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Scion–Rootstock Combination Determines Pruning Responses in Young Almond Trees

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Abstract. **Almond growers are seeking ways to reduce costs but maintain yield. Intensive planting systems with greater planting densities using trees on growth-controlling rootstocks, combined with mechanical pruning and shake-and-catch harvesting are becoming popular. In this study we examined the responses of six almond cultivars with distinctive architecture grafted onto five rootstocks with varying degrees of vigor control. Trees were planted in 2018 in a nursery row and left to grow without pruning until Winter 2021. Pruning involved a rudimentary hedging treatment akin to mechanical pruning. Branching and tree structure were recorded in 2020, before pruning, and again at the end of 2021, after one season's growth following pruning. A rating system was developed to record qualitative data on central leader dominance and the number, length, basal diameter, and, in some cases, branching angle of axillary shoots and including scaffold branches. Relatively few changes were recorded in the basic growth habit of these trees in response to pruning. Before pruning, the most common rootstock effect was on axillary shoot production. After pruning, the most common rootstock effects were on scaffold branching and the length of subterminal axillary shoots. Further studies are required to determine how these differences produced by the interaction between pruning and rootstock may affect the productivity of fruit-bearing trees. Although in this study with young trees we were not able to record crop yield, the results highlight that it is mainly the scion–rootstock combination, with or without pruning, that determines the potential productivity of fruiting canopies. Scion–rootstock combinations that produce narrow upright canopies naturally with strong central leader dominance and highly branched canopies are preferred for superintensive growing systems with or without use of mechanical hedging.**

The almond tree [*Prunus amygdalus* (L.) Batsch, syn. *Prunus dulcis* (Mill.)] is the dominant tree nut crop worldwide, with 1,363,703 Mt produced, equal to 31% of the production of all nut crops (International Nut and Dried Fruit Council 2020). The most important almond-producing countries in the Mediterranean basin are Spain and Italy (R Socias i Company et al. 2009). More intensive growing systems with smaller trees have been adopted by several of the major temperate tree fruit industries, with resulting optimization of light distribution and uniform crop maturity, and would be transformational for almonds (Thorp et al. 2021). The growing demand for innovation in cultivation techniques has led to the development of highly efficient and sustainable systems in addition to the traditional open-vase tree shape and its several versions. New agronomic models for almond production are based on growth-controlling rootstocks to allow orchard intensification with narrow rows and canopies to improve the efficiency of inputs, particularly labor and mechanization, and to increase orchard precocity (Ghelfi and Palmieri 2015). The most popular of these is the super-high-density (SHD) system, also named edge or sustainable and efficient systems, promoted by the Agromillora nursery (Barcelona, Spain) (Casanova-Gascón et al. 2019; Iglesias and Torrents 2022; Iglesias et al. 2021). Maximizing branching density within the canopies of SHD trees is important to establish and maintain the productive potential of hedge-pruned trees. The SHD system is also used for other relevant crops, such as olive (*Olea europaeae*), and is characterized by a greater density of trees per hectare and the complete mechanization of cultivation operations, such as harvesting and pruning, and improving water-use efficiency (Romero-Trigueros et al. 2019). Row orientation and tree height are important variants in this system because they affect the outcome in terms of light interception and distribution within the tree canopies (Maldera et al. 2021, 2023). Choice of growing system for tree crops is also based on the plant's physiological response to pruning and to rootstock (Sansavini and Musacchi 1994), and the economic viability of a system essentially relies on the management strategy adopted by the farmer (Jiménez-Brenes et al. 2017).

Pruning is essential for the effective and efficient management of the orchard, affecting physiological responses to the environment and the optimization of biomass production and partitioning (Ferguson et al. 2012; Fumey et al. 2011; Rajaona et al. 2011; Vivaldi et al. 2015). Research on canopy architecture and light interception, especially in relation to flowering and fruit quality, should consider tree architecture or the natural growth habit of the cultivar and how this is modified by pruning and training (Stephan et al. 2007). Pruning will determine the ratio of shoot types produced and may increase or decrease vegetative vigor, depending on the timing and severity of pruning (Asai et al. 1996; Negrón et al. 2015). Tree manipulation may affect shoot leaf area distribution in space significantly. Mechanization of pruning, as with SHD growing systems, could be of great benefit to growers if it allowed a more consistent product, given the fact that each tree is pruned according to the same rules (Franzen and Hirst 2016). It is important to understand how different scion–rootstock combinations will respond to this type of pruning. Selecting the appropriate cultivar continues to be among the most effective methods for securing the agronomic and economic viability of high-density cropping systems (Vivaldi et al. 2015). Tree architecture and pruning may also influence pest management, modifying life conditions of pests and influencing the ability of natural enemies to prey on them (Simon et al. 2007).

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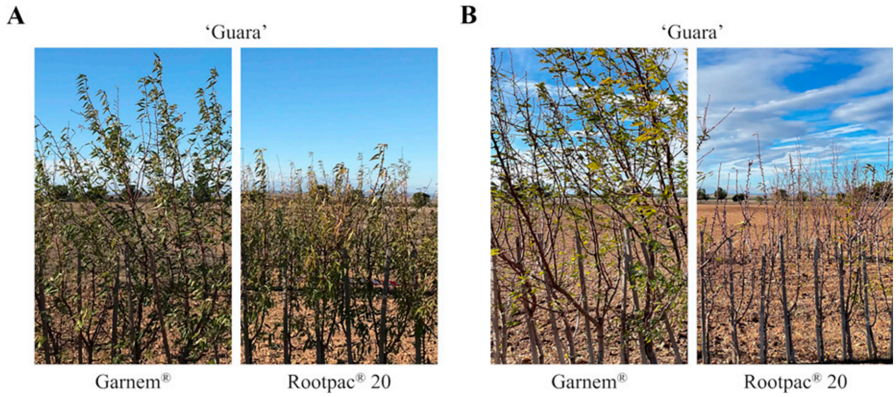

Fig. 1. 'Guara' almond trees grafted on Garnem® or Rootpac® 20 rootstocks. Trees were planted in 2018 and left to grow without pruning for 2 years. Images were taken in Feb 2021 before pruning (**A**) and in Dec 2021, one season after pruning (**B**).

The choice of scion–rootstock combinations is very important for the success of a new orchard. This choice is driven mainly by economic considerations and how well the chosen scion–rootstock combination is suited to the market and locational requirements, whereas the planting system is often designed with consideration of technical issues around tree management and mechanical access (Lauri et al. 2009). In other species, such as apple (*Malus ×domestica*), the use of semidwarfing or dwarfing rootstocks makes it possible to control canopy height and volume adequately, as well as precocity (Lauri 2005). In almond, the choice of different rootstocks could lead to different branching and architectural development (Montesinos et al. 2021, 2022; Negrón et al. 2013).

The aim of our research was to evaluate the impact of mechanical pruning on the growth habit and branching patterns of a range of young almond trees with different scion architectures growing on a range of rootstocks and producing differences in the vigor of scion growth, and to determine how this factor might influence choice of scion–rootstock combinations for SHD almond orchards.

Materials and Methods

Plant material. Six almond cultivars with distinctive architecture were grafted onto five rootstocks with various degrees of vigor control, resulting in 30 different combinations. The scion cultivars selected were 'Isabelona' [synonym (syn.) 'Belona'], 'Soleta', 'Guara', 'Vialfas', 'Diamar' (syn. 'Mardía') and 'Lauranne'; each is an economically important cultivar in Spain. The rootstocks studied were one breeding selection 'GN-8', and four commercial rootstocks: Rootpac® 20 ('Densipac'), Rootpac® 40 ('Nanopac'), Rootpac® R ('Replantpac') and Garnem® (GN15). All are interspecific hybrid rootstocks of different origins. Garnem® and 'GN-8' are both almond × peach [*P. amygdalus* (L.) Batsch, syn. *P. dulcis* (Mill.). × *Prunus persica* (L.) Batsch] hybrid rootstocks, whereas the three others are from the commercial Rootpac® series including Rootpac® 40 [*P. amygdalus* (L.) Batsch, syn. *P. dulcis* (Mill.). × *P. persica* (L.) Batsch], Rootpac® 20 (*Prunus cerasifera* × *Prunus besseyi*), and Rootpac® R [*P. cerasifera* × *P. amygdalus* (L.) Batsch, syn. *P. dulcis* (Mill.)]. Grafted plants of the four commercial rootstocks and the breeding selection were supplied by the Agromillora Iberia S.L. nursery (Barcelona, Spain) in 2018. Trees were planted in Fall (Oct) 2018 at the Centro de Investigación y Tecnología Agroalimentaria de Aragón experimental orchard El Vedado Bajo el Horno (Zuera, Zaragoza; lat. 41°51'46.5"N, long. 0°39'09.2"W). Twenty-five trees per combination were planted as single, unpruned stems supported by wooden stakes, in nursery rows with trees 0.5 m apart. Trees were then left without pruning during the first 2 years of growth so they could express their natural growth habit unaltered (Fig. 1A). After that, they were pruned in Winter (Feb) 2021 and allowed to grow for another full season (Fig. 1B). Pruning involved heading back the primary growth axis (trunk) to a height of 1 m and cutting back axillary shoots to a 10- to 15-cm length to produce a canopy ~0.75 m wide, as is standard practice during the establishment phase of SHD growing systems (Iglesias et al. 2021). Conventional orchard practices were used for weed control and drip irrigation. Soil type was calcareous with a pH around 7 to 8.

Data collection. A rating system based on 11 qualitative parameters, divided into four categories depending on which tree part was studied: trunk, scaffold branch, axillary shoot near the apex of the parent shoot (subterminal shoots), and axillary shoots near the base of the parent shoot (dart-type shoots) were used to record growth responses (Table 1). Subterminal shoots are generally clustered near the terminal bud on the parent shoot and are formed by prolepsis from resting axillary buds. Dart-type axillary shoots are generally located along the lower to mid section of the parent shoot and develop by syllepsis at the same time as the parent shoot (Gradziel 2012). Key attributes recorded included dominance of the trunk [central leader dominance (CLD)], number, length, diameter, and orientation of scaffold branches; and number, length, and diameter of sylleptic dart-type shoots and proleptic subterminal shoots. Central leader dominance refers to the relative dominance of the main growth axis (trunk) over the formation and vigor of scaffold branches. All qualitative parameters ranged from 1 to 3 points. Data were collected before pruning in winter (Feb 2021) and again at the end of the growing season (Dec 2021). Ten trees per scion–rootstock combination were measured, resulting in 300 individuals.

Statistical analyses. Field data collected were analyzed by analysis of variance, followed by nonparametric post hoc testing (Dunn test) using R ver. 4.1.2 (R Foundation for Statistical Computing, Vienna, Austria).

Results

Pruning responses according to rootstock. Rootstocks influenced most growth attributes recorded, with responses variable across cultivars. Before pruning, rootstock affected CLD, but only for 'Lauranne'. Scaffold branching was affected with 'Guara', 'Isabelona', and 'Vialfas'; and subterminal shoots were affected with 'Diamar', 'Soleta', and 'Vialfas' (Table 2). Rootstock made a significant difference to the number of dart-type shoots across all cultivars, but dart length was different only for 'Diamar' and 'Guara', and dart diameter was different with 'Guara'. The number of subterminal shoots was the only parameter in which rootstock had no effect.

Table 1. Qualitative parameters used to describe almond tree growth before and after pruning, and their corresponding notation and rating values.

			Rating value		
Parameter	Organ	Notation[i]	1	2	3
Central leader dominance	Trunk	CLD	Weak	Moderate	Strong
Number	Scaffold branch	Sca_Nb	Few	Medium	Numerous
Length	Scaffold branch	Sca_L	Short	Medium	Long
Diameter	Scaffold branch	Sca_D	Weak	Medium	Strong
Orientation	Scaffold branch	Sca_A	Horizontal	Mixed	Upright
Number	Subterminal shoot	SubT_Nb	Few	Medium	Numerous
Length	Subterminal shoot	SubT_L	Short	Medium	Long
Diameter	Subterminal shoot	SubT_D	Weak	Medium	Strong
Number	Dart-type shoot	Da_Nb	Few	Medium	Numerous
Length	Dart-type shoot	Da_L	Short	Medium	Long
Diameter	Dart-type shoot	Da_D	Weak	Medium	Strong

[i] A = orientation; CLD = central leader dominance; D = diameter; Da = dart-type shoots; L = length; Nb = number; Sca = scaffold branches; SubT = subterminal shoots.

Table 2. Analysis of tree growth of six almond cultivars grafted on five different rootstocks after 2 years of unpruned growth.[i]

	Trunk[ii]	Scaffold branches[ii]				Subterminal shoots[ii]			Dart-type shoots[ii]		
Cultivar	CLD	Sca_Nb	Sca_L	Sca_D	Angle	SubT_Nb	SubT_L	SubT_D	Da_Nb	Da_L	Da_D
Diamar								X[iii]	X	X	
Guara		X			X				X	X	X
Isabelona		X		X	X				X		
Lauranne	X								X		
Soleta								X	X		
Vialfas			X				X		X		

[i] Trees were planted in 2018 and left to grow for 2 years without pruning. Data were collected in Jan 2021, before pruning.
[ii] Attributes recorded were central leader dominance (CLD), and number (Nb), length (L), diameter (D), and angle of scaffold branches (Sca), subterminal branches (SubT), and dart-type shoots (Da).
[iii] X indicates that a significant difference ($P < 0.05$) was observed between rootstocks within the same scion cultivar.

Pruning changed the effect of rootstock genotype on most growth parameters recorded, but as with data collected before pruning, the responses were variable across cultivars. Rootstock choice heavily influenced scaffold branches and subterminal shoots, especially for scaffold branch length and diameter and subterminal shoot length, whereas minimal differences were observed for dart-type shoots (Table 3). No statistical differences were observed for CLD, angle and dart-type shoot length for any cultivar.

Regardless of rootstock genotype, there was a trend for a negative relationship between CLD and branching both before and after pruning. For example, 'Lauranne' trees presented a weak CLD and strong scaffolding and subterminal branching, whereas 'Isabelona' had a strong CLD and weak scaffolding and subterminal branching (data not presented).

In summary, rootstocks had a strong effect on the number of dart-type shoots produced on the young trees before pruning, whereas, after pruning, rootstock effects were mainly related to the vigor (length and/or diameter) of scaffold branches and subterminal shoots. Further details on individual scion cultivar and rootstock responses are provided next.

Central leader dominance. Central leader dominance was generally not influenced by rootstock genotype, except before pruning for 'Lauranne' trees, which had a lower CLD rating on Rootpac® 20 than on Rootpac® R (Table 4). Central leader dominance values were lower with 'Lauranne' than with the other scion cultivars, and ratings were similar before and after pruning. 'Diamar' and 'Soleta' demonstrated a slight decline in almost all combinations after pruning, except for the Rootpac® 20 rootstock, which showed increased values. 'Guara' and 'Vialfas' presented an opposite trend, with greater CLD values in most combinations, except for Garnem® and Rootpac® 40. A clear trend was not observable for 'Isabelona' and 'Lauranne'. Note, however, that none of these trends were significant.

Scaffold branch formation. There were few significant differences across rootstocks in the relative number, length, and orientation of scaffold branches of the scion cultivar before and after pruning. In February, before pruning, ratings for the number of scaffold branches varied among rootstocks for 'Guara' and 'Isabelona', whereas in December, after pruning, differences were significant for 'Lauranne', 'Soleta', and 'Vialfas' (Table 5). Before pruning for 'Guara', scaffold branch number values were greater when grafted onto Garnem® (a vigorous rootstock) than on 'GN-8', whereas with 'Isabelona', the greater value was for trees on Rootpac® 20 (a dwarfing rootstock). Apart from 'Vialfas', few differences were recorded in the length of scaffold branches before pruning, but all cultivars, except 'Lauranne', showed rootstock effects in December, after pruning. The greatest scaffold branch lengths were observed in all cultivars in combination with Garnem® as rootstock, followed by combinations with Rootpac® R and Rootpac® 40. Scion cultivars grafted onto Rootpac® 20 rootstocks were generally less vigorous, with shorter scaffold branch lengths than those seen in the other rootstocks.

Higher ratings were recorded for scaffold branch diameter after pruning than before, which could have been an influence of tree age rather than pruning response (Table 5). There were no significant differences in scaffold branch diameter among rootstocks for most cultivars in February (before pruning), apart from 'Isabelona', where combinations with Rootpac® 20 and Rootpac® 40 had higher ratings for scaffold branch diameter than the rest. Similar relationships were found after pruning. Cultivars grafted onto Garnem® presented the highest scaffold branch diameters for all cultivars, but this variable was reduced when grafted onto Rootpac® 20. Combinations with 'Lauranne' showed no significant differences before or after pruning.

Values for scaffold branch angle were generally unaffected by rootstock genotype or by pruning. Some differences were found before pruning, with combinations of 'Guara' and 'Isabelona' scion cultivars grafted with Rootpac® 20 having narrower branch angles than branch angles on other rootstocks. However, when grafted with Rootpac® 40, Garnem® displayed more horizontal scaffold branches than on other rootstocks (Table 5). Pruning had a contrasting effect among cultivars. 'Guara', 'Lauranne', and 'Vialfas' showed lower scaffold branch angle values after pruning, whereas ratings for 'Isabelona' and 'Soleta' were higher. No clear differences were observed for 'Diamar'.

Axillary shoot production. Subterminal shoots were affected by rootstock genotype both before and after pruning. Pruning increased the relative number of subterminal shoots but decreased the length and diameter of these shoots across most scion–rootstock combinations (Table 6). The number of subterminal shoots was unaffected by rootstock genotype before or after pruning, except for 'Lauranne' trees, which produced more subterminal shoots after pruning when grown on Rootpac® R than on 'GN-8' rootstock. Although a greater number of subterminal shoots was observed in combinations with Garnem®

Table 3. Analysis of tree growth of six almond cultivars grafted on five different rootstocks, 10 months after pruning of 2-year-old trees.[i]

	Trunk[ii]	Scaffold branches[ii]				Subterminal shoots[ii]			Dart-type shoots[ii]		
Cultivar	CLD	Sca_Nb	Sca_L	Sca_D	Angle	SubT_Nb	SubT_L	SubT_D	Da_Nb	Da_L	Da_D
Diamar			X[iii]	X			X				
Guara			X	X			X		X		X
Isabelona			X	X				X			
Lauranne		X				X					
Soleta		X	X	X			X				
Vialfas		X	X				X				

[i] Trees were planted in 2018 and left to grow for 2 years before being pruned. Data were collected in Dec 2021, one season after pruning.
[ii] Attributes recorded were central leader dominance (CLD), and number (Nb), length (L), diameter (D), and angle of scaffold branches (Sca), subterminal branches (SubT), and dart-type shoots (Da).
[iii] X indicates that a significant difference ($P < 0.05$) was observed between rootstocks within the same scion cultivar.

Table 4. Qualitative ratings for central leader dominance of six almond cultivars grafted on five different rootstocks before and after pruning.[i]

Combination		Central leader dominance rating[ii]	
Scion cultivar	Rootstock	Before pruning	After pruning
Diamar	Garnem®	2.3 a[iii]	1.8 a
	'GN-8'	2.5 a	2.3 a
	Rootpac® 20	2.8 a	2.9 a
	Rootpac® 40	2.3 a	2.0 a
	Rootpac® R	2.6 a	2.2 a
Guara	Garnem®	1.9 a	1.9 a
	'GN-8'	2.0 a	2.5 a
	Rootpac® 20	1.9 a	2.4 a
	Rootpac® 40	2.5 a	2.0 a
	Rootpac® R	2.3 a	2.7 a
Isabelona	Garnem®	2.8 a	2.7 a
	'GN-8'	2.8 a	2.6 a
	Rootpac® 20	2.3 a	2.9 a
	Rootpac® 40	2.6 a	2.6 a
	Rootpac® R	2.8 a	2.8 a
Lauranne	Garnem®	1.2 ab	1.2 a
	'GN-8'	1.6 ab	1.7 a
	Rootpac® 20	1.0 b	1.4 a
	Rootpac® 40	1.3 ab	1.1 a
	Rootpac® R	2.0 a	1.6 a
Soleta	Garnem®	2.6 a	2.4 a
	'GN-8'	2.7 a	2.3 a
	Rootpac® 20	2.2 a	2.6 a
	Rootpac® 40	2.7 a	2.6 a
	Rootpac® R	2.8 a	2.6 a
Vialfas	Garnem®	2.8 a	1.6 a
	'GN-8'	2.0 a	2.2 a
	Rootpac® 20	1.9 a	2.3 a
	Rootpac® 40	2.2 a	2.1 a
	Rootpac® R	2.0 a	2.6 a

[i] Trees were planted in 2018, left to grow without pruning for 2 years, then pruned in Feb 2021. Data were collected in February before pruning and in December, one season after pruning.
[ii] Ratings for central leader dominance range from 1 (weak) to 3 (strong).
[iii] Values within columns for each scion cultivar followed by the same letter were not significantly different ($P > 0.05$).

Table 5. Qualitative ratings for scaffold branch growth of six almond cultivars grafted on five different rootstocks before and after pruning.[i]

Combination		Scaffold branch growth rating[ii]							
		No.		Length		Diameter		Angle	
Scion cultivar	Rootstock	Before pruning	After pruning	Before pruning	After pruning	Before pruning	After pruning	Before pruning	After pruning
Diamar	Garnem®	1.3 a[iii]	1.8 a	1.8 a	2.5 a	1.0 a	2.2 a	1.6 a	2.1 a
	'GN-8'	1.1 a	1.3 a	1.5 a	2.3 a	1.0 a	2.0 ab	2.3 a	2.4 a
	Rootpac® 20	1.1 a	1.0 a	1.7 a	1.1 b	1.0 a	1.3 b	2.3 a	2.1 a
	Rootpac® 40	1.1 a	1.7 a	1.8 a	2.3 a	1.3 a	2.2 ab	1.8 a	2.0 a
	Rootpac® R	1.2 a	1.6 a	2.0 a	1.8 ab	1.0 a	1.8 ab	2.0 a	1.8 a
Guara	Garnem®	1.8 a	1.8 a	2.6 a	2.7 a	1.6 a	2.7 a	2.1 ab	1.6 a
	'GN-8'	1.0 b	1.1 a	2.0 a	2.2 ab	1.9 a	2.0 ab	2.4 ab	2.3 a
	Rootpac® 20	1.2 ab	1.0 a	2.8 a	1.7 b	2.0 a	1.8 b	2.8 a	2.2 a
	Rootpac® 40	1.3 ab	1.3 a	2.2 a	2.3 ab	1.6 a	2.4 ab	1.9 b	1.6 a
	Rootpac® R	1.2 ab	1.4 a	2.7 a	2.2 ab	1.3 a	2.6 a	2.7 a	1.9 a
Isabelona	Garnem®	1.1 ab	1.2 a	1.4 a	2.6 a	1.0 b	2.4 a	1.3 b	2.7 a
	'GN-8'	1.0 b	1.0 a	1.0 a	1.3 b	1.0 b	1.6 ab	2.0 ab	2.7 a
	Rootpac® 20	1.4 a	1.0 a	1.9 a	1.1 b	1.8 a	1.0 b	2.4 a	2.2 a
	Rootpac® 40	1.1 ab	1.0 a	1.3 a	1.3 b	1.8 a	1.8 ab	1.8 ab	2.2 a
	Rootpac® R	1.0 b	1.1 a	1.5 a	1.6 b	1.0 b	1.7 ab	1.5 ab	2.4 a
Lauranne	Garnem®	1.8 a	2.3 a	3.0 a	2.9 a	2.7 a	2.8 a	2.5 a	2.3 a
	'GN-8'	1.0 a	1.5 ab	3.0 a	2.5 a	1.9 a	2.4 a	2.2 a	2.1 a
	Rootpac® 20	1.3 a	1.3 b	3.0 a	2.3 a	2.1 a	2.1 a	2.6 a	2.3 a
	Rootpac® 40	1.5 a	2.1 ab	2.9 a	2.7 a	2.0 a	2.4 a	2.3 a	2.2 a
	Rootpac® R	1.8 a	1.8 ab	3.0 a	2.7 a	2.4 a	2.6 a	2.7 a	2.3 a
Soleta	Garnem®	1.4 a	1.7 a	1.9 a	2.6 a	2.7 a	2.6 a	1.9 a	2.6 a
	'GN-8'	1.3 a	1.2 ab	2.4 a	2.0 ab	1.9 a	1.9 b	2.6 a	2.5 a
	Rootpac® 20	1.3 a	1.2 ab	1.6 a	1.2 c	2.1 a	1.4 b	2.5 a	2.6 a
	Rootpac® 40	1.1 a	1.0 b	1.8 a	1.7 bc	2.0 a	1.8 b	2.0 a	2.4 a
	Rootpac® R	1.2 a	1.0 b	2.3 a	2.4 ab	2.4 a	2.2 ab	2.3 a	2.5 a
Vialfas	Garnem®	1.3 a	1.9 a	3.0 a	2.9 a	1.5 a	2.6 a	2.2 a	2.3 a
	'GN-8'	1.0 a	1.4 ab	2.1 ab	1.9 b	1.4 a	1.9 a	3.0 a	1.9 a
	Rootpac® 20	1.1 a	1.3 ab	1.9 b	1.7 b	1.2 a	1.9 a	2.4 a	2.1 a
	Rootpac® 40	1.3 a	1.4 ab	1.8 ab	2.0 ab	1.8 a	2.0 a	2.5 a	1.4 a
	Rootpac® R	1.1 a	1.0 b	1.5 b	2.0 b	1.0 a	2.2 a	2.0 a	1.8 a

[i] Trees were planted in 2018 and left to grow without pruning for 2 years. Data were collected in Feb 2021 before pruning and in Dec 2021, one season after pruning.
[ii] Attributes scored were number (from 1 = few to 3 = numerous), length (from 1 = short to 3 = long), diameter (from 1 = weak to 3 = strong), and angle (from 1 = horizontal to 3 = upright).
[iii] Values within columns for each scion cultivar followed by the same letter were not significantly different ($P > 0.05$).

and Rootpac® R, no statistical differences were found.

Ratings for the length of subterminal shoots produced after pruning were generally less than those produced before pruning (Table 6). Before pruning, only 'Vialfas' had significant differences in subterminal shoot length between rootstock genotypes, with longer shoots when grafted onto Garnem® and Rootpac® 20. After pruning, four cultivars showed significant differences in shoot length: 'Diamar', 'Guara', 'Soleta', and 'Vialfas'. In all four cultivars, combinations with Rootpac® 20 generally had the shortest subterminal shoot length.

Subterminal shoot diameter values were generally smaller after pruning (Table 6). Before pruning, significant differences among rootstocks were observed only for 'Diamar' and 'Soleta' scion varieties. 'Diamar' had the highest subterminal shoot diameter values when grafted onto Rootpac® 20 and Rootpac® 40, whereas combinations with Rootpac® R had the lowest ratings. On the other hand, 'Soleta' grafted with either Garnem® or 'GN-8' rootstock had higher subterminal shoot diameter values than when grafted with Rootpac® 20. After pruning, however, statistical differences were observed only for 'Isabelona', with higher subterminal shoot diameter values with Garnem® rootstock and lower values when grafted onto 'GN-8'.

Ratings for the number of dart-type shoots varied significantly between the two seasons. In February, before pruning, there were significant differences in the number of dart-type shoots among rootstocks for all scion cultivars (Table 7). 'Guara', 'Isabelona', 'Lauranne', 'Soleta', and 'Vialfas' had greater dart-type shoot numbers when grafted with Garnem® than with the other rootstocks. Similar values were observed in combinations with Rootpac® R for 'Diamar', 'Guara', and 'Soleta'. Cultivars grafted onto Rootpac® 20 consistently had lower values for dart-type shoot number. After pruning, statistical differences were observed only for 'Guara', in which case a completely opposite trend was observed. 'Guara' and Rootpac® 20 had the highest number of dart-type shoots, whereas combinations with Garnem® and Rootpac® 40 had the lowest. A variation in the number of dart-type shoots before and after pruning was also recorded. Lower dart-type shoot number values were observed in December, except for 'Guara' and 'Vialfas', which had higher ratings for dart-type shoots, and 'Diamar', which showed no differences between the two seasons.

Ratings for dart-type shoot length and diameter across all scion–rootstock combinations were consistently lower in December, after pruning, than before pruning in February (Table 7). Minimal statistical differences in dart-type shoot length were recorded between rootstocks. Before pruning, only 'Diamar' and 'Guara' had higher dart-type shoot length values recorded when scions were grafted onto Garnem® and Rootpac® R, whereas lower values were recorded when grafted onto Rootpac® 20. After pruning, no statistical differences were observed in any combination. Dart-type diameter did not appear to be affected by rootstock genotype, with only 'Guara' showing a modest response.

Discussion

In our study we examined the effects of pruning on almond tree growth in multiple scion–rootstock combinations available in Spain with distinctive scion architecture.

Table 6. Qualitative ratings for subterminal shoot growth of six almond cultivars grafted on five different rootstocks.[i]

Combination		Subterminal shoot growth rating[ii]					
		No.		Length		Diameter	
Scion cultivar	Rootstock	Before pruning	After pruning	Before pruning	After pruning	Before pruning	After pruning
Diamar	Garnem®	1.2 a[iii]	1.7 a	2.4 a	1.8 a	2.0 ab	1.1 a
	'GN-8'	1.1 a	1.8 a	2.3 a	1.7 ab	2.2 ab	1.0 a
	Rootpac® 20	1.0 a	1.9 a	2.0 a	1.1 b	2.5 a	1.0 a
	Rootpac® 40	1.1 a	1.7 a	2.2 a	1.8 ab	2.5 a	1.0 a
	Rootpac® R	1.5 a	1.5 a	2.0 a	1.4 ab	1.9 b	1.0 a
Guara	Garnem®	1.2 a	1.0 a	2.4 a	2.7 a	2.4 a	1.9 a
	'GN-8'	1.0 a	1.2 a	2.8 a	2.2 ab	2.3 a	1.8 a
	Rootpac® 20	1.0 a	1.3 a	1.7 a	1.1 c	2.7 a	1.4 a
	Rootpac® 40	1.3 a	1.4 a	2.0 a	1.8 b	2.5 a	1.4 a
	Rootpac® R	1.2 a	1.1 a	2.1 a	2.7 a	2.3 a	1.9 a
Isabelona	Garnem®	1.0 a	1.5 a	1.2 a	1.9 a	1.2 a	1.7 a
	'GN-8'	1.1 a	1.1 a	1.3 a	1.6 a	1.2 a	1.0 b
	Rootpac® 20	1.1 a	1.1 a	2.0 a	1.4 a	1.6 a	1.1 ab
	Rootpac® 40	1.0 a	1.6 a	1.8 a	1.8 a	1.5 a	1.3 ab
	Rootpac® R	1.3 a	1.3 a	1.4 a	1.2 a	1.3 a	1.1 ab
Lauranne	Garnem®	1.2 a	1.4 ab	3.0 a	1.0 a	2.4 a	1.0 a
	'GN-8'	1.0 a	1.3 b	3.0 a	1.5 a	2.7 a	1.0 a
	Rootpac® 20	1.0 a	1.4 ab	3.0 a	1.5 a	2.0 a	1.0 a
	Rootpac® 40	1.4 a	1.7 ab	2.9 a	1.4 a	2.6 a	1.0 a
	Rootpac® R	1.4 a	2.0 a	3.0 a	1.2 a	2.3 a	1.0 a
Soleta	Garnem®	1.5 a	1.7 a	2.2 a	2.0 a	2.0 a	1.6 a
	'GN-8'	1.4 a	1.6 a	2.3 a	1.4 ab	2.0 a	1.0 a
	Rootpac® 20	1.1 a	1.3 a	1.8 a	1.1 a	1.2 b	1.0 a
	Rootpac® 40	1.4 a	1.4 a	1.8 a	1.4 ab	1.5 ab	1.1 a
	Rootpac® R	1.2 a	1.4 a	1.8 a	1.6 ab	1.7 ab	1.1 a
Vialfas	Garnem®	1.1 a	1.7 a	2.7 a	1.5 ab	2.4 a	1.0 a
	'GN-8'	1.0 a	1.9 a	2.0 b	1.5 ab	1.8 a	1.0 a
	Rootpac® 20	1.0 a	1.5 a	2.8 a	1.0 b	2.3 a	1.0 a
	Rootpac® 40	1.1 a	1.3 a	2.0 b	1.9 a	2.4 a	1.0 a
	Rootpac® R	1.0 a	1.7 a	2.0 b	1.1 ab	2.2 a	1.0 a

[i] Trees were planted in 2018 and left to grow without pruning for 2 years. Data were collected in February before pruning and in December, one season after pruning.

[ii] Attributes recorded were number (from 1 = few to 3 = numerous), length (from 1 = short to 3 = long), and diameter (from 1 = weak to 3 = strong).

[iii] Values within columns for each scion cultivar followed by the same letter were not significantly different ($P > 0.05$).

Previous studies in almond already demonstrated that rootstock genotype might affect the growth habit of scion cultivars, including shoot development (Montesinos et al. 2021, 2022). Other researchers have also characterized the pruning effect on shoot development in a limited number of almond cultivars grown in California (Negrón et al. 2015). Previous experiments in apple showed that the combination of rootstock choice and pruning may lead to completely different growth habits (Lauri 2002; Lauri et al. 2011). We grafted six commercial almond cultivars with distinctive architecture onto five different hybrid rootstocks available in Spain. Key attributes included CLD, scaffold branch formation, and axillary shoot production.

During early tree development, apical dominance is defined as the capacity exerted by the apex to regulate the formation and development of new shoots (Hollender and Dardick 2015). Strong apical dominance is associated with few or no axillary shoots; weak apical dominance means numerous axillary shoots. Apical control determines the relative dominance of the primary growth axis (trunk) over scaffold branch formation as trees become older and exhibit their natural growth habit or tree architecture. These processes are regulated by multiple hormones, with auxin, strigolactones, or cytokinins playing a core role (Barbier et al. 2019; Wang et al. 2018). In our study we examined apical control and CLD in almond. We observed a limited effect of the rootstock genotype on this trait both before and after pruning, which contrasts with previous reports in which we observed a rootstock influence in trunk length for some cultivars in younger trees (Montesinos et al. 2021). Nevertheless, we did observe a trend for reduced CLD values, especially with plants grafted onto Garnem® rootstock, and thus a reduction in apical dominance/control strength in response to pruning (Table 4). Although this could have been a consequence of pruning, favoring the relocation of resources to scaffold branch development, it is also possible that this reduction in CLD is caused by the tree being a year older.

Scaffold branches, which have been affected in other species by rootstock choice, are fundamental in defining the final structure of the tree (Warner 1991; Weibel et al. 2003). We note that pruning modified the degree of rootstock influence on scaffold branch development. Before pruning, combinations with Garnem® as rootstock presented more scaffold branches than the other rootstocks in this study (Table 5), although this response was not consistent throughout all scion cultivars. However, the influence of Garnem® was more evident after pruning, with all scion cultivars presenting the greatest scaffold branch numbers when grafted onto Garnem® than other rootstock cultivars. This influence is consistent with previous experiments, where it was observed that Garnem® affected apical dominance negatively, promoting the formation of several new axillary shoots (Montesinos et al. 2021, 2022). 'Isabelona' displayed the lowest number of scaffold branches, which is also consistent with the previously strong CLD phenotype reported for this cultivar (Montesinos et al. 2021, 2022).

Although almost no significant differences were observed regarding rootstock influence on scaffold branch growth before pruning, a clear effect was observed after pruning (Table 5). Scaffold branch length and diameter were clearly reduced in cultivars grafted onto Rootpac® 20, a rootstock that has already been described as a promotor of apical dominance in the scion (Montesinos et al. 2021, 2022). After pruning, combinations with Rootpac® 20 rootstock were the only ones able to limit the development of scaffold branches. This influence is even more apparent in cultivars with a strong or intermediate apical dominance phenotype such as 'Isabelona', 'Diamar', and 'Soleta'. These differences in adaptability to pruning have been reported previously in apple (Lauri and Corelli Grappadelli 2014), differentiating between "plastic" and "nonplastic" cultivars, depending on how affected they are by pruning. Although pruning accentuates previous differences in branching, cultivars maintained similar branch-density phenotypes before and after pruning, which indicates that pruning is not able to modify the basic growth habit of a scion–rootstock combination. This highlights the importance of selecting a correct scion–rootstock combination from the start, which can vary depending on the planting system.

A high density in branching after pruning is desired for SHD systems. This was best seen with 'Lauranne', which exhibited less CLD before and after pruning (Table 4), more scaffold branching after pruning (Table 5), shorter subterminal shoots after pruning (Table 6), and more dart-type shoots after pruning (Table 7) compared with the other scion cultivars, regardless of rootstock vigor. Strong CLD, as seen in 'Diamar', could be an issue for SHD planting systems because they would require more pruning to build a homogeneous and complete hedgerow. The best rootstock in combination with 'Lauranne' was Rootpac® 20, followed by 'GN-8', with both reducing scaffold branch length and diameter. Rootstock did not influence scaffold branch angle either before or after pruning (Table 5). This is in line with a previous report (Montesinos et al. 2021) that noted that branch angle was deemed to be caused by the scion genotype.

The rootstock effect on both subterminal shoots and dart-type shoots was unaffected

Table 7 Qualitative ratings for dart-type shoot growth of six almond cultivars grafted on five different rootstocks.[i]

Combination		Dart-type shoot growth rating[ii]					
		Number		Length		Diameter	
Scion cultivar	Rootstock	Before pruning	After pruning	Before pruning	After pruning	Before pruning	After pruning
Diamar	Garnem®	1.1 ab[iii]	1.0 a	2.2 a	1.0 a	1.5 a	1.0 a
	'GN-8'	1.0 b	1.0 a	1.8 ab	1.0 a	1.8 a	1.0 a
	Rootpac® 20	1.0 b	1.0 a	1.1 b	1.0 a	1.9 a	1.0 a
	Rootpac® 40	1.1 ab	1.0 a	1.9 ab	1.0 a	1.8 a	1.0 a
	Rootpac® R	1.4 a	1.2 a	2.3 a	1.0 a	1.7 a	1.0 a
Guara	Garnem®	2.0 a	1.1 b	3.0 a	1.0 a	2.0 ab	1.0 b
	'GN-8'	1.3 b	1.3 ab	2.4 a	1.0 a	2.2 ab	1.0 b
	Rootpac® 20	1.0 b	2.0 a	1.0 b	1.0 a	2.6 a	1.7 a
	Rootpac® 40	1.1 b	1.1 b	2.4 a	1.0 a	1.7 b	1.0 b
	Rootpac® R	1.9 a	1.3 ab	2.9 a	1.0 a	2.1 ab	1.0 b
Isabelona	Garnem®	2.7 a	1.3 a	2.2 a	1.0 a	1.6 a	1.0 a
	'GN-8'	1.5 bc	1.7 a	1.9 a	1.0 a	1.8 a	1.0 a
	Rootpac® 20	1.0 c	1.1 a	1.5 a	1.1 a	1.5 a	1.0 a
	Rootpac® 40	2.0 ab	1.3 a	1.8 a	1.1 a	1.3 a	1.0 a
	Rootpac® R	1.7 bc	1.5 a	1.3 a	1.0 a	1.7 a	1.0 a
Lauranne	Garnem®	2.5 a	1.9 a	2.7 a	1.0 a	1.4 a	1.0 a
	'GN-8'	1.2 b	2.3 a	2.7 a	1.0 a	1.3 a	1.0 a
	Rootpac® 20	1.1 b	2.4 a	2.4 a	1.0 a	1.1 a	1.0 a
	Rootpac® 40	1.3 b	2.3 a	2.3 a	1.0 a	1.8 a	1.0 a
	Rootpac® R	1.5 b	1.7 a	2.5 a	1.0 a	1.6 a	1.0 a
Soleta	Garnem®	2.5 a	1.3 a	2.7 a	1.0 a	1.7 a	1.0 a
	'GN-8'	1.4 bc	1.8 a	1.9 a	1.0 a	1.9 a	1.0 a
	Rootpac® 20	1.0 c	2.0 a	1.8 a	1.0 a	1.6 a	1.0 a
	Rootpac® 40	2.1 ab	1.8 a	2.2 a	1.0 a	2.2 a	1.0 a
	Rootpac® R	2.7 a	1.9 a	2.2 a	1.0 a	2.0 a	1.0 a
Vialfas	Garnem®	1.8 a	1.9 a	2.8 a	1.0 a	2.0 a	1.0 a
	'GN-8'	1.6 a	1.7 a	2.7 a	1.0 a	2.0 a	1.0 a
	Rootpac® 20	1.0 b	1.8 a	1.9 a	1.0 a	2.0 a	1.0 a
	Rootpac® 40	1.3 ab	1.9 a	2.6 a	1.0 a	2.0 a	1.0 a
	Rootpac® R	1.3 ab	1.9 a	2.5 a	1.0 a	2.0 a	1.0 a

[i] Trees were planted in 2018 and left to grow without pruning for 2 years. Data were collected in February before pruning and in Dec 2021, one season after pruning.

[ii] Attributes recorded were number (from 1 = few to 3 = numerous), length (from 1 = short to 3 = long), and diameter from 1 = weak to 3 = strong).

[iii] Values within columns for each scion cultivar followed by the same letter were not significantly different ($P > 0.05$).

by pruning (Tables 6 and 7). Their production seemed to depend mostly on cultivar characteristics, with some limiting influence of the rootstock genotype. This was even more apparent in cultivars with a reduced rootstock influence such as 'Lauranne', which presented consistently a phenotype with a weak CLD, and strong scaffold and subterminal branching. The opposite was observed in 'Isabelona', which displayed a strong CLD and limited scaffold and subterminal branching in all combinations. For SHD systems, more subterminal and dart-type shoots are preferred. For this reason, combinations with 'Lauranne' showed the best performance for both shoot types, followed by 'Vialfas'. Considering the characteristics individually, 'Diamar' showed interesting values for the number of subterminal shoots, whereas 'Soleta' exhibited interesting values for the number of dart-type shoots.

In contrast, 'Isabelona' had a low branching density with a relatively strong CLD before and after pruning (Table 4), fewer and shorter scaffold branches before and after pruning (Table 5), longer subterminal shoots after pruning (Table 6), and fewer dart-type shoots after pruning (Table 7) compared with 'Lauranne'. When grafted with Rootpac® 20, a low-vigor rootstock, 'Isabelona' trees produced fewer dart-type shoots, which might restrict the productivity of this scion–rootstock combination. When grafted with Garnem®, an invigorating rootstock, 'Isabelona' trees had longer scaffold branches after pruning and produced more dart-type shoots than when grafted with other less-vigorous rootstock genotypes, which might improve the productivity of this scion cultivar growing in SHD systems.

Conclusion

Mechanical hedging of almond trees in SHD plantings is now widely adopted in Spain and elsewhere. In this experiment, we examined how rootstocks and pruning influence the growth of scion cultivars during the first years of tree establishment of SHD systems. Although we report that it is the scion–rootstock combination that has the greatest influence over the structure and potential productivity of the fruiting canopies of almond trees, pruning to simulate hedge trimming had only a modest effect on the growth characteristics or architecture of the scion cultivar. Scions that naturally produce narrow, upright canopies with strong CLD and highly branched canopies are ideal for establishing and maintaining the productive potential of SHD trees (Iglesias et al. 2021). In this context, our results show that among the scion–rootstock combinations studied, the best combinations for SHD systems were 'Lauranne' grafted with Rootpac® 20, Rootpac® R, or 'GN-8'. The worst combination we could identify was 'Diamar' grafted with Rootpac® 20. Our research has shown that growers can be confident that a scion–rootstock combination that naturally produces a densely branched and productive canopy will produce the same canopy type in response to hedge pruning with SHD systems. Conversely, combinations that produce strong scaffold branching with minimal fruiting will have a lower number of branches and should be avoided in SHD systems.

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