per tree was also determined. The Pollizo Adesoto consistently showed the highest number of root suckers, as previously described by Moreno et al. (1995a) and Reighard et al. (2008). Excessive rootstock suckering is a common drawback observed with some plums (Reighard et al., 1997, 2008; Salesses et al., 1998). A fewer number of suckers, nearly always in the form of crown suckers, were observed for Barrier, Cadaman, Felinem, GF 677 and Replantpac. Adarcias and Tetra did not produce suckers during all the cropping years (Table 2), as reported by Nicotra and Moser (1997) for Tetra.

3.5.Leaf chlorophyll content

Leaf SPAD readings were higher for Replantpac, although it did not differ from Barrier, Cadaman, Felinem and Mayor (Table 3). Lower values were found on Adarcias, although differences were not significant when compared with Adesoto, Barrier, Cadaman, GF 677, Mayor and Tetra. However, Jiménez et al. (2008) classified Adesoto and GF 677 as tolerant to iron chlorosis according to their capacity to reduce iron from the soil. SPAD values were in the same range as previously reported (Jiménez et al., 2011; Zarrouk et al., 2005).

3.6.Leaf mineral nutrients and DOP index

The results showed that most nutrients were affected by the choice of rootstock (Table 4). Leaf N concentration was higher on Cadaman but not different from GF 677 and Replantpac, and lower on Adarcias and Felinem although differences were not significant from Adesoto, Barrier, Mayor and Tetra. The tendency of Cadaman and GF 677 to show higher leaf N concentration than Adarcias and Felinem was also described by Zarrouk et al. (2005) with different cultivars. All rootstocks showed N deficiency, according to reference values (Leece et al., 1975), but comparable N concentration has been previously reported (Zarrouk et al., 2005) in similar growing conditions. The P concentration was higher on Adarcias, whereas it was lower on Adesoto and Cadaman, although it did not differ when compared with the other rootstocks. Nevertheless, leaf P concentrations were considered to be adequate for all rootstocks according to Leece (1975). In similar soil conditions, Adarcias showed lower P values than Cadaman (Zarrouk et al., 2005). The highest leaf K concentration was obtained on the plums Adesoto and Tetra, showing values higher than optimum (Leece, 1975). They were followed by the plum-almond Replantpac with optimum values. In contrast, Adarcias and Felinem induced lower values, but they did not differ significantly from Cadaman and Mayor, all of them presenting marginal values (Leece, 1975). It is interesting to note that plum-based rootstocks increase K uptake more than peach-based rootstocks in these soil conditions. Other authors reported K deficiency for peach (Zarrouk et al., 2005) and cherry cultivars (Jiménez et al., 2007; Moreno et al., 1996, 2001) grown in calcareous soils probably due to poor uptake of this element in this type of soils. Johnson and Uriu (1989) reported that lower leaf K concentration is probably due to its fixation by clay particles in the soil. The clay-loam texture in our growing conditions could also explain the lower leaf concentration of K for some of the evaluated rootstocks, especially for peach-based rootstocks. Leaf Ca concentration was higher on Adarcias, Felinem, GF 677 and Tetra than on the other rootstocks, showing values slightly higher than optimum (Leece, 1975). The higher leaf Ca concentration of trees budded on Felinem has been previously reported (Zarrouk et al., 2005). The Mg concentration was higher on Barrier and lower on Adesoto and Tetra, although it did not differ from the other rootstocks, exhibiting all of them optimum values (Leece, 1975) with the exception of Tetra. The low values of Mg in the case of Tetra could be explained by the antagonism of Mg with some elements such as Ca in heavy-calcareous soil conditions (Zarrouk et al., 2005).

Lower leaf macronutrients concentration has been reported in less vigorous rootstocks for peach (Zarrouk et al., 2005), cherry (Moreno et al., 2001), and apricot (Rosati et al., 1997), suggesting that dwarfing rootstocks could be less efficient in the absorption of some macronutrients from the soil.

The highest Fe concentration was shown on Adesoto, and the lowest on the peach × *P. davidiana* Barrier and Cadaman, but they did not differ significantly from the other rootstocks. The performance of Adesoto to induce higher Fe concentration than other rootstocks shows the interest of Adesoto in calcareous soils. Nevertheless, all rootstocks presented lower Fe concentrations than the optimum according to Leece (1975), especially Barrier as previously reported by Jiménez et al. (2008). Low iron bioavailability is mainly the result of its insolubility at higher pH values, especially in calcareous soils, where roots of some species are unable to acquire Fe (Hell and Stephan, 2003). Most tolerant rootstocks to iron chlorosis are, in general, *P. amygdalus* × *P. persica* hybrids. However, plum rootstocks (Adesoto and Tetra) did also appear to be more tolerant to iron-chlorosis than *P. persica* × *P. davidiana* rootstocks. The Cu concentration was higher on Adesoto, and lower on Barrier, Cadaman and Tetra, although they did not differ from the other rootstocks. Leaf Cu concentration was adequate for all rootstocks, except for Adesoto with slightly higher values compared to the optimum (Leece, 1975). The highest Mn concentration was observed on Replantpac, althought it did not differ from Mayor. According to reference values (Leece, 1975), all rootstocks showed Mn values lower than optimum except Replantpac. Mn deficiency has been also reported for peach and cherry grown in calcareous soils (Jiménez et al., 2004; Moreno et al., 1996, 2001; Zarrouk et al., 2005) probably due to the insolubilization of this element in this type of soil. Furthermore, increased Ca in soil or an excess of phosphoric acid fertilization might decrease or block Mn uptake (Johnson and Uriu, 1989). Zarrouk et al. (2005) reported significant correlations between chlorophyll concentration and K and Mn leaf concentration. The performance of Replantpac to show higher SPAD, and K and Mn values is related with the role that Mn plays in the photosynthesis process, and K in the tree vegetative development as was reported for cherry (Jiménez et al., 2004). The highest Zn concentration was found on Tetra, but not significantly different from Adesoto and Barrier, showing Adesoto and Tetra optimum values (Leece, 1975).

According to the ΣDOP index, Barrier and Cadaman showed wider imbalanced nutritional values, whereas Tetra showed the best balanced in nutritional values, although it did not differ from GF 677 and Mayor.

3.7.Principal component analysis

The first two PCs (PC1 and PC2) accounted 59% of the total variance (Fig. 3). PC1 represented 36% of the variance and PC2 showed the 23% of the variance. Main sources of variability with the highest Eigen vectors in each PC were as follows. PC1: DOP, Fe, Ca, TCSA, CY, and Mg; PC2: suckering, K, Cu and P. The results of the analysis of PCA showed that rootstocks on the negative side of PC1 corresponding to Replantpac, Cadaman and Barrier induced in general higher TCSA, CY and leaf Mg concentration, and lower DOP and Fe and Ca leaf concentrations, whereas Adesoto and Tetra induced the contrary. In addition, Replantpac showed higher values on FW, N and SPAD. Rootstocks on the positive side of PC1 and PC2, including Adesoto, showed higher suckering values and higher K and Cu leaf concentrations, and lower values of DOP, P and Ca.

The results obtained with the PCA confirm that the good adaptation of Replantpac to the growing conditions probably favoured higher vigour, cumulative yield and fruit weight, as well as higher N leaf content and SPAD values.

4.Conclusions

Performance of 'Big Top' nectarine was influenced by *Prunus* rootstock adaptive capacity to the growing conditions. The choice of rootstock requires careful analysis of the interaction between graft combination and agronomic characteristics of the area considered.

In replant and heavy-calcareous soil conditions, the best adaptation of Replantpac is highlighted by the absence of dead trees, thirteenth years after planting, especially when compared with the peach-almond hybrids Adafuel, Garnem and Monegro, likely more susceptible to root asphyxia. In addition, Replantpac rootstock appears suitable for peach production when planting on marginal soils or under replanting conditions, showing higher vigour and cumulative yields. In contrast, the lower vigour and good yield efficiency of Adarcias, Adesoto and Tetra rootstocks may be suitable for reducing excessive growth of peach cultivars in fertile soils and to increase planting density.

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Table 1

List of studied rootstocks, description and origin

Rootstock	Species	Genetic background	Origin[a]	References
Adafuel	*P. amygdalus* × *P. persica*	'Marcona' seedlings (open-pollinated)	CSIC, Spain	Cambra (1990)
Adarcias	*P. amygdalus* × *P. persica*	Open-pollinated	CSIC, Spain	Moreno and Cambra (1994); Moreno et al. (1994)
Adesoto	*P. insititia*	Open-pollinated	CSIC, Spain	Moreno et al. (1995a)
Barrier	*P. davidiana* × *P. persica*	Open-pollinated	ISF, Italy	De Salvador et al. (2002)
Cadaman	*P. davidiana* × *P. persica*	Controlled cross	INRA (France-Hungary)	Edin and Garcin (1994)
Felinem	*P. amygdalus* × *P. persica*	'Garfi' almond × 'Nemared' peach	CITA, Spain	Felipe (2009)
Garnem	*P. amygdalus* × *P. persica*	'Garfi' almond × 'Nemared' peach	CITA, Spain	Felipe (2009)
Monegro	*P. amygdalus* × *P. persica*	'Garfi' almond × 'Nemared' peach	CITA, Spain	Felipe (2009)
GF 677	*P. amygdalus* × *P. persica*	Open-pollinated	INRA, France	Bernhard and Grasselly (1981)
Mayor	*P. amygdalus* × *P. persica*	Open-pollinated	CIDA, Spain	Cos et al. (2004)
Replantpac	*P. cerasifera* × *P. amygdalus*	Open-pollinated	AI, Spain	Pinochet (2010)
Tetra	*P. domestica*	Open-pollinated	ISF, Italy	Nicotra and Moser (1997)

[a] AI = Agromillora Iberia S.L. private nursery, Spain; CITA = Centro de Investigación y Tecnología Agroalimentaria de Aragón; CIDA = Centro de Investigación y Desarrollo Agroalimentario de Murcia; ISF = Istituto Sperimentale per la Frutticoltura di Roma; CSIC = Consejo Superior de Investigaciones Científicas; INRA = Institut National de la Recherche Agronomique.

Table 2

Trunk cross-sectional area (TCSA), cumulative yield, yield efficiency and root or crown suckering of 'Big Top' budded on different rootstocks, at the thirteenth year after planting (2013). Mean values (2009-2013) of fruit weight.

Rootstock	TCSA (cm2)		CY (kg tree^{-1})		YE (kg cm^{-2})		SCK (suckers tree^{-1})		AFW (g)	
Adarcias	207.1	ab	156.8	abc	0.76	bc	0.0	a	202.6	ab
Adesoto	173.6	a	130.3	a	0.75	abc	7.2	b	212.6	ab
Barrier	272.2	abc	218.9	bc	0.80	bc	1.0	a	226.7	b
Cadaman	356.7	c	230.8	c	0.65	ab	2.0	a	217.4	ab
Felinem	259.3	ab	155.1	abc	0.70	abc	0.3	a	188.2	a
GF 677	263.7	abc	207.4	abc	0.84	c	0.2	a	210.6	ab
Mayor	292.4	bc	170.5	abc	0.56	a	0.8	a	192.6	a
Replantpac	342.2	c	217.9	bc	0.63	ab	1.2	a	214.7	ab
Tetra	204.7	ab	138.2	ab	0.66	abc	0.0	a	210.9	ab

For each rootstock means followed by the same letter in each column are not significantly different at $P<0.05$ according to Duncan's Multiple Range Test.
Abbreviations: AFW, average fruit weight; CY, cumulative yield; SCK, root and crown suckering; TCSA, trunk cross sectional area; YE, Yield efficiency.

Table 3

Effect of rootstock on leaf chlorophyll concentration, measured as SPAD values, of 'Big Top' nectarine cultivar, at the twelfth year after planting (2012).

Rootstock	SPAD
Adarcias	37.3 a
Adesoto	38.0 ab
Barrier	38.2 abc
Cadaman	38.2 abc
Felinem	39.3 bc
GF 677	37.7 ab
Mayor	38.6 abc
Replantpac	39.7 c
Tetra	37.7 ab

Means followed by the same letter in each column are not significantly different at P $\leq$ 0.05 according to Duncan' multiple rang test.

Table 4

Rootstock effects on leaf mineral element concentrations of 'Big Top' at 120 days (110 D) after full bloom, by the twelfth year after planting (2012). Results for N, P, K, Ca and Mg are expressed as percentage of dry matter and for Fe, Mn, Cu and Zn, as mg kg^{-1}.

Rootstock	N	P	K	Ca	Mg	Fe	Cu	Mn	Zn	∑ DOP
Adarcias	2.4 a	0.21 b	1.6 a	2.8 e	0.37 abc	76.9 abc	7.4 ab	32.6 a	12.1 ab	- 276.2 bcd
Adesoto	2.5 abc	0.15 a	3.3 d	1.9 cd	0.30 ab	86.3 c	19.5 b	30.6 a	20.0 ef	- 271.7 bcd
Barrier	2.4 ab	0.16 ab	1.9 b	1.1 ab	0.47 c	59.8 a	8.2 a	26.2 a	19.4 ef	- 337.6 d
Cadaman	2.8 d	0.15 a	1.9 ab	1.6 bc	0.37 abc	67.3 ab	8.0 a	33.7 a	16.5 cd	- 320.8 d
Felinem	2.4 a	0.17 ab	1.3 a	2.9 e	0.38 abc	83.4 bc	8.5 ab	29.3 a	14.3 bc	- 298.4 bc
GF 677	2.7 bcd	0.16 ab	1.8 b	3.0 e	0.37 abc	73.1 abc	9.3 ab	31.7 a	18.2 de	- 217.9 ab
Mayor	2.5 abc	0.20 ab	1.5 ab	2.4 de	0.36 abc	83.5 bc	12.4 ab	37.0 ab	17.9 de	- 242.2 abc
Replantpac	2.7 cd	0.17 ab	2.8 c	0.6 a	0.39 abc	76.9 abc	10.2 ab	46.1 b	11.1 a	- 290.6 cd
Tetra	2.6 abc	0.18 ab	3.5 d	3.0 e	0.24 a	83.2 bc	7.3 a	35.5 a	21.6 f	- 191.3 a

Means followed by the same letter in each column are not significantly different at $P \leq 0.05$ according to Duncan's multiple range test.

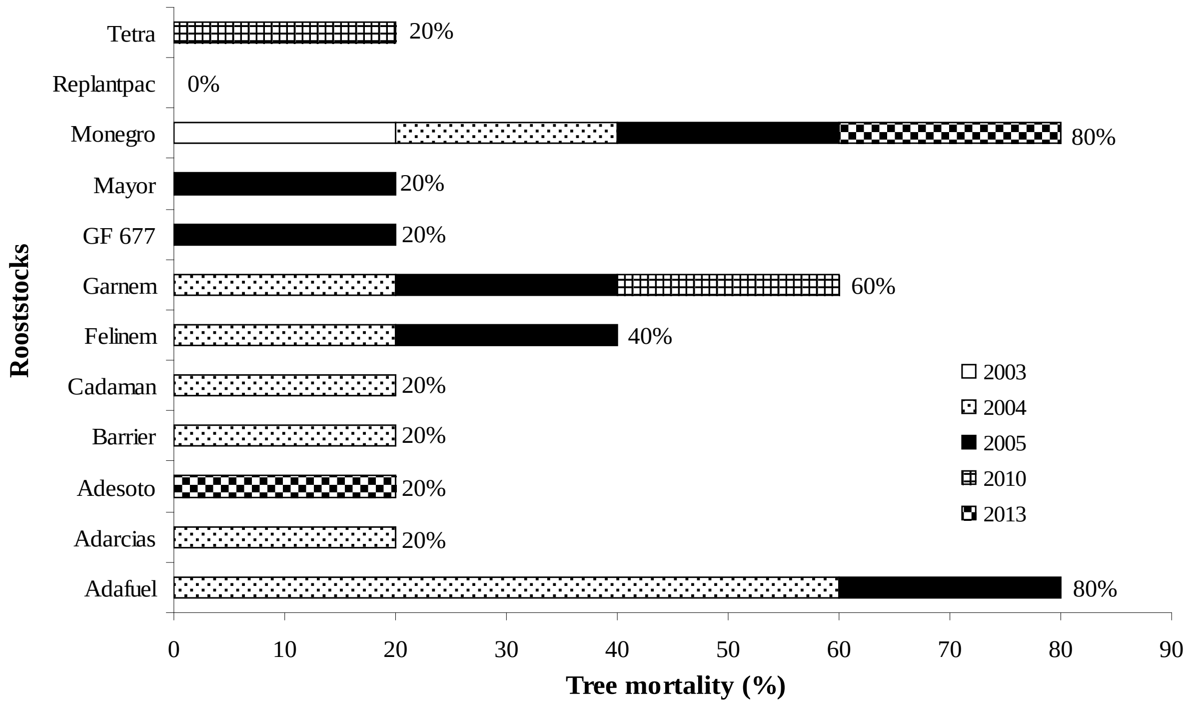

Fig. 1. Tree mortality rate (%) from the third (2003) to the thirteenth (2013) year after planting in the orchard trial. Percentages values right side of the bars indicated accumulated mortality rate at the end of the experiment.

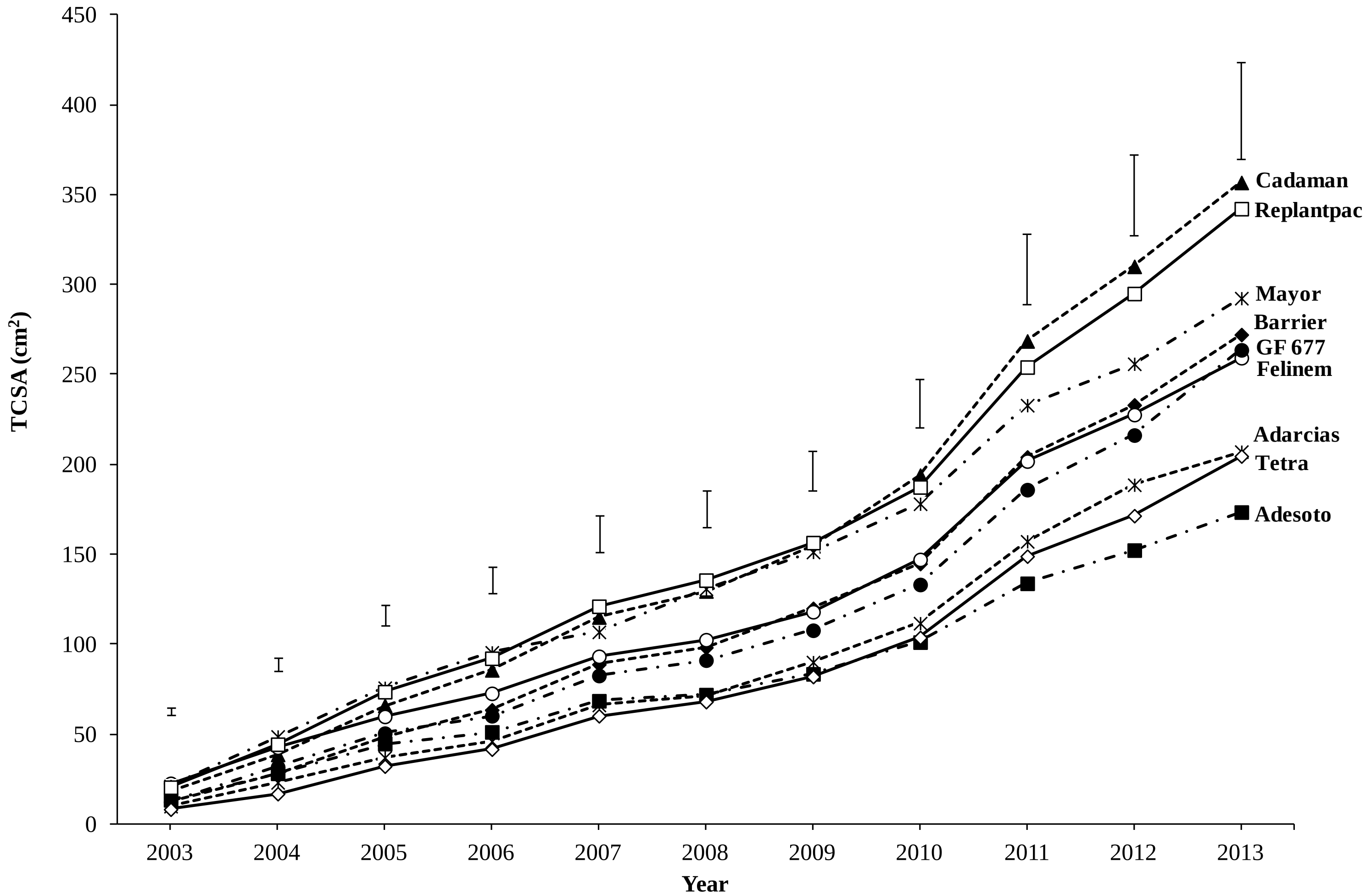

Fig. 2. Rootstock effects on TCSA (cm^2) of 'Big Top' cultivar from the third (2003) to the thirteenth (2013) year after planting in the orchard. Vertical lines indicate LSD ($P \leq 0.05$)

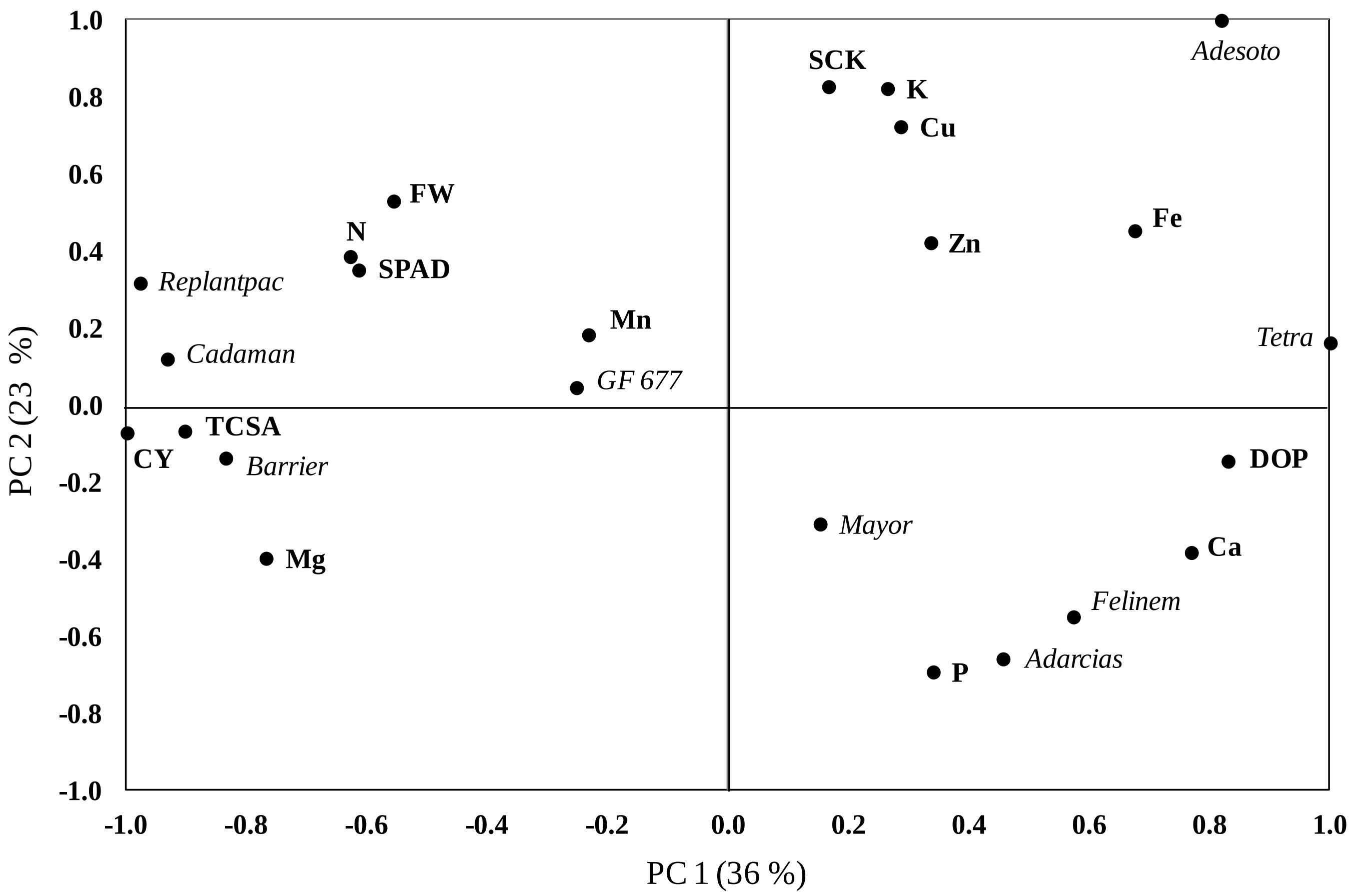

Fig. 3. Principal component analysis for agronomic and leaf traits evaluated on different rootstocks budded with 'Big Top' nectarine cultivar. Abbreviations: Cu, copper; CY, cumulative yield; DOP, deviation from optimum percentage index; Fe, iron; FW, fruit weight; K, potassium; Na, sodium, Mg, magnesium; Mn, manganese; N, nitrogen; P, phosphorus; SCK, root and crown suckering, TCSA, trunk cross sectional area; Zn, zinc.