Effects of Rootstock, Tree Density and Training System on Early Growth, Yield and Fruit Quality of Blush Pear

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Abstract. Vegetative growth, orchard productivity, fruit quality and marketable yield were evaluated for rootstock (D6, BP1 and Quince A), tree density (741–4444 trees/ha), and training system (Open Tatura trellis, two-dimensional vertical and three-dimensional traditional) effects on young trees of the blush pear cultivar ‘ANP-0131’. ‘ANP-0131’ is a vigorous scion and vegetative growth, precocity, and yield were influenced by the selected rootstocks. Tree density and training system treatments exerted a substantial effect on canopy radiation interception while increasing tree density improved yield. Increasing tree density from 2222 (high density) to 4444 (ultra-high density) trees/ha did not improve cumulative yield. Crop load affected fruit size, such that “marketable” yield (yield of fruit weighing between 150 and 260 g) was greatest for trees on D6 rootstock and trained to Open Tatura trellis at high and ultra-high densities.

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for canning market production, they pose difficulties for orchardists producing high-quality fruit for the fresh market with an increasingly expensive and inexperienced workforce. Australia has no pear rootstock breeding program and limited, nonreplicated demonstration sites for a small number of rootstocks. Consequently, the ability of orchardists to choose precocious rootstocks suited to modern, high-density training systems and Australian conditions is limited. Use of dwarfing rootstocks, two-dimensional training systems, and high tree density are widely seen as the way of the future for pear orchard design. Reported benefits include: improved fruit quality, controlling vegetative vigor, simplifying pruning and harvest, enabling the use of picking platforms (or robotics), and decreasing the time to full production. Comparisons of training systems and tree densities for pears have been undertaken in South Africa, Canada, the United States, New Zealand, Europe, and Brazil, with different rootstocks available in these regions (Asin et al., 2005; du Plooy and van Huyssteen, 2000; Elkins and DeJong, 2002; Kappel and Brownlee, 2001; Lordan et al., 2017; Musacchi, 2011; Musacchi et al., 2005; Palmer, 2002; Pasa et al., 2015; Robinson, 2008; Robinson and Dominguez, 2015; Vercammen, 2011). No such studies have been undertaken in Australia.

The aim of this study was to evaluate growth, precocity, yield, and fruit quality of the blush pear cultivar ‘ANP-0131’ (Turpin et al., 2016) in response to rootstock, tree density, and training system in the Goulburn Valley, Australia. Rootstocks used were D6 (*Pyrus calleryana*), the most commonly used pear rootstock in Australia, BP1 (*Pyrus communis*), and Quince A (*Cydonia oblonga*). Graft incompatibility is a common problem with quince rootstocks (Webster, 2003) and consequently a ‘Beurre Hardy’ (*Pyrus communis*) interstem was used with Quince A. D6 is a vigorous rootstock, whereas BP1 and Quince A are considered semivigorous or semidwarfing (du Plooy and van Huyssteen, 2000; Stern et al., 2007; Webster, 2003). Quince rootstocks have been associated with increased precocity in some studies (Iglesias and Asin, 2011; Webster, 2003). Open Tatura trellis and two-dimensional vertical trellis systems (hereafter referred to as Vertical) were compared with more traditional, three-dimensional systems (hereafter referred to as Traditional) including vase and central-leader treatments. Four categories of tree density were used, ranging from “Low” (similar to that used for cannery pears) to “UltraHigh” treatments. This is the first study of this kind to be undertaken with blush pear ‘ANP-0131’ and the first comparison of planting systems for pears in Australia. This study reports early (to the fifth season after planting, year 5) vegetative growth, yield, and fruit quality responses to rootstock, training system, and tree density.

Materials and Methods

Study site. The site for the experiment was the Agriculture Victoria SmartFarm at Tatura

The Goulburn Valley in Victoria is the major pear production region in Australia, producing 85% of the nation's crop of 103,748 t in 2017–18 (ABS, 2019). Pear orchardists in Australia have faced market and production challenges over the last 15 years that caused a decline in production from 147,688 t in 2005 (ABS, 2019). Labor costs, drought (and subsequent low irrigation allocations), reductions in intake of pears by the local cannery, and a stagnant domestic market have contributed to this decline. Nowadays, ≈60% of the annual crop is sold on the fresh domestic market, 5% of the crop is exported fresh and the remainder is processed (mainly for juice). Despite the current circumstances, orchardists have begun to invest in plantings of blush and red pear cultivars with the aim of creating demand domestically and internationally, particularly in Asian markets. Early yields and fruit quality will be important factors determining returns on such investments (Stott et al., 2018; Tomkins, 2018).

Traditionally, pears in the Goulburn Valley were grown on trees trained as vase, planted at low tree density (6 × 6 m planting square) with D6 rootstock. While these production systems are considered appropriate

(36.44° S, 145.27° E; 114 m APSL) in the Goulburn Valley region of Victoria, Australia. The soil is a Red Sodosol (Isbell, 2002) known locally as a Lemnos loam (Skene and Poutsma, 1962). The region has a temperate climate with average annual rainfall of ≈ 480 mm. Annual average reference crop evapotranspiration (ET_0 , Allen et al., 1998) is ≈ 1190 mm (22-year mean, <http://www.longpaddock.qld.gov.au/silo/>).

Treatments and experimental design. ‘ANP-0131’ scions were grafted in Winter 2013 on three rootstocks (D6, BP1, and Quince A with ‘Beurre Hardy’ interstem) and planted in three training systems (Open Tatura trellis, Vertical, and Traditional) at four tree densities (Table 1). A split-plot randomized complete block design with three replicates of each treatment was used. Training systems were allocated to whole rows. Training systems were split into combinations of rootstock and tree density. Tree densities of 4444, 2222, 1482, and 1111 trees per hectare were compared in the Open Tatura trellis training system. Tree densities of 4444, 2222, 1111, and 741 trees per hectare were compared in the Vertical and Traditional training systems. Each plot was 14 m in length and consisted of a central measurement row with two guard rows. Corella and ‘ANP-0534’ trees were alternately planted between each plot in every row as pollinizers. Row orientation and spacing was north–south and 4.5 m, respectively. Soil preparation; nutrient and irrigation applications; and pest, disease, and weed management were the same for all treatments. Retractable overhead netting was installed in Winter 2015 and deployed after flowering until after harvest each season.

The Open Tatura trellis had a top-wire height of 2.5 m. The Vertical and Traditional training systems had a top-wire height of 3.8 m. Vase trees (Traditional training system at low tree density) were trained with six main branches, while the remaining Traditional systems had single leaders. Multileader trees had two apical buds rubbed from the scion in spring of the first season after planting (2013–14 growing season) to encourage multiple buds to burst and develop. Four- and two-leader trees were trained by allowing four or two shoots to grow from the scion and removing all other shoots during the spring and summer of the first season. Six- and eight-leader cordon systems were trained by thinning to two shoots in the first season, laying these down to form cordons along the lower wire during the second season (2014–15), and selecting shoots to form leaders in the second and third (2015–16)

seasons. Leaders in the Vertical and Open Tatura trellis systems were spaced 50 cm apart for all tree densities.

Measurements. Measurements were made in year 2 (2014–5), year 3 (2015–16), year 4 (2016–17), and year 5 (2017–18). Three or five trees (dependent on tree density) in the central row of each plot were used to record measurements of tree growth, yield, and fruit quality variables. Radiation interception was measured over the length of the central row, excluding pollinizers.

Tree growth. All vegetative material pruned from the measurement trees was collected and oven dried at 65 °C and then weighed. Prunings were collected from the start of year 2 to the end of year 5 (including winter pruning). Cross-sectional area of leaders was calculated from measures of leader circumference 10 cm from the base of the leader (at ≈ 0.4 -m height) and summed to give total leader cross-sectional area for each tree.

Canopy radiation interception. Canopy radiation interception was measured three times in a day at about monthly intervals during year 3, 4, and 5. Radiation interception was estimated from measurements of photo-synthetically active radiation (PAR) interception at solar noon and 3 h before and after solar noon using a combination of a handheld ceptometer (Sunfleck Ceptometer; Decagon, Pullman, USA) and a light trolley (Tranzflo, New Zealand) to capture the daytime dynamics of shade under the rootstock-training system-tree density treatments (Goodwin et al., 2006). The light trolley held 24 light sensors at 0.125-m intervals along a 3 m bar, 0.4 m aboveground-level on a wheeled base. A data logger (CR850, Campbell Scientific, Garbutt, Au) recorded measurements at 1-s intervals. Measurements of transmitted PAR (PAR_t) were made over the planting square of the central trees in each plot on clear sky days. The ceptometer and light trolley sensors were held horizontally below the canopy, perpendicular to the row direction, and moved at a slow walking speed with the ceptometer being used to measure PAR_t in those areas of the planting square not easily accessible to the light trolley. Unobstructed incoming PAR (PAR_i) was measured in an open area. Radiation interception was estimated as the mean value of intercepted PAR {i.e., $[1 - (PAR_t/PAR_i)]$ at solar noon, solar noon – 3 h, and solar noon + 3 h}. Measurements commenced 30–40 d after full bloom and mean seasonal radiation interception is presented.

Yield and fruit quality. Total yield and fruit number were determined by counting and weighing all fruit from the measurement

trees at harvest. In year 3, average fruit weight (grams fresh weight) was calculated from total yield and fruit number per tree. Thereafter, a commercial fruit grader equipped with optical sensors and a load cell (Compac InVision 9000, Compac Sorting Equipment Ltd, Australia) was used at harvest and individual fruit weight was measured. ‘Marketable’ yield was defined as the yield of fruit within the weight range 150–260 g. Fruit were harvested on 18 Feb. 2016 (149 DAFB, year 3), 8 Mar. 2017 (163 DAFB, year 4), and 28 Feb. 2018 (159 DAFB, year 5).

Fruit samples were taken at harvest for fruit quality and composition analysis (up to 10 fruit per measurement tree in 2016 and 10 fruit per plot in 2017 and 2018). Fruit diameter, weight, firmness, and soluble solids concentration (i.e., grams sucrose equivalents per gram juice expressed as percent) were measured on individual fruit. Fruit firmness was measured on two opposing cheeks with a penetrometer using an 8-mm probe. Soluble solids concentration was measured on expressed juice from two opposing cheeks using a digital handheld refractometer (Model PR-1; Atago Co. Ltd., Tokyo, Japan). Before destructive measurements, sampled fruit were visually assessed for blush (red peel) coverage, expressed as a percentage of fruit surface. All harvested fruit in year 4 and 5 were assessed for blush coverage by a RGB color sensor mounted on the grading line. Linear regression of visual and grader assessments of blush coverage showed strong agreement between the two methods [$\text{Blush coverage}_{\text{grader}} = 1.04 (\pm 0.057) \times \text{blush coverage}_{\text{visual}}$ (t pr. < 0.001) + 4.72 (± 2.81), (t pr. 0.099), $n = 73$, $P < 0.001$, $R^2 = 0.85$] over a large range of blush coverage (5% to 80% based on visual estimate).

Statistical analysis. Treatment differences were determined by ANOVA with Genstat 18.2 (VSN International Ltd., England, United Kingdom). Statistical significance of difference between any two treatments was assessed using Fisher’s unrestricted least significant difference at $P = 0.05$. Correlations between fruit quality variables and crop load indices and canopy radiation interception were determined with Genstat 18.2 (VSN International Ltd.).

Results

Tree growth and canopy radiation interception. Rootstock significantly affected tree growth and canopy radiation interception, independent of training system and tree density treatments. Trees on D6 were more vigorous than those on Quince A and BP1, as evidenced by significantly greater cumulative

Table 1. Description of training system and tree density treatments applied to ‘ANP-0131’ scions on three rootstocks (D6, BP1, and Quince A with ‘Beurre Hardy’ interstem).

Tree Density	Training system		
	Open Tatura trellis (Two-dimensional)	Vertical (Two-dimensional)	Traditional (Three-dimensional)
Low	Eight-leader cordon, 1111 trees/ha	Six-leader cordon, 741 trees/ha	Vase, 741 trees/ha
Moderate	Six-leader cordon, 1482 trees/ha	Four-leader, 1111 trees/ha	Central leader, 1111 trees/ha
High	Four-leader, 2222 trees/ha	Two-leader, 2222 trees/ha	Spindle, 2222 trees/ha
UltraHigh	Two-leader, 4444 trees/ha	One-leader, 4444 trees/ha	Slender spindle, 4444 trees/ha

pruning weights and total leader cross-sectional areas at the end of year 5 (Table 2). Likewise, canopy radiation interception during year 3, 4, and 5 was greatest for trees on D6 and lower for trees on Quince A and BP1 (Table 2).

Tree density and training system significantly affected vegetative growth parameters. Except for cumulative pruning weight, interactions occurred between training system and tree density treatments for vegetative growth parameters (F pr. < 0.001–0.011). Pruning weights tended to increase with increasing tree density (F pr. < 0.001) but did not differ significantly between training systems (F pr. = 0.125, Fig. 1). Overall, radiation interception peaked in the Open Tatura trellis UltraHigh treatments at 0.50 (Fig. 2). By contrast, the lowest radiation interception (0.23) occurred in the Vertical Low (i.e., six-leader cordon) treatment. Radiation interception of the Traditional Low treatments (i.e., vase; 0.27) was similar to that of Vertical Moderate (i.e., four-leader) and Traditional Moderate (i.e., central leader) treatments (0.28 and 0.29, respectively). The response pattern of total leader cross-sectional area differed in that it decreased with increasing tree density and was greatest in the Traditional Low treatment (i.e., vase; F pr. < 0.001, 0.013, and < 0.001 for tree density, training system, and training system $\times$ tree density, respectively, Fig. 3).

Yield and fruit number. Year 3 was the first season trees bore fruit. As expected with young trees, yields were low and many trees did not bear fruit. Mean fruit weight was “oversize” (greater than 260 g) in most treatments. In year 4, yields remained low (less than 11 t/ha in all treatments). In year 5, yields ranged from 17 to 74 t/ha.

Quince A rootstocks with a “Beurre Hardy” interstem increased precocity and yield. Differences in precocity were highlighted by absence of fruit in some plots in year 3. About one-third of plots with BP1 rootstock bore fruit in year 3, whereas 60% of the plots on D6 and 90% of plots on Quince A bore fruit. Cumulative yield was greatest for trees on Quince A, followed by trees on D6 (Table 3). The cumulative yield difference between Quince A and D6 treatments was largely established in year 3 and was due to significantly greater fruit numbers

in Quince A treatments each season. Fruit numbers, and consequently yield, of trees on BP1 were comparatively low each season. Some interactions occurred between rootstock and tree density treatments in year 3 and 5, mostly due to differences of magnitude of response.

Fruit number and, consequently, yield increased with increasing tree density in year 3 and 5 (Table 4). Moderate tree density treatments performed comparatively well in year 4 but yields were low overall and were only significantly different between Moderate and Low tree density treatments. Substantial differences in cumulative yield occurred with Low and Moderate tree density treatments producing 60% and 30% less yield, respectively, than UltraHigh tree density treatments. Cumulatively over the three seasons, yields of UltraHigh and High tree density treatments were similar. Training system did not significantly affect yield (Table 4). However, significant interactions occurred between training system and tree density for yield in year 4 and cumulative fruit number and yield. Notably, cumulative fruit number/ha in the Moderate tree density treatments was 35% and 45% lower in the Open Tatura trellis compared with the Vertical and Traditional training systems, respectively, whereas relative differences at Low (–5% and +15%), High (–20% and –10%), and UltraHigh (–5% and –10%) densities were less substantial.

Fruit weight and “marketable” yield in year 5. Overall, mean fruit weight was greater in treatments with D6 and BP1 rootstocks than those with Quince A rootstocks (F pr. < 0.001), and fruit weight decreased with increasing tree density (F pr. < 0.001) from Low to High treatments (Fig. 4). There was a tendency for greater fruit weights in Open Tatura trellis than Vertical or Traditional training systems; however, differences were not statistically significant. Interactions occurred between rootstock and tree density: rootstock responses were not significant in UltraHigh treatments and did not differ between BP1 and Quince A rootstock treatments with High and Moderate tree densities (F pr. = 0.01).

Overall, “marketable” yield (yield of fruit between 150 and 260 g) was greatest in D6 rootstock treatments (F pr. < 0.001) and Open Tatura trellis systems treatments (F pr. = 0.035) and lowest in the Low tree density treatments (F pr. = 0.002). “Marketable” yield was influenced by rootstock $\times$ tree density (F pr. = 0.002) and training system $\times$ tree density interactions (F pr. = 0.002). At Low tree densities,

trees on Quince A rootstock produced the best “marketable” yields, in part because D6 and BP1 treatments lost a proportion of fruit to oversizing (i.e., $\approx$ 30% of fruit were greater than 260 g vs. 1% of fruit from Quince A treatments). At Moderate, High and UltraHigh tree densities, D6 produced the best “marketable” yields. “Marketable” yields were similar for different training systems at Low and Moderate tree densities but were significantly better for Open Tatura trellis than Vertical and Traditional training systems at High and UltraHigh tree densities. D6 rootstock trained on Open Tatura trellis at High or UltraHigh tree densities resulted in the best “marketable” yields (46.0 and 47.9 t/ha, respectively). The impacts of treatment on fruit number and, subsequently, the yield, fruit weight and “marketable” yield responses are illustrated in Fig. 5.

Fruit quality in year 5. Overall, maturity (indicated by firmness) and sugar accumulation (indicated by soluble solids concentration) were advanced by BP1 compared with D6 and Quince A rootstocks, while in Low tree density treatments, maturity was delayed and sugar accumulation advanced compared with other tree densities (Table 5). Table 6 shows negative correlations between crop load (expressed as fruit number, fruit number normalized for leader cross-sectional area, or fruit number normalized for seasonal radiation interception) and fruit weight, fruit firmness and soluble solids concentration. These crop load indices—fruit quality relationships illustrate that under high crop loads, fruit maturity was advanced and fruit accumulated less sugar.

Blush coverage tended to decrease with increasing tree densities and tended to be highest with Quince A rootstocks (Table 5, Fig. 6). Interactions between training system and tree density occurred (F pr. $\leq$ 0.001) such that the greatest blush coverages were attained in the Vertical Low (51%), Open Tatura trellis Low (48%), and Vertical Moderate (48%) treatments, and the lowest blush coverages occurred in the Open Tatura trellis UltraHigh and Open Tatura trellis High treatments (33% and 36%, respectively). Interactions between rootstock and tree density for blush coverage occurred with Quince A rootstocks tending to have higher coverage in UltraHigh and High tree density treatments than D6 and BP1 rootstocks but similar blush coverage in Low and Moderate tree density treatments (F pr. = 0.002). Blush coverage was

Table 2. Effect of rootstock on vegetative growth parameters of ‘ANP-0131’. Pruning weight is cumulative dry weight for all pruning conducted from year 2 to winter following year 5. Total leader cross-sectional area is the sum of cross-sectional area of the leaders in year 5. Radiation interception is the average of fractional canopy radiation interception measured three times per day (solar noon $\pm$ 3 h) at monthly intervals throughout the season.

Rootstock	Pruning wt (kg/m of tree row)	Total leader cross-sectional area (cm ² /tree)	Radiation interception (yr 3)	Radiation interception (yr 4)	Radiation interception (yr 5)
D6	3.23	43.81	0.20	0.29	0.37
BP1	2.06	36.25	0.17	0.24	0.32
Quince A	2.29	32.90	0.18	0.27	0.33
F pr.	<0.001	<0.001	<0.001	<0.001	<0.001
LSD	0.41	3.67	0.01	0.02	0.01

Fig. 1. Effect of (A) training system and (B) tree density on pruning weight of 'ANP-0131'. Pruning weight is cumulative dry weight for all pruning material from year 2 to winter following year 5. Error bars represent least significant difference ($P = 0.05$).

Fig. 2. Effect of training system (OT = Open Tatura trellis, V = Vertical, T = Traditional) and tree density on seasonal radiation interception of 'ANP-0131' in year 3 (Yr 3), year 4 (Yr 4), and year 5 (Yr 5). Canopy radiation interception is the average of fractional canopy radiation interception measured three times per day (solar noon $\pm$ 3.5 h) at monthly intervals throughout the season. Error bars represent least significant difference ($P = 0.05$) for training system $\times$ tree density.

Fig. 3. Effect of training system and tree density on total leader cross-sectional area (LCSA, cm²) of 'ANP-0131' following year 5. Total LCSA is the sum of cross-sectional areas of the leaders. Error bar represents least significant difference ($P = 0.05$) for training system $\times$ tree density.

negatively correlated with radiation interception (Table 6).

Discussion

This study showed vegetative growth, yield, and fruit quality of 'ANP-0131' were affected by rootstock, tree density, and training system. Decisions made by orchardists regarding cultivar, rootstock, training system, and tree density have significant implications for the production potential of new orchards. Orchard design must be tailored to suit local conditions (Strydom and Cook, 2005). New blush cultivars, such as 'ANP-0131', provide an opportunity to revitalize the Australian pear industry and develop new markets, provided yields are economical and fruit quality meets the expectations of the

target market. Modeling by Stott et al. (2018), based on current orchard establishment and management costs, yields of 60–80 t/ha at maturity (sixth season after planting) and a (0% to 20%) price premium for blush pears, indicated that 'ANP-0131' planted at high densities would have a payback period of 7 to 11 years. In this study, 'ANP-0131' achieved yields in excess of 60 t/ha, in High and UltraHigh tree density treatments with D6 and Quince A rootstocks, in the fifth season after planting. "Marketable" yield (based on fruit weight) peaked at 46.0 and 47.9 t/ha for trees on D6 at High and UltraHigh tree density and trained to the Open Tatura trellis. Continued measurements at harvest are required to ascertain if these yields are sustainable over the life of the orchard.

Rootstocks clearly affected vegetative growth and precocity in this study. As expected, D6 proved to be the most vigorous rootstock for all measured vegetative parameters, whereas BP1 and Quince A showed little difference in vegetative vigor. In other studies, pears on BP1 were reported to be more vigorous (based on trunk circumference) than pears on Quince A (du Plooy and van Huyssteen, 2000; North and Cook, 2008; Stern et al., 2007; Stern and Doron, 2009), although strong initial growth of trees on quince rootstocks has been noted (Necas et al., 2015; North and Cook, 2008). Data collected in this study showed significantly greater extension growth of leaders for trees on Quince A and D6 than those on BP1 during year 1 (data not shown). In terms of yield (t/ha), trees on Quince A rootstocks outperformed those on D6 (in year 3 and 4 and cumulatively) and BP1 (year 3, 4, and 5 and cumulatively). Similarly, greater yields for trees on Quince A than more vigorous rootstocks (including BP1) were reported for 'Forelle' (du Plooy and van Huyssteen, 2000) and 'Conference' (Iglesias et al., 2004; Iglesias and Asin, 2011). Unlike du Plooy and van Huyssteen (2000), Iglesias et al. (2004), and Iglesias and Asin (2011), we did not observe greater fruit weight in response to Quince A rootstocks. By contrast, North and Cook (2008) reported no difference in fruit number and yield of 'Forelle' on BP1 and Quince A in the first 2 years of production. Stern et al. (2007) reported lower cumulative yields for trees on Quince A than on BP1 with no evidence of increased precocity resulting from the use of quince rootstocks; at a cooler site, cumulative yield differences between trees on Quince A and BP1 became nonsignificant, but remained large (equivalent to 74 t/ha over six seasons; Stern and Doron, 2009). BP1 cannot be recommended for use as a rootstock under conditions similar to those in this study due to comparatively poor yields (Table 3). Furthermore, trees on BP1 in this and other experimental blocks at the site appear to be more susceptible to water stress and waterlogging than those on alternative rootstocks. While some responses to rootstock in this study were consistent with other studies, there were also contrasts. Whether this is entirely due to environmental conditions, or if the material sold as (for example) BP1 in Australia is genetically different to that available in other regions is unknown. Regardless, the contrasting results highlight the value of evaluating the rootstocks and scions available to orchardists in the regions they are to be grown in.

Increasing tree density increased yield (t/ha) from young pear trees, as has been shown previously (Pasa et al., 2015; Robinson 2008). Cumulatively, Low and Moderate tree density treatments reduced yield by 42 and 21 t/ha, respectively, compared with the UltraHigh tree density treatments (Table 4). In a comparison of single-leader training systems, Robinson (2008) found a positive quadratic relationship between cumulative yield (t/ha) of young trees (third and fourth seasons after planting) and

Table 3. Effect of rootstock and rootstock × tree density on fruit number and yield of ‘ANP-0131’.

Treatment	Yr 3		Yr 4		Yr 5		Cumulative	
	Fruit number (1000 s/ha)	Yield (t/ha)	Fruit number (1000 s/ha)	Yield (t/ha)	Fruit number (1000 s/ha)	Yield (t/ha)	Fruit number (1000 s/ha)	Yield (t/ha)
D6	6.375	1.8	5.104	0.9	318.366	50.8	329.845	53.5
BP1	1.284	0.4	5.396	0.9	276.224	40.9	282.904	42.2
Quince A	29.457	7.4	22.698	3.5	397.913	53.9	450.068	64.8
F pr.	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
LSD	7.107	1.5	9.175	1.2	37.380	4.5	40.827	5.3
D6 Low	0.027	0.01	2.266	0.51	101.668	22.6	103.961	23.1
BP1 Low	0	0	3.278	0.6	93.358	19.9	96.636	20.5
QA Low	3.786	1.09	4.988	1.1	241.907	39.1	250.681	41.3
D6 Moderate	1.029	0.32	6.395	1.26	305.424	51.2	312.848	52.7
BP1 Moderate	0.790	0.24	11.342	1.98	243.342	36.9	255.474	39.1
QA Moderate	14.782	4.19	36.667	5.25	330.584	46	382.033	55.5
D6 High	10.321	2.84	5.037	0.85	440.691	66.7	456.049	70.4
BP1 High	1.383	0.43	5.086	0.92	375.506	52.3	381.975	53.6
QA High	27.259	8.14	26.716	4.17	501.136	63.3	555.111	75.6
D6 UltraHigh	14.123	3.97	6.716	1.02	425.679	62.8	446.518	67.8
BP1 UltraHigh	2.963	0.77	1.877	0.28	392.691	54.5	397.531	55.6
QA UltraHigh	72.000	16.03	22.42	3.54	518.025	67.1	612.445	86.7
F pr.	<0.001	<0.001	0.41	0.426	0.506	0.037	0.556	0.122
LSD	14.213	2.98	18.350	2.414	74.7594	9.04	81.654	10.56

tree density. Longer-term evaluation of that experiment showed that cumulative yield (t/ha) 11 years after planting and net income were greatest for tree densities of 2243/ha or 5382/ha, depending on cultivar, and lowest for trees at low density spacings (598/ha; Robinson and Dominguez, 2015). Likewise, in this study, yield increased with increasing tree density, but increasing tree number from 2222/ha to 4444/ha did not significantly improve year 4, year 5, or cumulative yield (Table 4). A weaker scion/

rootstock combination than those used in this study (i.e., a tree that will be slow to fill its allotted space even at “High” tree densities) may improve yields at tree densities greater than 2222/ha, but for ‘ANP-0131’ the added cost of doubling the number of trees could not be justified. Seasonal radiation interception of trees planted in the Low tree density treatments was 20% to 40% less than trees in the Ultra-High tree density treatments, depending on training system, in year 5 (Fig. 2). Trees in the

High and UltraHigh tree density treatments could suffer yield or fruit quality losses in the future due to excessive shading. Management of lateral shoots, to ensure adequate light distribution throughout the canopy and replacement of ageing shoots, will be key to longer-term productivity of these systems. In any case, as trees in the Low and Moderate tree density treatments fill their space and reach full bearing, the radiation interception and annual yield differences between these and higher tree density

Table 4. Effects of training system, tree density and training system × tree density on fruit number and yield of ‘ANP-0131’.

Treatment	Yr 3		Yr 4		Yr 5		Cumulative	
	Fruit number (1000 s/ha)	Yield (t/ha)	Fruit number (1000 s/ha)	Yield (t/ha)	Fruit number (1000 s/ha)	Yield (t/ha)	Fruit number (1000 s/ha)	Yield (t/ha)
Open Tatura	10.852	2.7	6.360	1.2	296.794	48.3	314.006	52.2
Vertical	8.540	2.4	10.455	1.7	356.363	49.5	375.358	53.6
Traditional	17.724	4.4	16.382	2.5	339.346	47.8	373.452	54.7
F pr.	0.417	0.349	0.431	0.452	0.428	0.934	0.456	0.924
LSD	17.9195	3.531	19.326	2.662	117.1587	13.25	139.781	17.46
Low	1.271	0.4	3.511	0.7	145.644	27.2	150.426	28.3
Moderate	5.534	1.6	18.134	2.8	293.117	44.7	316.785	49.1
High	12.988	3.8	12.280	2.0	439.111	60.8	464.379	66.5
UltraHigh	29.695	6.9	10.337	1.6	445.465	61.5	485.497	70.0
F pr.	<0.001	<0.001	0.061	0.033	<0.001	<0.001	<0.001	<0.001
LSD	8.206	1.721	10.594	1.394	43.1624	5.22	47.143	6.1
OT. Low	0.412	0.13	1.506	0.35	153.284	28.1	155.202	28.6
V. Low	0.631	0.2	4.115	0.91	157.476	28.9	162.222	30
T. Low	2.771	0.76	4.911	0.95	126.173	24.6	133.855	26.4
OT. Moderate	1.514	0.39	3.786	0.73	211.819	38.6	217.119	39.7
V. Moderate	0.741	0.23	11.086	2.05	317.802	46.4	329.629	48.7
T. Moderate	14.346	4.13	39.531	5.7	349.728	49	403.605	58.8
OT. High	8.296	2.45	11.358	2.01	398.963	61.2	418.617	65.7
V. High	16.395	4.78	13.778	2.03	485.383	63	515.556	69.8
T. High	14.272	4.17	11.704	1.9	432.988	58.1	458.964	64.1
OT. UltraHigh	33.185	8	8.79	1.55	423.111	65.1	465.086	74.7
V. UltraHigh	16.395	4.34	12.84	1.87	464.79	59.8	494.025	66
T. UltraHigh	39.506	8.43	9.383	1.42	448.494	59.6	497.383	69.4
F pr.	0.135	0.065	0.066	0.046	0.088	0.178	0.02	0.018
LSD	19.153	3.853	22.1087	2.986	118.7269	13.61	139.716	17.54
LSD-TS	14.213	2.98	18.35	2.414	74.759	9.04	81.654	10.56

LSD-TS = least significant difference when comparing means with the same level of training system.

Fig. 4. Effect of rootstock, training system (OT = Open Tatura trellis, V = Vertical, T = Traditional), and tree density (Low, Mod = Moderate, High and UH = UltraHigh) on (A) fruit weight and (B) "marketable" yield (yield of fruit between 150 and 260 g) of 'ANP-0131' in year 5. Error bars represent least significant difference ($P = 0.05$) for rootstock $\times$ training system $\times$ tree density.

treatments are expected to lessen. However, in the initial bearing years, the establishment of multileader cordon and vase tree training systems (Open Tatura trellis Low and Moderate, Vertical

Low and Traditional Low treatments) will lead to yield penalties due to low fruit numbers.

Similar to increasing tree density, the canopy arrangement in Open Tatura trellis

treatments increased radiation interception (15% to 48% in year 5) and hence, production potential compared with the Vertical and Traditional treatments. However, yield (t/ha) improvements were not realized. This contrasts with comparisons of Y-type or Tatura trellis systems and vertical training systems (e.g., Vertical axe and slender spindle) using young 'Conference' trees. Kappel and Brownlee (2001) showed that a Y-trellis doubled radiation interception and resulted in significantly greater yields and lower fruit size. Asín et al. (2005) reported greater yields from Tatura trellis systems and similar fruit size. In both cases, the maximum cumulative difference was 20 t/ha three (Kappel and Brownlee, 2001) and four (Asín et al., 2005) seasons after planting. Later evaluation showed trees on Tatura trellis cumulatively yielded 40 t/ha more than trees at the same density trained to a vertical axis 10 seasons after planting (Lordan et al., 2017). Notwithstanding the lack of statistically significant main effects of training systems for yield and yield parameters in this study, there was a tendency for lower fruit numbers and higher fruit weights in Open Tatura trellis compared with Vertical and Traditional training systems. In year 5, "marketable" yield was improved by

Fig. 5. Yield, fruit weight and "marketable" yield responses to fruit number/ha showing main treatments of rootstock (A–C), training system (D–F), and tree density (G–I) in year 5.

Table 5. Main effects of rootstock, training system and tree density on fruit maturity (firmness), soluble solids concentration (SSC), and blush coverage of ‘ANP-0131’ in year 5 (2017–18 season).

Treatment	Firmness (kgf)	SSC (%)	Blush coverage (%)
D6	5.3	13.1	42
BP1	5.1	13.8	42
Quince A	5.2	13.3	45
F pr.	0.004	<0.001	0.007
LSD	0.1	0.2	2
Open Tatura	5.4	13.6	40
Vertical	5.1	13.3	46
Traditional	5.1	13.2	43
F pr.	0.043	0.28	0.057
LSD	0.2	0.6	5
Low	5.5	13.7	47
Moderate	5.2	13.1	46
High	5.0	13.2	40
UltraHigh	5.1	13.4	40
F pr.	<0.001	<0.001	<0.001
LSD	0.1	0.2	3

Fig. 6. Effect of rootstock, training system (OT = Open Tatura trellis, V = Vertical, T = Traditional), and tree density (Low, Mod = moderate, High, UH = UltraHigh) on blush coverage of ‘ANP-0131’ fruit in year 5. Error bars represent least significant difference ($P = 0.05$) for rootstock × training system × tree density.

Table 6. Correlations between fruit quality parameters of ‘ANP-0131’ in year 5 (2017/18 season) at harvest and crop load indices [fruit/ha, fruit/tree normalized for total leader cross-sectional area (LCSA), fruit/ha normalized for seasonal radiation interception] and seasonal radiation interception at the plot scale ($n = 108$).

Fruit quality	Fruit/ha	Fruit/tree/ LCSA	Fruit/ha/Radiation interception	Radiation interception
Firmness (kgf)	−0.51	−0.42	−0.58	−0.04
Soluble solids concentration (%)	−0.48	−0.52	−0.54	−0.03
Blush coverage (%)	−0.21	0.16	0.05	−0.65
Fruit weight (g)	−0.87	−0.71	−0.89	−0.23

Open Tatura trellis when yield was lost in High and UltraHigh tree density treatments of Vertical and Traditional training systems due to undersizing of fruit.

Robinson (2008) and Palmer (2011) warned that increases in yield need to be balanced against decreases in fruit size that have been observed in association with the higher crop loads of some multileader and high-density systems. In this study, small fruit size was associated with higher fruit numbers. Orchardists aim for fruit size between 150 and 260 g for ‘ANP-0131’. Consideration of “marketable” yield on this basis showed that fruit size was compromised by both low and high fruit numbers. While Quince A rootstocks increased early production in this study, high fruit numbers in year 5 contributed to lower “marketable” yields of fruit compared with trees on D6 in Moderate to

UltraHigh tree density treatments, due to decreased fruit size. Additionally, Open Tatura trellis High and UltraHigh treatments supported a combination of moderate to high fruit numbers and adequate fruit size, such that “marketable” yield was greater in these treatments than all other training system × tree density combinations. In practical terms, this means orchardists would need to thin fruit at least in some seasons to ensure target fruit weights are reached. Conversely, ‘ANP-0131’ has demonstrated an ability to considerably “oversize” fruit when fruit numbers are low; the largest fruit weight recorded during this study was 509 g (from a D6 Open Tatura trellis Low plot in year 5). Interventions, such as application of plant growth regulators (to improve fruit set) and deficit irrigation (to control fruit size), may be required in some seasons to avoid loss of

marketable production due to excessive fruit growth. ‘ANP-0131’ on D6 will be more likely to require such interventions while trees on Quince A will be more prone to requiring fruit thinning. These results demonstrate the importance of managing crop load for ‘ANP-0131’; continued monitoring as trees reach full production would enable identification of appropriate cropping levels.

Target ranges for firmness and soluble solids concentration of 5.4–4.7 kgf and 13% to 16%, respectively, are suggested for harvest of ‘ANP-0131’ (HIN a,b). Orchardists aim for a minimum blush coverage of 20%. Differences in quality parameters were statistically significant (Table 5) but mean firmness and soluble solids concentration fell within the target ranges for most treatments at harvest in year 5. Mean blush coverage exceeded the minimum target in all treatments. Recent studies undertaken at Tatura indicate that light is required for development of red color in ‘ANP-0131’ (Peavey et al., 2020). The negative correlation between blush coverage and radiation interception in year 5 (Table 6) was most likely due to difference between treatments in light extinction and suggests that the fraction of radiation intercepted over the planting square was a reasonable proxy for fruit exposure to light.

Conclusions

Orchardists seeking to maximize yield of the new blush pear cultivar ‘ANP-0131’ should consider high density (≈ 2200 trees/ha) plantings on D6 or Quince A/Beurre Hardy rootstocks. Quince A/Beurre Hardy rootstocks produce fruit earlier and set fruit well, but the high crop loads increase the likelihood of needing thinning intervention to ensure adequate fruit size. Conversely, in years with low fruit set, trees may lose “marketable” yield due to oversizing of fruit. BP1 is not recommended due to lower yield potential.

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