Tree Architecture and Development of New Growing Systems

Project No.: **20-HORT30-Thorp (COC)**

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A. SUMMARY

Almond orchards of the future will need to be more efficient, with more cost effective and sustainable growing and harvesting systems. A multi-year program of collaborative research, started in Australia in 2014 and in California in 2016, has been researching almond tree architecture and the development of advanced production systems. Led by Dr Grant Thorp from The New Zealand Institute for Plant and Food Research Limited (PFR), the main collaborators in California were Dr Tom Gradziel and Dr Bruce Lampinen from University California (UC), Davis, Dr Gurreet Brar from California State University (CSU), Fresno, and Burchell Nursery. This is the final report to the Almond Board of California (ABC), for project work completed in California during the period March 2017 to December 2020.

Research described in this report was intended to contribute to the debate around orchard intensification for the almond industry. A key strength of the research has been that new trials in California and Australia were planted using different combinations of scion cultivars and rootstocks, including new highly productive self-fertile cultivars recently released from local breeding programs. New growing concepts were tested with these novel genotypes, including working with central leader trees planted at high density and narrow-pruned to eliminate any branches that, if left, would ultimately become large scaffold branches growing into the center of the rows.

A full report of the related Australian studies can be downloaded from the Hort Innovation website (https://www.horticulture.com.au/growers/help-your-business-grow/research-reports-publications-fact-sheets-and-more/al14007/).

Research undertaken in California covered three objectives:

1. **Tree architecture**. Here the objective was to work with almond breeders to develop techniques to accelerate the identification, breeding and commercialization of almond varieties suitable for high density orchards.
2. **Pruning responses**. Two projects were established to optimize pruning systems for commercial high density planting systems using current and future almond varieties.
3. **Trunk girdling**. In this small project we wished to optimize the use of trunk girdling to reduce the time taken for young almond trees to produce their first commercial crop.

Architectural studies aimed to describe the deficiencies in current cultivars in terms of tree architecture and to identify architectural traits that would be desirable in high density growing systems. Our ambition was to encourage a shift in breeding targets to place more emphasis on traits associated with tree architecture and productivity. While shell and kernel quality are important breeding targets for almonds, as are self-fertility, delayed flowering and pest and disease tolerance, our belief is that new cultivars stacked with architectural traits associated with high productivity will enable a step change in productivity and almond grower profits.

Our research model was that new cultivars will naturally form narrow, upright tree canopies, providing the right fruiting platform for high productivity, with low/minimal cost, in high density orchards. We confirmed that the natural growth habit (tree architecture) of trees in breeding populations can easily be observed in years 1 and 2. Our suggestion is that it would accelerate the breeding pipeline if trees with negative architectural traits were eliminated before the trees produced their first crop.

In the course of this research both quantitative and qualitative attributes were identified for breeders to use when screening breeding populations in their first- or second-leaf for desired architectural traits for high density growing systems. Implications for designing a screening program included:

- Seedlings from breeding populations growing on their own roots typically show large variation in vigor, which is not seen in commercial trees on clonal rootstocks. It would make the breeding pipeline more efficient if all breeding progeny were budded and evaluated on clonal rootstocks.
- A compact, upright tree with excurrent branching would be easier to manage in high density blocks than trees with wide, spreading canopies and decurrent branching. These differences are obvious within the first two years of growth.
- First-leaf trees in the nursery show a range of branching habits typical for each variety. Desired attributes for central leader trees would be to have uniform branching, evenly distributed along the trunk, as tends to happen with ‘Nonpareil’ and BA2 (Shasta®). This could be screened for in first and second-leaf trees.

- While strong axillary shoot production is important to increase the number of potential fruiting sites, these shoots (dards) need to be robust enough to survive in low light conditions and sustain high productivity. This attribute can be identified in second-leaf trees.
- Strong branching from terminal and subterminal buds can produce long barren sections of wood; this undesirable habit can be observed in second-leaf trees.
- Uniform extension of the central leader is desired at the transition zone between one growth flush and the next; compared with poor central leader development caused by dominant axillary branching or weak terminal bud development. These differences can be seen in first- and second-leaf trees.

Our research also considered the cropping potential of young almond trees and the negative effect that high yields can have on tree structure causing the collapse of young fruiting canopies. This risk of canopy collapse is especially evident with some new high yielding cultivars. While growers may want to sacrifice early yields by severe pruning in order to obtain stronger fruiting canopies, our research demonstrated alternative strategies. These included planting unpruned, central leader trees and managing these trees with combinations of leader-release pruning on new trees and minimal dormant and in-season pruning of 2- and 3-year-old trees, to help produce stronger fruiting canopies without compromising yield. Following this method, kernel yields from third leaf trees ranged from 1.1 to 1.9 kg of kernel per tree for the different pruning treatments. These yields are the equivalent of 1.09 and 1.87 t/ha for the model planting system in this trial (2.3 x 4.6 m spacing, 945 trees per ha). It will take another four harvests to confirm the long-term benefit of these growing systems and range of cultivars and genotypes.

Trunk girdling was also evaluated as a mechanism to further increase cropping on young trees. These treatments did not increase kernel yield but did reduce tree vigour which could ultimately be useful as an alternative to growth reducing rootstocks.

B. RESEARCH OBJECTIVES

The Australian and Californian almond industries are undergoing a period of rapid growth with the establishment of new orchards and conversion of existing orchards over to new cultivars and rootstocks. This is an ideal time to take a fresh look at almond orchards and to challenge current paradigms around almond production and harvesting.

Almonds tend to be grown in traditional low density “large tree” orchard systems, with high vegetative vigour, poor light distribution and low partitioning of resources to fruiting. Tree architecture in these crops is poorly understood, leading to relatively unsophisticated canopy management. The objective of research described here was to provide growers with the knowledge, tools and confidence to intensify their orchard operations and to focus on more efficient and sustainable use of both capital and natural resources.

Standard planting regimes and management systems are based on orchards with approximately 350 trees per ha (142 trees per acre). In these orchards, trees are trained to produce multiple large scaffold branches that form a fully covered, closed canopy by Year 7. Growers are reluctant to change planting systems as this means changing orchard machinery. Smaller trees, with narrow fruiting canopies, planted closer together within and between rows, are likely to be more suitable for orchard intensification than traditional systems. With this in consideration, the model planting system we used in our studies consisted of free-standing trees planted at 2.3 x 4.6 m spacing and 945 trees per ha (7.5 x 15 ft spacing and 387 trees per acre).

Key objectives of our studies were:

1) **Tree architecture:** To develop techniques to accelerate the identification, breeding and commercialization of almond varieties with architectural features associated with high productivity in high density orchards.
2) **Pruning responses**: To optimize pruning systems for commercial high density plantings systems using current and future almond varieties.
3) **Trunk girdling:** To optimize use of trunk girdling to reduce the time taken for almond trees to produce their first commercial crop.

C. RESEARCH PROJECTS

1. Tree Architecture

In commercial tree fruit production, architectural features are typically modified by pruning and training to suit a particular growing system or orchard design. These modifications can commence in the nursery or when the young tree is first planted in the orchard. For example, almond trees generally exhibit a strong basitonic growth habit, producing a set of very large scaffold branches near the base of the trees. Growers promote this natural growth tendency by cutting the trunks of young trees back to 90 cm to stimulate the formation of these large scaffold branches. With heavy cropping varieties this can result in unstable fruiting canopies that require considerable pruning and training to maintain productivity. While this growth habit is suited to current large-tree growing systems, it is not suited to more intensive small-tree growing systems. Our objective has been to work with almond breeders and develop techniques that will help them to accelerate identification, breeding and commercialization of new almond varieties better suited to high density orchards than current varieties.

1.1. Materials and methods

In a series of short-term studies we characterized desirable architectural traits in current and future almond varieties, starting with “unpruned” trees in their first leaf budded onto clonal rootstocks.

Trees were planted in February 2018, with a range of standard commercial varieties planted alongside a number of advanced selection genotypes from the UC Davis and Burchell breeding programs, which had been identified to have an upright dard type growth habit with numerous side shoots similar to the variety ‘Winters’. The following 14 genotypes were included:

i) 'Nonpareil' Control -— diffuse branching
ii) 'Winters' Control — dard type
iii) 'Monterey' Control — zonal, horizontal branching
iv) Shasta® Burchell variety — diffuse branching, upright habit
v) Pyrenees® Burchell variety — moderate spur type
vi) Lassen™ Burchell advanced selection — diffuse branching
vii) X4-5E Burchell advanced selection — diffuse branching
viii) UCD 1-232 UC Davis variety — dard type, cascading growth habit
ix) UCD 8-201 UC Davis variety — upright dard type
x) A05, 11-60 UC Davis advanced selection — vigorous upright spur type
xi) A06, 3-542 UC Davis advanced selection — upright dard type
xii) A07, 2-292 UC Davis advanced selection — upright dard type
xiii) A05, 8-69 UC Davis advanced selection — upright spur type
xiv) A04, 5-252 UC Davis advanced selection — compact upright dard type.

All trees were budded on container grown 'Cornerstone' rootstock in June 2017 and field planted in February 2018 in a high density block with trees at 2.3 x 4.6 m spacing and 945 trees per ha (7.5 x 15 ft spacing and 387 trees per acre). There were five replicates of two trees each per genotype extending across five rows, with 30 trees per row (150 trees) in a randomized complete block design. Each row included one pair of trees per genotype.

Tree management

All trees were planted as largely unpruned, central leader trees. The only pruning had been to create a clean trunk 60–70 cm high with no side branches, after which the trees were left to develop for 2 years without further pruning so that the true natural growth habit of each genotype could be observed.

Tree dimensions

Before planting in February 2018, we recorded a range of architectural traits for 10 trees of the six UC Davis advanced selections, one Burchell advanced selection and 'Nonpareil' and 'Winters' as controls. Traits measured included tree height, number of axillary shoots, trunk diameter of the rootstock below the graft and diameter of the scion above the graft at the first extended internode, at the mid-point along the trunk and near the apex of the plant at the last extended internode.

A new device was constructed to record the flexural rigidity (tensile strength or bending stiffness) of young trees still in the nursery with the ambition that this might be useful to identify genotypes with branches that easily bend under the weight of the developing crop. Flexural rigidity was measured as the kilograms force (kgf) required to achieve a 45° bend in the trunk. Pressure was measured using an Imada ZTA Digital Force Gauge (www.imada.com). A device was developed based on a three-point fulcrum with the tree being held in place at the lower two points and the Imada pressure gauge applied at the upper point with pressure applied at right angles to the stem until a 45° angle was obtained.

Obviously, large diameter stems required more pressure to bend than small diameter stems so trunk diameter was used as a co-variate in analyses. Plotting flexural rigidity against the possible covariates, there appeared to be a good overall relationship between trunk diameter above the base of the bud union and flex. Analysis was carried out using Genstat version 17 (2014, VSNi Ltd, Hemel Hempstead, UK). Data are presented as the original means and standard errors (SE), and as the covariate-adjusted means with a LSD (least significant difference).

Tree height and trunk diameter (at 50 cm) from all 14 genotypes were recorded in January 2019, when the trees had been in the orchard for 12 months. Tags were attached to the primary growth axis (trunk) and to a single axillary scaffold branch on each tree to mark the transition point at the base of the 2018 season's extension growth. Each tagged branch usually included two or three sections of new growth. Basal diameter and length of each tagged branch and the number of axillary shoots and flowers were recorded in February and March 2019, and the number of fruit per branch counted in May 2019 to give percent fruit set. In May 2019, we also recorded data from the tagged scaffold branch, including the growth stage at each node recorded as either 2 = 2018 shoot; 3 = dormant bud; 4 = leafy spur; or 5 = new shoot..

A prototype rating system based on these quantitative data was also developed to provide a qualitative description of the propensity for each genotype to produce a strong central leader. Key attributes included: dominance of the trunk; number, length, diameter and orientation of scaffold branches; and number, length and diameter of sylleptic dard shoots and proleptic subterminal shoots. Dards are mainly sylleptic axillary shoots that develop at the same time as the parent shoot; they are generally located along the lower to mid-section of the parent shoot. Subterminal shoots are mainly proleptic axillary shoots that develop after a period of rest; they are generally clustered near the terminal bud on the parent shoot. These data were collected in February 2019 as observational data, with a single value obtained from observations of five pairs of trees per genotype.

Unless otherwise indicated, analyses were completed using analysis of variance with Minitab® v18.1. Percentage data were arcsin transformed for analysis and then back-transformed for presentation.

2020 Harvest data

The first crops were hand harvested from these trees during August and September 2020 with the crop from each replicate of 2 trees combined (n = 5). Total fresh weight of whole fruit (hull + shell + kernel) was recorded. A subsample of approximately 2 kg was then taken for each replicate and weighed prior to hulling and shelling to determine kernel yield. Moisture content of the kernel was measured in approximately 10 g of kernel using an Ag-IQ Handheld Almond Moisture Meter Ver: 2020.4 (Ag-IQ, Australia). Kernel yield data were then converted to kg of kernel at 5% moisture content per tree.

Data on whole fruit yield, kernel yield and moisture content were analysed using analysis of variance with Minitab® v18.1 and mean separation by Tukey's pairwise comparison method. Harvest data were sqrt transformed for analysis and then back-transformed for presentation.

1.2. Results and discussion

In the course of this research both quantitative and qualitative attributes were identified for breeders to use when screening breeding populations. Examples of these data that can be collected from unpruned, first- and second-leaf trees budded on clonal rootstocks are described below.

In the nursery, before planting, trees were approximately 1.0 m tall, ranging from 0.7 m for genotype A04, 5-252 to 1.36 m for A05, 8-69 (Table 1). Trunk diameter at the first extended internode above the bud union ranged from 6.9 mm for genotype A04, 5-252 to 10.2 mm for 'Nonpareil'. The most obvious difference between the varieties was in the number of axillary dard-type shoots formed above 60 cm on the trunk (shoots below this point had been removed during the propagation process). While some genotypes had relatively few shoots per tree (<6), for example A04, 5-252 and Pyrenees®, others had several axillary shoots (up to 18), for example A06, 3-542, A05, 11-60 and 'Winters'.

Table 1. Tree height and trunk diameter of the scion at the first extended internode above the bud union, and number of axillary shoots above 60 cm on the trunk of almond trees in the Tree Architecture trial at Burchell Nursery, Fowler. The trees were budded in June 2017 onto 'Cornerstone' rootstock and grown as central leader trees at Burchell Nursery, Fowler. Tree data were recorded in December 2017. Values are averages for each genotype (n = 10). Means within columns followed by the same letter were not significantly different.

Genotype	Tree height (m)	Trunk diameter (mm)	No. of axillary shoots
A04, 5-252	0.70 d	6.9 e	4.4 c
A05, 11-60	1.07 c	8.9 c	17.0 a
A05, 8-69	1.36 a	8.6 c	9.6 b
A06, 3-542	1.19 b	9.9 a	17.5 a
A07, 2-292	1.19 b	8.6 c	11.7 b
'Nonpareil'	1.18 b	10.2 a	5.7 c
Pyrenees®	1.15 b	9.7 ab	4.0 c
'Winters'	1.20 b	9.1 bc	16.4 a
Least significant difference	*0.049*	*0.508*	*1.710*
p-value	*<0.001*	*<0.001*	*<0.001*

Flexural rigidity

A useful range of values for flexural rigidity were recorded among the genotypes measured, ranging from 4.9 kgf for the genotype A05, 8-69 to 1.2 kgf for 'Winters' (Table 2). Whether this range proves to be significant in the mature tree and shows up as a difference in stature of the mature cropping trees remains to be seen.

The ultimate use of this measurement technique is to screen large groups of individuals in breeding populations to identify undesirable individuals with stem flex below a minimum threshold value. This would involve measuring the basal stem diameter (above the graft union) and the flexural rigidity of every individual and then using the relationship between these two attributes to correct the flex values. These adjusted values could then be used to eliminate individuals with flex below a (yet to be determined) minimum flex threshold value.

Table 2. Flexural rigidity (kgf) of almond trees in the Tree Architecture trial at Burchell Nursery, Fowler. Trees were budded in June 2017 onto 'Cornerstone' rootstock and grown with a single trunk. Tree data were recorded in December 2017. Original values were also adjusted using stem thickness of the scion at the first extended internode above the bud union as a covariate. Values are averages for each genotype ± SE (n = 10).

	Flexural rigidity (kgf)	
Genotype	**Original values**	**Adjusted values**
A05, 8-69	4.7 ± 0.37	4.9
A05, 11-60	2.5 ± 0.19	2.6
'Nonpareil'	2.3 ± 0.23	1.9
Pyrenees®	2.0 ± 0.16	1.7
A06, 3-542	1.8 ± 0.12	1.4
A07, 2-292	1.5 ± 0.15	1.7
'Winters'	1.2 ± 0.09	1.2
Least significant difference	*0.6*	*0.6*
p-value	*<0.001*	*<0.001*

Further data were collected during 2019 from the 14 genotypes to record tree growth and branching in January, flowering in February/March, and fruit set in May. A05, 252 trees were among the smallest in height, trunk diameter, central leader extension and length of tagged axillary branches, and 'Nonpareil' trees were among the tallest, with the largest trunk diameter, longest central leader extension and longest axillary branches (Table 3). The number of flowers on the central leader extension ranged from 3 to 46 flowers per shoot on A05, 11-60 and A06, 3-542, respectively. A06, 3-542 also had the highest number of flowers on their axillary shoots, more than double the number recorded on the other genotypes, indicating high production potential (precocity) on these young trees. Fruit set percent was variable, ranging from 9% to 95% set on the central leader extension and from 6% to 64% set on the axillary shoots. In many, but not all instances, fruit set was higher on the central leader extension than on the axillary branch.

Table 3. Tree and branch dimensions and flowering/fruit set on 2-year-old central leader almond trees in the Tree Architecture trial at Burchell Nursery, Fowler. Ten trees of each genotype were budded on 'Cornerstone' rootstock in June 2017 and planted as unpruned, central leader trees in January 2018. Tree and branch dimension data were collected in January 2019, with flowering recorded in March and fruit set in May 2019. Values are averages for each genotype (n = 10). Significance: ** = p<0.01; *** = p<0.001. Means within columns followed by the same letter were not significantly different.

Genotype	Tree height (m)	Trunk diameter (cm)	Central leader[1] extension (m)	Axillary branch[1] length (cm)	No. of flowers on central leader extension	No. of flowers on axillary branch	Fruit set (%) on central leader extension	Fruit set (%) on axillary branch
A05, 11-60	1.98 bcd	3.6 ab	1.01 ab	96 ab	3 c	2 b	19 cd	17 bc
A06, 3-542	2.04 abcd	3.5 ab	1.04 ab	71 abc	46 a	34 a	29 cd	27 bc
A07, 2-292	2.46 ab	3.6 ab	1.10 ab	101 ab	16 bc	5 b	59 abc	53 abc
A05, 8-69	2.40 ab	2.9 bc	1.08 ab	85 ab	18 bc	5 b	18 cd	22 abc
A04, 5-252	1.26 e	2.5 c	0.56 b	43 c	17 bc	2 b	9 d	25 abc
'Nonpareil'	2.54 a	3.8 a	1.51 a	113 a	14 bc	3 b	31 cd	20 abc
Pyrenees®	2.17 abc	3.4 ab	1.27 ab	69 abc	27 ab	11 b	82 ab	64 ab
'Winters'	1.56 de	3.3 ab	0.87 ab	72 abc	8 bc	8 b	38 cd	37 abc
Shasta®	2.34 abc	3.3 ab	1.04 ab	92 ab	19 bc	7 b	59 abc	42 abc
'Monterey'	1.88 cd	3.2 abc	0.95 ab	67 bc	16 bc	5 b	49 bcd	66 ab
X4-5E	2.01 bcd	3.8 a	1.00 ab	72 abc	16 bc	12 b	29 cd	6 c
Lassen™	2.24 abc	3.6 ab	1.21 ab	87 ab	14 bc	3 b	43 bcd	48 abc
UCD 1-232	2.32 abc	3.8 a	1.19 ab	93 ab	31 ab	8 b	74 ab	71 a
UCD 8-201	2.00 bcd	3.8 a	0.59 b	63 bc	26 abc	16 ab	95 a	44 abc
Significance	***	***	**	***	***	***	***	***
p-value	*<0.001*	*<0.001*	*0.004*	*<0.001*	*<0.001*	*<0.001*	*<0.001*	*<0.001*

[1] The central leader extension is the 2018 extension of the trunk; the selected axillary branches were located on the trunk below this point.

Working again with the 14 genotypes, four of the these (A05, 11-60, A06, 3-542, A07, 2-292 and 'Winters') had relatively high numbers of 2018 axillary shoots on the tagged scaffold branches, compared with the other genotypes (Table 4).

Overall, % budbreak on the tagged scaffold branches ranged from 59 to 91% for A04, 5-252 and Shasta® trees, respectively. Shasta® had high % budbreak because it produced a high number of leafy buds and only a moderate number of new shoots (Tables 4). The tagged scaffold branch on the A04, 5-252 trees had low percent budbreak, with unusually low numbers of leafy spurs, but the branches were relatively short with few nodes. 'Nonpareil' trees were among the tallest trees and had the most nodes in the orchard, 1 year after planting (Table 3), but they had the highest number of buds that remained dormant which reduced the overall percent budbreak for this cultivar (Table 3).

Qualitative data collected from 2-year-old trees of all genotypes using an informal rating protocol gave the highest ratings to UCD 8-201 and A06, 3-542 and the lowest to Pyrenees® (Table 5). UCD 8-201 and A06, 3-542 both had strong ratings for central leader development, with medium vigour upright scaffold branching, moderate numbers of short to medium dards and subterminal shoots that were relatively few in numbers and did not dominate the branch.

Table 4. Number of shoots, leafy spurs and dormant buds on axillary branches of 2-year-old central leader almond trees in the Tree Architecture trial at Burchell Nursery, Fowler. Ten trees of each genotype were budded on 'Cornerstone' rootstock in June 2017 and planted as unpruned, central leader trees in January 2018. Data were collected in May 2019 from one 2018-season branch per tree. Values are averages for each genotype (n = 10). Significance: ** = p<0.01; *** = p<0.001. Means within columns followed by the same letter were not significantly different.

Genotype	2018 shoots	Dormant buds	Leafy spurs	New axillary shoots	Total nodes	Budbreak (%)[1]
A05, 11-60	14.4 ab	18.2 b	22 cd	21 ab	76 abc	75 cd
A06, 3-542	16.1 a	11.6 bc	27 bc	10 b	65 abcd	85 abc
A07, 2-292	3.3 abc	14.1 bc	46 ab	14 ab	87 ab	83 abc
A05, 8-69	2.8 d	11.9 bc	34 bc	18 ab	67 abcd	84 abc
A04, 5-252	1.6 d	15.4 bc	6 d	14 ab	37 d	59 d
'Nonpareil'	5.1 bcd	35.3 a	30 bc	27 ab	97 a	63 d
Pyrenees®	22.2 cd	9.6 bc	39 bc	10 ab	60 abcd	85 abc
'Winters'	7.7 abcd	14.3 bc	20 cd	13 ab	54 bcd	76 bcd
Shasta®	2.4 d	8.6 bc	63 a	13 ab	87 ab	91 ab
'Monterey'	1.9 d	9.3 bc	31 bc	17 ab	60 abcd	86 abc
X4-5E	2.4 d	4.9 c	31 bc	22 ab	60 bcd	91 a
Lassen™	1.0 d	12.0 bc	39 b	26 ab	78 abc	84 abc
UCD 1-232	1.4 d	9.3 bc	34 bc	30 a	74 abcd	88 abc
UCD 8-201	5.3 bcd	4.9 c	21 cd	14 ab	45 cd	89 abc
Significance	***	***	***	**	***	***
p-value	*<0.001*	*<0.001*	*<0.001*	*0.002*	*<0.001*	*<0.001*

[1] % budbreak was determined as sum of leafy spurs and shoots produced per total number of nodes per branch

Table 5. Rating protocol for qualitative description of central leader trunk development and branching on 2-year-old almond trees in the Tree Architecture trial at Burchell Nursery, Fowler. Ten trees of each genotype were budded on 'Cornerstone' rootstock in June 2017 and planted as unpruned, central leader trees. Data were collected in February 2019, as observational data with a single value obtained from observations of 10 trees per genotype. Attributes were rated from 1 to 3 with 1 regarded as undesirable and 3 as desirable. Values are the single rating score for each genotype.

	Trunk	**Scaffold branches**				**Axillary shoots (current year)**						
	Central leader (dominance)	Vigour (length)	Strength (diam)	Number (count)	Orientation (angle)	Dards[1] (count)	Dards[1] (length)	Dards[1] (diam)	Subterminal shoots[2] (count)	Subterminal shoots[2] (length)	Subterminal shoots[2] (diam)	
Rating scale: **Genotype**	1-weak 2-mod 3-strong	1-long 2-med 3-short	1-weak 2-strong 3-med	1-few 2-med 3-many	1-horizontal 2-upright 3-compact	1-few 2-many 3-med	1-long 2-short 3-med	1-weak 2-med 3-strong	1-many 2-med 3-few	1-long 2-short 3-med	1-weak 2-med 3-strong	**Rating index[3]**
A05, 11-60	1	1	3	2.5	1.5	3	2.5	1	2	3	1	1.7
A06, 3-542	3	3	2	3	1	2	2.5	2	0	-	-	2.3
A07, 2-292	2	2	2	2	1	3	2.5	2	2.5	2.5	2	2.1
A05, 8-69	2	2.5	1	1	1	3	1.5	2	0	-	-	1.7
A04, 5-252	1	3	2	2	2	1	3	3	3	3	3	2.0
'Nonpareil'	2	1	3	2	1.5	1	2	1	3	3	1	1.9
'Pyrenees®'	1.5	2	3	2	1	0	-	-	0	-	-	1.2
'Winters'	1	2	3	2	2	2	3	1	3	3	2	1.9
Shasta®	2	1	3	2	1.5	1	3	2	3	1.5	2	2.0
'Monterey'	2	1	3	3	2	0	-	-	2	3	1	1.9
X4-5E	2	2	2	3	1	0	-	-	3	2.5	3	2.0
Lassen™	1.5	3	2	3	2	1	3	1	0	-	-	1.8
UCD 1-232	2	1	2	3	1.5	1	2	2	3	1.5	2	1.9
UCD 8-201	3	3	3	2	2	2.5	2.5	2	3	2.5	1	2.6

[1] Dards are mainly sylleptic axillary shoots that develop at the same time as the parent shoot; they are generally located along the lower section of the parent shoot

[2] Subterminal shoots are mainly proleptic axillary shoots that develop after a period of rest; they are generally clustered around the terminal bud on the parent shoot

[3] Rating index is sum of rating values for the trunk, average of values for scaffold branches and average of values for axillary shoots, then dividing by three to give an overall score for that genotype

2020 Harvest

Kernel yields in 2020 ranged from Shasta® and UCD 1-232 trees producing more than 1.7 kg/tree (1.7 t/ha) to A04, 5-252 trees producing 0.33 kg/tree (0.31 t/ha) (Table 6). This was the first crop to be harvested from these trees. It will take another four harvests to obtain meaningful data on the productive potential of these almond varieties and novel genotypes and back-correlate them with data presented here on the architectural features of 1- and 2-year-old trees.

Table 6. Fresh weight of whole fruit (hull + shell + kernel), kernel moisture content and kernel yield per tree of almond trees in the Architectural Studies trial at Burchell Nursery, Fowler. Trees were budded in spring (May) 2017 on container-grown 'Cornerstone' rootstock and planted in Winter (January) 2018 at 2.3 x 4.6 m spacing (945 trees per ha). Trees were planted with a central leader and then left without pruning. Values are genotype averages ± SE (n = 5 groups of 2 trees each). Means within columns followed by the same letter were not significantly different.

Genotype	Fresh weight (kg/tree)	Kernel moisture (%)	Kernel weight (kg/tree)[1]	Kernel weight (t/ha)
Shasta®	7.56 ± 1.1 a	4.5 ± 0.2	1.76 ± 0.32 a	1.67 ± 0.26 a
UCD 1-232	7.16 ± 0.7 a	4.2 ± 0.2	1.73 ± 0.12 a	1.63 ± 0.11 a
UCD 8-201	5.81 ± 1.0 abc	4.5 ± 0.2	1.55 ± 0.28 a	1.47 ± 0.26 a
X4-5E	6.79 ± 0.5 ab	4.3 ± 0.2	1.45 ± 0.14 ab	1.37 ± 0.14 ab
A05, 8-69	6.13 ± 0.8 abc	4.3 ± 0.2	1.41 ± 0.19 ab	1.34 ± 0.18 ab
'Winters'	5.27 ± 0.5 abc	4.4 ± 0.2	1.39 ± 0.13 ab	1.31 ± 0.12 ab
A07, 2-292	5.40 ± 0.9 abc	4.4 ± 0.2	1.27 ± 0.21 ab	1.20 ± 0.19 ab
'Nonpareil'	5.59 ±0.9 abc	4.1 ± 0.1	1.21 ± 0.17 ab	1.14 ± 0.16 ab
Lassen™	4.62 ± 0.8 abc	4.3 ± 0.1	1.18 ± 0.30 ab	1.11 ± 0.29 ab
'Monterey'	4.11 ± 1.0 abc	4.0 ± 0.1	1.04 ± 0.25 abc	0.98 ± 0.24 abc
A05, 11-60	4.37 ± 0.5 abc	4.5 ± 0.1	1.00 ± 0.12 abc	0.95 ± 0.11 abc
A06, 3-542	3.17 ± 0.6 bcd	4.3 ± 0.2	0.81 ± 0.16 abc	0.77 ± 0.15 abc
'Pyrenees'	2.56 ± 0.3 cd	4.4 ± 0.1	0.56 ± 0.07 bc	0.53 ± 0.07 bc
A04, 5-252	1.16 ± 0.2 d	4.3 ± 0.2	0.33 ± 0.05 c	0.31 ± 0.05 c
Significance	***	*NS*	***	***
p-value	*<0.001*	*0.756*	*<0.001*	*<0.001*

[1] Kernel yield data adjusted to 5% moisture content

1.3. Concluding comments

A range of architectural traits were investigated in this research for their suitability as selection criteria when breeding for high productivity in new almond cultivars planted in high density orchards. The question was, is it possible, from the growth of 1-year-old trees in the nursery and the development of tree structure and bearing capacity of 2- and 3-year-old trees in the orchard, to predict the growth habit and ultimate cropping potential of the mature tree? Our data indicated that, with some provisos, this is possible.

In addition to the data presented here, field observations indicated that the production of too many sylleptic axillary shoots (dards) could be regarded as a negative trait, especially when this shoot type is thin and sensitive to cold and dry conditions (Figure 1). On the other hand, numerous, strong dards that remain productive in low light conditions would be a very positive trait in a new cultivar.

Figure 1. Poor (left) and strong (right) survival rate and productivity of axillary shoots (dards).

The alternative situation, where trees produce relatively few axillary shoots with growth dominated by long, vigorous subterminal proleptic shoots competing with the central leader, would also be a negative trait, especially as this can result in long barren sections of wood with no axillary growth (Figure 2).

Figure 2. Strong branching from terminal and subterminal buds can produce long barren sections of wood; this undesirable habit can be observed in second-leaf trees.

2. Pruning responses

In this project we established two trials at the Burchell Nursery in Fowler to evaluate a range of pruning methods suitable for growing almond trees planted at high density. The first trial was with Shasta®, a new self-fertile cultivar with an upright growth habit. The second trial involved a combination of existing cultivars available to growers and advanced genotypes from the UC Davis and Burchell Nursery breeding programs.

2.1. Shasta® Pruning Responses trial

2.1.1. Materials and methods

In this project we evaluated five pruning treatments on Shasta® trees spring budded onto field grown seedling 'Nemaguard' rootstock and planted at Fowler in February 2018 (Year 1) in a high density block with trees at 2.3 x 4.6 m spacing and 945 trees per ha.

Five experimental pruning treatments were applied:

i) **Control — narrow prune:** Trees headed back in the nursery to 90 cm (3 ft) and all side shoots cut back to 2 buds before planting in February 2018, then narrow pruned in June 2018 (Year 1), and again in January and May 2019 (Year 2).

ii) **Central leader — narrow prune:** Planted in February 2018 (Year 1) as central leader trees, then narrow pruned in June 2018, and again in January and May 2019 (Year 2).

iii) **Central leader — bare pole Year 1**: Planted in February 2018 (Year 1) as central leader trees with all side shoots cut back to 2 buds, then narrow pruned in January and May 2019 (Year 2).

iv) **Central leader — bare pole Year 2**: Planted in February 2018 (Year 1) as central leader trees, then narrow pruned in June 2018. In January 2019 (Year 2) all side branches were cut back to 4 cm (1.5 in) followed by a single narrow prune in May 2019.

v) **Central leader — hedging:** Planted in February 2018 (Year 1) as central leader trees, then narrow pruned in May 2019 (Year 2).

There were eight experimental blocks of three trees each per pruning treatment extending across four rows with 30 trees per row (120 trees) in a randomized complete block design with each pruning treatment represented twice in each row. Either one or two trees at the ends of each row were included as guard trees.

Tree management

All trees were pruned to remove low branches forming below 70 cm (2.3 ft) on the trunk and provide future access for tree shakers. In many instances with the central leader treatment trees we found that several subterminal shoots developed immediately below the terminal shoot, creating congestion and restricting growth of the terminal shoot and thus extension of a strong central leader. Leader release pruning was therefore employed to avoid this congestion. Leader release pruning involved application of a heading cut approximately 8 cm (3 inches) below the terminal bud. This heading cut was placed so that it forced the growth of a single strong lateral bud on the windward side of the trunk to take over extension growth as the central leader. Any existing lateral shoots that had formed 15–20 cm (6–8 in) below the point of this heading cut were also cut back to two or three buds. All pruning treatments also included narrow pruning either in Year 1 or Year 2. This involved use of a battery powered hedge trimmer and/or pruning shears to cut back all shoots growing out towards the centre of the row. This treatment was applied to all trees in all rows to ensure that an open alleyway could be maintained with the narrow rows employed in this high density trial.

Tree dimensions

With COVID-19 travel restrictions in 2020 we were not able to record tree dimensions for this project.

2020 Harvest data

Trees were hand harvested on 24 August 2020 and the crop from each replicate of three trees combined (n = 8). Whole fruit yield, kernel yield and moisture content data were recorded and analysed as described previously.

2.1.2. Results and discussion

No significant differences in fresh weight of whole fruit, kernel moisture content and kernel yield per tree were recorded between pruning treatments with trees in their third leaf (Table 7). Yields ranged from 1.1 to 1.9 kg of kernel per tree for the different pruning treatments, which is equivalent to 1.09 and 1.87 t/ha. The bare pole treatments were of interest as this pruning technique resulted in side branches forming at a flatter, more horizontal angle than branches on the unpruned treatment trees. It will take another four harvests to confirm the long-term return from this set of pruning treatments applied to young Shasta® trees.

Table 7. Fresh weight of whole fruit (hull + shell + kernel), kernel moisture content and kernel yield per tree of Shasta® almond trees in the Shasta® Pruning Responses trial at Burchell Nursery, Fowler. Trees were budded in spring (May) 2017 on 'Nemaguard' rootstock and planted in Winter (January) 2018. Values are replicate averages ± SE (n = 8).

Treatment (3rd leaf trees)	**Fresh weight (kg/tree)**	**Kernel moisture (%)**	**Kernel (kg/tree)[1]**
Control – narrow prune	6.80 ± 0.9	4.6 ± 0.2	1.88 ± 0.4
Central leader – hedging	5.43 ± 0.8	4.6 ± 0.1	1.42 ± 0.3
Central leader – narrow prune	5.38 ± 0.6	4.4 ± 0.2	1.33 ± 0.2
Central leader – bare pole Year 2	4.99 ± 0.4	4.5 ± 0.1	1.28 ± 0.2
Central leader – bare pole Year 1	4.55 ± 0.6	4.6 ± 0.1	1.10 ± 0.2
Significance	*NS*	*NS*	*NS*
p-value	*0.219*	*0.730*	*0.249*

[1] Kernel yield data adjusted to 5% moisture content

2.2. Novel Genotypes Pruning Responses trial

2.2.1. Materials and methods

Eleven genotypes, budded in June 2017 on container grown 'Cornerstone' rootstock, were planted at the Burchell Nursery, Fowler, in February 2018 in a high density block with trees at 2.3 x 4.6 m spacing and 945 trees per ha with one genotype per row. The genotypes included:

'Nonpareil'	Control — diffuse branching
'Winters'	Control — dard type
'Monterey'	Control — zonal branching, weeping habit
Shasta®	Burchell variety — diffuse branching, upright habit
Pyrenees®	Burchell variety — moderate spur type
Lassen™	Burchell advanced selection — diffuse branching
UCD 1-232	UC Davis variety — dard type, cascading growth habit
UCD 8-201	UC Davis variety — upright dard type
A06, 3-542	UC Davis advanced selection — upright dard type
A07, 2-292	UC Davis advanced selection — upright dard type
A04, 7-180	UC Davis advanced selection — upright dard type.

Three experimental pruning treatments were applied from Year 2:

i) **Central leader — narrow prune**: Planted in February 2018 (Year 1) as central leader trees, then narrow pruned in January and May 2019 (Year 2).

ii) **Central leader — bare pole**: Planted in February 2018 (Year 1) as central leader trees, then all side shoots cut back to 2 buds in January 2019 (Year 2) followed by a single round of narrow pruning in May 2019.

iii) **Central leader — scaffold branches**: Planted in February 2018 (Year 1) as central leader trees. A set of strong scaffold branches were then selected in January 2019 (Year 2) and excess new shoot growth removed during the subsequent summer.

Pruning treatments were applied to groups of three trees each with three groups per genotype for each of the three pruning treatments (nine trees per treatment). The trial extended across 11 rows (one genotype per row) with 27 trees per row (297 trees) in a randomized complete block design along each row. External rows and one tree at the ends of each row were included as guard trees.

Tree management

As before, all trees were pruned to remove branches forming below 70 cm (2.3 ft) on the trunk to provide future access for tree shakers. Leader release pruning was also applied during Year 1 to promote extension of the terminal shoot to form a strong central leader, and as indicated trees were narrow pruned in Year 2.

Tree dimensions

Observational field notes were taken in May 2018, during the first year of growth, to describe qualitatively tree vigour, branching density and shoot types, and ease of promoting extension growth of the trunk as a central leader.

These observational data were backed up by quantitative data recorded in December (winter) 2018, after a full season's growth. To do this, trees were marked to indicate the transition zone on the trunk between the original planted tree height and the extension of the trunk (primary growth axis) during the 2018 growing season. Measurements included tree height when planted, extension of the trunk beyond the transition zone, and height to the first axillary shoot (branch). Length of branching zone was calculated as the difference between total tree height and height to the first branch. Trunk diameters were measured at 50 cm (15 in) and at points immediately below and above the transition point. The number of primary shoots growing directly from the trunk were counted below and above the transition zone and branching density was calculated as the number of shoots per m of branching zone on the trunk. Tree dimension data were analysed using analysis of variance with Minitab® v18.1 and mean separation by Tukey's pairwise comparison method.

2020 Harvest data

Trees were hand harvested during August and September 2020 and the crop from each replicate of three trees combined (n = 3). Whole fruit yield, kernel yield and moisture content data were recorded and analysed as described previously.

Results and discussion

Key observations in 2018 were that with some of the genotypes the young trees were relatively easy to grow/train as a central leader tree with a uniform tree response and minimal pruning requirements. Examples of this were 'Shasta®' and UCD 8-201 (Figure 3). In contrast, some genotypes were difficult to train/grow as central leader trees mainly due to dieback of the terminal shoot, strong competition from axillary shoots growing from subterminal positions below the terminal shoot and/or dominance of thin dard-type shoots. Examples of this were 'Winters' and the three advanced selections: A06, 3-542; A07, 2-292; and A04, 7-180.

Note that the advanced selections from UC Davis included in this trial were chosen because they exhibited relatively upright trunk growth and also had strong dard-type shoot growth as with the 'Winters' variety. All are self-fertile and have good shell and kernel quality (T. Gradziel, personal communication).

Figure 3. Observations of tree growth and pruning responses of 11 almond varieties and advanced selections growing on 'Cornerstone' rootstock, planted at Burchell Nursery, Fowler in February 2018 and trained as a central leader tree. Observations were made in May 2018.

Genotype:	Tree growth and pruning responses:
'Nonpareil' 	▪ Moderate to vigorous tree ▪ Strong lateral shoots and few dard-type shoots ▪ Some issues with congestion (several shoots forming from subterminal buds restricting growth of terminal shoot) when growing central leader from terminal. No subsequent congestion develops once central leader is well established. ▪ Use of lateral shoot to take over as central leader, when required, has worked well but requires additional staking to re-orientate this shoot into a vertical position ▪ Uniform tree response along the row ▪ Easy to develop/maintain central leader
'Monterey' 	▪ Moderate to strong tree ▪ Practically no dard-type shoots on the central trunk or on the lateral shoots ▪ Vigorous terminal and lateral shoot growth including from subterminal buds on the central terminal shoot which creates a lot of competition restricting extension of the central terminal shoot ▪ Relatively difficult to develop central leader if need to cut back the central leader terminal shoot because it has become congested by strong subterminal growth ▪ Uniform tree response along the row ▪ Moderately easy to develop central leader if subterminal lateral shoots are removed at an early stage

Genotype:	Tree growth and pruning responses:
'Winters' 	▪ Moderate to weak tree ▪ Unusually high number of fine/thin dard shoots which appear to devigorate the terminal shoot ▪ There can also be an issue with numerous subterminal lateral shoots creating congestion at the base of the terminal shoot ▪ Frequent shoot dieback on terminal and axillary shoots ▪ Variable tree response along the row ▪ Extremely difficult to develop/maintain central leader growth
Shasta® 	▪ Vigorous tall narrow tree with strong terminal shoot to form central leader ▪ Moderate to high number of dard-type shoots that are initially thin but then fill out to become strong axillary shoots to give the appearance of a narrow upright tree ▪ Moderately strong lateral shoots growing from subterminal buds near the base of the terminal bud/shoot. These need to be removed to promote extension of the central terminal shoot ▪ Uniform tree response along the row ▪ Very easy to develop/maintain central leader
Pyrenees® 	▪ Moderately vigorous tree with strong lateral shoots that tend to be dominant and form a strong lower tier of branches ▪ Pronounced bud development at nodes produced during early spring. Few dard-type shoots are formed. Longer lateral shoots become decurrent (curved downwards) ▪ Most trees have central leader formed from a terminal bud/shoot, in rare occasions a lateral shoot needs to be used as a replacement ▪ Variable response along the row in terms of dominance/vigor of lateral shoots, a central leader is generally visible but may not have strong dominance over lateral growth ▪ Moderately difficult to develop/maintain central leader because of strong lateral growth further down trunk

Genotype:	Tree growth and pruning responses:
Lassen™ Burchell Nursery 	▪ Moderately vigorous tree with generally strong terminal shoot growth to form central leader ▪ Moderate to weak dard-type shoot growth. Very pronounced bud development at nodes produced during early spring but more dard-type shoot development at nodes produced later in spring ▪ Some issues with lateral shoots creating congestion around the base of the terminal shoot with loss of vigor to give tree an appearance of compact growth ▪ Lateral shoots are also strong and well positioned for one to take over as central leader if needed ▪ Moderately uniform tree response along the row ▪ Moderately difficult to develop/maintain central leader with strong axillary shoot growth from the pronounced buds on the spring flush wood
UCD 8-201 (UC Davis) 	▪ Vigorous tall narrow tree with very strong trunk growth ▪ Few to moderate number of dard-type shoots with most lateral shoot growth forming from subterminal buds near the base of the terminal bud/shoot. This gives the appearance of a narrow upright tree ▪ Some remedial pruning required to remove lateral shoots causing congestion around the base of the terminal shoot but not a big issue ▪ Very few examples of where a lateral shoot has been required to replace a terminal shoot as a central leader ▪ Uniform tree response along the row ▪ Very easy to develop/maintain central leader
UCD 1-232 (UC Davis) 	▪ Vigorous tree ▪ Relatively few dard-type shoots but moderately strong laterals so not as compact as UCD 8-201 ▪ Maintaining the central leader formed from a terminal bud/shoot requires cutting laterals further back down the tree. Congestion from subterminal buds is not a major issue with this genotype ▪ Growth is strong from the terminal bud but difficult to form a new central leader from lateral shoots with few examples of where this has worked ▪ Generally uniform response along the row apart from instances where central leader has been lost and a new one has been needed. ▪ Easy to develop/maintain a central leader from a terminal bud/shoot but a lot more difficult if have to use a lateral shoot

Genotype:	Tree growth and pruning responses:
A04, 7-180 (UC Davis) 	▪ Moderately vigorous tree ▪ Numerous dard-type shoots with moderate vigor ▪ Requires pruning to remove subterminal shoots and promote growth of terminal shoot to become the central leader ▪ Moderate vigor terminal bud that has often failed, giving a variable response along the row ▪ Difficult to develop as a central leader tree
A06, 3-542 (UC Davis) 	▪ Moderately vigorous tree ▪ Very high intensity of dard-type shoots that are thin and wiry as observed on mature cropping trees. Some shoot dieback as with ‘Winters’ ▪ Better tree structure/vigor than ‘Winters’ so easier to develop/form a central leader with no congestion from subterminal buds but not a strong trunk ▪ Lateral shoots quickly become decurrent so central leader needs support to become dominant ▪ Variable tree response along the row ▪ Difficult to develop/maintain central leader, even more difficult to main vertical aspect of central leader if developed from lateral shoot, requires staking and training
A07, 2-292 (UC Davis) 	▪ Moderate to vigorous tree ▪ Weak to moderate dard-type shoots that become moderately weak lateral shoots ▪ Strong terminal bud but this is congested with 3–4 strong subterminal buds becoming strong lateral shoots which have to be removed to enable extension of the central terminal shoot ▪ Often have dieback of the terminal shoot so need to cut back to promote new lateral shoot to become central leader ▪ Variable tree response along the row ▪ Difficult to form central leader tree due to frequent dieback of terminal shoot and congestion at the growth interval.

In support of the observational data summarised in Figure 3, we also quantified some key architectural traits associated with tree development, branching frequency and in particular ease of management as narrow, central leader trees.

Average tree height when planted in the orchard block ranged from 0.88 to 1.18 m for A04, 7-180 and 'Monterey', respectively (Table 8). Shasta® trees produced the strongest central leader extension, contributing 1.54 m to total tree height of 2.61 m by December. 'Winters' trees had among the smallest central leader extension growth and were the smallest trees with 1.44 m total tree height by December.

At the end of the first year's growth the genotypes A04, 7-180; A06, 3-542; A07, 2-292; and Shasta® had among the largest trunk diameters above and below the central leader transition zone (Table 8). These four genotypes had also produced unusually high numbers of axillary shoots along the primary growth axis of the trees (Table 9). A06, 3-542 and A04, 7-180 also had the highest branching density (number of axillary shoots per m of branching zone). Note that while we observed that 'Winters' trees also had unusually high numbers of fine/thin dard shoots in May (Figure 3), it appears that many of these shoots did not persist until December (Table 9).

These quantitative data in Tables 8 and 9 are consistent with the observational data collected in May and presented in Figure 3. As such, they are a means by which trunk vigor, branching density and potential ease of central leader management can be quantified in a format that breeders and growers can use with young trees to identify varieties with a natural tendency or tree architecture to be easily grown as narrow, central leader trees suitable for high density planting systems.

Comparing the observational data from 2-year-old, unpruned trees in Table 5, with observations from 1-year-old pruned trees in Figure 3, revealed interesting pruning responses. While UCD 8-201 trees developed a strong central leader with or without pruning, it was not so clear with A06, 3-542. Even with pruning, it was difficult to promote/maintain a strong central leader on the 1-year-old A06, 3-542 trees. However, when left unpruned it appeared that the trees would naturally select the strongest axillary shoot to become the dominant vertical shoot in Year 2. One-year-old Shasta® trees were also easily managed to develop a strong central leader, but this dominance was not so evident in the unpruned, 2-year-old unpruned trees. Pyrenees® trees were interesting because they produced very few axillary shoots along the scaffold branches on young trees, which made it difficult to develop/maintain a central leader (Figure 3) and lowered their overall rating in Table 5.

A05, 8-69 trees were an aberrant tree type with distorted, malformed branching; a negative trait easily observed in second-leaf trees.

The first crops were harvested from these trees in August and September 2020. Shasta® and A07, 2-292 trees produced among the highest yields with 1.86 and 1.34 kg/tree (respectively) and Pyrenees® trees produced among the lowest yields with 0.10 kg/tree (Table 10). There were no consistent differences in kernel yield between pruning treatments within each genotype so the data were combined. This range of yields is similar to that recorded for the pruning trial trees on the same 'Cornerstone' rootstocks (Table 6). Note also that the A04, 7-180 trees exhibited symptoms of severe non-infectious bud failure during the 2019 season so were excluded from the trial.

Overall these data indicated the positive attributes in terms of architecture and productive capacity of young Shasta® and A07, 2-292 trees. Both sets of trees responded well to minimal pruning and maintained a strong, uniform, narrow and upright growth habit during 2020 when trees were bearing their first commercial crop (Figure 4). With Covid-19 travel restrictions we were not able to record tree dimensions in 2020 for this project. As with the Shasta® pruning trial (Section 2.1), it will take another four harvests to confirm the long-term return from this set of pruning treatments applied to these almond varieties and novel genotypes.

Table 8. Tree and branch dimensions on 1-year-old central leader almond trees in the Novel Genotypes Pruning Responses trial at Burchell Nursery, Fowler. Trees were budded on 'Cornerstone' rootstock in June 2017 and planted in Winter (January) 2018. Data were collected in December 2018 before application of pruning treatments. Values are averages for each genotype (n = 27). Significance: * = *p*<0.001. Means within columns followed by the same letter were not significantly different.**

Genotype	Tree height when planted (m)	Central leader extension (m)	Total tree height (m)	Trunk diameter (mm)		
				At 50 cm height on trunk	Below transition zone	Above transition zone
A04, 7-180	0.88 e	0.98 b	1.86 bcd	30.1 bcd	17.8 ab	16.2 ab
A06, 3-542	0.96 cde	1.03 b	1.99 bc	31.5 bc	16.3 ab	15.1 abc
A07, 2-292	1.00 bcde	1.06 b	2.06 b	30.6 bcd	17.5 ab	16.1 ab
Lassen™	1.13 ab	0.66 cde	1.79 cd	28.2 cde	12.2 cd	10.8 ef
'Monterey'	1.18 a	0.54 de	1.72 d	24.2 ef	10.5 d	9.1 f
'Nonpareil'	1.03 bcd	1.03 b	2.06 b	31.0 bc	16.3 ab	13.6 bcde
Pyrenees®	0.92 de	0.80 bcd	1.72 d	26.7 def	16.1 b	11.8 def
Shasta®	1.07 abc	1.54 a	2.61 a	36.8 a	19.9 a	17.8 a
UCD 1-232	1.07 abc	0.90 bc	1.97 bcd	29.6 bcd	14.3 bc	12.4 cde
UCD 8-201	1.03 bcd	0.86 bc	1.89 bcd	33.2 ab	17.2 ab	14.4 bcd
'Winters'	1.02 bcd	0.42 e	1.44 e	23.8 f	10.1 d	8.8 f
Significance	***	***	***	***	***	***
p-value	*<0.001*	*<0.001*	*<0.001*	*<0.001*	*<0.001*	*<0.001*

Table 9. Branching frequency and distribution on 1-year-old central leader almond trees in the Novel Genotypes Pruning Responses trial at Burchell Nursery, Fowler. Data were collected in December 2018 before application of pruning treatments. Values are averages for each genotype (n = 27). Significance: * = *p*<0.001. Means within columns followed by the same letter were not significantly different.**

Genotype	Branching frequency (no. of shoots on primary axis)		Branching zone on primary axis (m)	Branching density (shoots per m of branching zone)
	Below transition zone	Above transition zone		
A04, 7-180	6.0 d	19.7 b	1.23 bcd	21.1 b
A06, 3-542	8.8 bcd	31.2 a	1.36 bc	28.6 a
A07, 2-292	8.1 cd	15.0 bc	1.44 b	16.5 c
Lassen™	11.7 ab	3.9 de	1.15 cd	13.6 c
'Monterey'	12.7 a	1.9 e	1.05 d	14.0 c
'Nonpareil'	12.8 a	7.1 de	1.40 b	14.4 c
Pyrenees®	11.8 ab	2.0 e	1.12 cd	13.3 c
Shasta®	10.4 abc	19.1 b	1.95 a	15.0 c
UCD 1-232	10.8 abc	6.4 de	1.32 bc	13.6 c
UCD 8-201	10.6 abc	10.4 cd	1.25 bcd	16.8 c
'Winters'	6.8 d	4.7 de	0.78 e	14.1 c
Significance	***	***	***	***
p-value	*<0.001*	*<0.001*	*<0.001*	*<0.001*

Table 10. Fresh weight of whole fruit, kernel moisture content and kernel weight from almond trees in the Novel Genotypes Pruning Responses trial at Burchell Nursery, Fowler. Trees were budded in spring (May) 2017 on container-grown 'Cornerstone' rootstock and planted in Winter (January) 2018 at 2.3 x 4.6 m spacing (945 trees per ha). Data from pruning treatments were pooled. Values are genotype averages ± SE (n = 9 groups of 3 trees each). Significance: *** = p<0.001. Means within columns followed by the same letter were not significantly different.

Genotype (3rd leaf trees)	**Fresh weight (kg/tree)**	**Kernel moisture (%)**	**Kernel weight (kg/tree)[1]**
Shasta®	7.90 ± 0.6 a	4.29 ± 0.1 c	1.86 ± 0.16 a
A07, 2-292	5.70 ± 0.6 ab	4.37 ± 0.1 bc	1.34 ± 0.14 ab
UCD 8-201	4.39 ± 0.3 bc	4.32 ± 0.1 c	1.22 ± 0.08 b
A06, 3-542	3.85 ± 0.3 bcde	4.63 ± 0.1 abc	1.01 ± 0.07 bc
UCD 1-232	3.65 ± 0.4 cd	5.08 ± 0.2 ab	0.73 ± 0.08 c
'Winters'	2.60 ± 0.4 de	5.12 ± 0.1 a	0.68 ± 0.11 c
'Nonpareil'	2.62 ± 0.3 de	4.46 ± 0.1 abc	0.60 ± 0.07 c
Lassen™	2.56 ± 0.2 de	4.91 ± 0.1 abc	0.59 ± 0.05 c
'Monterey'	2.18 ± 0.3 e	4.38 ± 0.1 bc	0.50 ± 0.08 c
Pyrenees®	0.53 ± 0.1 f	5.18 ± 0.4 a	0.10 ± 0.01 d
Significance	***	***	***
p-value	*<0.001*	*<0.001*	*<0.001*

[1] Kernel yield data adjusted to 5% moisture content

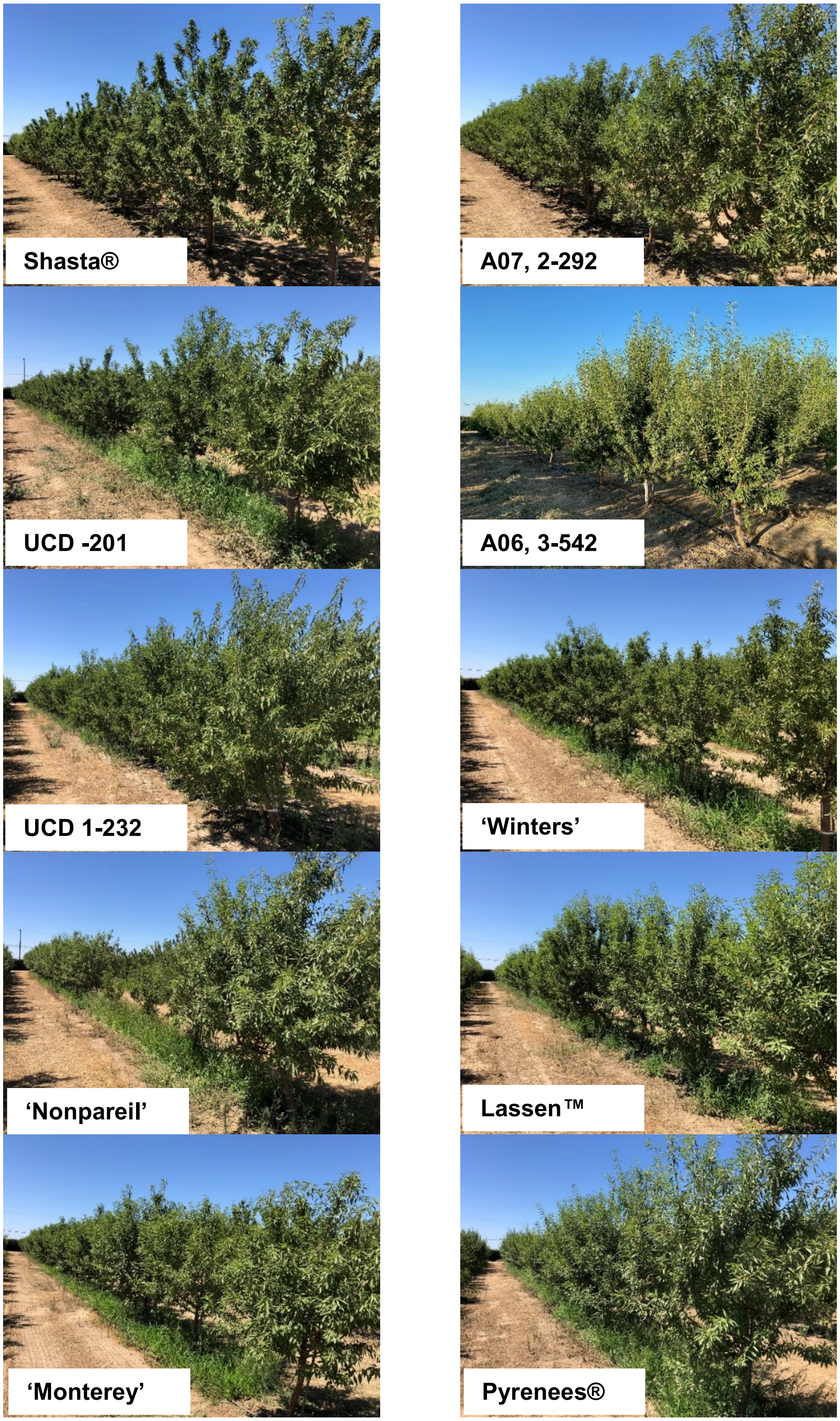

Figure 4. Trees in the Novel Genotypes Pruning Responses trial at Burchell Nursery, Fowler. Trees were planted in Winter (January) 2018. Images taken August 2020. Images were provided by Jeremey Bahne from Burchell Nursery.

3. Trunk girdling

Increasing yields from young trees and thus reducing the time to first commercial harvest is a key target for growers establishing new orchards. By commercial harvest we mean there must be sufficient crop on the trees to warrant the use of mechanical harvesters to collect it.

Trunk girdling, i.e. removing a strip of bark from the trunk of trees, is one technique used in several fruit industries to increase flowering and cropping. This project evaluated the use of trunk girdling young almond trees on orchards in late-summer, to increase flowering on trees about to set their first commercial crop.

3.1. Materials and methods

The project was located on a private grower property near Fowler using Shasta® trees spring-budded on 'Nemaguard' rootstock and planted in January 2015 at 4.6 x 6.4 m (15 x 21 ft) spacing (340 trees per ha).

A complete trunk girdle was applied to 10 trees using a 1/8th inch VACA girdling knife on 10 October 2017, and 10 trees were left ungirdled as a control, in a systematic design with Girdled and Control trees alternating along the same row.

Tree dimensions

Tree height and canopy volume were recorded in October 2017 and August 2018. Tree canopy volume was determined from digital images taken at right angles to each tree along the row. ImageJ Fiji software (http://imagej.nih.gov/ij) was then used to trace the perimeter of the tree canopy from which to calculate cross-sectional canopy area. This cross-sectional area was then converted to a circle from which it was possible to calculate radius. Canopy volume (V) was calculated as $V = 4/3*\pi*radius^3$. All trees were isolated and not growing into each other so it was valid to assume a uniform canopy cross-section regardless of the angle at which the digital image was taken.

2018 Harvest data

Yield data were determined on 9 August 2018 by hand harvesting each tree and recording the total fresh weight of whole fruit per tree. A subsample of approx. 2 kg was then taken for each tree. This subsample was weighed before the fruit were hulled, the nut-in-shell was weighed again then shelled to produce the kernel only which was weighed. Moisture content of the kernel was measured in approx. 100 g of kernel using a Dickey-John GAC 2100 Moisture Meter located at Hughson Nut Co. in Modesto CA. Yield data were then converted to kg of kernel at 5% moisture content per tree.

For statistical analyses, tree dimensions, yield and kernel quality data were collected from each data tree (n=10). Analyses were completed using analysis of variance with Minitab® v18.1 with mean separation by Tukey's pairwise comparison method. Percentage data were arcsin transformed for analysis and then back-transformed for presentation.

3.2. Results and discussion

Tree height and canopy volume were similar for the Girdled and ungirdled Control trees at the start of the project in October 2017 (Table 11). All trees were of similar height at harvest in August 2018 as all trees had been machine pruned by the grower in early summer 2018 to reduce tree height. However, ungirdled Control trees had a significantly greater increase in canopy volume than the Girdled trees.

Table 11. Tree height and canopy volume of 3-year-old Shasta® almond trees in October 2017 and August 2018. Treatment trees were girdled in October 2017 with a 1/8th inch wide girdle and nuts were harvested in August 2018. Significance: NS = not significant; * = p<0.05

	Tree height (m)	Tree volume (m^3)	Tree height (m)	Tree volume (m^3)
	October 2017		August 2018	
Control — No girdle	3.3 ± 0.1	9.9 ± 0.6	3.7 ± 0.1	17.6 ± 0.7
Girdled	3.2 ± 0.1	10.2 ± 0.9	3.5 ± 0.1	14.4 ± 1.3
Significance	*NS*	*NS*	*NS*	*
p-value	*0.856*	*0.796*	*0.229*	*0.043*

The total fresh weight of the crop was less on the Girdled than non-girdled Control trees (Table 12). When corrected for moisture content, the kernel yield was slightly less on Girdled than Control trees. These data need to be taken with some degree of caution as moisture content values over 10% are not particularly reliable and could have exaggerated sample variability within treatments. To mitigate this, moisture readings were repeated three times for each sample and the average value used in these analyses.

Table 12. Total fresh weight per tree, kernel moisture content, kernel weight per tree, per hectare and per canopy volume of the crop harvested in August 2018 from Shasta® almond trees. Trees had been girdled in October 2017, when trees were 3-years-old, with a 1/8th inch wide girdle. Significance: NS = not significant; (*) = p<0.10; * = p<0.05.

Treatment	Total fresh weight[a] (kg)	Kernel moisture (%)	Kernel weight[b]		
			per tree (kg/tree)	per hectare (kg/ha)[c]	per canopy volume (g/m^3 canopy)
Control (no girdle)	18.6 ± 1.0	16 ± 0.4	3.2 ± 0.1	1088 ± 46	185 ± 14
Girdled	15.4 ± 0.7	14 ± 0.9	2.8 ± 0.1	952 ± 46	209 ± 22
Significance	*	*NS*	(*)	(*)	NS
p-value	*0.016*	*0.121*	*0.056*	0.056	0.363

[a] *Fresh weight of whole fruit (hull, shell and kernel)*
[b] *Adjusted to 5.0% moisture content*
[c] *Based on 340 trees/ha (4.6 x 6.4 m spacing)*

Similar attempts were made in Australia to promote precocity and increase yields on young almond trees by trunk girdling, but none were particularly successful (https://www.horticulture.com.au/growers/help-your-business-grow/research-reports-publications-fact-sheets-and-more/al14007/). However, the long-term response to trunk girdling in both Australia and California was a reduction in tree size with no adverse effect on yield. This may be of interest to growers as an alternative to growth-controlling rootstocks.

D. OUTREACH ACTIVITIES

1. Almond: Tree architecture and development of new growing systems … what has and hasn't worked. Invited presentation to ABC Workshop in Modesto, 2 May 2017 (15+ participants).
2. Using scion architecture of 1-year-old budded trees as a guide to optimize almond orchard systems design using central leader trees. Presentation to ISHS VII International Symposium on Almonds and Pistachios in Adelaide, 5–9 November 2017 (150+ participants).
3. Update on almond field trials at Burchell Nursery, Fowler. Site visit with Almond Board of Australia (ABA) Directors and growers on 30 November 2017 (10+ participants).
4. High density almond orchards — progress from down under. Invited presentation to ABC Annual Conference in Sacramento on 5 December 2017 (200+ participants).
5. Review of Australian and Californian research activities. ABC business meeting with ABA and Hort Innovation (Australia) in Modesto, 23 April 2018 (15+ participants).
6. Update on almond field trials at Burchell Nursery, Fowler and CSU Fresno. Site visits with ABC staff (Bob Curtis, Sebastian Saa) on 25 April 2018 (four participants).
7. Visit with Grant Zaiger, almond breeder, at Zaiger Genetics in Modesto to review our Australian and Californian based projects. Site visits on 1 June 2018 (two participants).
8. Meeting with ABC staff (Karen Lapsley, Sebastian Saa, Guangwei Huang) in Modesto to review our Australian and Californian based projects on 1 June 2018 (four participants).
9. Update on almond field trials at Burchell Nursery, Fowler and CSU Fresno. Site visits with ABA Directors and growers on 7 December 2018 (10+ participants).
10. Review of almond field trials at Burchell Nursery, Fowler and CSU Fresno with Sebastian Saa (ABC), Dr Ted de Jong (UC Davis) and Dr Gurreet Brar (CSU Fresno) on 23 May 2019.

E. MATERIALS AND METHODS

As detailed under individual projects.

F. PUBLICATIONS THAT EMERGED FROM THIS WORK

Grant Thorp, David Traeger, Ann Smith, Belinda Jenkins, Neil White, Thomas Gradziel 2017. Using scion architecture of one-year-old budded trees as a guide to optimize almond orchard systems design using central leader trees (ABSTRACT). ISHS International Symposium on Almonds & Pistachios, Adelaide, 5–9 November.

Grant Thorp 2017. Transforming almond orchards – tree architecture and advanced production systems. Poster presented to the Almond Board of California Annual Conference in Sacramento, 4–7 December (Appendix I).

Grant Thorp 2018. High density almond orchards – progress from down under. Poster presented to the Almond Board of California Annual Conference in Sacramento, 4–6 December (Appendix II).

Grant Thorp and Ann Smith 2019. Tree architecture – important traits for new almond varieties. Poster presented to the Almond Board of California Annual Conference in Sacramento, 10–12 December (Appendix III).

Acknowledgements:

This project was funded by the Almond Board of California and by the Australian Hort Frontiers Advanced Production Systems Fund, part of the Hort Frontiers strategic partnership initiative developed by Hort Innovation, with co-investment from Plant & Food Research and contributions from Hort Innovation using the Almond research and development levy and from the Australian Government. Hort Innovation is the grower-owned, not-for-profit research and development corporation for Australian horticulture.

The research forms part of a collaborative research program with Dr Tom Gradziel and Dr Bruce Lampinen from UC Davis, Dr Gurreet Brar and Madison Hedge from CSU Fresno and John Slaughter and Kaylan Roberts from Wawona Packing. We also thank Tom Burchell and Jeremy Bahne and the staff at Burchell Nursery for their patience in providing the plant material required for these trials and for providing the land and labor to have research trials planted and maintained at their Fowler nursery site.

Appendices:

Appendix I. Grant Thorp, David Traeger, Ann Smith, Belinda Jenkins, Neil White, Thomas Gradziel 2017. Using scion architecture of 1-year-old budded trees as a guide to optimize almond orchard systems design using central leader trees (ABSTRACT). ISHS International Symposium on Almonds & Pistachios, Adelaide, 5–9 November.

Appendix I. Grant Thorp 2017. Transforming almond orchards – tree architecture and advanced production systems. Poster presented to the Almond Board of California Annual Conference in Sacramento, 4–7 December.

Appendix II. Grant Thorp 2018. Tree architecture and development of new growing systems. Poster presented to the Almond Board of California Annual Conference in Sacramento, 4–6 December.

Appendix III. Grant Thorp and Ann Smith 2019. Tree architecture – important traits for new almond varieties. Poster presented to the Almond Board of California Annual Conference in Sacramento, 10–12 December.

Appendix I. Grant Thorp, David Traeger, Ann Smith, Belinda Jenkins, Neil White, Thomas Gradziel 2017. Using scion architecture of one-year-old budded trees as a guide to optimize almond orchard systems design using central leader trees (ABSTRACT). ISHS International Symposium on Almonds & Pistachios, Adelaide, 5–9 November.

Using scion architecture of one-year-old budded trees as a guide to optimise almond orchard systems design using central leader trees

Grant Thorp, David Traeger, Ann Smith, Belinda Jenkins, Neil White, Thomas Gradziel

In commercial fruit growing, tree architecture or the natural growth habit of the tree is typically modified by pruning and training and/or by chemical means to suit a particular growing system or orchard design. These modifications can commence in the nursery or when the young tree is first planted in the orchard. The problem with this approach is that for many fruit crops the chosen growing system does not fully utilise or take advantage of the natural growth habit of the plant. This is typical for crops such as almond, avocado and macadamia, where detailed canopy management is not usually practised after the initial tree establishment phase. Our approach with almonds has been to describe the "unmodified" architecture of one-year-old budded trees of a range of cultivars/genotypes so that we can take this information into account when designing new, more productive growing systems. The almond cultivars 'Carmel' and 'Wood Colony' produced concentrated zones with relatively few, large/vigorous shoots along the primary growth axis (trunk), whereas 'Nonpareil' and 'Aldrich' produced more diffuse branching zones with numerous, relatively small/non-vigorous shoots. While 'Carmel' and 'Wood Colony' may be well suited to multiple-axis trees used by most almond growers, they may not be suitable for single-axis "central leader" growing systems being evaluated for new, high-density growing systems. Progress to date with the development of central leader growing systems for almonds will be presented and the potential of this approach to phenotype breeding populations for desirable architectural features will be discussed.

Appendix II. Grant Thorp 2017. Transforming almond orchards — tree architecture and advanced production systems. Poster presented to the Almond Board of California Annual Conference in Sacramento, 4–7 December.

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Plant & Food **RESEARCH**
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Transforming almond orchards – tree architecture and advanced production systems

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THE NEW ZEALAND INSTITUTE FOR PLANT & FOOD RESEARCH LIMITED

The Almond Board of California and the Almond Board of Australia are supporting a programme of collaborative research to increase production and profits from existing and future almond orchards.

The research is focused on tree architecture and the development of production systems that involve no or minimal additional cost to the grower; reduce the time taken to reach break-even point on the orchard investment and that increase productive yield per hectare and grower profits.

Light management

Research in Australia on light management in high density orchards (planted at 10 x 20 ft) demonstrated that reflective ground covers and selective limb removal pruning can increase light transmission and nut bearing in the lower canopy zones of 'Nonpareil' trees (Table 1, Figure 1).

- However, the additional fruit produced in the lower canopy zones of these trees were slow to mature and were not ready for harvest until 2 to 3 weeks after the main crop (Figure 2). There was also no change to the total yield on these trees (Table 2).
- The "grower" solution has been to start a program of mechanical pruning/trimming to allow more light into the lower canopy and thus stimulate growth of new fruiting wood (Figure 3)
- The "long-term" solution is to produce pyramid-shaped trees (wider at their base than at their tops) with narrow canopies. This shape is the most efficient at capturing light and converting that light into high value crops. New pruning systems are required to achieve this tree shape.

Table 1: Effect of reflective ground covers and selective limb removal pruning on kernel moisture content and yield at commercial harvest in the lower canopy zone (0 to 9 ft) of 8th leaf 'Nonpareil' almond trees on Nemaguard rootstock in Australia. Trees were planted at 10 x 20 ft spacing.

Treatment	Kernel moisture (%)	Kernel weight (lb/tree)[a]	Kernel weight (lb/acre)[a]
Control	16.3	0.73	156
Pruned + Reflective covers	8.7	1.79	389
Significance[b]	**	***	***

[a] Adjusted to 5% moisture content
[b] Significance: ** = P<0.01, *** = P<0.001

Table 2: Effect of reflective ground covers and selective limb removal pruning on total kernel yield of 'Nonpareil' almond trees on Nemaguard rootstock in Australia. Trees were planted in 2009 at 10 x 20 ft spacing.

	Kernel weight (lb/acre)[a]		
Treatment	2015 6th leaf	2016 7th leaf	2017 8th leaf
Control	2247	4840	3716
Pruned + Reflective covers	2679	4926	3975
Significance[b]	NS	NS	NS

[a] Adjusted to 5% moisture content
[b] Significance: NS = not significant (P=0.05)

Figure 1: Reflective ground covers were installed beneath 'Nonpareil' almond trees planted at 10 x 20 ft spacing to increase the amount of light and fruit yield in the lower canopy zones.

Figure 2: Fruit in the lower canopy (right) were not ready for harvest when fruit from the upper canopy (left) were harvested, the lower canopy fruit were ready 2-3 weeks later.

Figure 3: Mechanical pruning in winter, starting in Year 6 after planting, is used as a "grower" solution to reduce shading in 'Nonpareil' almond trees planted at 10 x 20 ft spacing.

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This project has been funded by the Almond Board of California and by Hort Innovation using the almond research and development levy and contributions from the Australian Government.

New pruning systems

Research in Australia has demonstrated that "palmette" style pruning of young 'Nonpareil' trees will produce a narrow tree canopy suitable for blocks with closer row spacing (Figure 4).

- Trees were planted in 2012 at 10 x 20 ft on Nemaguard rootstock. Tree yields were similar on the pruned and unpruned pruned trees (Table 3)
- This "palmette" style of pruning would be suitable for planting trees at 10 x 16.5 ft, which would increase potential yields by 21%
- New trials have been planted in Australia at these closer spacings and with a wider range of varieties to evaluate this option. Similar projects will be planted in California in the 2017/18 winter.

Figure 4: A single round of "palmette" style pruning was applied to 'Nonpareil' almond trees (foreground) in winter at Year 2 from planting to produce trees with a narrow canopy, suitable for high density blocks. The objective was to prevent any "big wood" from growing out into the rows and blocking machinery access.

Table 3: Total kernel yield from 'Nonpareil' almond trees on Nemaguard rootstock. Trees were planted in 2012 at 10 x 20 ft spacing and treatment trees were pruned in winter 2014 to produce a narrow 'palmette' style canopy.

	Kernel weight (lb/acre)[a]		
Treatment	2015 3rd leaf	2016 4th leaf	2017 5th leaf
Control	424	3371	3284
Pruned	467	2766	2766
Significance[b]	NS	NS	NS

[a] Adjusted to 5% moisture content
[b] Significance: NS = not significant (P=0.05)

Central leader trees for high density orchards

Our research in Australia and California also aims to identify varieties and management systems that with no or minimal pruning will produce central leader trees with a slender pyramid shape suitable for planting in high density orchards.

These projects start with trees taken directly from the nursery with no pruning, apart from removal of side shoots below 2 ft on the trunk to provide a clear trunk for shaking.

Key results/observations in 2017 from Australian trials planted in 2016 include:

- 'Nonpareil' and 'Price' trees maintained a central leader with strong scaffold branching (Figure 5)
- Although 'Monterey' trees produced numerous side shoots, few of these were strong enough to be scaffold branches able to support the weight of a developing crop
- Heavy flowering on 'Carmel' trees restricted the growth of the central leader and promoted the dominance of side branches

New trials to be planted in California in winter 2017/18 will compare a wider range of tree types and how these respond to a range of pruning methods designed to produce a narrow, slender pyramid tree shape.

Figure 5: 'Nonpareil' and 'Price' trees planted in Australia in July (winter) 2016 as "unpruned" trees direct from the nursery and trained with a central leader (left), compared with traditional "pruned" trees (right) that were headed back to 3 ft and grown as multi-axis trees. Images were taken in October (spring) 2017.

Research Team

- **PFR Australia:** Grant Thorp, Andrew Granger, David Traeger, Belinda Jenkins, Ann Smith
- **PFR New Zealand:** Stuart Tustin, Jill Stanley, Carlo van den Dijssel, Steve Green, Edouard Périé, Andrew Barnett, Michael Blattmann, Vincent Mangin
- **California:** Gurreet Brar (CSU Fresno), Bruce Lampinen (UC Davis), John Slaughter and Kaylan Roberts (Burchell Nursery)

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california almonds Almond Board of California

Appendix III. Grant Thorp 2018. Tree architecture and development of new growing systems. Poster presented to the Almond Board of California Annual Conference in Sacramento, 4–6 December.

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Tree architecture and development of new growing systems

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Project summary

The Almond Board of California (ABC) and the Almond Board of Australia (ABA) are supporting an international program of collaborative research to increase production and profits from existing and future almond orchards.

Our research in this program is focused on tree architecture and the development of improved production systems for almond growers. In this context, new systems must include:

- No or minimal additional cost to the grower
- Reduced time for orchards to produce their first commercial crop and reach break-even point
- Tree shape suitable for off-ground and dustless harvesting with more uniform crop maturity and quality
- Increased productive yield per hectare and grower profit over the life of the orchard.

High density, central leader trees

Our basic model for high-density orchards that we are testing in California and Australia is to plant trees with a strong central leader (Figure 1).

To achieve this, we receive trees from the nursery that have not had their terminal shoot (trunk) cut back (headed) prior to digging and despatch. Although the trees are pruned in the nursery to remove all side shoots on the trunk below 2.5 ft. and to remove any overly dominant shoots above this point, these trees are planted in the orchard as "unpruned" central leader trees. Depending on variety and time of budding the central leader trees are normally 6 to 8 ft. tall when planted.

Figure 1. Unpruned, central leader almond trees ready for field planting.

Tree management

At planting we apply a heading cut approximately 3 inches below the terminal bud to force the growth of a strong lateral shoot on the windward side of the trunk to take over extension growth as the central leader (Figure 2). Without this pruning cut a cluster of shoots can grow at the apex of the tree which subsequently can become crowded and prevent development of a strong central leader.

In early summer we cut back any lateral shoots competing with the new central leader shoot, once again to force extension growth and ensure dominance of the central leader (Figure 3). At this time we also trim, by approximately one third, all lateral shoots growing out towards the centre of the row, to produce a narrow canopy (Figure 4). We prune shoots on the leeward side harder than on the windward side to promote more growth on the windward side of trees.

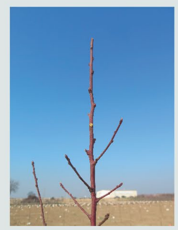

Figure 2. The terminal shoots of central leader almond trees are cut back at planting to force growth of a strong lateral shoot on the windward side of the trunk. This shoot is then trained to take over extension growth as the central leader.

Figure 3. In early summer any lateral shoots competing with the new central leader shoot of the almond tree are cut back, to ensure the dominance of the central leader (L = before, R = after).

Figure 4. All lateral shoots growing out towards the centre of the row on central leader almond trees are trimmed in early summer to produce a narrow canopy (L = before, R = after). In these images, the predominant wind direction was from right to left, so more foliage was left on the windward (right) side than on the leeward side of trees.

Figure 5. Almond genotypes have distinctive architecture, ranging from decurrent (left) to excurrent (centre) to compact columnar growth habit (right). The decurrent growth habit is produced when branches extend downward and the adult tree does not develop a strong central leader. Excurrent tree types form a symmetrical "Christmas tree" shape with a distinctive central leader. Trees with a columnar growth habit also form a central leader but with short lateral shoots to form a narrow compact tree canopy.

Tree architecture

Our projects include a wide diversity of genotypes with distinctive architecture, ranging from decurrent (branches extending downward) to excurrent (symmetrical "Christmas tree" shape) and compact columnar growth habit (Figure 5). Obviously genotypes with a more compact columnar and/or excurrent tree architecture will be easier to grow as central leader trees and will be more suitable for high-density growing systems than decurrent tree types that tend to produce mature trees with a very wide, spreading canopy.

Flexural rigidity (stiffness, flex) of the trunk and branches is also an important architectural feature of almond trees. Once trees begin cropping, if the trunk/branches are too soft and bend too easily under the weight of the fruit, then this will produce a weeping or cascading growth habit that will be difficult and expensive to manage in high-density orchards (Figure 6).

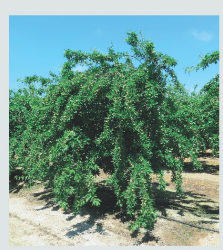

Figure 6. Example of weak almond tree structure with branches bending down under the weight of the fruit to give a cascading fruiting canopy with no or very little extension growth for next season.

Project Co-operators and Personnel:
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california almonds Almond Board of California | Hort Innovation Strategic levy investment | ALMOND FUND | australian almonds ALMOND BOARD OF AUSTRALIA

This project has been funded by the Almond Board of California and by Hort Innovation using the almond research and development levy and contributions from the Australian Government.

Appendix IV. Grant Thorp and Ann Smith 2019. Tree architecture — important traits for new almond varieties. Poster presented to the Almond Board of California Annual Conference in Sacramento, 10–12 December.

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PROJECT ID: 18.HORT30.THORP

Tree architecture – important traits for new almond varieties

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Project summary

Research is underway in California and Australia to redesign almond orchards using more intensive management systems and new varieties to increase orchard productivity and grower profits.

The approach requires a fresh look at orchard design. Our key research hypothesis is that orchard yields and grower profits can be doubled by planting trees at high density and growing these trees with minimal pruning to produce a slender pyramid tree shape that optimizes orchard light interception, crop yield and quality.

A major consideration is that many of the current varieties in California and Australia are not compatible with this type of orchard intensification. New varieties are required that have architectural attributes better suited to high density orchards and to new pruning/training systems required to sustain high yields over the long term.

An important question in this research is can the breeding cycle for trees with high productivity be accelerated by screening for desired architectural traits in 1st leaf trees budded onto clonal rootstocks and by screening for desired fruit bearing traits in 2nd and 3rd leaf trees?

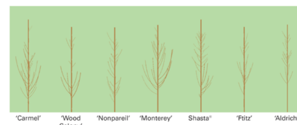
Tree architecture

Understanding tree architecture, or the natural growth habit of trees and their responses to manipulation, is fundamental to orchard system design and developing new management systems specific for each crop and variety. By understanding tree architecture, we are better able to describe physiological mechanisms and to identify/quantify architectural traits determining/limiting productivity.

As with many *Prunus* spp., almond trees generally exhibit a strong basitonic growth habit that produces a set of very large scaffold branches near the base of the tree. With heavy cropping varieties this can result in unstable fruiting canopies that require considerable pruning and training to maintain productivity. While this growth habit is suited to traditional large-tree growing systems, it is not suited to more intensive small-tree growing systems.

"At the same time as we redesign almond orchards, we need to redesign almond varieties!"

A compact, upright tree with excurrent branching (left) will be easier to manage in high density blocks than trees with wide, spreading canopies and decurrent branching (right). These differences are obvious within the first two years of tree growth.

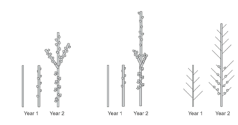


First-leaf trees in the nursery show a range of branching habits typical for each variety. Desired attributes for central leader trees would be to have uniform branching, evenly distributed along the trunk, as tends to happen with 'Nonpareil' and Shasta®.

Uniform extension of the central leader is desired at the transition zone between one growth flush and the next (left); compared with poor central leader development caused by dominant axillary branching (centre) or weak terminal bud development (right).

Tree architecture among breeding populations can easily be observed in years 1 and 2. Would it accelerate the breeding pipeline if trees with negative architectural traits were eliminated before the trees produced their first crop?

While strong axillary shoot production is important to increase the number of potential fruiting sites, these shoots (dards) need to be robust enough to survive in low light conditions and sustain high productivity. This attribute can be identified in second-leaf trees.



Bud and spur development on contrasting varieties. Is strong axillary growth in year 1 at the expense of strong bud and spur development in years 1 and 2, respectively?

Seedlings from breeding populations growing on their own roots typically show large variation in vigour (left), which is not seen in commercial trees on clonal rootstocks (right). Would it make the breeding pipeline more efficient if all breeding progeny were budded and evaluated on clonal rootstocks?

Strong branching from terminal and subterminal buds can produce long barren sections of wood; this undesirable habit can be observed in second-leaf trees.

Long-term viability of spurs will be important for sustained high productivity, as will the generation of new fruiting wood. At what stage in the breeding cycle can we predict spur longevity?

Examples of qualitative and quantitative data that can be used when screening breeding populations for desired architectural traits in the first- and second-leaf trees budded on clonal rootstocks.

Qualitative data:

Trunk	Scaffold branches				Axillary shoots (current year)					
					Dards (mainly sylleptic)			Subterminal (mainly proleptic)		
Dominance of central leader	Vigour (length)	Strength (diameter)	Number (count)	Orientation (angle)	(count)	(length)	(diameter)	(count)	(length)	(diameter)
1 = weak	1 = short	1 = weak	1 = few	1 = horizontal	1 = few	1 = short	1 = weak	1 = few	1 = short	1 = weak
2 = moderate	2 = medium	2 = medium	2 = medium	2 = mixed	2 = medium	2 = medium	2 = medium	2 = medium	2 = medium	2 = medium
3 = strong	3 = long	3 = strong	3 = numerous	3 = upright	3 = numerous	3 = long	3 = strong	3 = numerous	3 = long	3 = strong

Quantitative data:

Tree height		Branching		Trunk diameter		
Planted tree ht	Extension of central leader	Primary branches below transition	Branches above Transition zone	Trunk @ 50 cm diameter	Trunk diameter below transition	Trunk diameter above transition
(m)	(m)	Count (>8mm)	Count	(mm)	(mm)	(mm)

Project Collaborations:
John Slaughter and Kaylan Roberts, Wawona Packing Company CA
Bruce Lampinen and Tom Gradziel, UC Davis CA; Gurreet Brar, CSU Fresno CA
Michelle Wirthensohn, University of Adelaide; Dr Neil White, University of Queensland in Australia
Maria Jose Rubio Cabetas, CITA; Ignasi Batlle and Xavier Miarnau, IRTA in Spain

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DISCLAIMER

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