ROOT GROWTH DYNAMICS AND CONSTRAINTS ON ABOVE GROUND GROWTH AND YIELD OF WALNUTS

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ABSTRACT

There are three components to this project. The first is a minirhizotron root growth study that was installed to monitor seasonal root growth patterns in an existing Chandler pruning and irrigation trial. The peak in root growth occurred in late June in both the fourth and fifth growing seasons. In the fourth growing season, initiation of roots was greatest in the minimal pruned treatment and in the fifth growing season root initiation was greatest in the heavily pruned treatments. The peak of root growth in the minimally and heavily pruned treatments tended to be at a shallower depth compared to the peak in both the deficit and untrained/unpruned treatments. The root growth patterns observed were quite different from those in the Walnut Production Manual. Our results showed a single peak occurring right between the two peaks in the manual. The second component is a clonal rootstock replant trial that was initiated in a Howard orchard which had lost hundreds of trees to the yellow Howard problem. The third component is a a new experiment that was planted in the winter of 2013 which is looking at different rootstock and scion interactions as influenced by irrigation with the goal of understanding the yellow Howard problem. These experiments are providing some of the first field level observations of root growth patterns in walnut orchards over the season as well as with depth.

PROBLEM AND ITS SIGNIFICANCE

Optimization of walnut management under current and future climates requires better knowledge of root growth dynamics and root growth interactions with aboveground growth. Several current problems in walnut cultivation, such as canopy yellowing in years with wet springs and increased pathogenesis of soil borne pathogens with soil moisture (Lampinen *et al.*, 1994), may be due to constraints on fine root growth and functioning. In Yuba and Sutter Counties where the yellowing problem was acute in 2011, yellow-leafed trees comprised 30% of many orchards. Observations collected during the 2006 and 2011 season suggest that yellow-leafed trees either had overall stunted root systems or lacked ephemeral fine roots that function in nutrient uptake and appeared unable to resume growth within the same growing season after wet spring conditions ceased. There is a need to understand if root growth (or subsequent re-growth if spring roots are lost to wet conditions) is genetically controlled by rootstocks, scions, or interactions between rootstocks and scions to insure that proper recommendations are made for new plantings of current and new clonal rootstocks and scions. Better information on root dynamics could open possibilities of making a broad range of advancements to orchard management as well as provide solutions for current problems such as the yellowing Howard problem.

Patterns of walnut root growth commonly found in text books are based on limited data sets (*e.g.* Root Physiology and Rootstock Characteristics chapter in Walnut Production Manual, 1998) and likely vary for different varieties, management, and sites. Fundamental aspects of environmental and plant controls over root dynamics and function have begun to be explored (Tierney *et al.*, 2003; Comas *et al.*, 2005; Basile *et al.*, 2007) but many open questions remain especially on conditions that constrain root growth (Basile *et al.*, 2007; Comas *et al.*, 2010). Recent advances in techniques have made it easier to study roots (*e.g.* Comas *et al.*, 2000; Zeng *et al.*, 2008). This project provides actual root growth data for walnuts under field conditions as influenced by pruning treatments, soil moisture, and temperature.

OBJECTIVES

Using one existing walnut trial, one cooperating grower orchard and one new experiment, we propose to address the following questions:

1. Is there plasticity in the seasonal timing of root growth to canopy and irrigation management? Is the timing of root growth responsive to plant demands or constrained by soil moisture and temperature? (added a minirhizotron study in 2011 to an on-going pruning + irrigation trial at Nickels Soil Lab)
2. Is the degree of canopy yellowing determined by the scion? (grafting 3 scions in 2011 on previously yellow Howard trees in a Howard orchard planted in 2005 with a cooperator in Sutter County). This objective was modified since the original yellow Howard tree root systems were compromised enough that the grafts would not take. The objective was changed to a yellow Howard replant trial in the same orchard with 20 individual tree replications each of Paradox seedling, RX1, Vlach and VX211 rootstocks which were fall budded to Howard in 2013.
3. **3.** Is canopy yellowing after wet springs due to root losses in saturated soils and/or constraints on root growth? Is the timing and quantity of root growth (and re-growth if root death occurs from wet springs) determined by rootstocks, scions, or interactions between rootstocks and scions? Do root dynamics vary among rootstocks differing in vigor and *Phytophthora* resistance? Is the sensitivity to yellowing of particular scion/rootstock combinations due to restrictions in their graft union (i.e. do rootstocks/scion combinations differ in hydraulic conductance across their graft union)? (experiment at the Plant Sciences department field facility was planted in March 2013).

PROCEDURES

<u>Experiment 1</u>: This part of the project was overlaid on an existing project funded as part of the Orchard Management Project (Debuse, Edstrom, Hasey and Lampinen- Walnut Hedgerow Pruning and Training Trial). The current project added minirhizotron camera assessment of root growth in the Chandler pruning and irrigation trial that was planted in 2008. In March 2011, minirhizotron tubes were installed in the Chandlers on seedling Paradox rootstock under three pruning treatments (unpruned, minimally and heavily pruned) with conventional irrigation and one treatment of minimally pruned trees under deficit irrigation at Nickels Soil Lab (55” tubes; 4 treatments x 5 blocks x 2 tubes = 40 tubes). Root observation tubes 55” long were installed in this experiment because this orchard has trees planted on a 12” berm and because pruning and

irrigation in other systems have been show to affect the vertical distribution of roots down to 3' (Comas et al., 2005). Root growth in the soil berm and down to a soil depth of 24" will be monitored. Two trees in each treatment (total of 8 trees) also have soil temperature and moisture monitored at three depths (12, 24 and 36") adjacent to minirhizotron tubes. Aboveground measures taken as part of the existing experiment (canopy light interception, midday stem water potential, trunk growth, and yield) will be related to root growth patterns.

Experiment 2: In 2011, scion growth and signs of yellowing were monitored on new grafts on trees that had yellow canopies in 2010 in a 65 acre 5-year-old Howard orchard in Sutter County. Yellow trees in this orchard were determined to have limited fine and woody roots in 2010. A minimum of eighteen trees of uniform size with yellow canopies in 2010 were randomly selected and grafted in 2011 with one of three scions: Howard, Chandler and Tulare. The goal is to see if any of these scions grow better on Paradox rootstock where Howards were previously yellow and stunted. The root systems in this trial proved to be too compromised to support the scion growth so this experiment was abandoned. Instead, a trial was initiated in the same Howard on Paradox orchard which was planted in 2005 and has lost hundreds of trees to the yellow Howard problem. Twenty individual tree replications were planted in March 2013 with each of four rootstocks (Paradox seedling, RX1, Vlach and VX211). They were budded in the fall of 2013.

Experiment 3: A new experiment to quantify scion growth as well as root growth with a minirhizotron camera for Howard and Chandler grafted on VX211, RX1, Northen California Black, and seedling Paradox rootstocks, growing under conventional and wet spring soil conditions was planted in March 2013 (see Fig. 10 for site map). Trees were grown in a commercial nursery and were planted in February 2013 at the UC-Davis Plant Sciences experimental fields. Root growth is being monitored in minirhizotron tubes (3' tubes; 2 tubes x 5 blocks x 8 scion/rootstock combinations x 2 treatments = 160 tubes). Root growth down to a soil depth of 24" is monitored. The experimental unit for each scion/rootstock combination and treatment in each block is a group of 4 trees with the middle two trees designated as experimental trees and one buffer tree on either end. A buffer row was planted on either side of the experiment. Canopy development will be followed through the season using the mobile platform light bar starting in 2014. Stem water potential will be measured throughout the season. Onset of canopy yellowing will be monitored on a weekly basis. Trunk diameter will be measured the first spring and each fall thereafter. Three Howard on seedling Paradox under conventional and wet conditions (6 trees in total) will have soil temperature and moisture monitored at three depths each, adjacent to the minirhizotron tubes. Flushes of root growth will be related to aboveground growth and water status. The experiment will be followed for three years.

The normal irrigation treatment is designed to keep the trees within a range down to approximately 2 bars below the baseline while avoiding prolonged periods at or wetter than the baseline. The excess irrigation treatment is designed to simulate conditions that occur in a wet spring such as we have seen in previous years when yellow Howards have been a problem.

Because there was a large amount of variability in tree size as received from the nursery, a decision was made to concentrate on establishing trees in 2013 and not to impose differential irrigation treatments until the 2014 season. In addition, to variability in tree size, many of the guard trees had to be planted as clonal rootstocks and field grafted during the 2013 season. Art Ruble from Dave Wilson Nursery worked to teach us how to do in-season green grafting. This technique can be done from about June through July or even into August with success. The technique is essentially analogous to using normal dormant grafts but instead currently season shoots (from at least 16" back from the growing tip) are used for grafting. A piece of green shoot with two to three buds is grafted and then immediately completely wrapped with Buddy Tape (Shigyo Company, 12335 Viking Way, Truckee, CA 96161) or painted with a solution of Doc Farwell's Seal and Heal (Farwell Products, Wenatchee, WA 98801) diluted 1:1 with water to keep them from drying out. We had a higher success rate with Buddy tape than with Doc Farwell's Seal and Heal. These grafts started growing in as little as 7 days.

Three Irrometer dataloggers (each with seven Watermark soil moisture sensors at 8, 16 and 24" depths, and one temperature sensor at 16" depth) were installed in three reps of the Howard on Paradox seedling normal water treatments. In addition, three irrometer dataloggers with similar configurations were installed in three reps of the Howard on seedling Paradox excess water treatments. Watermark and soil temperature probe configurations are shown in Fig. 11. In addition to these loggers, three eKo wireless irrigation controllers with three Watermark sensors on each were installed in two reps with sensors again in the Howard on Paradox seedling normal and excessive water treatments. Soil moisture data from these eKo nodes can be accessed via the internet. In addition, latch valves were installed to allow control of the irrigation system from the internet or from an iPhone.

In early October 2013, the height, distance to each internode, and the number of leaflets at each position was measured on all data trees in the trial (total of 166 trees). On Aug. 1, 2014, marks were placed 5 leaves back from the tip on two shoots on each data tree in treatments 1-8. This was done to have a reference point for leaf emergence dates to assess the impact of the water treatment on leaf damage symptoms.

An additional experiment was carried out in the guard rows on the east and west edge of the trial as well as near the southern edge of the trial. This consisted of four treatments with different heading heights at the time of planting. T1, T2, T3 and T4 were cut to approximately 3, 6, 9 or 12 buds (left full height from the nursery) respectively. These treatments were repeated 3 times on Howard on Northern California Black, 8 times on Chandler on Northern California Black, 2 times on Tulare on Northern California Black and 2 times on Tulare on VX211. The uneven numbers of reps on the different rootstock and scion combinations are because these were the only trees we could get to fill in these guard rows. Measurements described above (height, distance to each internode and the number of leaflets at each position were also carried out on the height of heading trial.

RESULTS AND DISCUSSION

Experiment 1. This experiment was concluded at the end of the 2013 season. For final results, see the 2013 report.

Experiment 2: Yellow Howard replant trials- the results from this part of the trial are presented in a separate report by Hasey et.al titled "Field performance of RX1, VX211, and Vlach clonal Paradox rootstock interplants in a yellow Howard on seedling Paradox orchard".

Experiment 3- This experiment was planted in March 2013. The soil is a Rincon silty clay loam and tree spacing is 12’ down the tree row and 15’ between rows. The trial was planted at a high density because the plan is to run the trial for about 3 years only. The main trial has six replications of each of 14 treatment combinations.

Irrigation and water potential

Because of the great variability in tree size as received from the nurseries, water management was quite difficult. Initially, the experiment was set up with three irrigation sets but because they had different numbers of trees in one of the three irrigation sets, these trees received approximately 20% more water through June (three irrigation events). At this time, the sprinkler heads were changed to ones with smaller output to allow the entire experiment to be irrigated at one time which lead to much better water distribution uniformity across the trial.

However, the 4 rows that received the 20% additional water for the first three irrigations did not grow nearly as well as the rest of the trial. Many of the trees stopped growing from excessive wetness in the root zone and some did not grow again all season. Fig. 8 shows the data from 4 soil moisture sensors at a depth of 18” in the rootzone beneath trees that were healthy, slightly yellow or yellow. The wetter the soil was, the worse the tree growth.

There was a cold period in early December 2013 when the in orchard temperatures dropped below 19°F. This period, likely combined with much warmer than normal January temperatures when daytime bud temperatures reached near 80°F while night time bud tmperatures fell below freezing due to radiation to the cold night sky, resulted in the uneven leafing that was seen in this trial (Fig. 1) as well as statewide. Many of the south to southwest buds either did not emerge at all or they emerged a month or more later with some not emerging until September. This did not appear to be due to cold damage in this orchard but perhaps due to carbohydrate depletion and/or chilling related issues. The temperatures experienced by the buds were up to 8-10°C colder than the sheltered air temperature in the orchard due to radiative losses to the night sky..

Differential irrigation treatments were implemented in 2014. The excess water treatment used the irrigation system to mimic rainfall patterns that occurred during previous seasons when the yellow Howard problem was prevalent. Water application data is shown in Fig. 2. Water was applied in the excess water treatment starting in January 2014 due to the dry winter. The goal was to simulate the conditions that have occurred in years when the yellow Howard pattern has been observed. The first irrigation was not applied to the normal water treatment on May 28, 2014 and by that point the excess water treatment had 14 inches applied (Fig. 2). Total water applied for the 2014 season was 24.9 inches for the normal water treatment and 50.5 inches for the excess water treatment. The orchard has full coverage microsprinklers as well as ground cover except for an approximately 5 foot herbicide sprayed strip in the tree row so much of this water went to support the ground cover.

The excess water treatments resulted in midday stem water potentials above the baseline in the early part of the season (Fig. 3). The normal water treatment trees tended to run about 1-2 bars drier than the excess water treatment trees (Fig. 3).

Trees that ran near or wetter than the baseline through the early part of summer had a number of leaf damage symptoms including yellow leaves, leaf tip burn, marginal browning of leaves, etc. Some examples of the symptoms that occurred on the wet trees are shown in Fig. 4. These symptoms were only seen on excessively wet trees and although many of them look like nutrient deficiencies or excesses, they are a result of excessively wet soil conditions. Under these conditions the roots may not be able to access nutrients so they could be related to deficiencies caused by nonfunctional roots under the wet conditions.

Minirhizotron

The total number of roots produced by season per square meter of minirhizotron window is shown in Fig. 5. The largest peak in root production occurred in spring of 2013. There were some treatment differences with Howard producing a bigger flush on Paradox compared to on NCB (Fig. 5). There were no clear differences in seasonal root production related to irrigation treatment (Fig. 5). Root production was considerably less in the spring of 2014 (Fig. 5). This may be due to a number of factors including the fact that the irrigation system is full coverage meaning there is a lot of soil for roots to explore. In addition, the soil texture is considerably finer that that at the previous trial at Nickels Soil Lab which should result in less need for roots to explore soil so vigorously due to higher water holding capacity of the soil. Finally, it appears that our minirhizotron tubes were not deep enough to capture the rooting zone since at the lowest level, in general root density was still increasing compared to in shallower soil levels for most rootstock and scion combinations (Fig. 6).

The number of living roots and number of dead roots by treatment over the 2014 season is shown in Fig. 7. Although the production of roots was quite low in the spring and summer of 2014, the total number of living roots by mid to late summer remained quite high (Fig. 7). In general, the roots in this trial appear to be living longer than those in the previous minirhizotron trial at Nickels Soil Lab. This may be due to some of the factors cited earlier such as the finer soil texture and full coverage irrigation system. In addition, the stress cycles at the Nickels trial tended to be much more severe than at the current trial. By late summer, the number of living roots tended to be greater for Howard on NCB compared to Howard on Paradox (Fig. 7). This was not expected and possibly might give some hints as to why the yellow Howard syndrome is mostly confined to Paradox rooted trees.

Fig. 8 shows the root growth pattern from the Walnut Production Manual versus the root growth patterns observed in our two minirhizotron trials.

Tree growth

The trees on NCB were generally larger than the seedling Paradox rooted trees at the time of planting (Tables 1 and 2) but as the 2014 season progressed the NCB rooted trees tended to lag behind the growth of the seedling Paradox rooted trees (Fig. 9). The clonal trees were budded after one season in the nursery and planted out in the field trial the following winter so they were all essentially one year younger than the nursery grafted NCB and Paradox rooted trees. In addition, many of these buds failed and had to be regrafted in the field. In general the excess water treatment trees tended to have larger trunk diameter and were taller in height than the normal water trees although the difference was less for Howard (Table 1 and 2; Fig. 9 and 10).

Within a scion and rootstock combination, there were interesting differences in trunk diameter increase over the 2014 season in response to seasonal average midday stem water potential. For trees with Chandler as the scion, the excess water trees tended to get larger with wetter (less negative) seasonal average midday stem water potentials (Fig. 11). For the normal watered Chandler, trunk diameter increase tended to be less with more stress once the seasonal average midday stem water potential averaged about 1 bar below the baseline. For Howard the response was quite different. For Howard on Paradox, the trees had the greatest increase in trunk circumference if water potential averaged about 1 bar less than the baseline but if the trees were either drier or wetter, trunk circumference growth decreased rapidly. For Howard on NCB, the excess water trees grew best on the drier side with the normal watered Howard on NCB doing best at a seasonal average midday stem water potential of about 1 bar below the baseline.

Part of these differences can be explained by the generally smaller stature of the Howards (Table 1). In addition, the leaf damage symptoms described earlier were much worse on Howard compared to Chandler.

Height of heading trial

For the height of heading trial, first year results were quite variable due to the fact that half of the trees were in one of the four rows impacted by the excess early season water. However, it did not appear that heading the trees had any beneficial impact in overcoming the water problems. A headed and unheaded tree from the row that received excess water are shown in Fig. 12. The headed and unheaded tree both were stunted and grew to the same final height by the end of the 2013 season. By the end of the 2014 season, the unheaded tree had put on slightly more elongation growth than the headed tree (Fig. 12).

Because sample size for the various scion and rootstock combinations in the height of heading trial were small, the data for all were combined for statistical analysis. There were no significant differences in trunk circumference after either the end of the 2013 or 2014 seasons (Table 3).The trees that were headed most severely (to 3 buds) were significantly shorter at the end of the 2013 season but no longer significantly shorter at the end of the 2014 season (Table 4).

Photos of both replications of the unheaded Tulare on Vlach trees and those that were headed to 3 buds are shown in Fig. 13. . The trees that were headed to 3 buds were significantly shorter than the other three treatments while the other three treatments were not significantly different in height at the end of the 2013 and 2014 season (data not shown).

PRELIMINARY CONCLUSIONS

This trial is providing root growth data for walnut that appear to contradict the root growth data in the Walnut Production manual. The peak in root growth in both seasons occurred in late June and we did not see a substantial later season peak in root production. There is some indication that excessive soil temperatures may be playing a role in limiting root growth, particularly in young walnut orchards. Water management during late May through early July may be particularly critical in young, developing orchards since root and canopy growth are both occurring at a rapid rate during this period. It is unclear how these conditions would differ with flood versus sprinkler irrigation compared to the double line drip used in the current study. More research is needed to investigate the role of different types of irrigation systems on soil temperature and root growth.

Experiment 3 was somewhat confounded by the large variation in tree size at the time of planting. Despite these problems (and partly because of these problems), results are quite interesting. Because of the large variation in tree size, there was an enhanced impact of the excess water treatments on the smaller trees within each rootstock and scion combination. In particular, the Howard on Paradox appeared to be very sensitive to either over or under watering and this may be related to their propensity to develop the yellow Howard syndrome. This study is providing documentation of many of the leaf damage symptoms that are seen in orchards that are excessively wet. Since these symptoms often mimic mineral deficiencies and toxicities this will be very useful information. Rooting in this trial is substantially deeper than in the previous trial at Nickels Soil Lab. This may be due to the larger coverage irrigation system, a finer soil texture and perhaps also the fact that the orchard was only irrigated approximately every 2 weeks which means the soil was wetted to a lower depth. Root longevity also appears to be longer in this trial.

Results from the height of heading trial suggest that under the conditions of this trial, there is no benefit associated with heading the trees at the time of planting. The concept of heading the trees is based on the idea that you are bringing the shoot and root into balance due to the loss of roots that occurs during the harvest process at the nursery. However, the initial root growth occurs largely from stored carbohydrate reserves and when you head the tree, much of this stored reserve is removed.

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Table 1. Chandler diameter (mm) by rootstock on different dates for normal (top) and excessive (bottom) irrigation treatments for Experiment 3.

Normal irrigation treatment

	Chandler			Howard		
Rootstock	**4/26/13**	**10/31/13**	**11/13/14**	**4/26/13**	**10/31/13**	**11/13/14**
Paradox seedling	23.44 bc	49.99 b	76.10 a	24.58 ab	50.21 a	65.34 a
VX211	27.16 b	39.08 c	68.70 ab	26.83 a	37.89 ab	54.38 ab
Vlach	25.61 b	42.19 c	65.89 ab	24.70 ab	39.44 ab	55.24 ab
RX1	19.93 c	38.77 d	61.71 b	19.20 c	30.38 b	53.08 b
NCB	38.50 a	58.02 a	78.11 a	22.35 bc	41.12 ab	57.68 ab

Excessive irrigation treatment

	Chandler			Howard		
Rootstock	**4/26/13**	**10/31/13**	**11/13/14**	**4/26/13**	**10/31/13**	**11/13/14**
Paradox seedling	22.29 b	52.81 a	93.97 a	24.97 a	46.78 a	74.14 a
NCB	35.25 a	55.50 a	91.83 a	23.54 a	42.22 a	69.77 a

Table 2. Chandler height (cm) by rootstock on different dates for normal (top) and excessive (bottom) irrigation treatments for Experiment 3.

Normal irrigation treatment

	Chandler			Howard		
Rootstock	**4/26/13**	**10/31/13**	**11/13/14**	**4/26/13**	**10/31/13**	**11/13/14**
Paradox seedling	53.69 ab	305.72 a	327.28 a	53.69 b	315.65 a	326.22 a
VX211	33.75 cd	204.52 b	277.45 a	35.70 cd	158.50 c	216.63 b
Vlach	44.24 bc	267.13 a	270.80 a	41.00 c	236.05 abc	252.73 b
RX1	28.66 d	267.55 a	272.50 a	30.23 d	193.90 bc	243.69 b
NCB	63.50 a	300.04 a	316.92 a	63.50 a	255.68 ab	266.17 b

Excessive irrigation treatment

	Chandler			Howard		
Rootstock	**4/26/13**	**11/13/14**	**11/13/14**	**4/26/13**	**10/31/13**	**11/13/14**
Paradox seedling	55.02 a	311.06 a	357.66 a	63.38 a	292.68 a	344.83 a
NCB	58.74 a	317.06 a	363.71 a	61.07 a	272.25 a	329.66 a

Table 3. Height of heading trial results for trunk diameter at two feet for all varieties and rootstocks combined for 2013 and 2014 seasons.

Heading treatment	Diam. at planting March 2013 (mm)	Diam. May 2014 (mm)	Diam. Dec. 2014 (mm)
T1- 3 buds	33.2 a	44.1 a	71.1 a
T2- 6 buds	34.1 a	44.4 a	70.4 a
T3- 9 buds	33.3 a	45.1 a	72.1 a
T4- 12 buds	33.8 a	47.0 a	75.2 a

Table 4. Height of heading trial results for tree height for all varieties and rootstocks combined for 2013 and 2014 seasons.

Heading treatment	Height at planting March 2013 (cm)	Height Oct. 2013 (cm)	Height Dec. 2014 (cm)
T1- 3 buds	61.0 d	240.4 b	283.2 a
T2- 6 buds	85.5 c	289.6 a	315.7 a
T3- 9 buds	114.3 b	315.3 a	293.1 a
T4- 12 buds	134.4 a	331.7 a	339.1 a

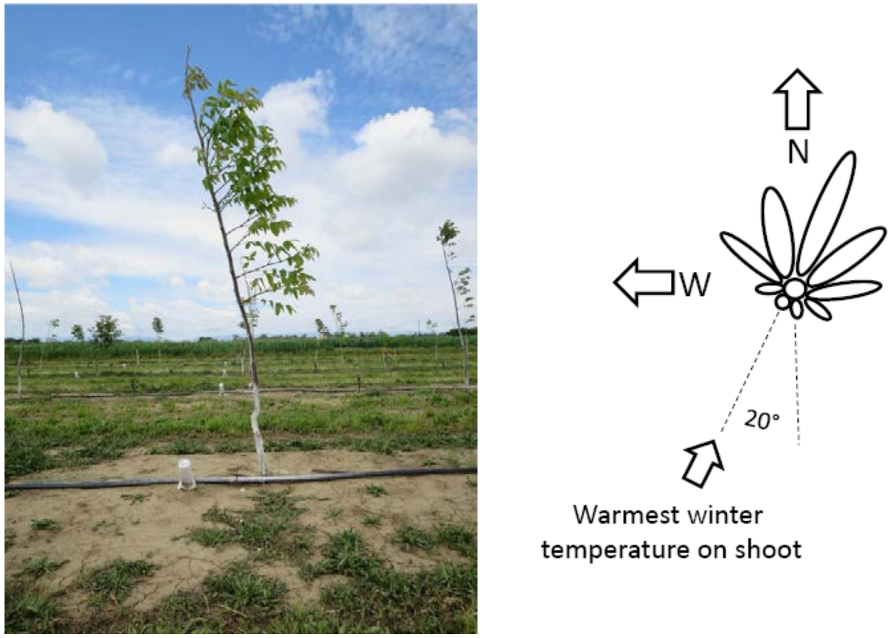

Fig. 1. Irregular growth on south (to the left in photo) and the north side of the on campus trial. The figure on the right shows the relative growth of shoots around the tree. The longest shoots were about 20 degrees to the east of north and the shortest 20 degrees to the west of south. Many of the south to southwest buds came out much later while in the spring while others came out in September.

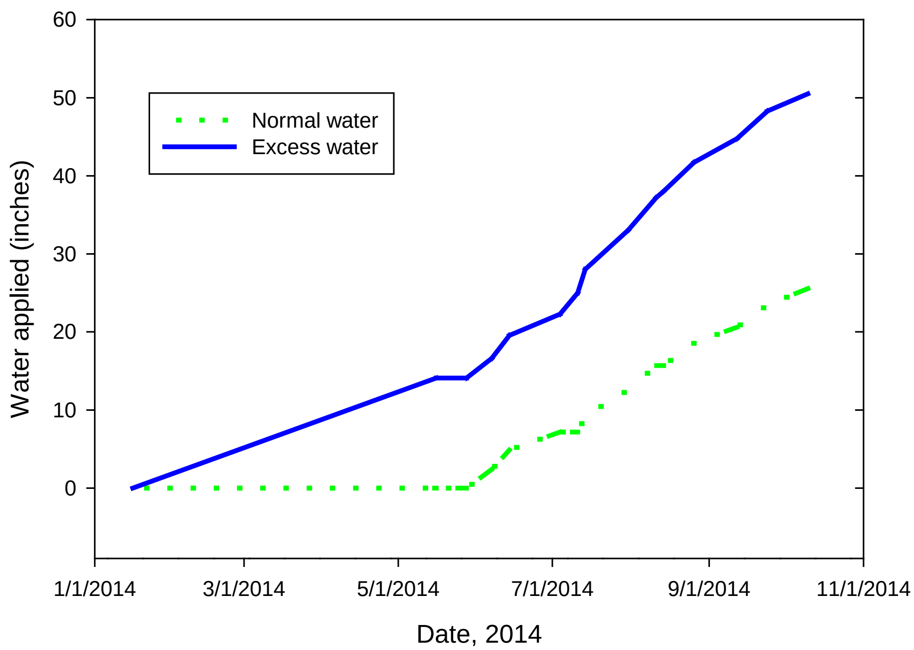

Fig. 2. Applied water over the 2014 season by irrigation treatment. Due to the dry period through January, water applications on the excess water treatment started in early January to fill the profile and simulate a wet winter/spring. First irrigation was applied on normal water treatment on May 28, 2014.

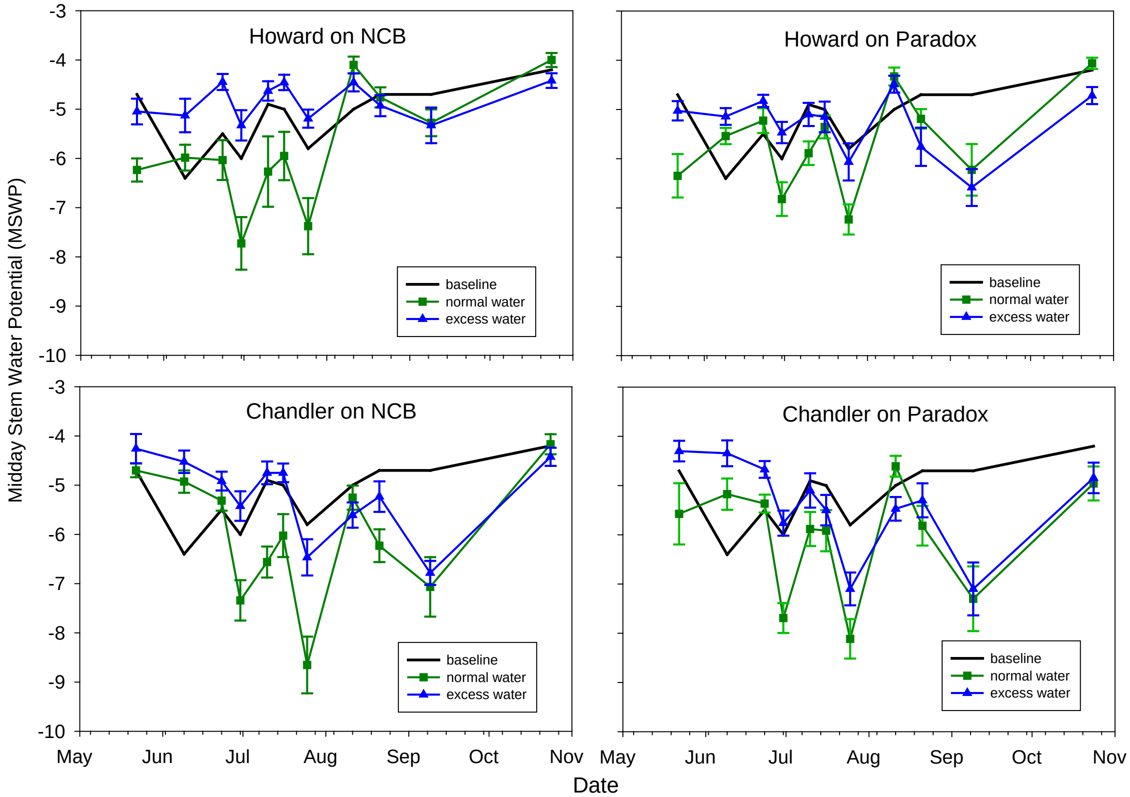

Fig.3. Midday stem water potential over the 2014 season by irrigation treatment for Howard on NCB (upper left), Howard on Paradox (upper right), Chandler on NCB (lower left) and Chandler on Paradox (lower right). pruning treatments in Experiment #3.

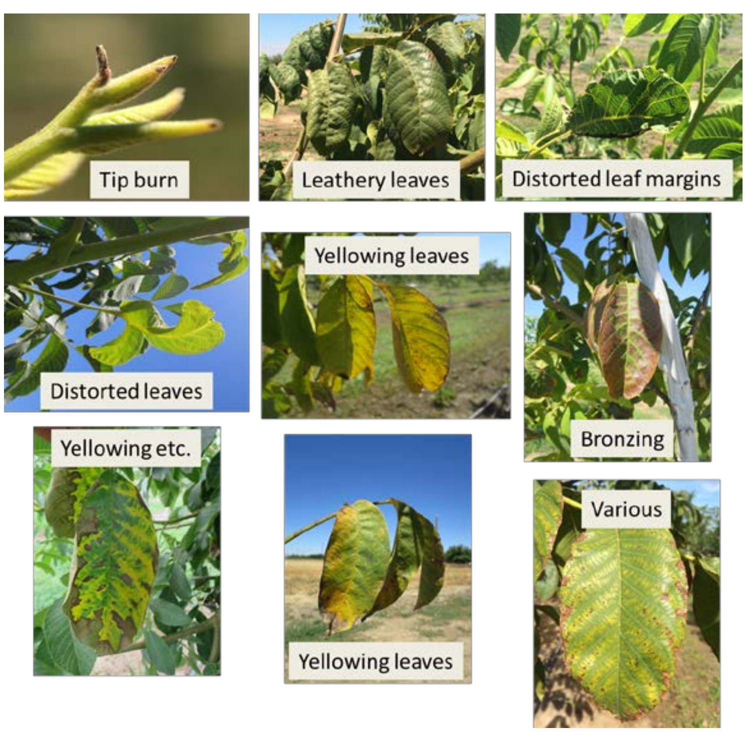

Fig.4. Leaf damage symptoms observed on trees that were running at or wetter than the baseline during early summer.

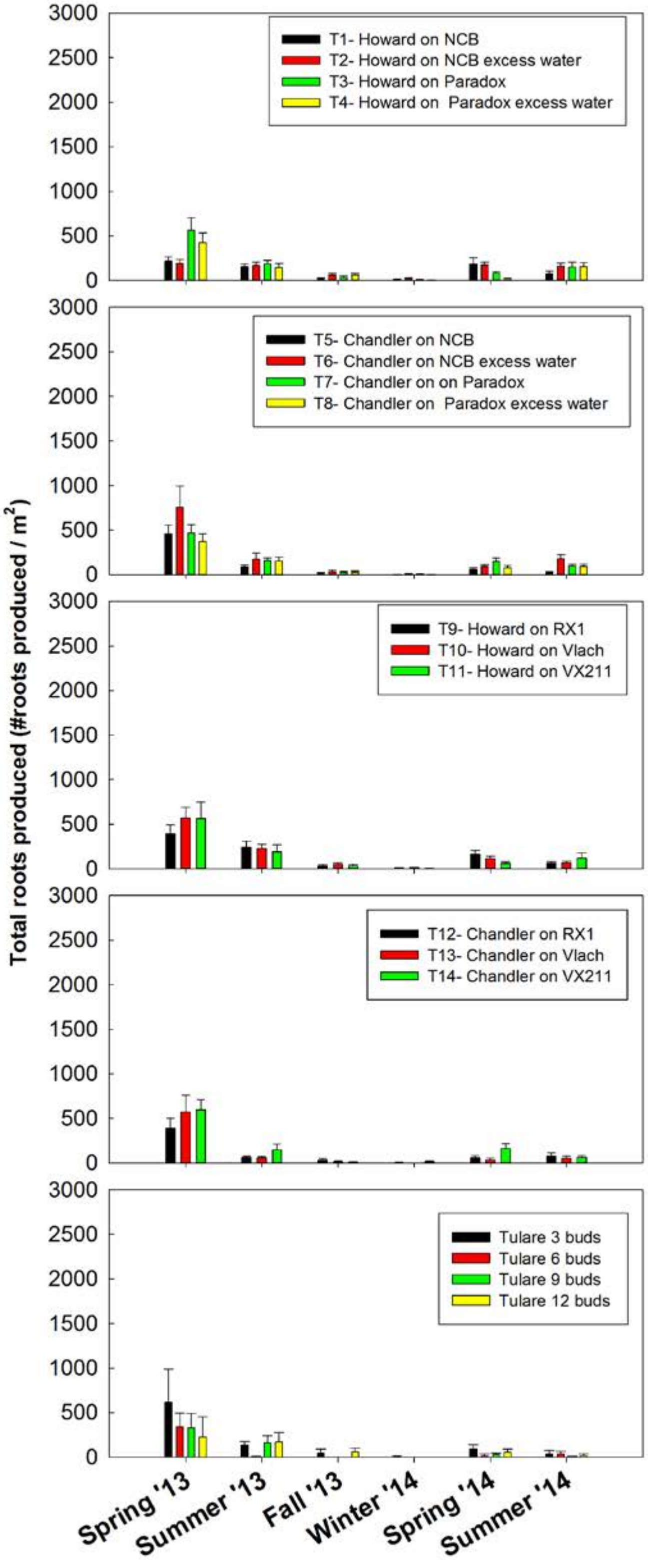

Fig. 5. Total number of roots produced per square meter of minirhizotron window by season for the 2013 and 2014 seasons.

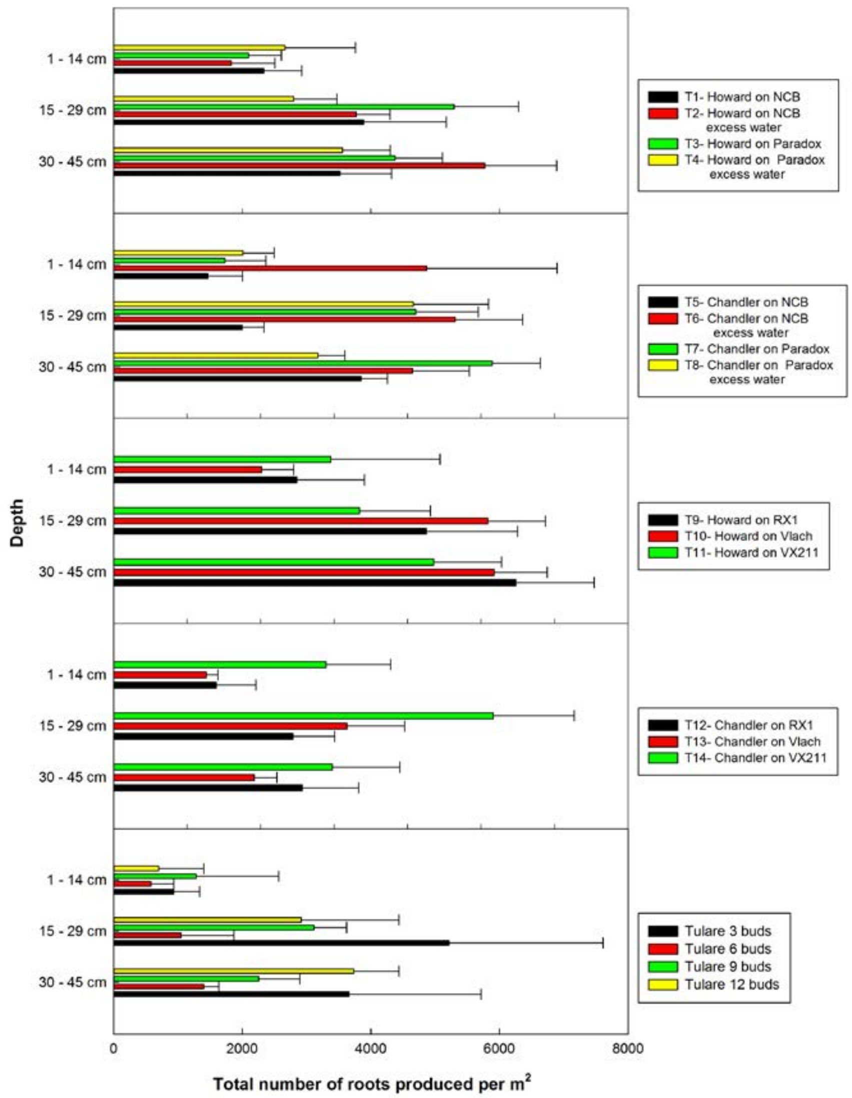

Fig.6. Total number of roots produced by treatment and depth per square meter of minirhizotron window.

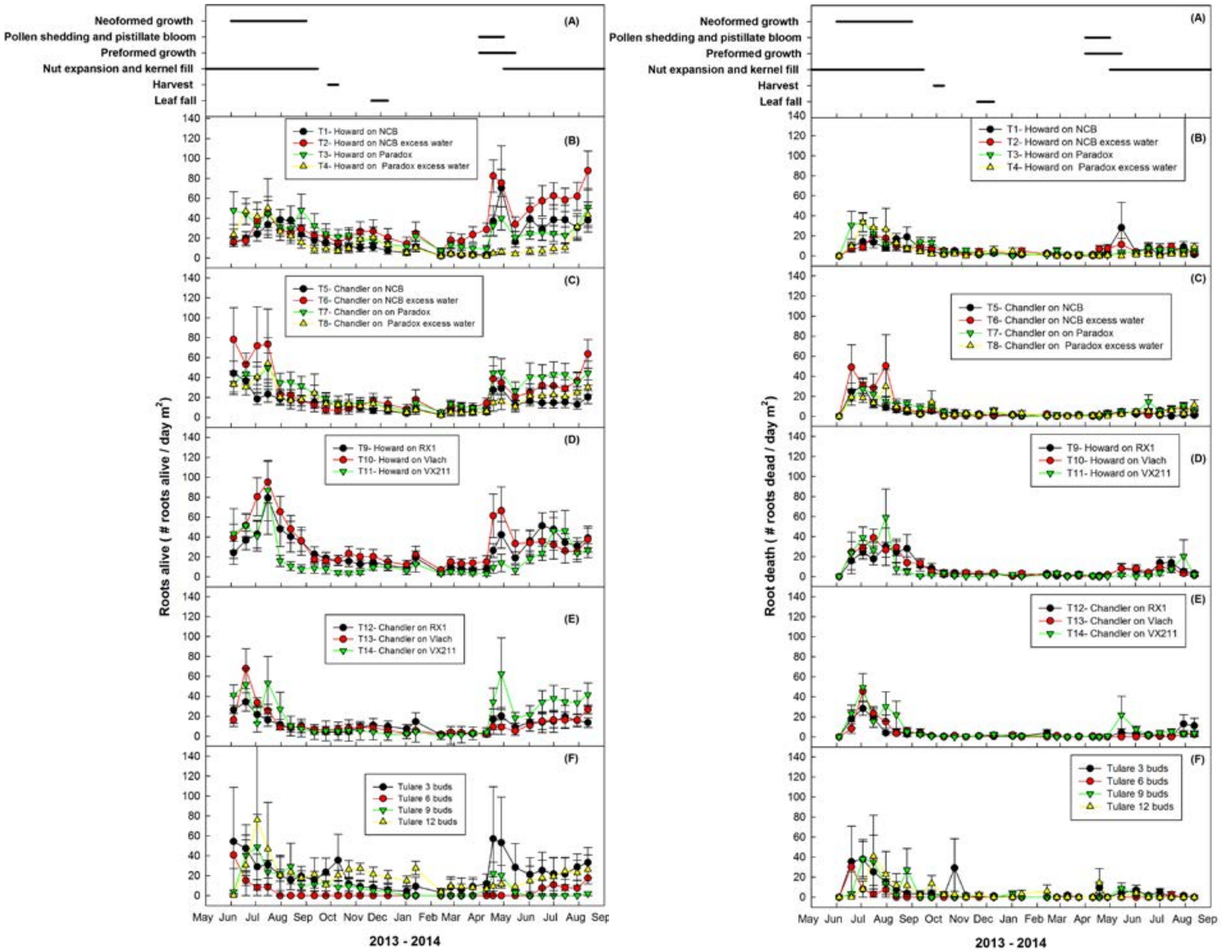

Fig.7. Total number of living roots per cm^2 of window area (left) and number of dead roots (right) on a daily basis for the 2013 and 2014 seasons by treatment.

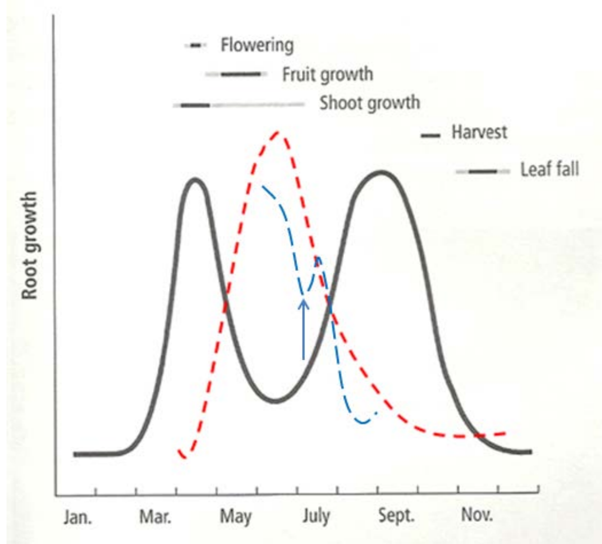

Fig. 8. The black line is the walnut root growth curve from the current walnut production manual. The red dashed line is the walnut growth curve observed in our 2011-12 minirhizotron trial for Chandler at Nickels Soil Lab. The blue dashed line is the root growth pattern observed in 1 year old walnuts in our on-campus walnut trial. The upward facing arrow indicates a period where trees in the on-campus trial were somewhat water stressed in order to attempt to balance out tree size by slowing growth of the biggest trees.

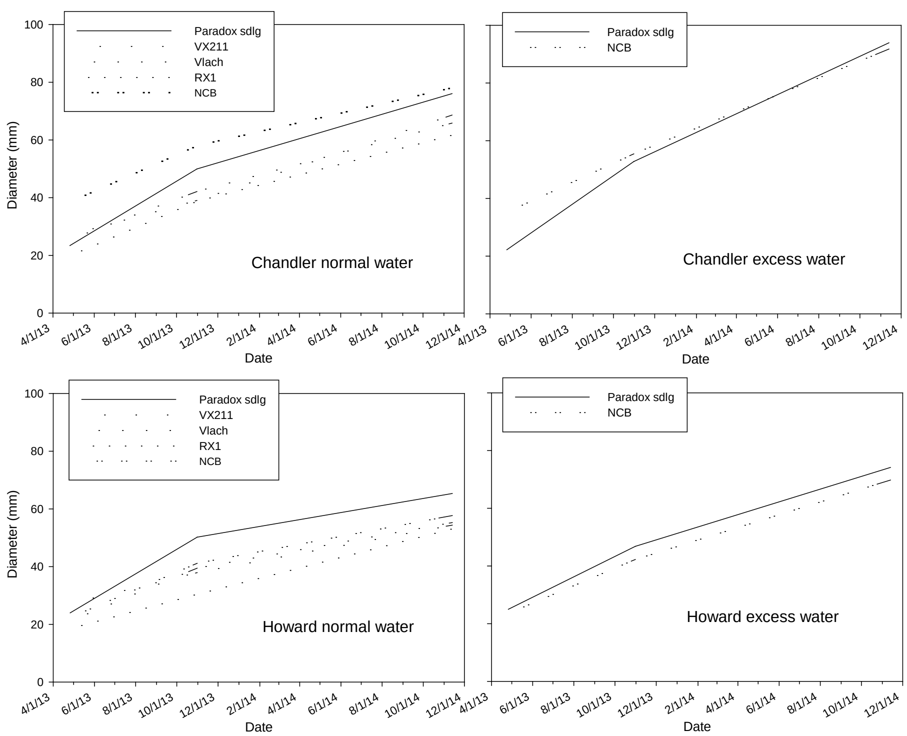

Fig. 9. Trunk diameter by rootstock on three measurement dates for Chandler normal water (upper left), Chandler excess water (upper right), Howard normal water (lower left), and Howard excess water (lower right).

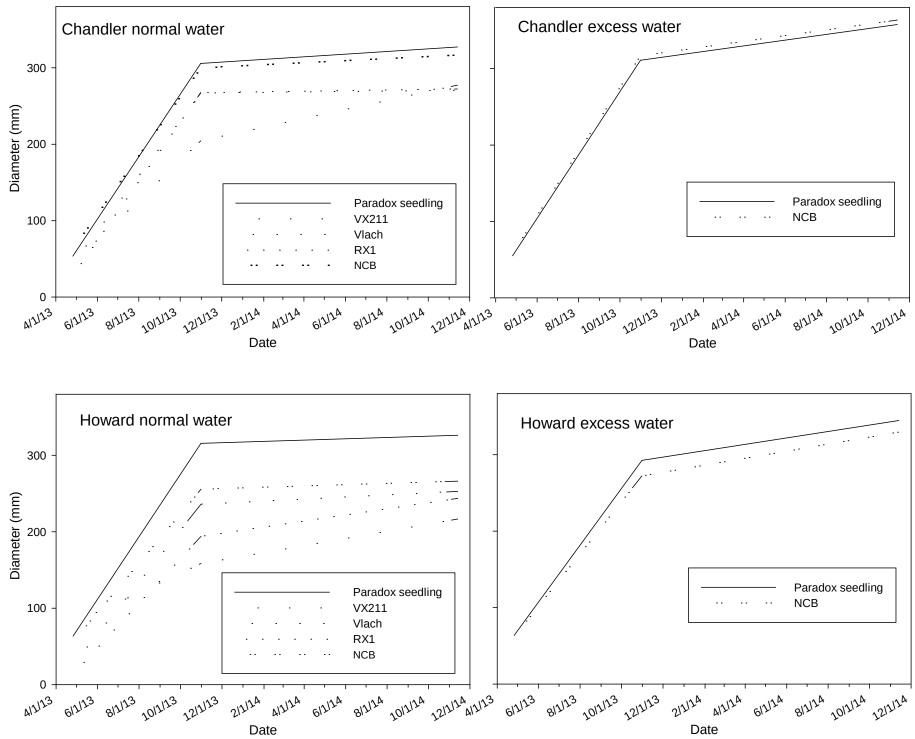

Fig. 10. Tree height by rootstock on three measurement dates for Chandler normal water (upper left), Chandler excess water (upper right), Howard normal water (lower left), and Howard excess water (lower right).

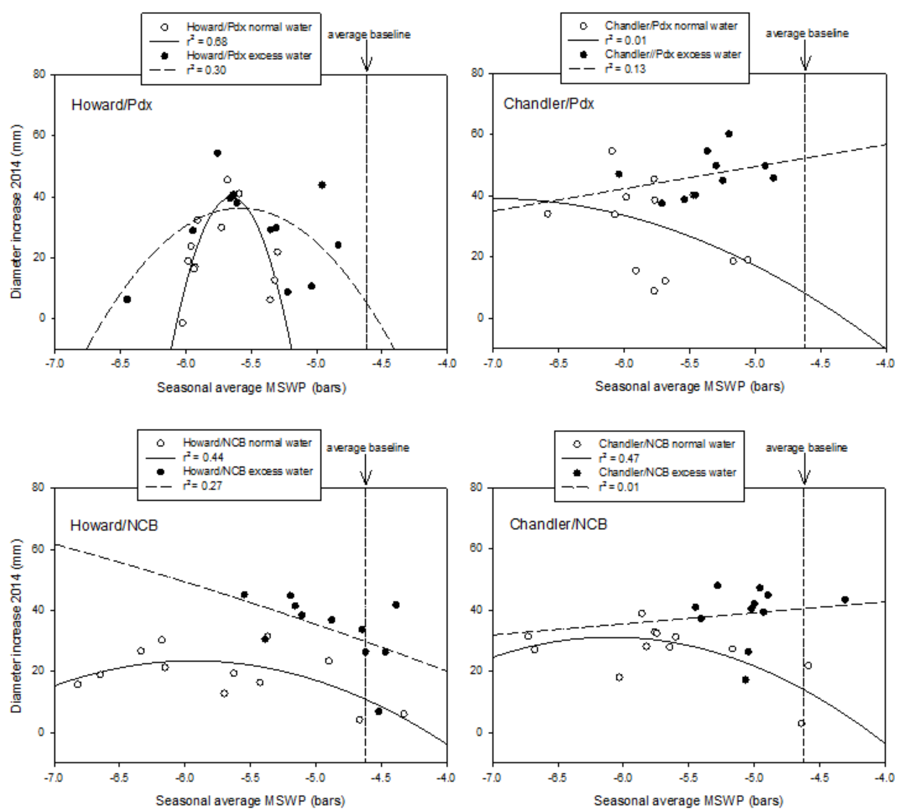

Fig. 11. Seasonal average midday stem water potential (MSWP) versus diameter increase by rootstock and scion for 2014 season.

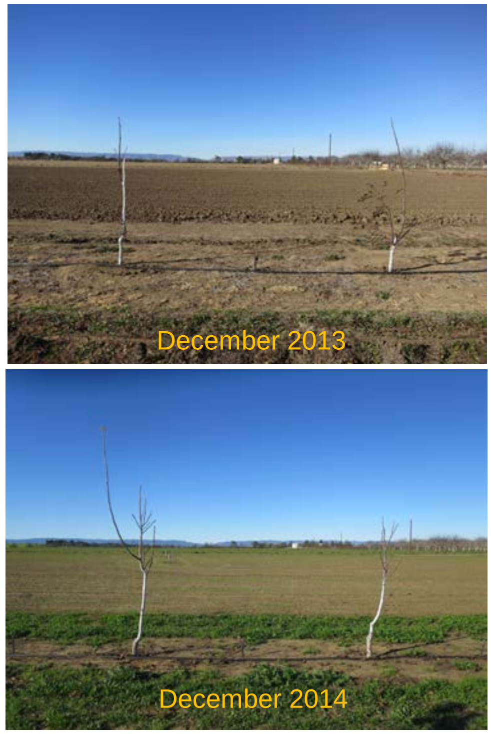

Fig. 12. Howard on Northern California Black tree that was left full length from nursery on the left, and on right, one that was cut to 3 buds at the time of planting. Top photo was taken in December 2013 and bottom photo in December 2014. Both trees were in rows that got stressed from excess water application through June in 2013.

Fig. 13. Tulare on Vlach that were left at height they arrived from nursery on left and trees that were headed to 3 buds on the right.