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RESEARCH ARTICLE

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Use of root pruning, paclobutrazol, and prohexadione-Ca combination strategies to control growth and improve productivity on pear trees

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Abstract

Growth control in pear orchards is essential, not just to reduce competition between vegetative and reproductive sinks, but also to improve return bloom, yield and fruit quality. The goal to optimize growth control, return bloom and yield must be pursued with the integration or combination of several strategies. Aim of this study was to assess the use of root pruning, paclobutrazol, and prohexadione-Ca (ProCa) either alone or in combination, to control growth and improve productivity on pear trees. The experiment was conducted during three years in a 10 year-old pear orchard with 'Blanquilla' as the scion cultivar. All of the different strategies that were assessed improved growth control in pear trees, with different grade depending on the strategy. Control trees had about 50% of the shoots shorter than 60 cm, root pruning 63%, ProCa 70%, paclobutrazol and root pruning plus ProCa 83%, and root pruning plus paclobutrazol 86%. In addition, yield, fruit weight and return bloom were more affected by applications of ProCa than paclobutrazol. Use of paclobutrazol either alone or in combination with root pruning seems to be most suitable for situations of high-vigor cultivars. The fact that use of paclobutrazol may be challenged again in the future, leave combinations of root pruning plus ProCa as the best shot for vigorous cultivars. In other situations of medium-low vigor, ProCa alone would be the best strategy.

Additional keywords: fruit weight; *Pyrus communis*; return bloom; shoot length; vigor; yield.

Abbreviations used: CCC (chlormequat); GA (gibberellin); ProCa (prohexadione-Ca); RootP (root pruning); TCSA (trunk-coss-sectional area).

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Introduction

Adoption of high-density pear orchards during the last decades has resulted in a significant improvement in yield and fruit quality. However, such high-density orchards can only be maintained by the use of dwarfing rootstocks and appropriate growth control techniques (Maas, 2005). In addition, full production is often achieved many years after orchard establishment and remains one of the main challenges in pear production (Sansavini *et al.*, 2007). While a positive correlation exists among yield, light interception and tree density (Palmer *et al.*, 1992), great vigor means diminution in light penetration, yield and fruit quality, and an increase in the cost of pruning and pest control (Miller, 1995). Jauset *et al.* (2000) reported that the greatest incidence of pear psylla (*Cacopsylla pyri* L., Homoptera: Psyllidae) tends to be associated with cultivars with the greatest vegetative development and highest concentrations of leaf nitrogen. Growth control in pear orchards is essential, not just to reduce competition between vegetative and reproductive sinks, but also to improve return bloom and select the best wood for production (Costa, 2017).

Rootstocks are crucial for tree establishment but also to make trees more manageable through vigor control (Sansavini & Musacchi, 2002). Pear orchards in North America are mostly planted on *Pyrus* seedling rootstocks, as quince (*Cydonia oblonga* Mill.) rootstocks routinely suffer from winter damage, fire blight (*Erwinia amylovora* Burill) infections and pear decline (Westwood & Lombard, 1983; Lind *et al.*, 2003; Mitcham & Elkins, 2007; Robinson, 2011). On the other hand, 'Quince Adams', 'MC', and 'Sydo' are the most used rootstocks in Europe (Deckers, 1992; Sansavini & Musacchi, 2002; Musacchi, 2008; Vercammen, 2014).

Italy and Spain are the most important pear producing countries in Europe (Deckers & Schoofs, 2008). While 'Conference' is the second most important cultivar grown in Italy (Deckers & Schoofs, 2008), it is the most important cultivar grown in Spain (Iglesias & Casals, 2013), and in Northern Europe, with 80% of the acreage in the Netherlands (Heijerman *et al.*, 2015), and 85% in Belgium (Vercammen, 2014). 'Blanquilla' used to be the most important pear cultivar in Spain, but the great vigor of this cultivar and the problem to manage it after the chemical growth retardant chlormequat (CCC) got banned in 2001 challenged its viability. In other areas such as the Netherlands and Belgium, growers started to use mechanical methods like root pruning and trunk incisions to manage growth control on 'Conference' and 'Doyenné du Comice' (Maas, 2005; Vercammen *et al.*, 2005).

Root pruning, by disturbing the shoot to root balance and limiting the gibberellin (GA) activity (Saure, 2007), has been reported to reduce growth in apple (Schupp & Ferree, 1988; Mitre *et al.*, 2012), grape (Lee & Kang, 1997; Ferree *et al.*, 1999), and pears (Vercammen *et al.*, 2005; Asin *et al.*, 2007; Maas, 2008; Janssens *et al.*, 2011). However, its use by fruit growers around the world is limited despite several promising reports (Saure, 2007). One of the reasons to explain this scarce use is the imprecision of this technique, mostly due to the genetic diversity of the rootstocks, and the heterogeneity of environmental conditions (Miller & Tworkoski, 2003). In addition, Schupp & Ferree (1988) reported the need to define pruning depth and distance from the trunk in order to optimize its performance.

Prohexadione-Ca (ProCa), a plant growth regulator that is absorbed by foliage and inhibits the biosynthesis of growth active gibberellins (GAs) (Evans *et al.*, 1999), is one of the newest and most interesting growth retardant authorized for apple and pear (Costa, 2017). Paclobutrazol, another plant growth regulator that inhibits GAs biosynthesis in the sub-apical meristem (Hedden & Graebe, 1985), has been used in apple and pear as well (Raese & Burts, 1983; Greene, 1986; Dheim & Browning, 1988; Sansavini *et al.*, 1988; Greene, 1991; Costa *et al.*, 1995). However, paclobutrazol has not been used in Italy until three years ago, when its authorization for pear orchards was requested and completed after most of the chemical plant regulators were banned (Costa, 2017). Use of paclobutrazol, ProCa, deficit irrigation, root pruning, and summer pruning were studied during three years in a pear orchard (Asin *et al.*, 2007). Nevertheless, all these strategies alone did not provide all of the CCC benefits at the same time, but each one contributed to growth control, return bloom, fruit set, and yield. Therefore, it seems than the goal to optimize growth control, return bloom and yield must be pursued with the integration or combination of several strategies. However, there is scarcity of studies where both applications of paclobutrazol and ProCa are compared together and in combination with root pruning.

The goal of this study was to assess the use of root pruning, paclobutrazol, and ProCa either alone or in combination to control growth and improve productivity on pear trees.

Material and methods

Trial site, design, and treatments

A field trial was conducted during three years at the experimental station of IRTA (Institute of Research and Technology, Food and Agriculture) in Gimenells, Spain (41°39'22.25"N; 0°23'25.37"E) where we compared six strategies to manage growth control on pear (*Pyrus communis* L.) trees. The experiment was conducted in a 10 year-old pear orchard with 'Blanquilla' as the scion cultivar grafted on quince 'M-A' clonal rootstock. Planting distance was 4 m × 2 m (1250 trees/ha). Trees were drip-irrigated (climate is semi-arid Mediterranean, with a mean annual rainfall of 350 mm). The plot was managed within integrated pest management (IPM) according to industry standards.

The experiment was organized in a randomized complete block design with four replications, with each experimental unit being a section of eight trees. For each replication data was collected on those three central trees that were more homogeneous and representative of each experimental unit.

Treatments included: (1) root pruning, (2) paclobutrazol (Cultar®, Syngenta, Basel, Switzerland), (3) ProCa (Regalis®, BASF, Ludwigshafen, Germany), (4) root pruning + paclobutrazol, (5) root pruning + ProCa, and (6) control trees.

Root pruning was performed every year at the end of February, using a tractor with a straight knife perpendicularly-oriented to the soil surface, cutting at 30 cm from the trunk and 40 cm depth on both sides of the trees. Paclobutrazol was applied as a foliar spray at 225 $mL·hL^{-1}$ once a year at 15-20 days after petal fall. ProCa was applied as a foliar spray at 150 $g·hL^{-1}$ three times per year. The first spray was applied three weeks after full bloom, and subsequent sprays were applied at three weeks intervals. All chemical treatments were applied with a handgun sprayer until run-off. The spray volumes were 1000 L·ha^{-1}. Control trees were unsprayed and had no root pruning whatsoever.

Data collection and analysis

Every year during the three years of the trial, the following data was recorded for each single tree: (1) total number of shoots, (2) length of shoots, measured the following winter on 50 shoots randomly-selected, (3) number of flower clusters, (4) fruit number, (5) yield, (6) fruit quality at harvest (flesh firmness and soluble solids), trunk circumference at 20 cm from the graft union (the following winter), and (7) return bloom.

In winter, number of pruning cuts and weight of the pruned wood were recorded for each block.

Trunk-cross-sectional area (TCSA [cm^2]), yield efficiency (yield [kg]/TCSA [cm^2]), and crop load (fruit [number]/TCSA [cm^2]) were calculated. Fruit set was calculated from the final number of fruit per tree and the initial number of flower clusters per tree. All harvested fruit from each tree were graded for fruit weight and caliper distribution by a weight sizer machine (MAF RODA Iberica, Alzira, Spain). A 20-fruit sample from each tree was collected for fruit quality. Firmness was measured at two opposite sides on the fruit equator using a digital firmness tester (Penefel; Ctifl, France) (Torres *et al.*, 2017). Soluble solids content (ºBrix) was determined using the freshly prepared juice of the whole sample. Soluble solid content was measured using a digital temperature compensated refractometer (model PR-101, Atago Co. Tokyo Japan). Return bloom was measured the following spring, by counting the total number of flower clusters per tree.

Response variables were modeled using linear mixed effect models. Mixed models including treatment as fixed factor and block as random factor were built to separate treatment effects for shoot number, shoot length, percentage of shoots <60 cm, percentage of shoots <40 cm, yield, percentage of yield >60 mm, fruit weight, fruit set, TCSA, crop load, yield efficiency, number of pruning cuts, pruning weight, fruit firmness, soluble solids, and return bloom. Fruit number was included as covariate to adjust fruit weight. Return bloom data was square root transformed to normalize data distribution. For all the models, when the main effect (treatment) was significant, comparisons among treatments were made by Tukey's HSD test at P values $\leq$ 0.05. Residual analysis (normal distribution of residuals) was performed to insure that model assumptions were met. Data were analyzed using the JMP statistical software package (Version 12; SAS Institute Inc., Cary, NC, USA).

Results

Shoot growth

There were no significant differences among treatments regarding the number of shoots per tree (Table 1). For all the years, shoots were longer on control trees, followed by root pruned trees (~12% shorter) and ProCa treated trees (~18% shorter). Paclobutrazol-treated trees, and the combination of root pruning with either ProCa or paclobutrazol had the shortest shoots in all the three years (~37% shorter).

Over the three years of the study, control trees had about 50% of the shoots shorter than 60 cm, root pruning ~63%, ProCa ~70%, paclobutrazol and RootP+ProCa ~83%, and RootP+paclobutrazol ~86% (Table 1). When looking at the percentage of shoots <40 cm, root pruning and control trees had similar values, then there was a group that included ProCa either alone or in combination with root pruning, and then paclobutrazol alone and in combination with root pruning, which had the highest percentage of shoots shorter than 40 cm.

Yield, fruit weight, and fruit set

There were no significant differences among treatments regarding yield in year 1 and 3 (Table 2). In year 2, trees that were treated with ProCa had less yield than when the combination of root pruning plus paclobutrazol was used.

Looking at the yield percentage for fruit larger than 60 mm, no significant differences were observed in year 1 (Table 2). In year 2, single sprays of either paclobutrazol or ProCa had higher values than control trees, whereas no significant differences were observed in year 3 for these treatments and control trees. ProCa and RootP+ProCa had higher values than paclobutrazol and RootP+paclobutrazol in year 3.

No significant differences were observed for fruit weight in year 1 (Table 2). In year 2 control trees had the smallest fruit, whereas paclobutrazol and RootP+paclobutrazol had the largest. RootP+ProCa had larger fruit than paclobutrazol in year 3, with no significant differences when paclobutrazol was applied in combination with root pruning.

There were no significant differences among treatments for any of the years regarding fruit set (Table 2).

TCSA, crop load, yield efficiency, pruning cuts and pruning weight

There were no significant differences in year 1 and 3 regarding TCSA (Table 3). In year 2, the combination

Table 1. Effect of treatment on shoot number, shoot length (cm), percentage of shoots <60 cm long, and percentage of shoots <40 cm long on 'Blanquilla' pear at IRTA Gimenells. Grey bars represent variable value. Means within a column followed by different letters denotes significant differences among treatments (Tukey's honestly significant difference, $p \leq 0.05$). [NS]Non-significant at $p \leq 0.05$.

		Year 1	Year 2	Year 3
Shoot #				
	Control	236	359	368
	Paclobutrazol	228	390	378
	ProhexadioneCa	278	389	379
	RootPruning	228	326	334
	RootP+Paclobutrazol	246	415	382
	RootP+ProhexadioneCa	229	364	327
	p	NS	NS	NS
Shoot length (cm)				
	Control	66.0 A	63.3 A	55.3 A
	Paclobutrazol	46.4 CD	39.5 B	33.2 C
	ProhexadioneCa	52.5 BC	57.4 A	41.2 B
	RootPruning	59.8 AB	56.9 A	45.8 B
	RootP+Paclobutrazol	41.7 D	37.3 B	32.9 C
	RootP+ProhexadioneCa	42.9 CD	42.6 B	33.3 C
	p	<0.0001	<0.0001	<0.0001
Shoots <60 cm (%)				
	Control	48 D	48 B	56 C
	Paclobutrazol	77 AB	83 A	89 A
	ProhexadioneCa	70 BC	58 B	81 A
	RootPruning	60 C	59 B	69 B
	RootP+Paclobutrazol	84 A	88 A	88 A
	RootP+ProhexadioneCa	78 AB	80 A	90 A
	p	<0.0001	<0.0001	<0.0001
Shoots <40 cm (%)				
	Control	21 D	23 D	35 D
	Paclobutrazol	56 AB	70 AB	78 A
	ProhexadioneCa	43 C	39 C	60 BC
	RootPruning	30 D	28 CD	50 C
	RootP+Paclobutrazol	63 A	73 A	76 A
	RootP+ProhexadioneCa	50 BC	58 B	70 AB
	p	<0.0001	<0.0001	<0.0001

of root pruning plus ProCa had smaller TCSA than when ProCa was applied alone. There were no significant differences for the rest of the treatments.

There were no significant differences for crop load and yield efficiency in year 1 (Table 3). On the other hand, in year 2 and 3, the smallest values for crop load and yield efficiency were when ProCa was applied alone, whereas in general terms, the highest values were when root pruning was combined with paclobutrazol or ProCa.

There were no significant differences in year 1 and 2 regarding the number of pruning cuts (Table 3). On the other hand, in year 3 the highest number of pruning cuts was for control trees, followed by ProCa, root pruning, RootP+paclobutrazol, paclobutrazol, and RootP+ProCa.

No significant differences for pruning weight were observed in year 1 (Table 3). In year 2 and 3, the highest pruning weight was for ProCa and control trees, followed by root pruning, paclobutrazol, and the combination of root pruning with either ProCa or paclobutrazol.

Fruit quality and return bloom

Overall for all of the three years, there were no significant differences among treatments regarding fruit quality (firmness and soluble solids) (Table 4). The exception was in year 1 when RootP+ProCa and root pruning alone had a slightly less fruit firmness than ProCa (5.3 kg *vs* 5.7 kg, respectively).

There were significant differences among treatments for all the years regarding return bloom (Table 4). In year 1, the highest return bloom was for RootP+paclobutrazol and paclobutrazol, whereas the lowest values were for ProCa. In year 2, root pruning

Table 2. Effect of treatment on yield (kg), percentage of yield >60 mm, fruit set (final fruit number/flower cluster), and fruit weight (g) on 'Blanquilla' pear at IRTA Gimenells. Grey bars represent variable value. Means within a column followed by different letters denotes significant differences among treatments (Tukey's honestly significant difference, $p \leq 0.05$). NSNon-significant at $p \leq 0.05$.

		Year 1	Year 2	Year 3
Yield (kg)				
	Control	50	14 AB	45 A
	Paclobutrazol	50	17 AB	51 A
	ProhexadioneCa	49	7 B	44 A
	RootPruning	48	14 AB	44 A
	RootP+Paclobutrazol	54	21 A	52 A
	RootP+ProhexadioneCa	50	11 B	54 A
	p	NS	0.0042	0.0104
Yield >60 mm (%)				
	Control	26	36 B	54 AB
	Paclobutrazol	31	61 A	40 B
	ProhexadioneCa	35	56 A	59 A
	RootPruning	30	46 AB	50 AB
	RootP+Paclobutrazol	24	48 AB	41 B
	RootP+ProhexadioneCa	35	54 AB	56 A
	p	NS	0.0038	0.0004
Fruit weight (g)				
	Control	104	127 C	115 AB
	Paclobutrazol	108	147 A	113 B
	ProhexadioneCa	109	134 BC	118 AB
	RootPruning	107	131 BC	115 AB
	RootP+Paclobutrazol	105	140 AB	114 AB
	RootP+ProhexadioneCa	110	135 ABC	122 A
	p	NS	0.0003	0.0207
Fruit set				
	Control	1.2	2.3	0.7
	Paclobutrazol	1.1	1.6	0.8
	ProhexadioneCa	1.0	2.4	0.8
	RootPruning	1.1	2.2	0.7
	RootP+Paclobutrazol	1.3	1.8	0.7
	RootP+ProhexadioneCa	1.0	1.8	0.8
	p	NS	NS	NS

with either paclobutrazol or ProCa and paclobutrazol alone had higher return bloom than when ProCa was used alone. In year 3 the highest values were for root pruning and RootP+paclobutrazol, whereas the lowest return bloom was for ProCa.

Discussion

Final number of shoots per tree, or even the TCSA were barely affected by the treatments. On the other hand, all the treatments that were tested in this study had a positive effect on tree growth control through the reduction of shoot length. However, that reduction on shoot length or percentage of shoots shorter than either 60 cm or 40 cm differed depending on the treatment. The final pruning weight tended to be lower (~50% less) when root pruning was combined with either paclobutrazol or ProCa, whereas the highest values were for Control trees and ProCa. In terms of shoot length, root pruning alone had the least effect, and in some cases, there were not even significant differences with control trees. This suggests that the reduction of the root system caused by the root pruning was not enough to imply a significant growth control. Root pruning has been reported to limit the carbohydrate supply, creating a lack of balance between reproductive organs (Khan *et al.*, 1998), and with stronger effect if it is performed closer to the trunk (Schupp & Ferree, 1988). However, growth control was unexpectedly lower in this study than in a previous one (Asin *et al.*, 2007), where root pruning was done farther from the trunk (30 cm *vs* 40 cm). In both experiments, pear trees presented similar growth, equal training system, rootstock, and orchard management. However, the current study was performed in a less fertile stony soil, suggesting that

Table 3. Effect of treatment on trunk-cross-sectional area (TCSA, cm^2), crop load (fruit number/TCSA cm^2), yield efficiency (yield kg/TCSA cm^2), number of pruning cuts, and pruning weight (kg) on 'Blanquilla' pear at IRTA Gimenells. Grey bars represent variable value. Means within a column followed by different letters denotes significant differences among treatments (Tukey's honestly significant difference, $p \leq 0.05$). ^{NS}Non-significant at $p \leq 0.05$.

		Year 1	Year 2	Year 3
TCSA (cm^2)				
	Control	189	205 AB	217
	Paclobutrazol	189	214 AB	225
	ProhexadioneCa	206	232 A	251
	RootPruning	185	208 AB	220
	RootP+Paclobutrazol	199	221 AB	226
	RootP+ProhexadioneCa	181	193 B	203
	p	NS	0.0363	NS
Crop load (Fruit #/TCSA cm^2)				
	Control	2.6	0.6 AB	1.8 AB
	Paclobutrazol	2.6	0.6 AB	2.3 AB
	ProhexadioneCa	2.2	0.2 B	1.5 B
	RootPruning	2.5	0.5 AB	1.9 AB
	RootP+Paclobutrazol	2.6	0.7 A	2.1 AB
	RootP+ProhexadioneCa	2.6	0.4 AB	2.4 A
	p	NS	0.0267	0.0173
Yield efficiency (Yield kg/TCSA cm^2)				
	Control	0.27	0.07 AB	0.21 AB
	Paclobutrazol	0.27	0.08 A	0.24 AB
	ProhexadioneCa	0.24	0.03 B	0.18 B
	RootPruning	0.27	0.06 AB	0.22 AB
	RootP+Paclobutrazol	0.26	0.10 A	0.24 AB
	RootP+ProhexadioneCa	0.28	0.05 AB	0.29 A
	p	NS	0.0074	0.0115
Pruning cuts #				
	Control	392	356	467 A
	Paclobutrazol	336	324	341 B
	ProhexadioneCa	368	362	448 AB
	RootPruning	332	365	417 AB
	RootP+Paclobutrazol	305	334	394 AB
	RootP+ProhexadioneCa	261	275	339 B
	p	NS	NS	0.007
Pruning weight (kg)				
	Control	30.5	38.0 AB	19.3 AB
	Paclobutrazol	27.9	30.2 AB	14.0 ABC
	ProhexadioneCa	34.3	44.7 A	20.0 A
	RootPruning	27.6	29.7 AB	14.3 ABC
	RootP+Paclobutrazol	22.4	26.3 B	11.3 BC
	RootP+ProhexadioneCa	20.0	25.8 B	9.9 C
	p	NS	0.0074	0.008

the absorbing roots were even more concentrated in the drip irrigation volume; thus, root pruning within a 10 cm difference was not enough to have a significant impact. Therefore, it is key to know where the main absorbing roots are located in order to estimate the percentage of absorbing roots that would be affected by the pruning. In addition, timing of root pruning can also affect vigor response. In our study, root pruning was performed in late winter, whereas higher vigor control would be attained if performed at bloom or later on the season. However, this was discarded in our conditions in order to not affect fruit set, already a limiting factor for pear growing in our area.

Applications of ProCa alone provided a growth reduction of ~18% in comparison to control trees. In previous studies, both root pruning and ProCa have been reported to reduce growth (Costa *et al.*, 2001; Elfving *et al.*, 2003; Maas, 2005; Smit *et al.*, 2005; Vercammen *et al.*, 2005; Asin *et al.*, 2007; Mitre *et al.*, 2012). Deckers *et al.* (2005) reported a strong growth control of ProCa on

Table 4. Effect of treatment on fruit quality such as fruit firmness (kg) and soluble solids (ºBrix), and return bloom (number of flower clusters per tree) on 'Blanquilla' pear at IRTA Gimenells. Grey bars represent variable value. Means within a column followed by different letters denotes significant differences among treatments (Tukey's honestly significant difference, $p \leq 0.05$). [NS]Non-significant at $p \leq 0.05$.

		Year 1	Year 2	Year 3
Firmness (kg)				
	Control	5.5 ABC	6.9	6.3
	Paclobutrazol	5.6 AB	6.8	6.3
	ProhexadioneCa	5.7 A	7.3	6.5
	RootPruning	5.3 BC	6.8	6.1
	RootP+Paclobutrazol	5.4 ABC	6.9	6.3
	RootP+ProhexadioneCa	5.3 C	6.7	6.0
	p	0.0028	NS	NS
SS (Brix)				
	Control	12.6	13.5	11.8
	Paclobutrazol	11.3	13.1	11.5
	ProhexadioneCa	12.5	13.0	11.7
	RootPruning	12.4	13.4	12.1
	RootP+Paclobutrazol	12.4	13.5	11.9
	RootP+ProhexadioneCa	12.2	13.4	11.6
	p	NS	NS	NS
Return bloom (Flower cluster #)				
	Control	54 AB	556 AB	134 AB
	Paclobutrazol	74 AB	634 A	134 AB
	ProhexadioneCa	23 C	465 B	86 B
	RootPruning	59 AB	567 AB	170 A
	RootP+Paclobutrazol	84 A	653 A	142 A
	RootP+ProhexadioneCa	41 BC	619 A	107 AB
	p	<0.0001	0.0057	0.003

'Doyenné du Comice', whereas the same treatment had a slight effect on 'Beurré Alexander Lucas'. These different responses may be due to different vegetative habits and vigor inherited by the cultivar, which may imply different behaviors. In our case, applications of ProCa on 'Blanquilla' had a good effect on growth control, but the effect of paclobutrazol was stronger. In a previous study, we observed shorter shoots when applying paclobutrazol in comparison with ProCa, but the effect was quicker when ProCa was applied (Asin & Vilardell, 2008). In addition, efficacy of paclobutrazol on growth control has been reported by Raese & Burts (1983) and Costa *et al.* (1995) in 'd'Anjou' and 'Blanquilla' pear orchards, respectively. However, there is scarcity of studies where both applications of paclobutrazol and ProCa are compared. Regarding that, Mouco *et al.* (2011) reported better growth control of paclobutrazol than ProCa in mango (*Magnifera indica* L.). In our study, combination of root pruning plus ProCa had a similar effect on growth control than paclobutrazol alone, whereas the combination of paclobutrazol plus root pruning provided the highest control, with ~86% or ~71% of the shoots shorter than 60 cm or 40 cm, respectively. This is the first time that we study the combination of root pruning with either paclobutrazol or ProCa. Carra *et al.* (2017) reported 69% reduction in shoot growth when ProCa was combined with root pruning at one side of the trees; however, no significant differences were observed when ProCa was applied alone.

Furthermore than growth control, we also assessed how the combination of these different strategies may affect yield and fruit caliper. Overall, there were no significant differences with control trees regarding yield, crop load or yield efficiency, but in some years trees that were treated with ProCa had less values than when the combination of root pruning plus paclobutrazol was used. In addition, there was one year in which trees treated with paclobutrazol had larger fruits than control trees or than when root pruning or ProCa alone were used. Carra *et al.* (2017) reported lower fruit weight when ProCa was applied together with root pruning, but no significant differences with control trees were reported when was applied alone. Conversely, Smit *et al.* (2005) reported smaller fruit size when ProCa was applied, most likely due to increased fruit set. No significant differences regarding fruit set were observed in our current study. In a previous study, no significant differences for ProCa *vs* control trees regarding fruit weight were observed, whereas in some years paclobutrazol sprays provided larger fruits than either control, root pruning, or ProCa alone (Asin & Vilardell, 2008).

In terms of fruit quality, none of the assessed strategies significantly affected either fruit firmness or soluble solids. Coinciding with our results, Southwick *et al.* (2004) and Maas (2008) did not see any effect of Proheaxdione-Ca or root pruning on fruit quality. Applications of paclobutrazol after petal fall have been suggested to improve fruit quality in apple (Greene, 1991). Elfving *et al.* (2003) reported ProCa to slightly affect fruit quality in 'Barlet' pears, but those changes disappeared after two months of air storage. Byers & Yoder (1999) reported very little if any effect of ProCa on fruit firmness, soluble solids, starch content or even cracking on apple trees.

There were differences regarding return bloom depending on the treatment. When comparing with control trees, root pruning did not affect return bloom. Application of paclobutrazol and paclobutrazol plus root pruning tended to have higher return bloom than control trees; however, no significant differences were observed. On the other hand, applications of ProCa did reduce return bloom in some years when comparing with control trees, and differences with root pruning plus paclobutrazol were always significant. Coinciding with our results, reduction of return bloom in pear orchards by application of ProCa has been reported in other studies (Sugar *et al.*, 2002; Gomand, 2003; Warnier, 2003; Asin *et al.*, 2005), and it seems to be related to the total amount of ProCa applied during the season in relation to the tree vigor. Risk to reduce return bloom seems to be related to high-dose application (Sugar *et al.*, 2002; Asin *et al.*, 2005; Deckers *et al.*, 2005). Nevertheless, there are some studies on pear in which no negative effects on return bloom were reported (Southwick *et al.*, 2004; Asin *et al.*, 2007). Furthermore, the trend that we observed that paclobutrazol increased return bloom has been reported in previous studies (Sansavini *et al.*, 1988; Rai & Bist, 1992; Asin *et al.*, 2007).

Combination of strategies for growth control is an interesting option in situations of vigorous orchards and/or cultivars. Williamson & Coston (1990) assessed the combination of root restriction and different levels of irrigation on a high-density peach orchard. Similar approaches have been performed in vineyards with the objective to enhance regulated deficit irrigation by combining it with cover crops (Lopes *et al.*, 2011). Tworkoski & Glenn (2010) assessed grass competition combined with pruning methods to evaluate their effects on growth and yield in a peach orchard. Maas (2008) studied the combination of root pruning and trunk incisions with applications of ProCa or Ethrel on a vigorous 'Conference' pear orchard. More recently, Carra *et al.* (2017) tested different configurations of root pruning in combination with ProCa.

In a three-year study, we assessed performance of strategies that included root pruning, application of either ProCa or paclobutrazol, and combinations of them. Overall, all the different strategies that were assessed improved growth control in pear trees, with different grade depending on the strategy. To get satisfactory results by solely performing root pruning, other than timing (winter *vs* full bloom for instance) understanding of the soil characteristics and how this affects root distribution is key. We did not assess different root pruning configurations in this experiment, but similar results were attained when comparing with previous studies where root pruning was performed closer to the trunk. In situations where the absorbing roots are very close to the irrigation volume, little differences were observed when cutting 40 cm to 30 cm from the trunk. Solely applications of ProCa reduced growth in comparison to control trees, with similar results than the root pruning. Thus, use of ProCa seems to be a good alternative to root pruning, with similar growth control and increased yield (>60 mm), and with less damage to the roots. Then, paclobutrazol alone or the combination of ProCa with root pruning increased the growth control, and the highest reductions were observed when paclobutrazol was applied in combination with root pruning. In addition, yield, crop load, yield efficiency, fruit weight and return bloom seemed to be more affected by applications of ProCa than paclobutrazol. Therefore, use of paclobutrazol either alone or in combination with root pruning, depending on the desired grade of growth control, seemed to be most suitable for situations of high-vigor cultivars, with trouble on their management. The fact that use of paclobutrazol may be challenged again in the future, leave combinations of root pruning plus ProCa as the best shot for vigorous cultivars. In other situations of medium-low vigor, ProCa alone would be the best strategy. Further research should address relations between the amount of absorbing roots that are cut and the affection it has, especially in combination with paclobutrazol and ProCa. In addition, timing of root pruning may play an important role not only on vigor control but on vegetative response and fruit set, hence, they should be addressed as well.

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