Final Report

Project Information

Title: Determination of root distribution, dynamics, phenology and physiology of almonds to optimize fertigation practices.

Period: 1/2012 – 12/2014

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A. Objectives

1 Determine almond root growth and phenology and characterize root distribution and nutrient uptake activity as influenced by tree nitrogen status, irrigation source, yield and plant characteristics.
2 Determine the patterns and biological dynamics (Km, Vmax, Cmin/max) of tree nitrogen uptake and the relationship to tree demand and phenology.
3 Integrate root phenology and uptake data into the HYDRUS 2D model to help interpret and extend findings to a wider range of soils, irrigation and demand scenarios.
4 Publication and extension of results.

B. Abstract

Optimal fertilization practice can only be developed if knowledge of the 4 R's (right source, right rate, right place, and right time) are explicitly developed for the Almond production context. To optimize nutrient use efficiency in fertigated almond it is essential that fertilizers injected into irrigation system are provided at the optimal concentration and time to ensure that deposition patterns coincide with maximal root nutrient uptake. To effectively fertigate information on the biology and phenology of roots and uptake must then be integrated with fertigation system design (micro-sprinkler, drip, volume, distribution pattern, etc.). In this project, two experiments have been set to determine almond root characteristics such as nitrate uptake physiology, root phenology and root distribution, according to different management practices. Results demonstrate considerable adaptability in nitrate uptake with changing soil nitrate concentrations. When soil nitrate concentrations are low, roots adapt and nitrate uptake mechanisms become more capable of removing nitrate form low concentrations. Plants adapted to high nitrate soils cannot effectively scavenge nitrate form low concentration soils. Plants adapted low nitrate conditions, however, are not well adapted to nitrate uptake from soils high in nitrate. In both scenarios root swill adapt to changing conditions though the speed with which this occurs is not known. From a practical perspective, fertilization strategies that maintain a near constant soil nitrate concentration (high frequency fertigation) will develop roots well adapted to scavenge nitrate from those soils.

The seasonal patterns and depth of root growth were investigated over a 2-year period utilizing soil excavation and mini-rhizotrons. Fine active roots are predominantly located in the 0-20 inch root depths, which coincides with the soil volume wetted during a typical fertigation event. Additional roots were present at depths of up to 60 inches though these tended to be large roots and were at a far lower root density. Two root flushes are observed in Almond, the first and major flush (>90% of root growth) occurs coincident with leaf out, with a second, but variable, flush commencing in October. The amount of root growth appears to be inversely proportional to yield, with lowest root production in high yield years.

The data from this experiment will inform the design of fertigation strategies and the timing and quantity of N application to achieve efficient nitrogen use.

C. Introduction

This project is designed to provide critical information on root growth and nutrient uptake to provide fundamental information on root adaptability to changing soil nitrate and the seasonality of root growth in Almond. This project complements the recently completed FREP project ‘Development of a nutrient budget approach and optimization of fertilizer management in almond' that has established the scale and timing of N demand in almond. Better understanding of the physiology and phenology of root growth and nitrogen uptake gained through this project is essential to the optimization of N application strategies.

In California, almonds are the most important tree crop species and are California’s most valuable export crop. Greater than 78% of almond growers currently provide N fertilization generally as fertigated product; however there has been very little research to explicitly optimize the use of fertilizers and to use the available fertigation systems to optimize nutrient use efficiency and to develop best fertilizers management practice. A recent survey of almond growers in California illustrated that most growers are dissatisfied with their current nutrient management practices and wanted greater information on the integration of irrigation and fertilization.

Optimal fertilization practice can only be developed if knowledge of the 4 R’s (right source, right rate, right place, and right time) are explicitly developed for the Almond production context. To optimize nutrient use efficiency in fertigated almond it is essential that fertilizers injected into irrigation system are provided at the optimal concentration and time to ensure that deposition patterns coincide with maximal root nutrient uptake. Unfortunately we have very little information to make these decisions and under the best of current practice growers merely attempt to inject fertilizers into irrigation sets so that the fertilizer band is ‘deposited’ in the middle of the vertical wetted zone. To date, there has been no explicit attempt to optimize the use of fertigation for almond nutrition from the perspective of plant biology and soil physics. In order to optimize fertigation in almond, information on the spatial and temporal distribution of nutrients and active roots in the soil profile, and knowledge of seasonal crop nutrient demand patterns is required.

Root nitrogen uptake characteristics have been well documented under controlled conditions in a wide range of species such as barley and corn (Kochian and Lucas, 1982; Siddiqi, Glass et al., 1990) and shown to be determined by nutrient concentration in soil, and plant demand. In trees, most of the attempts to measure nutrient uptake have been conducted using seedlings (Kelly and Barber, 1991; Kronzucker, Siddiqi et al., 1997) , which may not represent the condition in the field. In field experiments most of research has been focused in forest and ecological systems (Kronzucker, Siddiqi et al., 1995; BassiriRad, Prior et al., 1999; Yanai, McFarlane et al., 2009). This work has yielded valuable information of nutrient uptake at the root scale, and has concluded that uptake of a specific nutrient will depend on nutrient concentration in the medium and the demand of the plant for that specific nutrient at a determined time. To our knowledge there has been no attempt to measure and characterize nutrient uptake at the root scale in Almond trees in a field setting.

To develop fertilization best practices, knowledge of root phenology and nutrient uptake behavior and patterns of crop demand is a prerequisite. To effectively fertigate information on the biology and phenology of roots and uptake must then be integrated with fertigation system design (micro-sprinkler, drip, volume, distribution pattern etc), soil type and fertilizer source across the season. To address this complexity, computer models have been used to theoretically optimize the localization of water in the rooting profile with both soil and system specificity using the HYDRUS program (Andreu, Hopmans et al., 1997, Simunek et al, 1999; Gardenas, Hopmans et al., 2005). Currently the HYDRUS model uses generalized estimates of root uptake and crop demand that are derived from cereal crops and their relevance to tree crops is unknown. While HYDRUS-2D has great potential as management tool, modeling results remain only theoretical until results are compared with experimental field data by way of long term monitoring under field-established treatments with a broad range in irrigation water application and soil water stress conditions. The current proposal is designed to provide much of the experimental root nutrient uptake and distribution data that the model needs to function. The root nutrient uptake parameters obtained in the field and in the greenhouse settings will 'feed' the model in order to perform future simulations and obtain the best fertilization practice to provide growers with guidelines to optimize production and reduce environmental impacts.

D. Work Description

In order to achieve the objectives proposed in this project, two experimental trials have been used contrasting different rates of nitrogen (N), fertigation methods and irrigation methods.

1 Nitrogen rate experiment

The trees used in this proposed experiment have been selected from among those currently under investigation in related Board and FREP Projects (Brown/Smart/Sanden/Hopmans). The orchard is a high producing 13 year old Nonpareil/Monterey planting located south of Lost Hills in Kern County. The existing experiments provides preliminary individual tree data on yield, soil and plant water (neutron probe and plant based), plant nutrient status (5 in-season leaf samples), tree nutrient demand (sequential crop estimation and determination), leaf area index and photosynthesis and Et_0. The ongoing project of Brown has already established very clear differences in crop yield and nitrogen demand and represents an ideal field site for this work.

The treatments are described in table 1.

Table 1. Treatments utilized in the current project. Selected trees within RCBD with 6 x 15 tree replicates per treatment.

Treatment	N source	N amount (lbs/ac)
A	UAN32	125
B	UAN32	200
C	UAN32	275
D	UAN32	350

2 Fertigation method experiment

The effect of fertigation technique (pulsed, continuous, drip, microjet) will be examined in a subset of trees in the same orchard as above (Table 2) established in 2011.

Table 2. Fertigation treatments in the ongoing project. Selected trees within RCBD with 4 x 7 tree replicates per treatment.

Treatment	N source	K source	Irrigation Method	Fertilization method
E	100% UAN32	100% SOP	Fanjet	4 fertigation events / year
F	100% UAN32	60% SOP / 40% KTS	Fanjet	Continuous (fertilization in each irrigation
G	100% UAN32	100% SOP	Drip	4 fertigation events / year
H	100% UAN32	100% SOP	Drip	4 fertigation events / year

Task 1 / Objective 1: Determine almond root growth and phenology. Characterize root distribution and nutrient uptake activity as influenced by tree nitrogen status, irrigation source, yield and plant characteristics.

Forty minirhizotron access tubes were installed in both experimental trials to follow root phenology (root flushes, root lifespan, growth, etc.) over multiple seasons under four fertilization regimes. Root images have been collected during the 2012 and 2013 season in 2 week basis and with less intensity in 2014. Images will be analyzed recording number of roots, color, diameter and length. Image analysis was conducted in 2014 to generate the graphs seen here.

Additional analysis of the >300 hours of root growth images will be conducted independent of this project in 2015/16.

Individual trees have been analyzed for leaf nutrient analysis, yield, nut size and crackout percentage and contrasted among treatments (completed Dec 2014).

Task 2/ Objective 2: Determination of the patterns and biological dynamics (Km, Vmax, Cmin/max) of tree nutrient uptake and the relationship to tree demand and phenology.

A total of 80 root bags filled with media were installed in the different treatments and N uptake was measured in excised roots. The relationship between the parameters of root N uptake and tree demand will be determined once yield and N content are obtained by leaf and nut sampling at harvest. In addition, 72 soil solution access tubes (SSAT, “lysimeters”) have been installed in each treatment at 3 depths (30, 60, 90 cm) in order to sample soil solution and measure nitrate (NO_3) concentration and transport through the soil profile at each fertigation event. Data collection commenced in 2012. In 2013, and 2014 we repeated these experiments to address issues of excessive variability and to increase the range and intensity of uptake measurements (completed Dec 2014). Very considerable variability in experimental results compromised our ability to develop specific biological parameters. To compensate for this difficulty we modified objective 3 as outlined below.

Task 3/Objective 3: Integrate root phenology and uptake data into the HYDRUS 2D model to help interpret and extend findings to a wider range of soil, irrigation and demand scenarios.

The results obtained from the above tasks will be used to calibrate, validate and refine simulation models that can predict soil and nutrient transport, as well as nutrient uptake. The model will be used to perform simulations under different irrigation and fertilization practices. Data derived from the CDFA FREP funded project of Hopmans is being integrated with the results derived in this experiment to improve the modeling capability of HYDRUS. Results of the nitrate parameter determination introduced two complexities to this task that are not yet resolved. 1) There was very considerable variability in determination of soil nitrate concentrations and plant nitrate uptake parameters, 2) Plant nitrate uptake parameters are strongly determined by soil nitrate concentrations prevalent at time of sampling and change rapidly as soil nitrate changes. These two results add great complexity to Hydrus modeling that must be resolved under more highly controlled environments with more detailed measurement strategies. This is underway in a separate FREP project. Modifications to the original objectives 2 and 3 were added to compensate for our inability to resolve the biological parameters and develop Hydrus modeling strategies. A new experiment (Fertigation Strategy) described in Table 2 was initiated to replicate two typical fertigation strategies with the goal of developing semi-empirical information on the integrated effects of root distribution, tree N demand and fertilization strategy on the movement of nitrate through soils.

Task 4/Objective 4: Publication and extension of results.

This research is of use to growers, consultants and regulators. At the most fundamental level we are attempting to provide information to answer the question “how do I integrate nutrients into my irrigation regime to maximize efficiency of nutrient use”. With the information of root growth patterns and phenology, nutrient concentrations that result in optimum uptake, the interaction between above ground demand and nutrient uptake and the interactive effects of water movement and solute flow under diverse soil and irrigation schemes; we will be able to determine the best time and place for nutrients and therefore, minimize nutrient losses. In the short term the information derived on root uptake and distribution, nutrient efficiency and concentrations and patterns of annual demand represent valuable individual outcomes that can be extended directly to growers.

This project will be integrated with results derived from recently completed almond and pistachio nutrient budget projects to provide and integrated practice for fertilization rate and management. Data from this project forms an integral part of the ongoing CDFA/UC/CAPCA N Workshop Training series for CCA’s and has informed the development of new N management guidelines.

E. Results And Discussion

1 Root Growth

Patterns of root growth derived from the minirhizotron tubes are shown in figures 1 and 2, and show the pattern of root growth over the season. Irrespective of year, experiment or treatments, almond roots showed a consistent growth pattern with a dual cycle, with the majority of new roots being produced at two growth phases during the year (spring and fall). Spring root growth, occurring from mid-March to June was significantly higher than the fall growth, mainly occurring from mid-September to December. New root growth was very limited from Jun through September when maximal carbon demand for growing nuts occurred. There was very little root growth prior to leaf out with the predominant root growth period occurring after full leaf out. This result and results of prior experiments on whole tree nitrogen uptake verify that there is very little uptake of N from soil prior to leaf out in almonds.

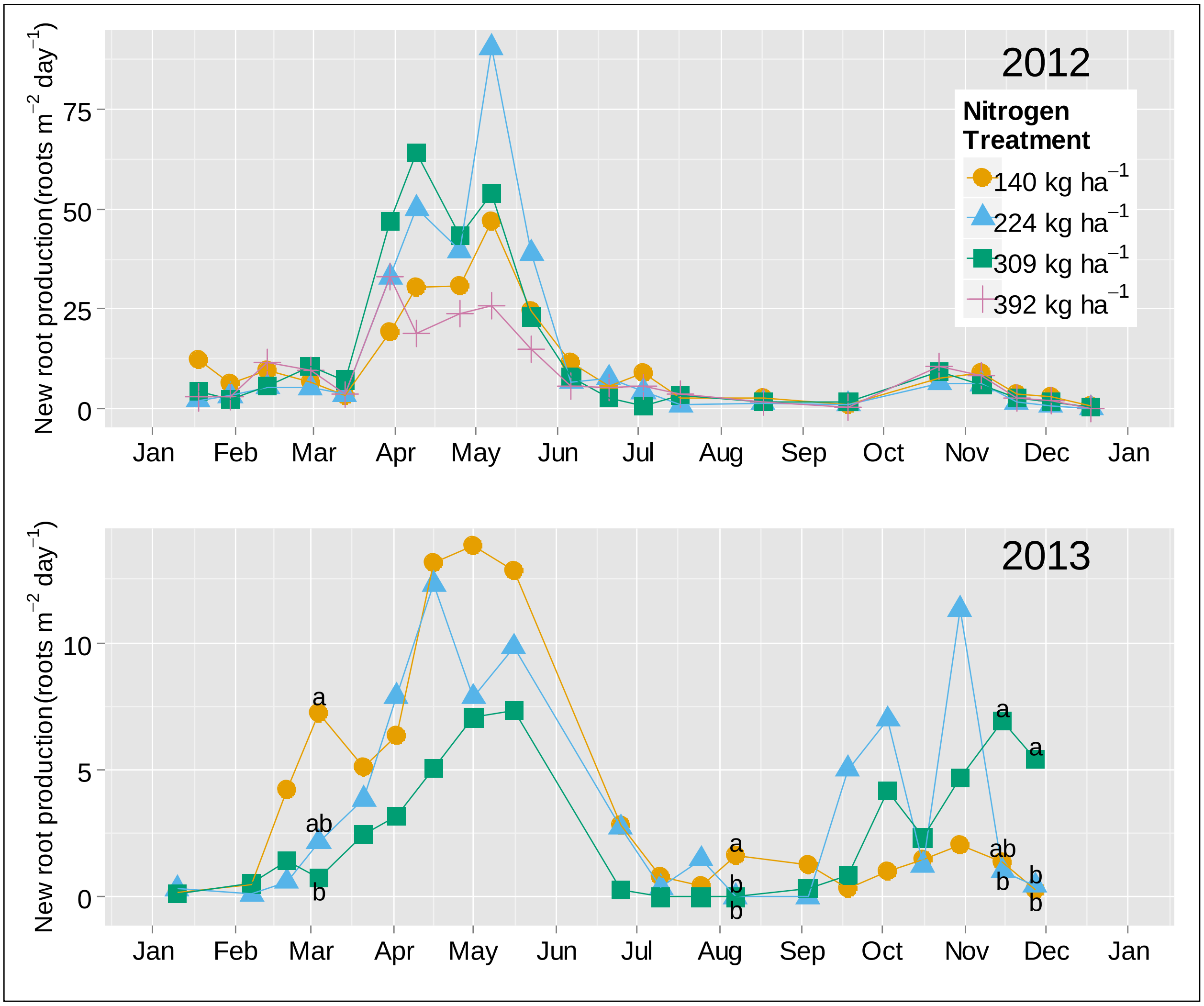

Figure 1 Number of new roots produced during the growing season in Experiment 1: N rate experiment. Note differences in scale used in these figures.

While the pattern of new root growth did not vary from year to year or between experiments the total amount of roots produced per season varied significantly from year to year (figure 1: note scales). Root growth in 2012 was significantly greater than in 2013. The reason for this is uncertain however it should be noted that yield in 2011 was exceptionally high (>4500 lbs acre) while in 2012 it was exceptionally low (900 lbs acre). The higher root growth in 2012 coincided with a very low fruit load suggesting that competition between shoots and roots defines the rate of new root growth. Interestingly this enhanced root growth occurred following an exceptionally high yield year during which tree carbohydrate reserves would have been severely depleted. This implies that new root growth is not dependent upon prior year carbohydrate storage. Similarly, the lower root growth observed in 2013 coincided with good fruit yield (3,500 lbs) further suggesting that current fruit load influences root growth. To further explore the relationship between yield and root growth a simple linear regression between yield and total amount of roots was performed (figure 3) and results showed that when yields are high, root production is low.

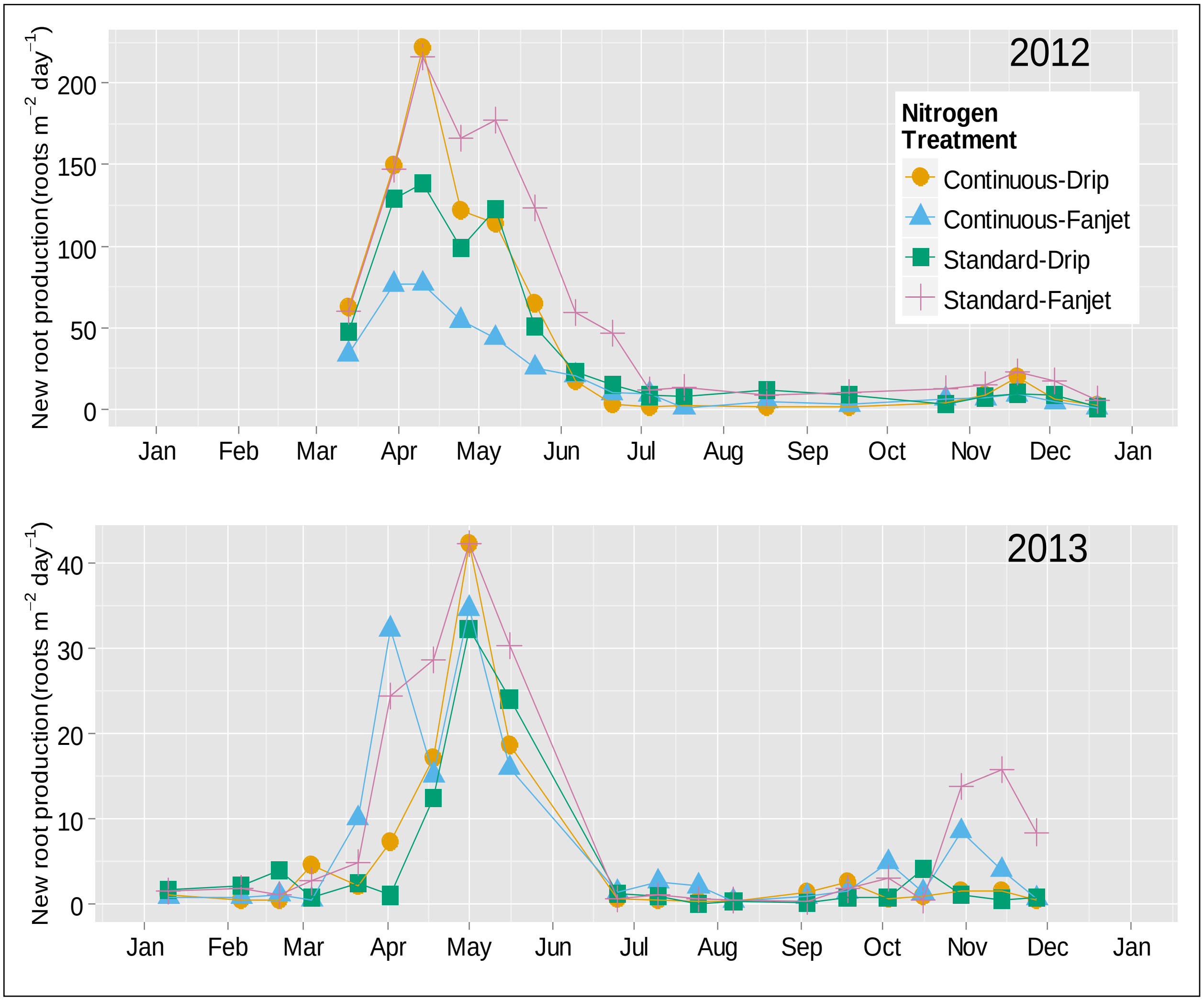

Figure 2 Number of new roots produced during the growing season in Experiment 2: Nitrogen Fertigation experiment.

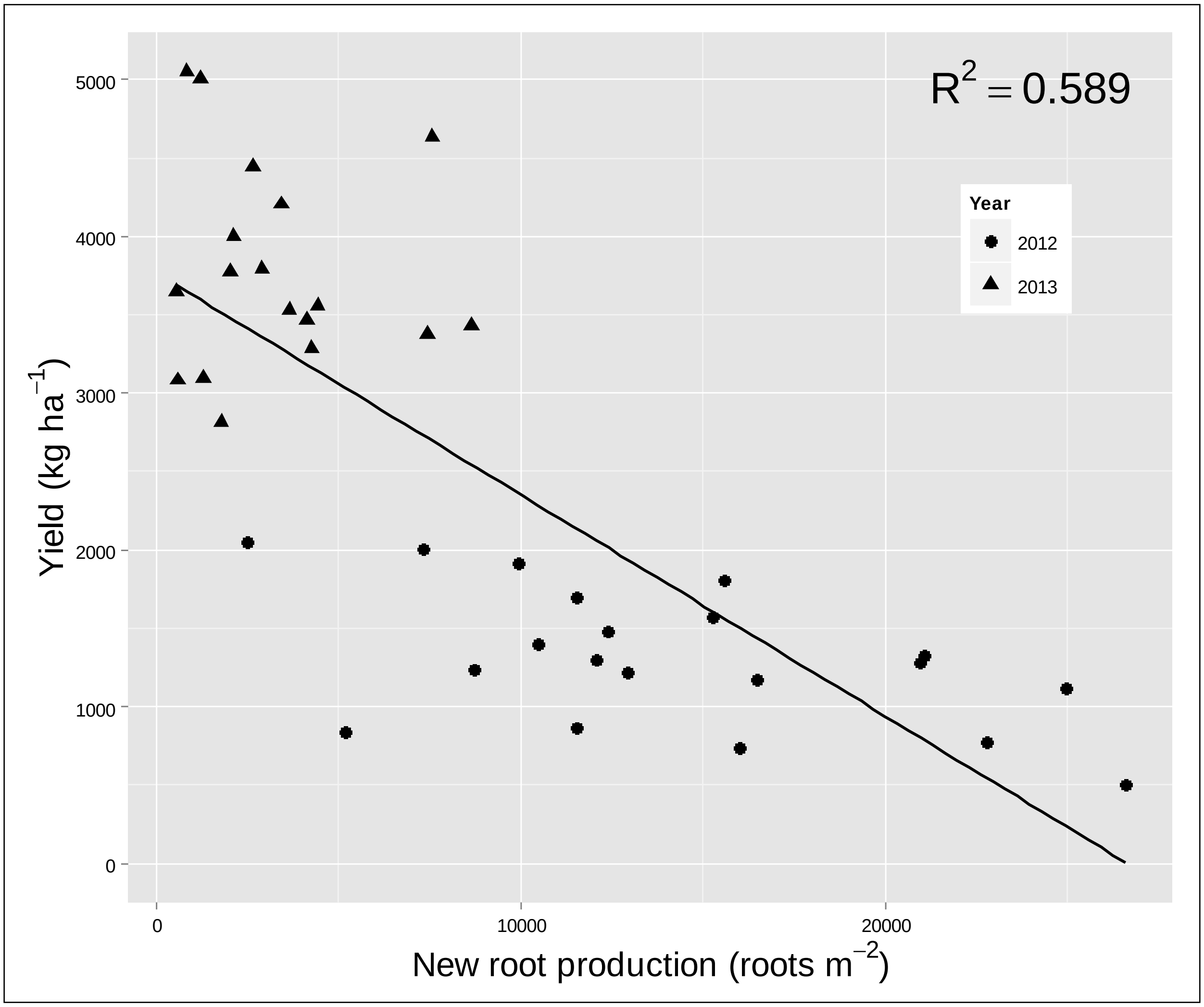

Figure 3: Correlation of new root production in 2012 with individual tree yield in that same year. Results suggest that current year yield has a significant negative effect on new root production

Patterns of root growth distribution by soil depth were determined by determining the number of new roots produce per 0.2 m interval (figure 4). There was no significant difference in root distribution or density between treatments. Despite, the wide variation in the amount of roots between years (figure 4, top graph), the percentage of roots per depth interval was similar. Virtually all the root growth is observed within 1.4 m depth, and 60-65% of the new roots are produced in between 0.2 and 0.6 m.

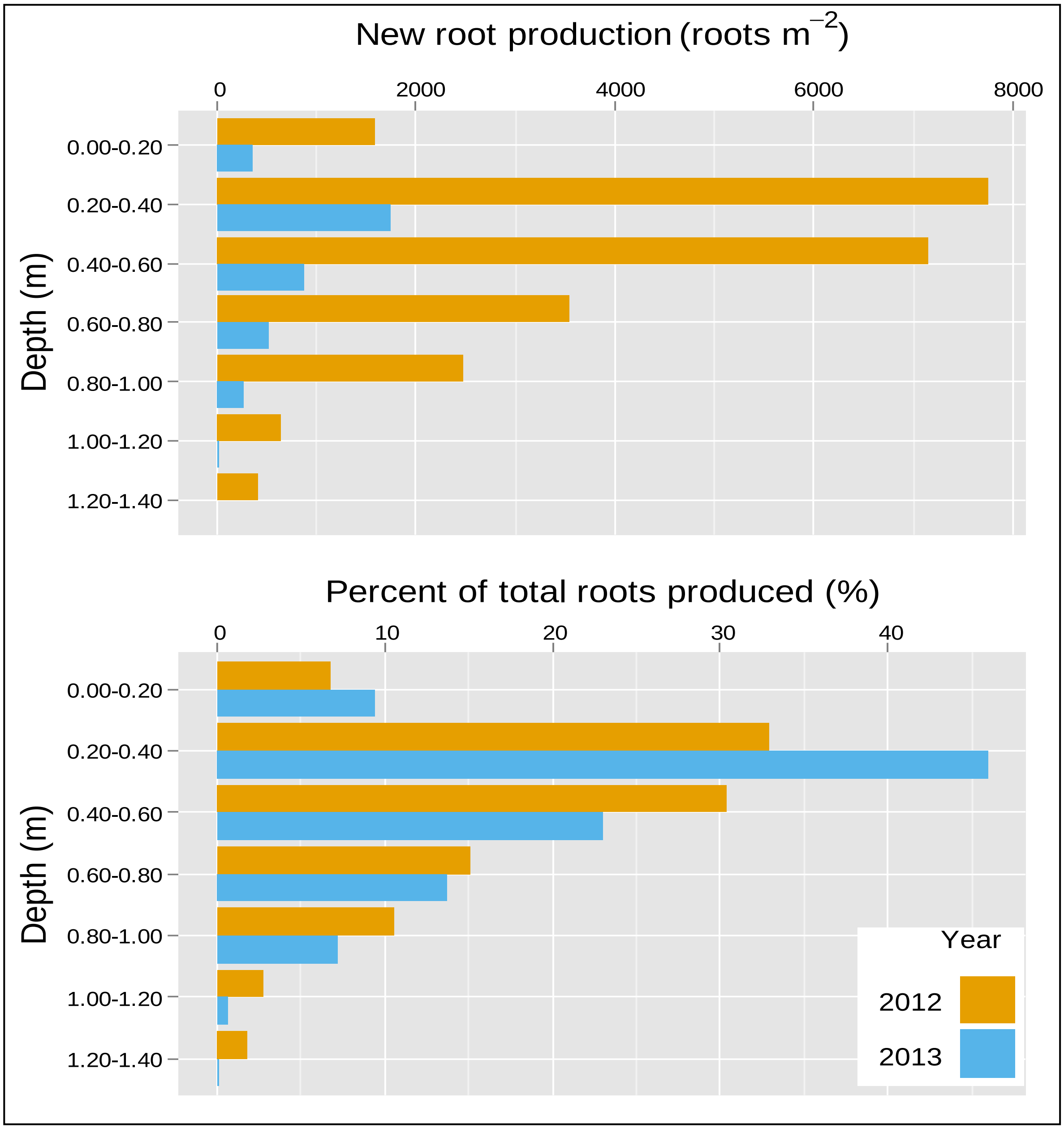

Figure 4: Root production with depth over two years expressed as total new root length per meter square of soil surface (top) and as percent of total root length (bottom).

2 Nitrate Uptake by roots

Determination of the impact of fertilization rate on root nitrate uptake under controlled conditions was compromised by an extreme variability in the results, nevertheless some valuable trends were observed. Experiments conducted in 2012 were repeated in 2013 at different concentration rates and repeated in a separate pot study in 2014 (results not shown). The following discussion is therefore preliminary but is consistent with results derived from experiments with different species. Fine roots from each treatment in experiment 1, were isolated, excised and then incubated in solutions of different NO_3 concentration for 30 minutes. The external concentration (i.e. soil solution concentration) was modified from the previous sampling year to more realistic conditions (i.e. actual NO_3 soil solution concentration), and ranged from 0.05 to 7.5 mmol·l^{-1} of N-NO_3 (0.42 to 100 ppm of N-NO_3). According to the literature, root uptake of fine roots will depend mostly on the concentration of the external solution as well as the demand of NO_3 by the plant (i.e. plant N status).

Results from this experiment are shown in Figure 5. When roots where incubated in solutions from a low range concentration of 0.05 to 0.5 mmol·l^{-1} of N-NO_3 (0.42 to 3.50 ppm of N-NO_3), all of the treatments showed an increase in uptake followed by a saturation at the end of this range; however, low N treatments exhibited a higher uptake capacity than the high N treatments, with no significant difference between treatments. This results suggests that N starved trees may up-regulate N uptake and can access N from lower NO_3 concentrations than trees with sufficient N content. At higher external N-NO_3 concentrations, ranging from 0.5 to 7.5 mmol·l^{-1} of N-NO_3 (7.01 to 14.01 ppm of N-NO_3), uptake rates significantly increased in comparison with lower external concentrations. In this case, low N trees exhibited lower uptake capacity than high N status trees.

These results suggest that roots of almond trees, may adapt to the prevalent external N concentrations and that a rapid change in that concentration (as occurs with a fertigation event) may temporally compromise uptake, especially in roots adapted to the low nitrate conditions that prevail prior to periodic but infrequent fertigation. Nitrate concentrations in the root zone can potentially be controlled within a narrow range by applying the required N in as many low concentration fertigation events as possible (every irrigation). Theoretically, this will result in less dramatic changes in soil nitrate concentration and development of root nitrate uptake parameters in close balance with soil nitrate levels. Infrequent fertigations clearly result in soil nitrate concentrations (>25 mmol·l^{-1} of N-NO_3) that greatly exceeds root uptake capacity and while that nitrate remains in the soil, prior to root uptake, it is at risk of loss below the root zone. Further research is required to further understand the potential impact of this dynamic. While this project has determined that low concentration nitrate applications may reduce uptake rates, there is no evidence of a detrimental effect of high nitrate concentrations on tree performance.

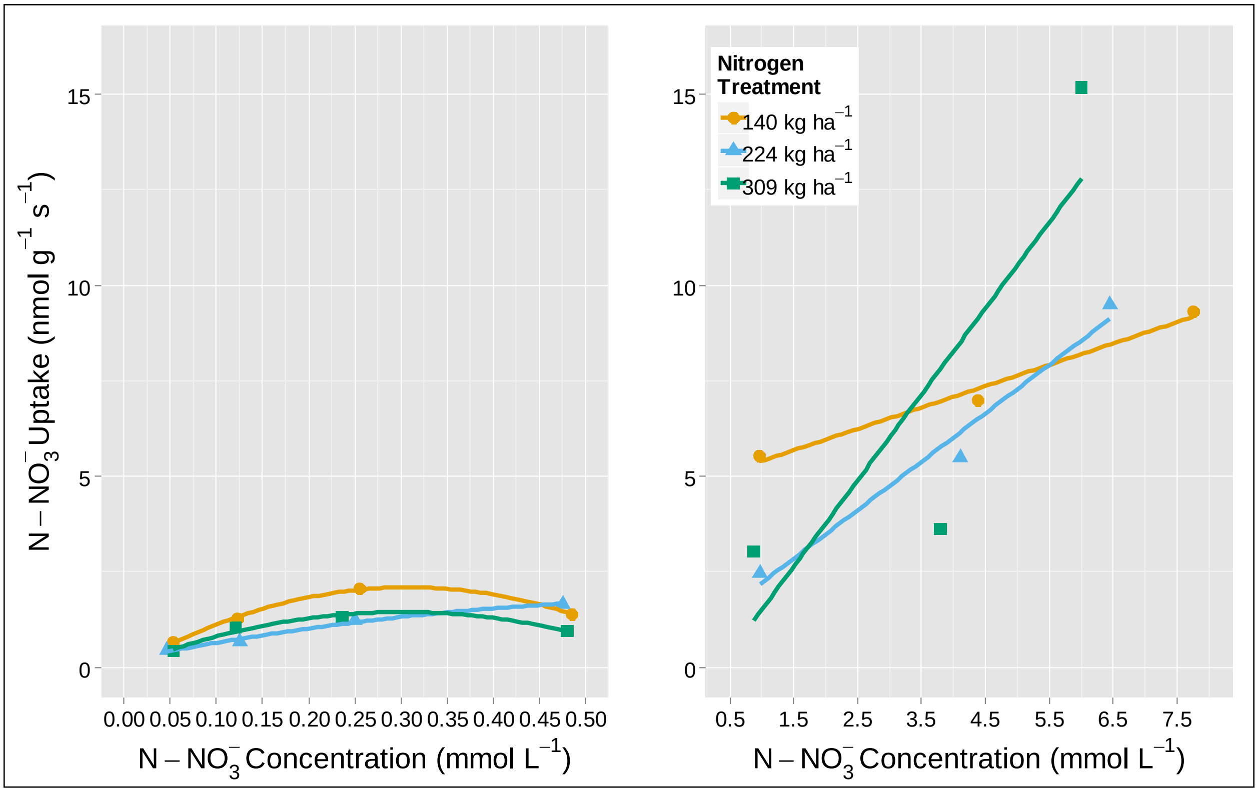

Figure 5. N-NO_3 uptake of almond roots grown at different fertilization rates and then excised and exposed to different N-NO_3 external concentrations (statistical)

3 Effect of Fertigation Method

The objective of this experiment was to determine the best fertigation practice for almonds orchards, and to contrast standard grower practice (4 fertigation events) with fertilizers applied at each irrigation event (continuous fertigation). The most important goal of a fertilization strategy is to reduce the contamination of groundwater with pollutants (NO_3) without reducing crop performance. This activity was conducted to take advantage of pre-existing treatments present in this orchard. Though not explicitly a component of the original objectives, the outcomes are relevant to the overall project goals.

Soil suction lysimeters were used to monitor nitrate movement in and below the root zone. As has been observed in the root uptake experiment, collection of soil nitrate concentration data is extremely variable, making interpretation of results difficult though trends can be seen that are consistent with expectations. Results from soil solution extraction at different soil depths under a range of fertilization treatments is shown in figures 6-8. In 2013 the methodology was changed to attempt to reduce sample-to-sample variability. Deeper tubes (150 and 250 cm) were also installed in order to monitor the potential leaching of each treatment. Unfortunately due to the drought in 2013 and 2014 no deep percolation (150 or 250 cm) of any kind was measured. Graphs represent the maximal N-NO_3

concentration measured over the season in 2013. The treatments were as follows:

C300-200KN = Fertilizer applied in every irrigation event in proportion to seasonal demand. 200 lbs acre K provided as potassium nitrate and 193 lbs N as UAN (total N 300 lbs)

C300-200KN = Fertilizer applied in every irrigation event in proportion to seasonal demand. 200SOP. 200 lbs acre K provided as potassium sulfate and 300 lbs N as UAN.

C300-275KN = Fertilizer applied in every irrigation event in proportion to seasonal demand. 125 lbs acre K provided as potassium sulfate and 75 lbs K provided as potassium nitrate. 273 lbs N provided as UAN (total N 300 lbs).

F300-275KN = Fertilizer applied in four fertigation events (March (20%), late April (30%), late May, early July) in proportion to seasonal demand. 125 lbs acre K provided as potassium sulfate and 75 lbs K provided as potassium nitrate. 273 lbs N provided as UAN (total N 300 lbs).

The following analysis of N movement through soils as monitored by suction lysimeter was performed immediately following the late May fertilization event. Prior to that date all treatments had received 80 lbs of N. Continous fertigation treatments (C) had received that amount distributed in 3 fertigation events while the fertigation (F) treatment had received 80lbs in a single fertigation event March 11th. On May 23rd, C treatments received 20 lbs of N (representing 1/5th of the May through July fertilizer demand, with the remaining 4/5th to be applied in 4 subsequent irrigation events prior to July fertilization) while F treatments received 100 lbs of N (representing the entire May – July N demand). This approach was designed to replicate field practice and contrast continuous with periodic fertigation management.

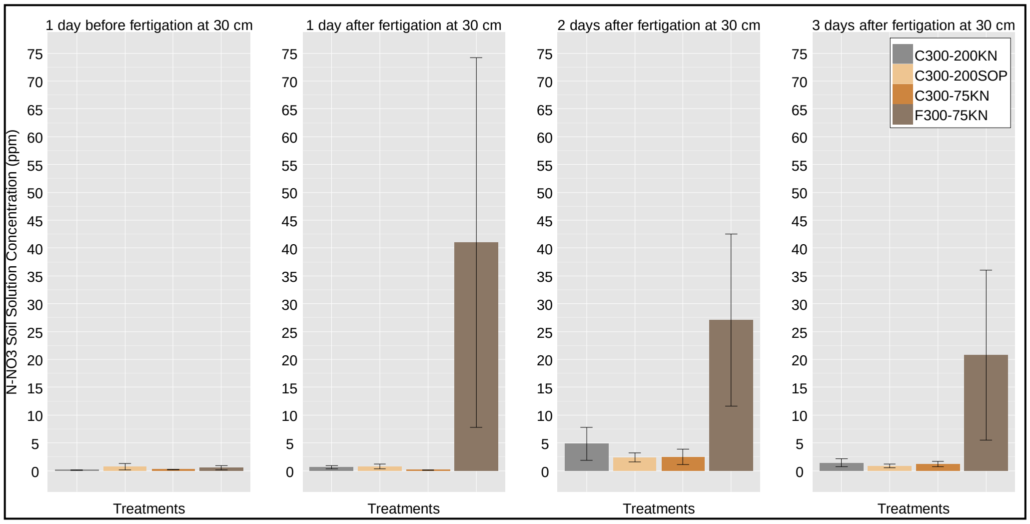

Figure 6. Soil solution N-NO_3 concentration (ppm) at 30 cm from soil surface

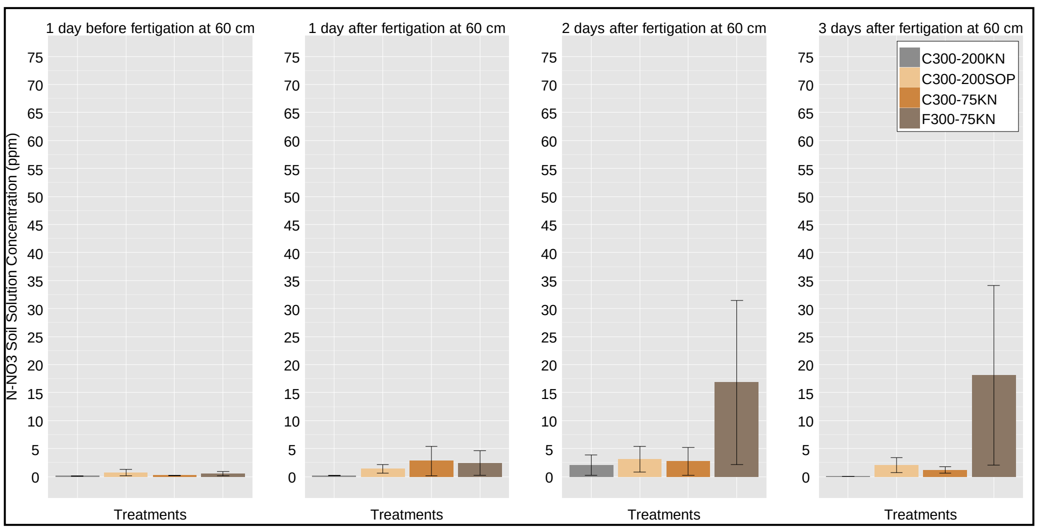

Figure 7. Soil solution NO3 concentration (ppm) at 60 cms from soil surface at different times relative to the fertigation treatment.

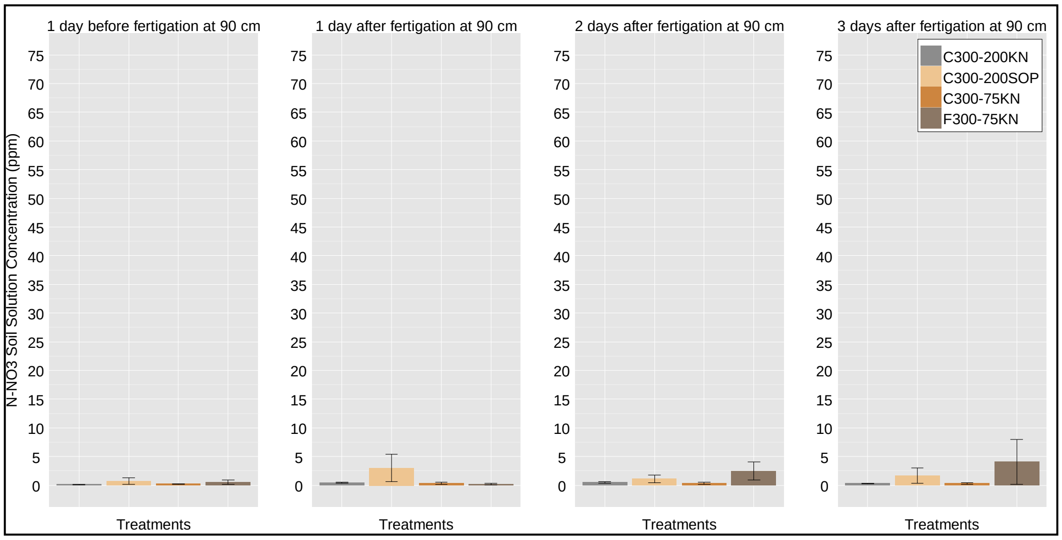

Figure 8. Soil solution NO3 concentration (ppm) at 90 cms from soil surface at different times relative to the fertigation treatment.

On the day immediately prior to the fertigation event, all soils and all depths exhibited very low levels of residual soil nitrate. This suggests that the trees had effectively scavenged previous fertilizer N applications. Deep leaching beyond the 90 cm monitoring zone is likely to be limited given the lack of deep-water movement in this drought year. Figures 6-8 illustrate the speed with which a high concentration N application (F) results in nitrate movement through the soil with significant nitrate appearing at 30 cm within 1 day, 60 cm within 2 days and 90 cm within 3 days of the fertigation event. Low concentration N applications (C) resulted in only very low levels of nitrate. The lack of deep movement of nitrate through the root zone suggests that soils retained these low nitrate applications effectively or that plant roots rapidly acquired the nitrate from the root volume.

These results illustrate the substantial potential that exists for large fertilization events to result in N loss from the root zone. While at this particular location given restrictions on irrigation volumes and absence of rain, a loss of nitrate from either fertilization strategy appears unlikely, a replication of this approach in regions where rain is possible or irrigation strategies routinely push water through the root zone, the presence of a concentrated band of soil nitrate at depth does represent a loss potential.

F. Discussion And Conclusion

Using excavation techniques and root windows, root production patterns in fruit trees such as almond (Catlin 1996), prune (Southwick 2012), pistachio (Rosecrance et al. 1996) and peach (Basile et al. 2007) have been reported to be bi-modal. In this study, Almond root growth primarily occurred in spring (early-March – early June) where approximately 70% - 95% of the new roots were produced. This intense period of new root growth is coincident with late flowering, leaf expansion and early fruit development, which may be in direct competition for carbohydrates with root production. A second, and much smaller, period of new root production occurred in the postharvest period prior to leaf fall. Depending on the year from 5-30% of new roots were produced in this period. The presence of fruit is known to be a factor affecting root growth patterns. Glenn (1993) observed that immature trees without bearing fruit had a constant root production pattern, even during summer and dry soil conditions, and a bimodal root production pattern when fruit was present. In our study we found that crop load can affect the amount of new root produced across years, but the seasonal pattern was the same in both years of the experiment, which also agrees with results reported by Mimoun and DeJong (2005).

The decline in root growth for 2013 may be explained by means of competition between above ground production and root production, since yield in 2013 was high (>3800 kg ha^{-1}) and 2012 kernel yield was exceptionally low (970 kg ha^{-1}) (Muhammad 2013). Similar results were found between on and off years in a mature pistachio orchard, which is a well-known alternate bearer (Rosecrance et al. 1996). Reduced root production in 2013 coincided with good fruit set that year, suggesting that current fruit load influences new root production. The enhanced root growth in 2012 followed an exceptionally high yield year during which tree carbohydrate reserves were expected to be severely depleted. This implies that new root growth may not be dependent upon prior year carbohydrate storage, or that during a low reserve storage year, trees tend to allocate those limited reserves to produce new roots rather than shoots. Similar results were observed in fruited and defruited French prunes fruited trees had reduced fine root growth compared to defruited trees (Weinbaum et al. 1994b). More research by means of manipulating crop load or root pruning, and then measuring carbohydrate availability, would have to be done to further explore the relationship between yield, carbohydrate storage and root production.

Patterns of new root distribution by soil depth were not affected by N application rate and despite the wide variation in the amount of new roots produced between years, the relative depth distribution patterns were similar (Figure 4). Differences in the amount of new root production per depth interval may be due a combination of soil factors. Shallow depths (0-20 cm) may not have a substantial amount of new root production since this soil layer may be defined as a transition layer, presenting large fluctuations in water content and soil temperature creating frequent non ideal conditions for optimal root growth. Soil temperature in particular may be too high for new root production between May and September. Most root new root production (about 80%) occurred between 20 and 80 cm soil depth, likely because soil water and temperature fluctuate much less in these layers and are more likely to stay within the range optimal for root growth. Similar results were found in peach (Baldi et al. 2010a) using a minirhizotron technique where most of the roots were present in the 20 to 80 cm depth. In almonds, Vrugt et al. (2001), using an inverse modeling technique, determined that the maximal water uptake depth was at 28 cm depth and root water uptake was limited to the first 40 cm depth, suggesting that that is the zone where the roots are most active and thus this is also the zone where new root production is most likely to occur.

As modern fertigation systems allow growers to easily control time, quantity and concentration of their fertilizer injections, the knowledge of root behavior and the interaction with aboveground processes can play a key role in the determination of best management practices. Our results showed clear patterns of root growth in time with a marked flushes in spring and a small flush in fall, irrespective of the fertilizer treatment, suggesting that temporal patterns are mainly controlled by environmental factors. Furthermore, root spatial patterns observed in our findings, and confirmed by other publications, showed that most of the active roots are confined within 80 cm depth, which is essential in proper water and nutrient management.

While it must be cautioned that data from uptake studies was highly variable results didsuggest that N starved trees can up-regulate N uptake and can access N from lower NO_3 concentrations than trees with sufficient N content. Trees pretreated with high N application showed a low capacity to absorb low concentrations of NO_3 and at the lowest NO_3 concentration (0.42 ppm) a net efflux of NO_3 from the roots system to the solution was observed. At high NO_3 concentration ranges (7.01 to 14.01 ppm of NO_3) however, low N trees exhibited lower uptake capacity than high N status trees.

The measurement of soil solution NO_3^- is notoriously difficult and inconsistent and in this experiment we observed extremely variable soil NO_3^-concncetrations following application of fertilizer N. Nevertheless clear effects of fertilizer strategy on soil NO_3^- were observed. The application of a smaller number of fertilizer events, in this instance fertilization in 4 events during the year (F), resulted in a substantially greater soil NO_3^- concentration and a rapid movement of that NO_3^- through the soil profile than the application of a lower NO_3^- in every irrigation event (C). This is undoubtedly a consequence of the higher NO_3^- applied in the F treatment however this is consistent with what would occur in this contrast under field conditions. The persistence of a higher and deeper soil solution NO_3^- pulse does represent a potential loss event if this pulse were to be followed by excessive irrigation or rain. Further research on the relative mobility of NO_3^- under low and high NO_3^- conditions and the impact on root uptake parameters would need to be conducted. The application of the soil flux model Hydrus would also be useful in estimating the relative risk of NO_3^- to leaching under each of these scenarios.

In summary this project has demonstrated that the peak root activity (capacity soil exploration and nutrient uptake) occurs in April through June when root proliferation and tree demand for nutrients is greatest. Roots are concentrated in the soil zone 20-80 cm depth. The late season root flush (September) may also provide an opportunity for nutrient uptake, though tree demand for N following harvest is minimal. Roots appear to adapt to the prevalent soil NO_3^- status and tree N status by altering the NO_3^- uptake parameters (Vmax, Km, Cmin), thus suggesting that the maintenance of a constant soil NO_3^- application adequate to satisfy but not oversupply tree N demand is preferable to infrequent N applications in which soil NO_3^- concentrations fluctuate dramatically. Data from the fertigation treatments imposed here further suggest that the potential for large concentration fluctuations and deep NO_3^- movement increases under infrequent but high concentration NO_3^- applications in contrast to constant low NO_3^- concentration fertigation. Additional quantitative analyses are underway to better characterize the parameters of NO_3^- uptake for use in Hydrus modeling. It is also unknown how quickly almond roots adapt to changing soil NO_3^- concentrations. Supplemental experimentation is underway and results are in preparation for publication.

I: Outreach Activities Summary

Below you can find a partial list of outreach activities in which results from this project has been presented.

A. Brown, P. 2012. Management of N in Almonds. CDFA-FREP and WPHA Annual Workshop. Modesto CA. 400 atten. Expert Panel Member presentation and discussion.
B. Brown, P. 2012. Nutrient Budget and development of new sampling strategies for N management. Northern San Joaquin Almond Day. Merced CA. 420 atten.
C. Sanden, B. 2012. "Irrigation Management to Maximize Almond Production in the SJV", Organic Almond Farming Workshop, Selma CA. 64 atten.
D. Sanden, B. 2012. Kern almond meeting, irrigation management and workshop. Kern Soil and Water Newsletter.
E. Sanden, B. et al. 2012. Almond Workgroup Tour, Kern County.
F. Brown, P. 2012. Nutrient Management of Almonds. Almond Board of California: Sacramento CA.1800 atten.
G. Western Nutrient Management Meeting, California Agronomy Society Meeting, Reno, March 7th, 2013. Managing Nitrogen in Orchards'.
H. Western Nutrient Management Meeting, CASS Meeting, Reno, March 7th, 2013
I. Brown, P. 2011. Update on Nutrient Management of Almonds. Almond Board of California:Modesto CA.1800 atten. Brown, P. 2011. CDFA-FREP Annual Conference. Management of N in Tree Crops. Paso Robles CA. 300 atten.
J. Brown, P. 2013. Nitrogen workshop. Almond Board of California: Sacramento CA.400 atten.
K. Olivos, A. 2013. Determination of Root Distribution and Physiological Parameters of Nitrogen Uptake in Almonds to Optimize Fertigation Practices. Poster presentation. Almond Board of California: Sacramento CA. 1800 atten.
L. Olivos, A. 2014. Determination of Root Distribution and Physiological Parameters of Nitrogen Uptake in Almonds to Optimize Fertigation Practices. Poster presentation. Almond Board of California: Sacramento CA. 1800 atten
M. Brown, P H. Nitrogen Training Workshop for CCA's. 140 minute and 120 minute presentation. Fresno, Jan 13, 2014 (145 attendees): Woodland, Feb 18. 75 attendees; Fresno Feb 25th (120 attendees); Tulare, March 12th (135 attendees).
N. Brown and Olivos, A. 2014. Determination of Root Distribution and Physiological Parameters of Nitrogen Uptake in Almonds to Optimize Fertigation Practices. FREP Conference. Modesto Oct 29-30th. (150 attendees)

J. Factsheet

1. Title: Determination of root distribution, dynamics, phenology and physiology of almonds to optimize fertigation practices.

2. FREP Grant Number: 11-0461-SA

3. Project Leader:
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4. **Period: 1/2012 – 12/2014**

5. Locations: Paramount Farms, Belridge and Davis, Campus.

6. County: Kern County and Yolo County

7. Highlights:

- The main period of root growth commences in April and is complete by early June, a secondary flush of roots may also occur in October. The majority of active almond roots are present in the 20-80 cm root depth.
- Evidence suggests that the key parameters of root nitrate uptake are determined by the N status of the tree, hence N replete trees are less capable of taking nitrate from low nitrate concentration soils.
- Application of nitrogen at lower concentrations in all irrigation events results eliminates periods of persistently high soil nitrate and may reduce the risk of nitrate loss.

8. Introduction:

Optimal fertilization practice can only be developed if knowledge of the 4 R's (right source, right rate, right place, and right time) are explicitly developed for the Almond production context. To optimize nutrient use efficiency in fertigated almond it is essential that fertilizers injected into irrigation system are provided at the optimal concentration and time to ensure that deposition patterns coincide with maximal root nutrient uptake. To effectively fertigate information on the biology and phenology of roots and uptake must then be integrated with fertigation system design (micro-sprinkler, drip, volume, distribution pattern, etc.). This project is designed to provide critical information on root growth and nutrient uptake to provide fundamental information on root adaptability to changing soil nitrate and the seasonality of root growth in Almond. A better understanding of the physiology and phenology of root growth and nitrogen uptake gained through this project is essential to the optimization of N application strategies.

9. Methods

Two long running N treatment experiments in mature almonds were used to determine almond root characteristics such as nitrate uptake physiology, root phenology and root distribution, under varying N and fertigation management practices. The seasonal patterns and depth of root growth were investigated over a 2-year period utilizing soil excavation and mini-rhizotrons. A total of 80 root bags filled with media were installed in the different treatments and N uptake was measured in excised roots. In addition, 72 soil solution access tubes (SSAT, "lysimeters") were installed to sample soil solution and measure nitrate (NO_3) concentration and transport through the soil profile at each fertigation event. A series of fertigation treatments varying in timing and type of fertigation were instigated to determine the effect of these treatments on plant productivity and nitrate movement through soils as monitored by suction lysimeters.

10. Findings

This project has demonstrated that the peak root activity (capacity soil exploration and nutrient uptake) occurs in April through June when root proliferation and tree demand for nutrients is greatest. Roots are concentrated in the soil zone 20-80 cm depth. The late season root flush (September) may also provide an opportunity for nutrient uptake, though tree demand for N following harvest is minimal. Roots appear to adapt to the prevalent soil NO_3^- status and tree N status by altering the NO_3^- uptake parameters (Vmax, Km, Cmin), thus suggesting that the maintenance of a constant soil NO_3^- application adequate to satisfy but not oversupply tree N demand is preferable to infrequent N applications in which soil NO_3^- concentrations fluctuate dramatically. It is also unknown how quickly almond roots adapt to changing soil NO_3^- concentrations. Data from the fertigation treatments imposed here further suggest that the potential for large concentration fluctuations and deep NO_3^- movement increases under infrequent but high concentration NO_3^- applications as would occur with fertilizers applied in 4 or less fertigation events. In contrast the application of N fertilizer in every irrigation results in a constant low NO_3^- concentration in the fertigation solution and a low concentration in soils. There was no effect of fertigation method on yields or root growth parameters. Soil suction lysimeters and field based nitrate uptake measurements are notoriously variable and as a consequence we did not succeed in definitively characterizing the parameters of NO_3^- uptake for use in Hydrus modeling. Additional experimentation is underway.