THE EFFECT OF WATER STRESS ON WALNUT TREE GROWTH, PRODUCTIVITY, AND ECONOMICS

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INTRODUCTION

Walnut has become the leading agricultural commodity in Tehama County as it nears about 14,000 acres of orchards. Water management is a fundamental cultural practice influencing orchard performance. This publication summarizes findings and experiences after five years (2000 to 2005) of on-farm experimentation with irrigation of Chandler and Howard English walnut varieties grown on Northern California Black and Paradox rootstocks. Our goal was to develop science-based information that would benefit walnut producers and support the walnut industry. One of our main objectives was to further the understanding of how crop water stress, as a result of irrigation management, influences the growth and development of modern walnut varieties and orchard designs, productivity, and the economics of walnut production. We also worked to develop and demonstrate practical applications of new irrigation management tools. We also considered this work valuable to help the position of the walnut industry given the growing competition for water resources.

WATER STRESS IN WALNUT

Causes of Water Stress

Water stress in walnut can either be the result of too much or too little water and sometimes the combination of both at different times in the life of an orchard. It may be expressed by relatively acute symptoms such as leaf wilt, reduced shoot growth, sunburn, and defoliation. Water stress may also be expressed by chronic symptoms such as shoot die-back, crown and root rot, and tree decline and eventual death. In some seasons and in some field settings too much water is the result of uncontrollable natural phenomena such as excessive rainfall, high water table, and flooding. In other situations, too much water may be the result of water management decisions such as starting the irrigation season too soon, applying too much water per irrigation, irrigating too frequently, operating irrigation systems that apply water non-uniformly, or exposing sensitive parts of the tree such as the root crown to excessive water. Conversely, too little water may result from starting the irrigation season too late, applying too little water per irrigation, irrigating too infrequently, or operating irrigation systems that apply water non-uniformly. When too much or too little water is applied repeatedly over the life of the orchard, it may be at the expense of overall productivity and orchard longevity.

Understanding Water Stress in Walnut

To understand the effects of water stress in walnut, it is helpful to have a way to qualify crop stress with some detail and to have a broad range of experience with different levels of water stress and walnut responses. Otherwise, water stress " is in the eye of the beholder" and what may appear as water stress in an orchard to one individual may not appear as water stress to another. In addition, if water stress and its effects on walnut can be better understood there may be opportunity to use water stress beneficially. Two such examples may be managing growth of non-bearing trees to reduce incidence of cold injury and to improve the effectiveness of pruning when training trees.

The two experiments conducted in Tehama County from 2000-2005 involved methods that quantified water stress in some detail and evaluated a broad range of water stress levels for effects on walnut. Water stress levels were quantified by measuring the amount of irrigation water applied with flow meters, measuring orchard water status with a pressure chamber and midday stem water potential, and measuring soil moisture levels with two different monitoring techniques, resistance blocks and a neutron probe.

One experiment, located in Cottonwood, was conducted on third and fourth leaf Howard walnuts on Paradox rootstock in 2001 and 2002. This experiment was relatively short-term where simple measurements of shoot growth were correlated with different levels of irrigation water, midday stem water potential, and soil moisture. Table 1 describes the range in irrigation water applied in the experiment in 2002.

Table 1. Description of irrigation levels evaluated on 4th leaf Howard walnut on Paradox rootstock at Cottonwood experiment in 2002.

Walnut Tree Stress Level	Irrigation Level – Applied Water (inches per acre)
Low Water Stress	22.0
Medium Water Stress	19.2
High Water Stress	14.0

The second experiment, west of Corning, was conducted on 8th – 11th leaf Chandler from 2002 through 2005. The orchard was hedgerow design with 81 trees per acre. Approximately every third tree was Chandler on Northern California Black rootstock and the other trees were Chandler on Paradox rootstock. The orchard was planted on a combination of relatively shallow, class I and II soils, which included the Maywood, Arbuckle, and Perkins Series. As a result, the soil water holding capacity was limited to 3 or 4 inches of available water storage in a five-foot deep profile. Table 2 describes the range in irrigation water applied and water stress evaluated in this experiment.

Table 2. Description of irrigation levels evaluated on 8th – 11th Chandler walnut on Paradox and Northern California Black rootstock at Corning experiment in 2002 - 2005.

Monthly Avg	Four-year Average SWP (-bars)		
	Low	Mild	Mod
May	-3.8	-4.0	-4.3
June	-4.2	-5.0	-5.8
July	-4.3	-6.9	-7.7
Aug	-3.8	-7.0	-8.6
Sept	-3.8	-7.9	-9.4
Season Avg	-4.0	-6.2	-7.2
Applied Water (in.)	42	28	23
% Less Water	----	36	46

Each orchard was irrigated with microsprinkler irrigation and comparisons were established primarily by reducing the water application rate with smaller nozzles and reduced irrigation set times of each irrigation event. On occasion, irrigation events were skipped to create differences in water stress. While four-year averages are provided in Table 2 to describe the Corning experiment, it is emphasized that water stress levels varied each season as a result of weather conditions and as time elapsed between irrigations. In general, water stress levels temporarily ranged from –2 to -6 bars tension above or below the average values reported in Table 2 depending on the circumstances.

Experimental plots were relatively small, under an acre, in the Cottonwood study. Experimental plots in the Corning study totaled ten acres. Randomized and replicated experimental designs were used to facilitate statistical analysis of the data and to evaluate repeatability of the results. This enabled us to establish a higher level of confidence in the findings. Other management variables were measured to ensure that other cultural practices did not affect orchard performance and bias the findings. A wide range of experimental data was collected routinely and frequently during each growing season, depending on the objectives of each experiment. This included amount of irrigation water and rainfall used by the crop, walnut tree water stress levels, soil moisture levels, plant nutrition levels, shoot growth, bud development, nut size development, dry in-shell yield, standard commercial walnut quality parameters, crop value and total payment, and tree health and longevity.

WALNUT RESPONSE TO WATER STRESS

Shoot Growth

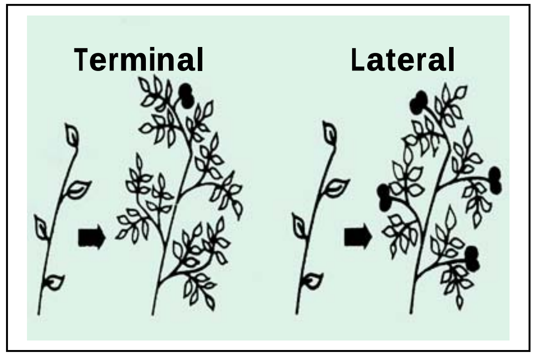

Figure 1. Illustration of shoots from terminal and lateral fruit bearing walnut varieties.

One important reason for conducting the experiments was to evaluate walnut growth responses to water stress of two of the predominant English walnut cultivars, Chandler and Howard varieties, currently produced by the industry. In young, non-bearing orchards rate of shoot growth can affect tree training, the length of time to bring a new orchard into production, and susceptibility of new growth to cold injury. In established, bearing orchards, these varieties are characterized as lateral fruit bearing varieties opposed to earlier varieties such as Hartley which are characterized as terminal fruit bearing varieties. With Chandler and Howard (lateral bearing) varieties, the question was how and to what extent is shoot growth affected by water stress? Is the number of buds on a fruiting branch, the fate of the buds, that is, whether buds are viable and whether they are vegetative or fruitful, and the number of flowers set and nuts produced affected by water stress and irrigation management?

Table 3 shows shoot growth of non-bearing Howard walnut is affected by irrigation management. In general, within reasonable bounds, more irrigation water stimulates shoot growth and withholding water can suppress growth. This indicates that irrigation management can be used to manipulate shoot growth to achieve desirable management goals.

Table 3. Effect of irrigation on growth of pruned walnut shoots, 4th leaf Howard variety, grown on Paradox rootstock at Cottonwood in 2002.
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Applied Water (inches/ac)	Average Seasonal Shoot Growth* (feet)
23.0	6.4
19.2	5.2
14.0	4.8

Figure 2 illustrates the relationship between shoot growth of bearing Chandler walnut trees and midday stem water potential measured with a pressure chamber. Shoot growth averaged between 8 and 18 inches (30 to 45 centimeters) per month when irrigation was managed to limit water stress to a monthly average between –3.5 and –5.0 bars tension. Increased levels of water stress as indicated by average monthly midday stem water potential levels of between –5.0 to –7.0 bars resulted in reduced rates of shoot growth ranging from 1 to 8 inches (2.5 to 20 centimeters) per month. Water stress levels averaging over –7.0 bars tension resulted in very little or no shoot growth. From these results, it is evident that water stress directly influences the growth rate of pruned shoots and midday stem water potential measurements with a pressure chamber are reliable for detecting water stress and to anticipate the effect of water stress on shoot growth.

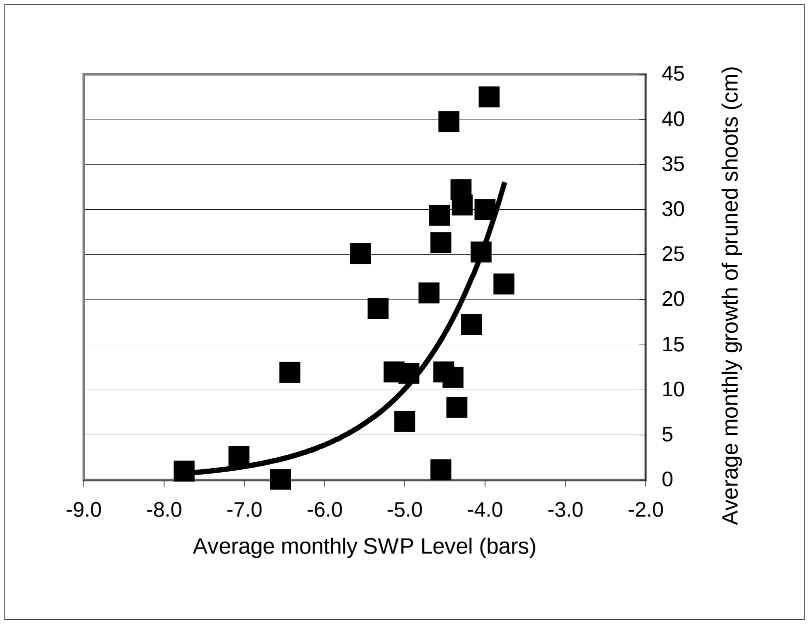

Figure 2. The relationship between growth of pruned shoots and water stress as indicated by midday stem water potential measurements.

Table 4 shows the effect of irrigation and water stress on the average seasonal shoot growth of 8th and 9th leaf Chandler walnuts at the Corning experiment. The findings show that there was not a significant reduction in shoot growth between trees where water stress averaged –3.4 bars tension over the season and where water stress averaged –6.2 bars tension but there was a significant reduction when water stress averaged –7.3 bars tension over the season. This did raise the question whether Chandler walnut could tolerate a mild level of water stress without effecting yield potential.

Bud Development and Nut Load

Table 5 describes the irrigation and water stress levels at the Corning experiment from 2002 through 2004. It also shows how water stress affected the total percentage of terminal shoots per fruiting branch, the percentage of terminal shoots with floral terminals, the percentage of flowers per floral terminal, and nut load. Results of the bud development data indicated that irrigation and water

Table 4. The effect of irrigation and water stress on seasonal shoot growth of pruned shoots on 8th and 9th leaf Chandler Walnut grown on Paradox rootstock, 2002 and 2003 seasons Corning experiment.

Two-year Average Applied Water (inches/ac)	Average Seasonal Midday SWP (- bars)	Average Seasonal Shoot Growth * (feet)
44.1	-3.4	3.5 a
28.7	-6.2	3.3 a
23.8	-7.3	2.4 b

stress did significantly affect bud development in Chandler walnut. Under mild and moderate levels of reduced irrigation where midday stem water potential averaged –6.2 bars and –7.2 bars tension over the season nut load was reduced by 24 and 31 percent, respectively. This occurred at mild levels of water stress even though seasonal shoot growth of pruned shoots (Table 4) was not significantly reduced. Water stress reduced nut load by decreasing the percentage of buds that opened after dormancy, the shoots that opened had a higher percentage of vegetative buds and a lower percentage of floral buds (bloom), and the floral buds had a lower percentage of flowers.

Table 5. Effect of three consecutive years of irrigation and water stress on bud development of first year fruit wood on Chandler walnut grown on Paradox rootstock, Corning experiment, 8th through 10th leaf from 2002 - 2004.

Three-year Average Applied Water (inches/ac)	Three-year Average Midday SWP (- bars)	Reduc-tion in buds that opened (%)	Reduction in floral buds (%)	Reduction of flowers per floral bud (%)	Reduction in nut load (%)
43.7	-3.5	0 a	0 a	0 a	0 a
28.0	-6.0	-1 a	-18 b	-3 a	-24 b
23.6	-7.2	-12 b	-12 b	-9 b	-31 b

Production

Tables 6 and 7 show the cumulative, four-year, effect of water stress as a result of different irrigation levels on dry in-shell yield of Chandler walnut when grown on Paradox and Northern California Black rootstock, respectively. Overall yield was significantly higher, 30 percent, for Chandler walnut on paradox rootstock than on Northern California Black rootstock when irrigation was not limiting either rootstock. This reflects the added hybrid vigor of the Paradox rootstock. When irrigation was withheld on Chandler walnut grown on Paradox rootstock, cumulative dry in-shell yield was reduced by 46 to 76 lbs per tree when water stress reached mild to moderate levels. On a per acre basis, the yearly average, dry in-shell yield of Chandler walnut on Paradox rootstock was reduced by 930 to 1540 lbs per acre per year depending on the level of water stress. Water stress decreased annual average dry in-shell yield of Chandler walnut on Northern California Black rootstock to comparable levels. Yield was reduced by 44 and 60 lbs per tree or the equivalent of 890 and 1215 lbs per acre per year at mild and moderate water stress levels, respectively. A reduction in nut load per tree was the primary reason for the yield loss.

Table 6. Cumulative, four-year, effect of irrigation and water stress on dry in-shell yield of Chandler walnut grown on Paradox rootstock, Corning experiment 2002 – 2005.

Avg Applied Water (in/ac)	Seasonal Avg SWP (-bars)	Yield (lbs/tree)	Percent less Yield	Total Number of Nuts per tree
42	-4.0	266 a	-----	12,052
28	-6.2	220 b	17	10,064
23	-7.4	190 c	29	8,914

Table 7. Cumulative, four-year, effect of irrigation and water stress on dry in-shell yield of Chandler walnut grown on Northern California Black rootstock, Corning experiment 2002 – 2005.

Avg Applied Water (in/ac)	Seasonal Avg SWP (-bars)	Yield (lbs/tree)	Percent less Yield
42	-4.0	185 a	-----
28	-6.2	141 b	24
23	-7.4	125 c	32

Walnut Quality and Crop Value

Table 8 shows the average annual crop value of Chandler walnut grown on Paradox and Northern California Black Rootstock. In three out of four years, the exception was 2004, walnut kernel color was lighter when water stress was maintained at lower levels with irrigation management. It resulted in significantly higher crop values on the order of five cents per pound. Lighter kernels and higher crop value resulting from less water stress was evident for Chandler walnut grown on both Paradox and Northern California Black rootstock.

Table 8. Average annual crop value after four years of irrigation and water stress in Chandler walnut grown on Paradox and Northern California Black rootstock, Corning experiment, 2002 – 2005.

Avg Applied Water (in/ac)	Seasonal Avg SWP (-bars)	Value Paradox ($/1000 lbs)	Value Black ($/1000 lbs)
42	-4.0	972.04 a	946.09 a
28	-6.2	927.77 b	920.75 b
23	-7.4	920.54 b	908.55 b

Tree Longevity

The photos in Figures 3 and 4 illustrate another perspective on irrigation and water stress, that is long-term tree health and longevity as affected by root diseases. Crown Gall (Figure 3a) and crown and root rot diseases (Figure 3b) such as Phytophthora are a concern with irrigation management. Both types of root diseases have historically been a challenge in the larger commercial orchard, Crown Gall on Paradox rootstock and crown and root rot diseases on Northern California Black rootstock. For the most part, the crown gall has been managed successfully with horticultural surgery techniques.

Figure 3. Photo of Crown Gall on Paradox rootstock.

Table 9 reports the percentage of Chandler trees grown on Paradox and Northern California Black rootstock showing mild to moderate symptoms of decline and severe decline or death for each irrigation level. Approximately 600 trees (about 400 were Paradox and 200 on Northern California Black) were evaluated in the experiment in 2005 at the end of the fourth year of experimentation. The results show very low incidence of tree decline with Paradox rootstock . There was no significant relationship between Chandler tree decline on Paradox rootstock and irrigation level after four years of experimentation.

Figure 3. Photo of crown rot Northern California Black rootstock, with inset.

In contrast, Table 9 shows a significant relationship between tree decline with Chandler on Northern California Black rootstock and irrigation. Incidence of long-term tree decline from crown and root rot diseases was significantly higher when more irrigation water was applied and water stress was lower. Approximately one out of every four trees on Northern California Black rootstock showed severe decline or had died where irrigation was most intense. Incidence of tree decline diminished greatly even to the point of no severe decline or death when irrigation was withheld to levels of imposing mild and moderate water stress. However, reducing long-term tree decline in Chandler on Northern California Black rootstock was at the expense of large reductions in productivity. It was unclear from this experiment whether the significant level of tree decline on Black rootstock was from too intensive of irrigation scheduling and associated with lower crop water stress levels or due to spinning microspinklers that directly sprayed the tree trunk and root crown with water each time the a 360° sprinkler revolution was completed (several thousands of times in a 24 hour irrigation set). In this instance, stream splitters on the microsprinklers may have been logical place to begin managing the tree loss.

Table 9. Effect of irrigation and water stress on Chandler tree health and longevity when grown on Paradox and Northern California Black rootstock, Corning experiment, 2002 –2005.

Rootstock	Avg Applied Water (in/ac)	Seasonal Avg SWP (-bars)	Percentage of trees in mild to moderate decline	Percentage of trees in severe decline or dead
Paradox	42	-4.0	0.0	0.0
Paradox	28	-6.2	2.7	1.3
Paradox	23	-7.4	1.3	1.3
Black	42	-4.0	10.3	24.2 a
Black	28	-6.2	6.3	3.0 b
Black	23	-7.4	3.1	0.0 b

ECONOMICS OF WATER MANAGEMENT IN WALNUT

Total Payment

Table 10 summarizes the four-year effect of crop water stress on total payment for Chandler walnut grown on both Paradox and Northern California Black rootstock. Total payment was significantly higher for Chandler walnut on Paradox rootstock when water stress was maintained at low levels with irrigation. Over four years, total payment was $57 and $87 per tree higher as the result of higher dry in-shell yield and higher crop value due to lighter kernel color. This was a very significant difference in total payment (an average of over $1400 per acre per year) when it is considered that there were 81 trees per acre at the Corning orchard.

Similarly, total payment was significantly higher with Chandler walnut on Northern California Black rootstock when water stress was maintained at low levels with irrigation, but only if the rootstock remained healthy. Over four years, total payment was $44 and $59 per tree higher due to higher yield and higher crop value due to lighter kernels. Likewise, total payment per acres was much higher, potentially up to an average of $1200 per acre per year, but only if the rootstock remained healthy.

Table 10. The effect of four consecutive years of crop water stress on total payment for Chandler walnut grown on both Paradox and Northern California Black rootstock.

Seasonal Avg SWP (-bars)	Total Payment Paradox ($/tree)	Paradox Percent Less Payment	Total Payment Black ($/tree)	Black Percent Less Payment
-4.0	267.23 a	----	181.31 a	----
-6.2	210.53 b	21	137.72 b	24
-7.4	180.12 c	33	122.24 b	33

The Relationship Between Irrigation and Other Management Decisions

It is appropriate to consider irrigation along with other management decisions such as rootstock selection, nutrition, and pruning. The success of each management consideration is dependent on the other decisions.

Referring back to Table 9 and the discussion related to tree decline with Chandler walnut on Northern California Black rootstock, clearly irrigation has affected the long-term health of the trees on Northern California Black rootstock and, conversely, the selection of rootstock has affected the success of the irrigation. This is a classic example of the interactions between irrigation and other cultural practices and the need to balance them.

Table 11 shows the effect of four consecutive years of crop water stress on total payment of Chandler walnut on both Paradox and Northern California Black rootstock as long as the rootstock remains healthy. Table 11 emphasizes that too much water stress by withholding water on Paradox rootstock may negate the investment made in the more costly hybrid rootstock.

Other possibilities for interactions may involve nutrition and pruning. Additional fertilization may not be beneficial if irrigation is limiting and vice-versa. Likewise, pruning may not be as effective if irrigation is limiting.

Table 11. The effect of irrigation and water stress on the productivity of Paradox and Northern California Black rootstock.

Rootstock	Avg Applied Water (in/ac)	Seasonal Avg SWP (-bars)	Four-year Avg Dry Inshell Yield (lbs/tree)	Four-year Total Payment ($/tree)
Paradox	42	-4.0	266 a	267.23 a
Paradox	28	-6.2	220 b	210.53 b
Paradox	23	-7.4	190 c	180.12 c
Black	42	-4.0	185 c	181.31 c
Black	28	-6.2	144 d	137.72 d
Black	23	-7.4	130 d	122.24 d

Summary

A number of lessons can be gleaned from this experience. Some highlights include, irrigation management is a basic cultural practice that can affect the horticultural and economic success of a walnut orchard. Because of its importance, irrigation scheduling is encouraged whether in the form of soil moisture or crop water stress monitoring or tracking crop water demand based upon real-time weather conditions. Measuring midday stem water potential with a pressure chamber can be useful to help understand crop water stress levels and irrigation needs and it can be used in concert with soil moisture monitoring and estimates of crop water use. Lastly, our experience affirms that modern English walnut varieties and orchard designs are quite sensitive to irrigation and crop water stress and securing a long-term, reliable and flexible water supply will be important to the industry in-lieu of the growing competition for water.