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Neoformed growth responses to dormant pruning in mature and immature pistachio trees grown on different rootstocks

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SUMMARY
The relationship between pruning and the production of neoformed growth in 'Kerman' pistachio (*Pistacia vera* L.) trees on different rootstocks was investigated to determine if the increased neoformed growth common in trees on more vigourous rootstocks was related solely to rootstock vigour, or was an artifact of pruning practices. While some neoformed growth was inherent in mature trees, pruning increased the amount produced on each tree regardless of rootstock or crop load. However, regardless of pruning severity, the least vigourous rootstock never produced as much neoformed growth as the two more vigourous rootstocks. Pruning cuts made into 2-year-old wood were the most stimulatory, while pruning cuts into 1-year-old wood resulted in growth similar to unpruned controls. The data presented indicate that the invigorating response to pruning in young trees is highly localised, and that pruning can be varied depending on the stage of tree development and the desired growth response. Overall, the data suggest that hand-pruning, while more costly in the short-term than mechanical pruning, may be useful in creating a more desirable canopy architecture, thereby potentially reducing long-term pruning needs and overall management costs.

Shoot growth of woody plants may be either preformed or neoformed. With preformed growth, the metamers composing a shoot are differentiated in a dormant bud (Hallé *et al*., 1978). This contrasts with neoformed growth, in which the metamers are not entirely differentiated in the dormant bud, and a portion of the vegetative growth is differentiated during the growing season. Understanding the origin of growth metamers, and the relationship between preformation and final shoot morphology, is particularly important to improving our understanding of the architecture of the tree canopy (Costes *et al*., 1992; De Reffye and Houllier, 1997). Information on the origin of growth metamers is useful for developing pruning and management strategies, and indicates limitations to manipulating trees in horticultural settings.

Canopy growth in mature pistachio trees has been shown to be composed mostly of preformed shoots, although a considerable amount of neoformed growth can occur in trees on some rootstocks (Spann *et al*., 2007). Increased vegetative growth is not necessarily a benefit in mature tree crops, as it may not be correlated specifically with increased yield (Johnson and Handley, 2000). Continued vegetative growth throughout the season may not lead to increased light interception, or net carbon assimilation, if the leaf area indices are already high, and may indeed lead to excessive shading of fruiting wood (Johnson and Handley, 2000). In pistachio trees, shoots with neoformed growth are excessively long, which decreases the efficiency of shaker harvesting. For this reason, growers routinely remove long shoots from the canopy during dormant pruning.

Dormant pruning generally has an invigorating effect on trees (Harris, 1983; Mika, 1986), particularly on an individual shoot basis. Wilson (1993) found that the total growth of pruned *Betula lenta* L. and *Acer rubrum* L. trees was similar to control trees after one season, but that the distribution of shoot lengths had been shifted toward longer lengths in pruned trees. Thus, he concluded that pruning induced some short shoots to grow as long shoots. Mika (1986), summarising many pruning experiments, concluded that pruning always induced the development of longer shoots that grew faster and for a longer portion of the growing season.

While stimulation of shoot growth by pruning is well-documented, characterisation of that stimulation in terms of preformation and neoformation is not well-documented. Davidson and Remphrey (1994) found that pruning, as well as the removal of buds, and thus potentially competing shoots, increased neoformation in *Fraxinus pennsylvanica* Marsh. However, their study was limited to young trees (4 – 5 years-old).

According to pruning dogma, during the first year following pruning, individual shoots are invigorated, but intra-shoot competition due to the stimulation of lateral bud growth may limit total growth (Harris, 1983). However, in mature pistachio trees, almost all lateral buds become inflorescences, thus there are few lateral vegetative buds (Crane and Iwakiri, 1985). This, along with the knowledge that most pistachio shoot growth is preformed (Spann *et al*., 2007), led us to hypothesise that total shoot growth would be greatest in the first year following pruning, because individual shoots would be

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vigorous, and intra-shoot competition would be negligible, since there are relatively few lateral vegetative buds. This would then be followed, in the next year, by a decrease in total growth as neoformation (stimulated in the first year by pruning) decreased, and a higher percentage of the total growth was preformed.

The objectives of this study were: (i) to determine the effects of pruning on growth in mature pistachio trees on different rootstocks and in young trees, with respect to preformation and neoformation; and (ii) to assess the implications of the pruning response with respect to the management of young and mature trees in an orchard setting.

MATERIALS AND METHODS

Mature trees – pruned

To examine the effects of pruning on the stimulation of neoformed growth in mature pistachio trees, a simulated topping trial was established in a pistachio rootstock block at Paramount Farms, Inc., Lost Hills, California, USA (35°37"24'N; 119°41"10'W). The block was planted in February 1989 with 1-year-old nursery seedlings that were field budded to *P. vera* 'Kerman' after planting. There were 20 rows with 20 trees per row spaced 5 m apart within rows, with 6 m between rows. The trees were planted in a randomised complete block design with 50 blocks. Each block spanned four rows and contained one tree of each of four rootstocks. This block was embedded in a commercial orchard, and pruning, fertilisation, irrigation and pest control were performed by the grower following standard commercial horticultural practices. One of the rootstocks in the original trial is no longer used commercially; thus, this study used only three of the four rootstocks in the planting: *P. atlantica* Desf. (Atl), *P. integerrima* Stew. selection Pioneer Gold I (PGI), and *P. atlantica* × *P. integerrima* selection UC Berkeley I (UCB).

During January 2004, 12 trees on each rootstock were selected for uniformity. Three trees on each rootstock were randomly assigned as control trees, or to one of three pruning treatments. The treatments are depicted in Figure 1. All pruning treatments were applied using hand-clippers across the top of the canopy only, no lower shoots were pruned. Control trees were left completely unpruned. In the first treatment (T1), only those shoots that had produced neoformed growth in 2003 were pruned. The neoformed growth was removed at its junction with the 2003 preformed portion of the shoot from which it arose. No other shoots in the canopy were pruned. The second treatment (T2) was applied to all shoots across the top of the canopy, regardless of preformed or neoformed status. All 2003 growth was removed completely at its junction with the 2002 growth. Treatment 3 (T3) was identical to T2, except that the pruning cut was made halfway along the length of the 2002 growth.

These treatments resulted in trees with all 1-year-old wood intact (control), all preformed 1-year-old wood intact (T1), all 1-year-old wood removed (T2), or all 1-year-old and half of the 2-year-old wood removed (T3), across the top of the canopy. This simulated the types of cuts that would have been made had the trees been mechanically topped at varying heights, but eliminated the random nature with which those treatments would have been applied to each tree.

The trees were harvested by shaking on 15 September 2004. Individual tree fresh weight (FW) nut yields were recorded, and a 9 kg sample was taken from each tree and sent to Paramount Farms, Inc. for commercial grading according to California Pistachio Commission/USDA standards. Based on these grade data, whole tree dry weight (DW) and yield components were extrapolated.

On 8 – 9 February 2005, all shoots that grew in the entire canopy of each tree in 2004 were removed by hand. The shoots were gathered for each tree and taken to a laboratory for measurements. Any wood older than 1 year that may have been harvested with the shoots in the field

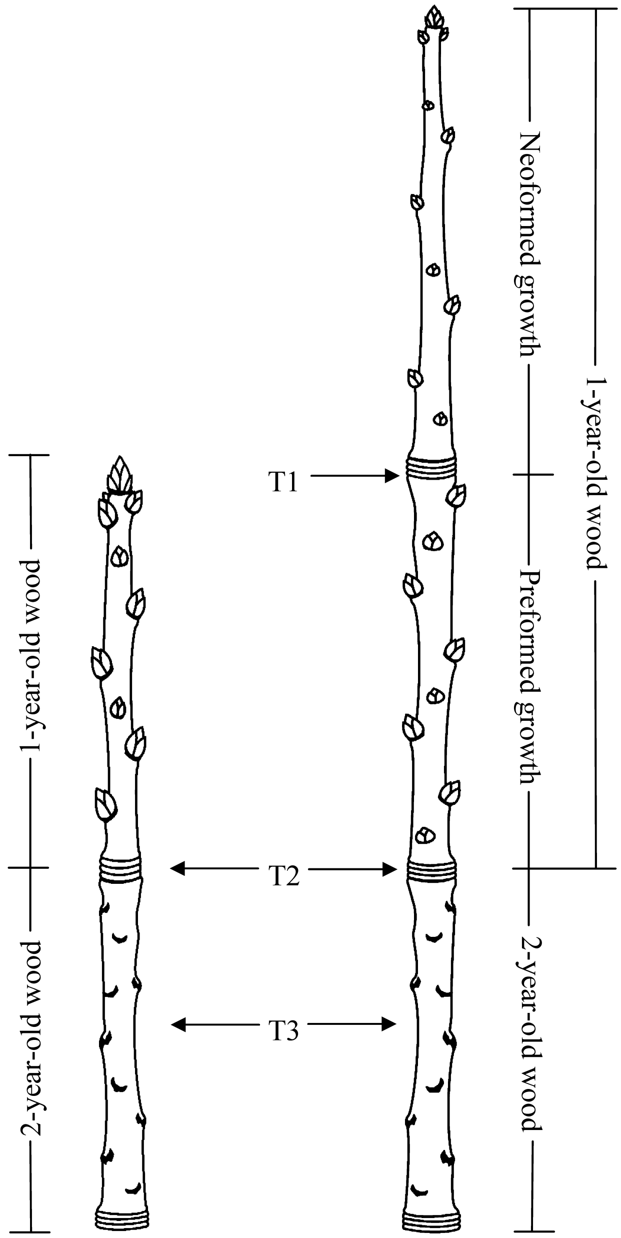

FIG. 1
Diagram of pistachio shoots showing 1-year-old and 2-year-old wood. The 1-year-old wood of the shoot on the left was entirely preformed. The 1-year-old wood of the shoot on the right was formed from preformed and neoformed growth. Arrows indicate the location of the pruning cut for the treatments (T1, T2, or T3) specified in the text.

was trimmed away. The total length of each shoot was measured, and for those shoots that had neoformed growth, the length of their preformed portion was also recorded. From these data, total shoot growth, as well as total preformed and neoformed growth, could be calculated for each tree. Previous studies have shown that preformed node number does not vary between seasons, and for neoformed growth, length is a better measurement of variability between shoots (Spann *et al*., 2007), thus the number of nodes on each shoot was not counted.

The tree was considered the experimental unit, and data were analysed as a factorial with three rootstocks and four pruning treatments. Variation in size among trees of a given rootstock was considerable. Thus, the total number of growing shoots per tree, as well as the number of shoots producing neoformed growth per tree, were normalised within a rootstock by trunk cross-sectional area (TCSA). In the analysis of total preformed and neoformed shoot lengths, the total number of growing points per tree was found to be independent of shoot length ($P = 0.8500$, $P = 0.8415$, and $P = 0.2157$ for Atl, PGI, and UCB, respectively), and so was used as a covariant to normalise these data.

Mature trees – unpruned

To determine if neoformed growth is inherent in pistachio, or is strictly a result of stimulation by pruning, a trial was established to measure the amount of neoformed growth produced by mature trees 1, 2 and 3 years after a standard commercial pruning. The trial was established in a rootstock trial block at the University of California Kearney Agricultural Center, Parlier, California, USA (36°36"42'N; 119°31"34'W). This rootstock block was planted at the same time as the one previously described, with the same experimental design, but was not embedded in a larger orchard. Until 2002, this block had received standard horticultural care, typical of commercial production, including dormant pruning, irrigation, fertilisation and pest control.

Following the 2001 – 2002 dormant season pruning, six trees on each rootstock (Atl, PGI and UCB) were selected from within eight rows of the block, avoiding trees on the perimeter. Three of the trees on each rootstock were selected at random, and all of the inflorescences were removed on 10 June 2002. This produced "off" trees in an otherwise "on" year. This alternate-bearing habit was maintained for the duration of the project. These trees were not pruned during the 2002 – 2003 and 2003 – 2004 dormant seasons.

During the 2004 – 2005 dormant season, all of the growth that had occurred during the three prior growing seasons (2002, 2003 and 2004) was removed from the trees. The wood was separated by age (1, 2 or 3 years-old), and each shoot was measured to determine total shoot growth for each season, following pruning. The total number of shoots and the number of shoots exhibiting neoformed growth were counted for each age of wood.

The "on" trees were shaker harvested at nut maturity each year. Individual tree FW yields were recorded and a sample was taken, as previously described, to determine whole tree DW and yield components.

The tree was considered the experimental unit, and data were analysed as a factorial with three rootstocks and 3 years from pruning.

Immature trees

A uniform, vigorous orchard of 2-year-old 'Kerman' pistachios on PGI rootstock was selected near Hanford, California, USA (36°19"39'N; 119°38"41'W) during the dormant season of 2004 – 2005. Twenty trees were selected from within a single row of the orchard, and five similar (based on length) shoots were selected within each tree. Each shoot was randomly assigned to one of five treatments. Treatments were applied by hand near the end of the dormant season on 11 March 2005.

One of the selected shoots in each tree was assigned as a control shoot and was not pruned. For treatment 1 (Y-T1), only the terminal bud was removed from the shoot. One quarter of the length of each shoot was removed in treatment 2 (Y-T2). One-half of the length of each shoot was removed in treatment 3 (Y-T3). Finally, three-quarters of the length of each shoot was removed in treatment 4 (Y-T4). The remaining shoots (*ca.* ten per tree) in each tree canopy were not pruned.

On 26 January 2006, the length and number of nodes of the shoots that grew from the terminal bud (control only), and each of the lateral buds on each treatment branch were recorded. The node position of each lateral shoot, relative to the terminal/pruning wound, and the positions of any buds that did not grow were recorded. From visual inspection, it was not possible to determine if a lateral bud that did not grow was dormant or had died.

The individual shoot was the experimental unit, and the effects of pruning on the various young tree growth parameters were analysed as a one-way ANOVA, with mean separation by Duncan's new multiple range test, $P = 0.05$.

RESULTS

Mature trees – pruned

Regardless of rootstock, pruning had no effect on the total length of preformed growth produced per tree (data not shown). Likewise, the total number of shoots that grew per tree on all rootstocks was not affected by pruning treatment (Table I). However, pruning increased the number of shoots producing neoformed growth for trees on PGI and UCB rootstocks (Table I). No differences were detected in the number of shoots with neoformed growth for trees on Atl rootstock. Similarly, pruning significantly increased the total length of neoformed growth produced per tree for trees on PGI and UCB rootstocks, but not for trees on Atl rootstock (Table I).

Mature trees – unpruned

Although not significant, pruning tended to stimulate more growth the first year after pruning when performed going into an "on" year compared with an "off" year for all rootstocks (Table II). This trend was maintained for the 3 years of the study, such that the total cumulative growth for the study period was greater for those trees that had been pruned prior to an "on" year, compared to an "off" year (Table II). Trees on Atl rootstock produced less cumulative total growth, regardless of pruning treatment, compared to trees on PGI and UCB rootstocks. Trees pruned going into an "on" year produced significantly more neoformed growth the first year after pruning than those going into an "off" year

TABLE I
Total number of shoots per tree, the number of those shoots with neoformed growth, and the total length of neoformed growth per tree for mature 'Kerman' pistachio trees on three rootstocks under three different pruning treatments

	Pruning treatment			
Rootstock[z]	Control	T1	T2	T3
	Total number of shoots per tree			
Atl	2,883.7	3,015.3	3,115.0	2,555.0
PGI	3,321.7	2,837.0	2,973.8	3,100.0
UCB	2,807.3	1,709.7	2,544.0	2,731.0
	Number of shoots with neoformed growth per tree			
Atl	92.0d[y]	113.3cd	151.5bcd	116.3cd
PGI	173.0bcd	100.7cd	268.5a	240.3ab
UCB	136.3cd	177.7bcd	189.7abc	240.3ab
	Total neoformed growth per tree (m)			
Atl	11.97d	18.97cd	41.97bcd	36.44bcd
PGI	15.50d	8.44d	68.31bc	79.09ab
UCB	22.13cd	24.50cd	50.91bcd	119.48a

[z]Atl = *Pistacia atlantica* Desf.; PGI = *P. integerrima* Stew. selection Pioneer Gold I; UCB = *P. atlantica* × *P. integerrima* selection UC Berkeley I.
[y]Mean separation by Duncan's new multiple range test, $P = 0.05$. Mean values followed by different lower-case letters within each parameter category differed significantly. (n = 3).

TABLE III
Mean number of shoots with neoformed growth during the 3 years following pruning when pruning was performed before an "on" or an "off" bearing year for mature 'Kerman' pistachio trees on three rootstocks

		Year after pruning		
Rootstock[z]	Bearing pattern	First	Second	Third
Atl	on-off-on	284.7a[y]	87.3cde	126.0bcd
	off-on-off	34.67e	160.3bc	117.7bcd
PGI	on-off-on	294.8a	124.3bcd	122.3bcd
	off-on-off	120.3bcd	141.7bcd	80.7de
UCB	on-off-on	348.0a	150.5bcd	110.0bcd
	off-on-off	123.0bcd	183.3b	124.3bcd

[z]Atl = *Pistacia atlantica* Desf.; PGI = *P. integerrima* Stew. selection Pioneer Gold I; UCB = *P. atlantica* × *P. integerrima* selection UC Berkeley I.
[y]Mean separation by Duncan's new multiple range test, $P = 0.05$. Mean values followed by different lower-case letters differed significantly. (n = 3).

(Table III). During the second and third year after pruning, there was no difference in the number of shoots with neoformed growth within a rootstock, regardless of bearing status. Overall, the number of neoformed shoots produced each year tended to decrease as time from pruning increased.

Mature trees – yield

Yield varied significantly among rootstocks, similar to previous reports (e.g., Ferguson *et al*., 2005), but did not vary significantly in response to pruning treatments (data not shown).

Immature trees

The number of lateral buds on each 1-year-old stem was similar for the control and Y-T1 treatments (51.95 and 49.95, respectively), and decreased proportionally with the severity of the pruning treatment (data not shown). The decrease in the number of lateral buds per 1-year-old stem, associated with increasing pruning severity, was reflected in the number of lateral shoots that grew on each stem (Table IV). However, the percentage of lateral buds that produced a lateral shoot increased with pruning severity. The number of lateral shoots producing neoformed growth was greatest in the Y-T2 treatment (10.8) and lowest in Y-T4 (5.4), the most severe treatment. However, the percentage of lateral shoots producing neoformed growth was greatest in the Y-T4 treatment (Table IV). The total length of all lateral shoot growth from 1-year-old stems was greatest in treatments Y-T2 and Y-T3 (Table IV). The majority of total shoot growth in treatments Y-T2, Y-T3 and Y-T4 occurred within the first five nodes relative to the pruning cut. Thus, as pruning severity increased, lateral shoot growth became more concentrated within the first five node positions relative to the pruning cut.

The average length of the lateral shoots produced from each of the first five node positions below the pruning cut (Y-T1 through Y-T4) or terminal bud (control) are shown in Table V. Significantly longer shoot growth was stimulated at the first node position in all pruning treatments compared with the control, and the stimulatory effect increased with pruning severity. The greatest growth of lateral shoots at nodes 1 – 3 was stimulated by treatments Y-T3 and Y-T4. Lateral shoot growth at nodes 2 – 5 for treatment Y-T1 was similar to the control treatment. There was no treatment effect on lateral shoot length at nodes 6 and higher (data not shown).

DISCUSSION

For most deciduous trees, pruning the distal end of shoots releases more proximal lateral vegetative buds from apical control, allowing more shoots to grow; although total individual shoot growth may be decreased due to competition among growing shoots (Harris, 1983). In mature pistachio trees, there are very few lateral vegetative buds on preformed shoots, since virtually all

TABLE II
Total length (m) of shoot growth per tree during the 3 years following pruning when pruning was performed before an "on" or an "off" bearing year for mature 'Kerman' pistachio trees on three rootstocks

		Total shoot growth per tree (m)			
		Year after pruning			
Rootstock[z]	Bearing pattern	First	Second	Third	Cumulative growth
Atl	on-off-on	72.99gh[y]	111.80efg	195.13bc	379.92b
	off-on-off	65.62gh	116.32efg	71.79gh	253.73c
PGI	on-off-on	69.87gh	142.28def	204.04b	416.19b
	off-on-off	58.30h	108.44efgh	145.00cdef	311.74bc
UCB	on-off-on	105.51efgh	181.51bcd	373.48a	660.50a
	off-on-off	93.91fgh	144.60cdef	155.80bcde	394.31b

[z]Atl = *Pistacia atlantica* Desf.; PGI = *P. integerrima* Stew. selection Pioneer Gold I; UCB = *P. atlantica* × *P. integerrima* selection UC Berkeley I.
[y]Mean separation by Duncan's new multiple range test, $P = 0.05$. Cumulative growth data were analysed separately from the overall factorial analysis. Mean values followed by different lower-case letters differed significantly. (n = 3).

Table IV

Parameters relating to the fate of lateral buds on 1-year-old shoots on 3-year-old 'Kerman' pistachio trees on PGI[z] rootstock, and the growth produced from those buds following dormant pruning

	Pruning treatment[y]				
Parameter	Control	Y-T1	Y-T2	Y-T3	Y-T4
No. of lateral shoots that grew per stem	23.15b[x]	26.90a	22.90b	13.80c	7.50d
Percentage of lateral shoots that grew per stem	45.69c	54.99b	63.56a	60.83ab	67.78a
Percentage of lateral shoots with neoformed growth	38.26d	36.92d	47.02c	59.57b	73.15a
Mean total growth from lateral buds (cm)	308.2b	370.9ab	422.9a	437.6a	340.73b
Percentage of total growth from nodes 1 – 5	24.9d	38.3c	57.2b	70.6a	93.1a

[z]PGI = *Pistacia integerrima* Stew. selection Pioneer Gold I.
[y]Control = unpruned; Y-T1 = terminal bud removed from each shoot; Y-T2 = one-quarter of each shoot's length removed; Y-T3 = one-half of each shoot's length removed; Y-T4 = three-quarters of each shoot's length removed.
[x]Mean separation within a parameter was by Duncan's new multiple range test, $P = 0.05$. Mean values followed by a different lower-case letter in each row differed significantly. (n = 20).

lateral buds differentiate into inflorescence buds (Crane and Iwakiri, 1985). This phenomenon resulted in the same total number of growing shoots on each tree, across pruning treatments, for all rootstocks. Thus, it can be inferred that removal of the terminal meristem resulted in the growth, on average, of only one replacement lateral bud for each terminal bud removed.

Another common response to pruning is invigoration of individual shoots (Harris, 1983). This was evident in the mature pistachio trees as a stimulation of neoformed growth on all rootstocks with increasing pruning severity. The similar number of shoots with neoformed growth across all pruning treatments for trees on Atl rootstock indicated that the stimulatory effect of pruning on this rootstock was limited to increasing the amount of neoformed growth per shoot. However, in trees on PGI and UCB rootstocks, the number of shoots producing neoformed growth tended to increase with pruning severity. Thus, there was a differential response to pruning across rootstocks.

These results differ from those reported by Beede *et al*. (1991; 1992) for trees on Atl rootstock, where no pruning treatments stimulated shoot growth longer than 30 cm, and the vigour of regrowth was characterised as insufficient for tree reconstruction. Beede *et al*. (1992) hypothesised that fruit growth and vegetative growth on the same shoot were competing for available photosynthates, thus limiting regrowth. The present study treatments removed all inflorescence buds on pruned shoots, thus shoot growth did not compete with fruit growth, and many shoots exceeded 30 cm (data not shown), supporting the hypothesis of Beede *et al*. (1992).

In young, non-bearing pistachio trees, there are many lateral vegetative buds that can potentially grow. Increasing the severity of pruning increased the growth response, when no more than half of the parent shoot was removed. However, when more than half of the parent shoot was removed (treatment Y-T4), total growth was similar to the unpruned control. This was probably due to the removal of buds, and thus the number of potential shoots that could grow, as opposed to competition. Suzuki (1990), working on mulberry (*Morus alba* L.), and Li *et al*. (1994), working on peach, found similar responses of lateral buds to pruning of individual stems and whole trees, respectively.

The mean number of lateral shoots that grew on each 1-year-old stem decreased with the severity of pruning, apparently because of the removal of lateral buds. However, when the number of shoots was expressed as a percentage of the buds remaining after pruning, the pattern was reversed. Likewise, the percentage of shoots that produced neoformed growth increased with pruning severity. Leakey and Longman (1986) reported a similar pattern for lateral shoot development in *Triplochiton scleroxylon* K. Schum.

The stimulatory effect of pruning was highly localised in young pistachio trees. As the severity of the pruning treatment increased, a greater portion of the total growth arose from the first five node positions, relative to the pruning cut. Similarly, the stimulatory effect of pruning was found to be greatest on shoots closest to the pruning wound for stems of mulberry (Suzuki, 1990; Suzuki and Kohno, 1987) and *T. scleroxylon* (Leakey and Longman, 1986), regardless of pruning severity. For pistachio, pruning resulted in shoots nearest to the pruning wound becoming long shoots, and lower lateral shoots remaining as short shoots, similar to mulberry and *T. scleroxylon*. Leakey and Longman (1986) referred to this as the dominant phase of bud growth. By performing early in-season pruning to remove the long shoots

Table V

Length ± SD (cm) of the lateral shoot produced at each node rank relative to the pruning cut (Y-T1 through Y-T4) or terminal bud (control) of 1-year-old stems on 3 year-old 'Kerman' pistachio trees on PGI rootstock[z]

		Treatment[y]			
Node	Control	Y-T1	Y-T2	Y-T3	Y-T4
1	23.3 ± 6.4d[x]	52.3 ± 10.1c	77.4 ± 10.2b	90.5 ± 9.6b	112.1 ± 10.1a
2	15.6 ± 2.2b	31.9 ± 7.4b	76.4 ± 11.5a	92.0 ± 11.7a	91.9 ± 11.2a
3	15.4 ± 3.5c	28.6 ± 8.0c	33.3 ± 8.1bc	81.8 ± 12.5a	48.1 ± 10.8b
4	12.4 ± 2.4b	14.4 ± 1.9b	38.3 ± 10.2a	35.7 ± 11.0a	33.1 ± 8.1a
5	10.1 ± 1.8b	14.9 ± 5.2b	16.5 ± 5.5ab	17.3 ± 6.3ab	24.0 ± 6.6a

[z]PGI = *Pistacia integerrima* Stew. selection Pioneer Gold I.
[y]Y-T1 = terminal bud removed from each shoot; Y-T2 = one-quarter of each shoot's length removed; Y-T3 = one-half of each shoot's length removed; Y-T4 = three quarters of each shoot's length removed.
[x]Mean separation within rows by Duncan's new multiple range test, $P = 0.05$. Mean values followed by a different lower-case letter differed significantly. (n = 20).

stimulated by dormant pruning, Suzuki and Kohno (1987) stimulated several short shoots subtending the new pruning wound to become long shoots, demonstrating that all lateral shoots had the potential to become long shoots when not dominated.

In general, the number of shoots with neoformed growth was greatest in the first year after pruning, as hypothesised. Total growth, for the 3-year study period, was greatest when trees were pruned prior to the "on" year, compared with pruning prior to the "off" year. This probably occurred because the greater neoformed growth produced the first year after pruning had many lateral vegetative buds, since inflorescence bud initiation was restricted to the preformed portion of the shoots (Spann *et al*., 2007). Thus, there were many lateral vegetative buds that could grow during the second and third year after pruning. This likely led to greater structural complexity, and may have increased intra-shoot competition (Hackett, 1985), resulting in the general decline in neoformed growth as time from pruning elapsed. Davidson and Remphrey (1994) found a similar decline in neoformed growth as *Fraxinus pennsylvanica* trees matured, and their architectural complexity increased.

This study showed that, while some neoformed growth was inherent in mature trees, pruning increased the amount produced on each tree regardless of rootstock or crop load. However, regardless of pruning severity, the least vigorous rootstock (Atl) never produced as much neoformed growth as the two more vigorous rootstocks. Pruning cuts made into 2 year-old wood were the most stimulatory; while pruning cuts into 1-year-old wood were similar to unpruned controls. These data suggest that hand-pruning, while more costly in the short-term than mechanical pruning, can reduce neoformed growth because of its precise nature, thereby potentially reducing long-term pruning needs and overall management costs.

In young pistachio trees, neoformed growth is desirable because it can help to develop the structure and canopy of the tree quickly, potentially reducing the time needed to develop a tree large enough to produce a harvestable crop. The data presented indicate that the invigorating response to pruning in young trees is highly localised. Therefore, for greatest invigoration, at least 50% of the parent shoot length should be removed by pruning to reduce the total number of buds that push, and reduce intra-shoot competition, thus maximising the elongation of the remaining shoots. On the other hand, as a young tree matures, and the goal becomes to reduce overall vigour and develop fruitwood, pruning should remove as little of the parent shoot as possible to maximise intra-shoot competition and reduce individual shoot vigour.

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REFERENCES

BEEDE, R., FERGUSON, L., ROSE, D. and PADILLA, J. (1991). Effect of pruning on the yield components of pistachio. *California Pistachio Industry Annual Report, Crop Year 1990-91*. 90–92.

BEEDE, R. H., ROSE, D., PADILLA, J. and THOMAS, D. (1992). Growth response from "on" year pruning and its effects on pistachio yield and nut quality for the following "off" year. *California Pistachio Industry Annual Report, Crop Year 1991-92*. 127–131.

COSTES, E., DE REFFYE, P., LICHOU, J., GUÉDON, Y., AUDUBERT, A. and JAY, M. (1992). Stochastic modelling of apricot growth unit and branching. *Acta Horticulturae*, **313,** 89–98.

CRANE, J. C. and IWAKIRI, B. T. (1985). Vegetative and reproductive apical dominance in pistachio. *HortScience*, **20,** 1092–1093.

DAVIDSON, C. G. and REMPHREY, W. R. (1994). Shoot neoformation in clones of *Fraxinus pennsylvanica* in relation to genotype, site and pruning treatments. *Trees: Structure and Function*, **8,** 205–212.

DE REFFYE, P. and HOULLIER, F. (1997). Modelling plant growth and architecture: some recent advances and applications to agronomy and forestry. *Current Science*, **73,** 984–992.

FERGUSON, L., BEEDE, R. H., FREEMAN, M. W., HAVILAND, D. R., HOLTZ, B. A. and KALLSEN, C. E. (2005). *Pistachio Production Manual*. 4th Edition. Fruit and Nut Research and Information Center, University of California, Davis, CA, USA. 256 pp.

HACKETT, W. P. (1985). Juvenility, maturation, and rejuvenation in woody plants. *Horticultural Reviews*, **7,** 109–155.

HALLÉ, F., OLDEMAN, R. A. A. and TOMLINSON, P. B. (1978). *Tropical Trees and Forests: An Architectural Analysis*. Springer-Verlag, New York, USA. 441 pp.

HARRIS, R. W. (1983). *Arboriculture: Care of Trees, Shrubs, and Vines in the Landscape*. Prentice-Hall, Englewood Cliffs, NJ, USA. 688 pp.

JOHNSON, R. S. and HANDLEY, D. F. (2000). Using water stress to control vegetative growth and productivity of temperate fruit trees. *HortScience*, **35,** 1048–1050.

LEAKEY, R. R. B. and LONGMAN, K. A. (1986). Physiological, environmental and genetic variation in apical dominance as determined by decapitation in *Triplochiton scleroxylon*. *Tree Physiology*, **1,** 193–207.

LI, S.-H., ZHANG, X.-P., MENG, Z.-Q. and WANG, X. (1994). Responses of peach trees to modified pruning 1. Vegetative growth. *New Zealand Journal of Crop and Horticultural Science*, **22,** 401–409.

MIKA, A. (1986). Physiological responses of fruit trees to pruning. *Horticultural Reviews*, **8,** 337–378.

SPANN, T. M., BEEDE, R. H. and DEJONG, T. M. (2007). Preformation in vegetative buds of pistachio (*Pistacia vera*): relationship to shoot morphology, crown structure and rootstock vigor. *Tree Physiology*, **27,** 1189–1196.

SUZUKI, T. (1990). Apical control of lateral bud development and shoot growth in mulberry (*Morus alba*). *Physiologia Plantarum*, **80,** 350–356.

SUZUKI, T. and KOHNO, K. (1987). Effects of pruning on the branching habit of *Morus alba* L. and the abscission of the apices of the short shoots. *New Phytologist*, **106,** 753–758.

WILSON, B. F. (1993). Compensatory shoot growth in young black birch and red maple trees. *Canadian Journal of Forest Research*, **23,** 302–306.