Almond Root Zone Study Plan
Phase 1

Administrative Draft

June 2015

Subject to Revision

SAN JOAQUIN RIVER
RESTORATION PROGRAM

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List of Abbreviations and Acronyms

ac	acre
Act	Public Law 111-11: The San Joaquin River Restoration Settlement Act
ATV	All-terrain vehicle
bgs	below ground surface
CCID	Central California Irrigation District
CDFA	California Department of Food and Agriculture
cm	centimeter
FAO	Food and Agriculture Organization of the United Nations
ft	foot
g	grams
GPR	Ground Penetrating Radar
in	inches
m	meter
lb	pound
meq	milliequivalent
mmhos	micro mhos
mm	millimeters
PG	Parcel Group
ppm	parts per million
Reclamation	U.S. Bureau of Reclamation
Settlement	Stipulation of Settlement in the case of Natural Resources Defense Council, et al. v. Kirk Rodgers, et al., United States District Court, Eastern District of California, No. CIV. S–88–1658–LKK/GGH
SJRRP	San Joaquin River Restoration Project
SMP	Seepage Management Plan
T-LiDAR	Terrestrial Light Detection and Ranging
UC	University of California
UCCE	University of California Cooperative Extension
WY	Water year

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1.0 Introduction

1.1 Background

In 1988, a coalition of environmental groups, led by the Natural Resources Defense Council (NRDC) filed a lawsuit, known as *NRDC, et al., v. Kirk Rodgers, et al.*, challenging the renewal of long-term water service contracts between the United States and the Central Valley Project (CVP) Friant Division contractors. On September 13, 2006, after more than 18 years of litigation, the Settling Parties, including NRDC, Friant Water Authority (FWA), and the U.S. Departments of the Interior and Commerce, agreed on the terms and conditions of a Settlement subsequently approved by the U.S. Eastern District Court of California (Court) on October 23, 2006. The San Joaquin River Restoration Settlement Act (Act), included in Public Law 111-11 and signed into law on March 30, 2009, authorizes and directs the Secretary of the Interior (Secretary) to implement the Settlement. The Settlement establishes two primary goals:

- Restoration Goal – To restore and maintain fish populations in "good condition" in the main stem San Joaquin River below Friant Dam to the confluence of the Merced River, including naturally reproducing and self-sustaining populations of salmon and other fish

- Water Management Goal – To reduce or avoid adverse water supply impacts on all of the Friant Division long-term contractors that may result from the Interim and Restoration flows provided for in the Settlement

To achieve the Restoration Goal, the Settlement calls for releases of water from Friant Dam to the confluence of the Merced River (referred to as Interim and Restoration flows), a combination of channel and structural modifications along the San Joaquin River below Friant Dam, and reintroduction of Chinook salmon. Restoration Flows are specific volumes of water to be released from Friant Dam during different water year types, according to Exhibit B of the Settlement and began on January 1, 2014. The Water Rights Order dated October 21, 2013 is a long-term authorization to modify Reclamation's water rights to implement Restoration Flows. Interim Flows were experimental flows that began in 2009 and continued until Restoration Flows were initiated, with the purpose of collecting relevant data concerning flows, temperatures, fish needs, seepage losses, recirculation, recapture, and reuse, pursuant to Order WR 2009-0058-DWR from the State Water Resources Control Board (SWRCB) and continued under Orders WR 2010-0029-DWR and the Order dated September 30, 2011.

To achieve the Water Management Goal, the Settlement calls for recirculation, recapture, reuse, exchange or transfer of the Interim and Restoration flows to reduce or avoid impacts to water deliveries to all of the Friant Division long-term contractors caused by the Interim and Restoration flows. In addition, the Settlement establishes a Recovered

Water Account (RWA) and program to make water available to all of the Friant Division long-term contractors who provide water to meet Interim or Restoration flows to reduce or avoid the impact of the Interim and Restoration flows on such contractors.

Both Condition 7 of the long-term Water Rights Order and Environmental Commitments EC-7 and EC-8 of the San Joaquin River Restoration Program (SJRRP) Programmatic Environmental Impact Statement / Environmental Impact Report require compliance with the Seepage Management Plan (SMP) for release of Restoration Flows. Reclamation developed the SMP to: (1) limit Interim and Restoration Flows to reduce or avoid material adverse groundwater seepage impacts through setting thresholds in over 200 groundwater monitoring wells, and (2) to identify a process to increase flows through construction of seepage projects. The seepage control projects may include a variety of realty (i.e., non-physical) and/or physical actions.

Physical projects that involve the design and construction of infrastructure to be installed in the field depend on a variety of site-specific conditions, including sediment texture in the shallow aquifer. Sedimentary deposits along the San Joaquin River system include alluvial deposits from both the Sierra Nevada and the Coast Range and fluvial deposits from the river itself. The resulting assemblage is a complex mixture of clay, silt and hardpan layers interspersed with sand and gravel deposits and various blends of these materials.

1.2 Study Purpose and Approach

Reclamation has developed a two phased approach to develop a further understanding of almond root zone characteristics.

1.2.1 Phase 1

The first phase of this work is provided in this document and includes the following:

- Interpretation of information from almond production experts (Section 2) and peer-reviewed scientific literature (Section 3) and to provide preliminary information about almond root zone depth, that may be used to guide the approach and design of a study plan; and

- Interpretation of existing information from parcels where seepage projects are anticipated and almonds currently, or are planned to be, planted (Section 4).

- A discussion of potential options for further study of almond root depths and a framework for observing almond roots in various soil environments where seepage projects are anticipated (Section 5 and Appendix B).

The approach to developing this study plan was to first obtain pertinent scientific literature and up-to-date information from University of California (UC) research and extension experts on almond tree growth, tree roots, and impacts of water and salinity on root systems. Experts were consulted to gain knowledge specific to San Joaquin River riparian almond culture literature review, and a literature review was conducted for general information on factors that influence root growth. With this information, parcel groups (PGs) were evaluated qualitatively to determine what commonalities and differences exist within properties considered for potential almond root zone field investigation. Lastly, recommended approaches for potential further investigation of almond root zone conditions were developed. These were developed for three study options representing various degrees of effort, time, cost, and levels of detail and site-specificity.

1.2.2 Phase 2

The second phase of this study will be developed after full consideration of the information developed in Phase 1. If Reclamation decides to proceed with a field investigation of almond root zone characteristics, a full field investigation program will be refined and implemented in Phase 2.

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2.0 UCCE Extension Advisory Outreach

University of California Cooperative Extension (UCCE) experts were interviewed to gain information on both almond root depth and on appropriate methods and factors to consider in a potential almond root depth field study. The UCCE experts were asked questions to help determine typical almond root depths, the effects of excess water and salinity on roots, and the potential effects of different orchard cultural practices on root depth. The list of UCCE experts contacted and their affiliations is provided in Table 2-1. All references refer to telephone conversations held in January and February 2015 (fully cited in References section).

Depending on the expertise of each UCCE staff, each was asked all or some of the following questions. The conversations with UCCE staff were not necessarily limited to responses to these particular questions.

1. What is the depth of almond roots observed in the field and recommended to growers?
2. What is the effect of saturation on the primary root zone and the total root zone?
3. What methods are appropriate for studying almond rooting depth?
4. What is the minimum age of almond trees at which peak root development occurs?
5. What is the effect of orchard density on almond root depth?
6. What is the effect of rootstock on almond root depth, and what are particular rootstocks (if any) an almond root study should include?

A summary of the responses to these questions is provided below, and the full log of the conservations with the UCCE experts in included in Appendix A.

Different terms are typically used to describe root depth. For the purpose of standardizing terminology in this document and for clarity of discussion, the following terms will be used throughout this document:

- **Maximum root depth** is the total depth that a tree’s roots can (but don’t necessarily) reach.
- **Effective root depth** is typically thought of as the zone where most of the roots are and where most of the root function, including anchorage, takes place. In other words, most of the water and nutrient uptake occurs in the effective root zone, and most of the tree’s physical stability results from roots in the effective root zone.
- **Active root zone** is the portion of the effective root zone where most of the nutrient and water uptake occur.

**Table 2-1.
University of California, Davis, and University of California Extension Experts Contacted**

Name	Title	Specialty and Research Interests
Dr. Roger Duncan	Pomology and Viticulture Advisor, UCCE Stanislaus County	Almonds, Pomology, Evaluation of rootstocks, Pruning systems, Alternatives to pre-plant fumigation, Labor reduction in peaches, Tree fertility and all aspects of integrated pest management.
Dr. Ted DeJong	Professor and Pomologist, UCCE, UC Davis	Environmental physiology; Tree crop physiology; Carbon partitioning and crop modeling; Pomology; Physiology and management of fruit tree crops; Peach rootstock development and physiology; Dried plum breeding.
Dr. Gurreet Brar	Nut Crops/Pomology Farm Advisor, UCCE Fresno and Madera Counties	Pomology horticulture, Plant propagation, Plant physiology and controlled environment systems; Designing and executing experiments.
Dr. Bruce Lampinen	Integrated Orchard Management/Walnut and Almond Specialist, UC Davis	Almonds and walnuts, Integrated orchard management, Plant management systems. Role of water and nitrogen management in spur longevity in almond, Canopy management approaches in high density walnut plantings and water management as it relates to insect and disease susceptibility in walnut and almond.
Dr. Ken Shackel	Professor and Pomologist, Dept. of Plant Sciences, UCCE, UC Davis	Environmental and integrative biology, Pomology, Impact of tree & vine water status on productivity and the water relations and physiological activity of fruit, Plant water relations, Responses and adaptations of plants to water limited conditions.
Dr. Brent Holtz	County Director and Farm Advisor, UCCE San Joaquin County	Pomology, almonds, plants and their systems, Pathogens and Nematodes Affecting Plants, Integrated Pest Management Systems, Natural Resources and Environment, Soil, Plant, Water, Nutrient Relationships.
Mr. Blake Sanden	Farm Advisor, UCCE Kern County	Almonds, Pistachios, Plants and their systems, Plant genetic resources, Natural resources and environment, Conservation and efficient use of water, Soil-plant-water-nutrient relationships, Management of saline and sodic soils and salinity, Agricultural engineering, Natural resource and biological engineering, Drainage and irrigation systems and facilities.
Dr. Astrid Volder	Assistant Professor, Department of Plant Sciences UC Davis	Plant root systems, Plant health, Water use and quality, Climate change, Ecosystems, Environment and natural resources, Food systems, Land use, Sustainability, Trees and forestry, Urban issues.
Dr. Franz Niederholzer	UCCE Sutter, Yolo, Colusa, Farm Advisor Orchard Systems	Plants and their systems, Plant product quality and utility (preharvest), Integrated pest management systems, Air resource protection and Management, Pollution prevention and mitigation, Agricultural, Natural resource and biological engineering, Engineering systems and equipment.

Table 2-1.
University of California, Davis, and University of California Extension Experts Contacted

Name	Title	Specialty and Research Interests
Dr. Patrick Brown	Professor, Department of Plant Sciences, UC Davis	Plant and soil nutrition. Perennial horticulture. Physiology and biochemistry of plant nutrient uptake, interactions of nutrition with disease resistance and the selection of crops with improved nutrient efficiency. Nutritional requirements of both annual and perennial systems, application technology and development of environmentally sound fertilizer use. Molecular and genetic aspects of nutrient acquisition and tolerance. Nutritional physiology. Boron, Nickel.
Dr. Alison Berry	Professor and Plant Biologist, Department of Plant Sciences, UC Davis	Tree root architecture, Biological nitrogen fixation; Root and rhizosphere plant-microbe associations, and applications in agroecology; Soil microbial ecology; Microbial genomics; Plant nutrition and ecophysiology; Microbial deconstruction of cellulosic biomass and microbial biofuels.

The information from UC experts strongly indicated that the active root zone of almonds, where the majority of nutrient and water uptake and transpiration occurs, is one to three feet. The effective rooting depth, where over 90 percent of almond roots grow including those that provide structural integrity, is three to five feet. The maximum root depth of irrigated almonds, that is not necessarily typical but can occur, is 10 to 13 feet. Therefore, the root zone from five to 13 feet may include some roots but is not considered the effective root zone. The impacts of seepage on almond tree health and production likely vary in these different zones depending on site-specific conditions. The influence of seepage is expected to be most impactful in the active zone and decreases with depth.

Question 1: What is the depth of almond roots observed in the field and recommended for production?

The experts agreed that most of the roots are in an upper or active root zone even though some roots can extend to relatively great depth (see references below). As corroborated by the literature review, almond roots can grow as deep as 10 to 13 feet. This maximum root depth has been affirmed by observations in studies discussed in the literature review section below. However, the effective root zone is relatively shallow, extending from three to five feet, according to observations by several of the UCCE and UC Davis experts contacted.

Dr. Gurreet Brar has observed that most almond roots (including both woody roots and secondary fine roots) are in the upper four to five feet, and most fine, secondary roots are in the top two feet. Dr. Astrid Volder, who specializes in how plant roots respond to stresses such as extreme heat or drought, also stated that most roots (including structural, woody roots and secondary roots) are in the top two feet, while it is common for woody roots to extend to a four to five foot depth. Mr. Roger Duncan clarified further that approximately 80 percent of the total roots are in the top two feet of soil.

Dr. Bruce Lampinen stated that commonly 90 percent of almond roots are in the top three feet, and Dr. Ted DeJong confirmed this statement saying that over 90 percent of roots are in the top four feet. Dr. Franz Niederholzer affirmed that root density decreases incrementally with depth (i.e., the top foot of soil has more roots than the one to two foot increment, which has more roots than the next deeper increment). Dr. Alison Berry stated that tree roots typically form an upside down umbrella shape, with most of the roots extending laterally in the top two to four feet. Beyond this depth, roots are not only lower in density, but take up a smaller area on the horizontal plane.

The UCCE experts also agreed that root depth is dependent on depth of irrigation water. Lampinen stated that if irrigation water is only being pushed down to one foot between irrigation cycles, then the top foot of soil is where the functional (active) roots will be. Sanden and Niederholzer confirmed specifically that root growth is highly influenced by irrigation practices. For example, Sanden specified that short duration high frequency irrigation results in relatively shallow root systems. He also noted that there is likely not much difference in rooting depth between drip and micro-sprinkler irrigated orchards, provided the micro-sprinkler orchards are managed well and assuming double-line drip. Single-line drip may result in smaller root structure overall and potentially smaller root depth.

All UCCE experts also agreed that soil type plays a role in determining root depth, and that several interacting factors such as soil physical and chemical properties interact on a site-specific basis. Typically, root growth is longer/deeper in coarse textured soils than in fine textured soils. The depth of roots varies due to both physical impediments caused by the more compact nature of fine-textured soils and the nature of soil moisture dynamics (water holding capacity, ability of water to move through various sizes of pores, saturated zones, etc.) Berry noted that roots have been shown in at least one study to “perch” in a fine-textured soil underlain by a coarse-textured soil. This “perching” of roots is likely because water cannot move through the micropores in clay soils unless the soils become saturated. Therefore, the deeper, coarser soil is not wetted because water is “trapped” in the fine-textured soil by the forces of capillary action. Berry agreed with the finding by Perry (1998) (Section 3.1.1) that soil stratification likely inhibits root growth to some extent.

Though the effective root zone commonly ranges from three feet as confirmed by the experts consulted during this effort and described above, most of the UCCE personnel recommended that additional depth beyond the primary root zone should be allowed for when developing/managing almond orchards. This additional depth provides for a leaching zone to avoid the detrimental effects of salinity on almond roots. Duncan stated that salinity is actually more harmful to almond roots than saturation. (This hypothesis is corroborated by Phogat et. al [2012] who found that salinity inhibited almond root growth more than excessive water. See Section 3.2.) For this reason, Duncan stated that a water table at five feet would be too shallow for almond growth. He stated that a water table at this depth would allow for the effective root zone but may not allow enough depth to leach salts from the root zone. Dr. Ken Shackel and Mr. Blake Sanden agreed that room for leaching is an important recommendation used by UCCE farm advisors when guiding growers. Sanden stated that the capillary fringe (the subsurface layer in which groundwater seeps up from a water table by capillary action to fill pores) can be up to three to four feet in some clay soils. It should be noted that this would only be in the case in very fine soils. Therefore, a six foot oxygenated root zone is recommended to account for 3-5 feet of effective root zone and potential and uncertain upward movement of water and salt (Sanden).

Dr. Brent Holtz reported that growers have pushed these recommended root zone limits, especially in recent years when water supply shortages, impaired water quality in some areas, and high almond prices have incentivized growers to plant almonds on sites where almonds have not traditionally been grown. According to Holtz, almonds are grown in riparian areas near Firebaugh where there is a shallow water table (approximately four to five feet deep). He also stated that very recently almonds have been planted on shallow soils in the Sacramento-San Joaquin Delta where almonds have never been grown before. The success of these orchards is unknown at this time. Holtz cautions that successfully growing almonds on shallow soils with shallow groundwater depends on access to good quality irrigation water. Sanden confirmed that almond orchards are increasingly planted in less than ideal soil and water conditions, though for optimal almond growth, planting in these conditions is not advised. Both Holtz and Sanden agreed that suboptimal yields are tolerated by growers given the current high price of almonds.

Niederholzer remarked that almonds would likely develop shallower roots if they were planted on a site with a high water table. Niederholzer stated that almonds planted on a site with a deeper water table that was then raised (groundwater levels increased in elevation) would not necessarily be able to adjust and may be adversely impacted. In other words, just because some almonds are observed to have shallow roots does not mean that all almonds on all sites have the same depth of roots because of the conditions in which they were established.

Question 2: What is the effect of saturation on the active, effective, and maximum root zone?

If roots vary in extent and function throughout the root zone, the topic of how excess water, saturation, and/or salinity affect various types of roots in different root zones arises. As noted above, UCCE expert opinion indicates that there is not necessarily a distinct boundary between the active, effective, and maximum root zone. Rather, root activity is inversely proportional to depth. In other words, root activity decreases as root depth increases.

As Shackel pointed out, deep roots usually function at a relatively low level of activity because soil moisture and nutrient concentrations are very low at depth. Trees must expend a great deal of energy to transport water and nutrients from maximum root zone depths. However, as described in the literature review section, deep roots can increase their activity when roots in the active root zone are stressed from lack of resources such as air, water or nutrients. Berry agreed that the main root functions occur in the top four to five feet and that beyond six feet, roots do not provide significant structural or uptake functions.

Therefore, the impacts of excessive water on deeper roots (beyond what is likely the effective root zone at three to five feet) are likely much less than the impacts of excessive water on shallow roots in the effective root zone, according to Shackel and Berry. However, Shackel cautions that trees experience detrimental impacts to growth long before they can be observed. In other words, trees "take a long time to die" and the effects of excess water and/or salinity may be more significant on deep roots in scenarios where highly functional roots lack water, as in drought or deficit irrigation, or soil nutrient deficiencies.

Brown was consulted for his expertise in nutrient and water uptake in plants, and for his expertise in almond nutrition. Both he and Sanden noted that during the period of mid-March to May (and sometimes into June) what is referred to as "June drop" occurs. During this period almonds lose some of their fruit as a carbohydrate balancing mechanism. During this period, boron, phosphate, manganese and copper nutrition is critical for fruit set, canopy growth, and cell division. Under conditions where the roots are saturated, nutrient availability and uptake may be inhibited. For this reason, in Brown's opinion, the effects of excess water would be much greater in the upper three feet of soil than in lower depths especially during this period from a crop nutrition perspective. He advised that it is critical for the upper three feet of soil to stay oxygenated. For example, if the soil in this increment was saturated for one to two weeks during spring, the tree health would be severely compromised. However, this duration of saturation would not have the same effect on deeper roots, though they might be affected depending on site conditions. These effects might vary at different times throughout the year. Sanden also pointed out that spring conditions are prime for phytopthera disease, which is a root disease promoted by saturated conditions, so spring saturation may promote disease more than saturation during other seasons.

These responses indicate that the timing, frequency and duration of saturation likely influence the degree to which an orchard would be potentially impacted by anoxic and/or saline conditions. For example, shorter periods of saturated conditions would likely affect all roots less than longer periods, but if the frequency of these periods increased, it is unknown (without doing a long term study) if these impacts would be more harmful to almond production (Shackel).

Question 3: What methods are appropriate for studying almond rooting depth?

Volder suggested that for the purposes of studying root depth, large scale excavation techniques would be more appropriate than either instrumental methods such as GPR or extracting small cores. She reasoned that instrumental methods are limited in the size of roots they can detect, and also in the site conditions in which they can be used. These limitations are confirmed in the literature review. Soil cores are commonly used to study roots in the active root zone, but roots are difficult to extract from soil cores and this process is extremely labor intensive and time consuming. In addition, the location of deeper roots (relative to the tree canopy on the horizontal plane) is unknown without complete excavation, so the random placement of soil cores would necessitate a large and potentially unwieldy number of replicates per tree to ensure that root depth was accurately represented.

Overall, Volder recommended that excavation would be a less labor intensive and more accurate method to study the depth of almond roots. All other experts contacted agreed with this approach, though very few have conducted comprehensive tree root studies. Those that have conducted root studies have concentrated on root function, including nutrient and moisture dynamics, in the upper two feet.

Berry described high pressure airstream excavation of native tree roots on San Joaquin River levees in detail. This method is highly accurate and can be used non-destructively, but it should be mentioned that it is also time-consuming, costly, and requires specialized equipment. (See section below on methods of studying roots.)

Berry also cautioned that observing root depth in the absence of other root parameters (such as diameter, length, and density) may provide minimal information on roots that is "out of context" because it does not provide information on root structure, function, growth, etc.

Question 4: What is the minimum age of almond trees at which peak root development occurs?

The answer to this question is unknown because there have been no long term studies conducted on almond root development in California to date. The literature review indicated that root growth (length, depth or density) does not continue to occur at the same rate throughout the life of the tree (Day and Wiseman, 2009). Root structure tends to slow or plateau after the main structure is achieved. Non-woody roots die off and regrow annually, while larger structural woody roots have longer lifespans. In the opinion of many of the experts, peak root development is likely concurrent with production maturity; i.e. trees at least seven or eight years old likely have their root systems fully developed, but this is only an assumption and has not been validated with field studies.

Question 5: What is the effect of orchard density on almond root depth?

In recent years orchards have been planted at greater densities than they have been traditionally planted. Growers have found that though trees are smaller, production is as high or higher in dense orchards. Therefore, newer orchards are likely to be denser than older orchards, and root growth may respond to this change in planting patterns. As the literature review found, the root growth of trees in natural systems is influenced by other tree roots that are nearby (Day and Wiseman, 2009).

The responses to this question were similar to those of Question 4; there are no studies known by the UC experts that definitively determine if root structure is affected by root density. However, Shackel and Berry are of the opinion that root systems in dense orchards are smaller in general because the trees are smaller, and so are shallower than those planted in less dense orchards. Berry stated that, to her knowledge, roots do not compensate for laterally constrained rooting zones by growing deeper. It is unknown if either of these influences would be significant in the presence of other important root limiting factors, such as nutrient, oxygen, and water availability.

Question 6: What is the effect of rootstock on almond root depth, and what are particular rootstocks (if any) an almond root study should include?

Note to reader: Almonds are propagated by grafting, or joining, rootstocks to scions. The scion is the shoot or upper portion of a plant. In stem grafting, the shoot of a plant variety is grafted on to the rootstock of another type, because they each have desirable characteristics.

Rootstock selection is a relatively recent development in orchard design and management (Duncan). Prior to approximately 10 years ago, the vast majority of almond trees were planted on Nemaguard rootstock because of its vigor and resistance to common root diseases. However, spurred by the recent challenges in water quality and availability, rootstock breeding programs have focused more and more on tolerance to salinity and water stress, including both drought and excess water. Now there are more rootstock varieties available than ever before; consequently, orchards vary more in their rootstocks than ever before.

Roostocks can vary in their typical rooting depth as well as their tolerance to salinity. For example peach hybrids have deeper roots (to scavenge for water) because they were bred for drought resistance, but they are also more tolerant to salinity. The plum rootstock Marianna is also relatively tolerant of wet and saline conditions, but is used with an inter-stock (mostly pollinator varieties) because it is not highly compatible with nonpareil scions (the most common in California) (Brar, Sanden). The rootstock Hanson 536 is also used in soils prone to alkalinity and salinity, but is not suitable for saturated soils (Brar). Though rootstock does influence rooting depth, salinity is likely the driving factor when it comes to root depth (Duncan). For this reason, salinity tolerance has become a major objective in rootstock breeding, but these developments are still relatively new and the depths of rooting, therefore, is unknown in these new rootstocks.

2.1 Summary of UCCE Extension Advisory Conversations

2.1.1 Typical Almond Root Depth

- The maximum root depth of irrigated almonds, that is not necessarily typical but can occur, is 10 to 13 feet.

- In general, the effective rooting depth, where over 90 percent of roots grow including those that are mainly structural, is three to five feet.

- The active root zone, where the majority of nutrient and water uptake and transpiration occurs, is two to three feet.

- These root depth ranges are typical and considered guidelines; however, there are not distinct boundaries between roots and their function because of the following factors:

  - Root depth and zones of different root function are influenced by site specific conditions;

  - Root function is inversely proportional to root depth, but incremental decreases in root activity with depth are not necessarily abrupt; and

  - Trees can increase the activity of deep roots when environmental stressors limit the function of the roots in the active root zone.

2.1.2 Factors That Influence Almond Root Depth

- The primary drivers of root growth and depth are likely soil texture, soil structure, salinity, groundwater elevation, and irrigation practices.

- Factors that influence root growth and depth to a lesser extent include other site-specific soil conditions such as oxygenation, temperature, and nutrient status; rootstock variety; and potentially orchard density.

- Root growth follows the depth to which irrigation water infiltrates the soil; however, large differences in irrigation methods and management may or may not be found within the project area because the vast majority of orchards are irrigated with micro-sprinkler and drip irrigation, and because the increasing scarcity and price of water incentivizes growers to irrigate as efficiently as possible, even sometimes to the point of deficit or regulated deficit irrigation.

- Though orchard density and rootstock may influence root length and depth, salinity in particular is likely more influential on root growth.

2.1.3 Effects of Saturated Soil on Almond Health

- The effects of saturated soil, including both anoxic and saline conditions, are likely greatest on roots in the active root zone, less in the effective root zone, and the least in the deep root zone.

- The difference in impacts to roots at various depths may vary by site.

- Seasonal timing, frequency, and duration of saturation likely influence how (nutrient uptake, disease) and how much roots are affected, though without a long term study on the varying effects of saturation soil conditions on roots at different depths and sites, it is not possible to estimate how these factors might interact.

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3.0 Literature Review

The following literature review discusses factors that affect almond root depth as described in peer-reviewed scientific studies.

The literature review indicated that variability in soil texture, soil salinity, and depth of water table should all be considered and represented as potentially influencing root depth. Additionally, almond orchard density and rootstocks also likely influence root depth. Orchard density has increased in recent years, and there are more rootstock varieties available than ever before. Some of these variables may also interact.

3.1 Root Type and Function

Perry (1982) wrote, *"Tree roots vary in size from large woody roots 30 centimeters (cm) or more in diameter to fine, non-woody roots less than 0.2 millimeters (mm) in diameter. The variation in size from large to small, and the variation in categories from woody to non-woody, perennial to ephemeral, and absorbing to non-absorbing, is continuous. This continuous variation makes the sorting of roots into various categories arbitrary. Nonetheless, classification and sorting are essential to comprehending the pattern and integrated function of the total root system.*"

Therefore, the following descriptions of roots are provided for clarity. There are two main types of roots, and two less common root types, as follows:

- **Woody roots**: These roots may also be called structural or lateral roots, because they primarily grow horizontally and/or radially from the root collar, where the root and tree stem meet at the soil surface. Woody roots include the primary or seminal root, which elongates from the seed at germination, and the secondary roots that branch out from the primary root. They have an outer bark that contains suberin, which "waterproofs" the tissues. Woody roots contain grow perennially resulting in the "tree rings" that are observed to compare annual growth and determine the age of trees. The main functions of woody roots are to physically support the tree, store energy reserves, and transport liquids that contain many types of soluble substances. Most root diseases start when root defense, which is based on energy storage, is low; as energy storage is depleted, opportunistic pathogens attack. Woody roots also synthesize substances such as growth regulators, amino acids and vitamins that are critical for growth.

- **Non-woody roots**: These roots are sometimes called feeder roots, because their primary function is to absorb nutrients and water for the tree. The nutrients and water are then transported to other parts of the tree by the woody root system. Non-woody roots do not store energy for the tree, transport nutrients or water, or provide anchorage. Non-woody roots grow ephemerally; they grow, die off, and are replaced rather than continuing to grow like wood roots. Therefore, they do not exhibit the rings observed in woody roots. Non-woody roots also do not have the suberin-rich protective outer layer, because their main purpose is to absorb, not deflect water.

- **Other less common root types**:
  - **Striker roots** form at intervals along the woody root framework, and either grow downward until an obstacle is met, such as a non-oxygenated layer of soil, or branch and form a 2nd layer of feeder roots deeper in the soil. These types of roots are typically observed in dry soils, and their primary function is to store water and plant nutrients.
  - **Adventitious roots** form at the root collar from woody roots, and usually develop as a result of injury to the tree.

Roots go through developmental stages as they age. Non-woody roots that are young and white or thin and brown are primarily involved in water and nutrient absorption. Many of these small thin roots die before developing through the process that leads them to become woody mature roots, which are primarily used by the plant for structure and anchorage. Though this process is generally the same for all tree roots, the ultimate architecture of a root system depends on environmental factors and rootstock variety factors (see Section 3.1).

Day and Wiseman (2009) stated that studies have shown that older trees put more resources into the metabolically costly production of fine absorbing roots and fewer into large structural roots. Day and Wiseman (2009) noted that roots have a non-uniform distribution around a tree, and root depth is related to trunk diameter in younger trees but not as much in older ones. Day and Wiseman (2009) also noted that the complex networks of fine roots have often been sampled in ways that fail to relate the structure of the intact system to resource acquisition.

Koumanov et al. (1997) stated that most active roots develop in the upper soil layers where organic matter content is highest, and cite several studies to support this claim. Interestingly, Koumanov et al. (2006) noted that “the almond tree appeared capable to redirect its root activity towards regions of the most favorable water regime with minimum soil water stress. After water applications, root water uptake occurred initially near the tree trunk and then progressed towards the root system periphery, thereby changing locations of maximum root water uptake and shifting to root zone regions with minimum soil water stress.” Koumanov et al. (1997) also stated that while there are some investigations on the root morphology of trees, including the spatial distribution of roots under localized water application, information to date on the spatial and temporal distribution of root water and nutrient uptake is limited, especially for partially-wetted soils.

Root systems, especially fine roots, are exceedingly difficult to study because they must be excavated to be observed, because of their fragility, and because of their dynamic nature – some fine roots develop to mature woody roots while others die off and are replaced by new young roots. Therefore, the information on the spatial and temporal distribution of fine almond roots and their respective functions of water and nutrient uptake is limited. Modeling root architecture and function has promise but must be calibrated and validated by field studies.

3.2 Factors that Affect Root Growth and Function

There are several environmental factors that affect root growth (UC Davis, 2014), including:

1. **Soil texture** affects soil permeability, water and nutrient transport, and root architecture directly.

2. **Soil structure** can also affect root growth (e.g., restrictive horizons), and is related to soil texture in some instances.

3. **Soil oxygen** affects ability of roots to respire. Oxygen concentrations over 10 percent are optimal, and those at three to five percent compromise root function. More nut trees die from lack of oxygen in water-logged soils than because of lack of water.

4. **Soil moisture** determines where roots grow. Soil texture is related to moisture because coarse soils are typically better drained, and roots may grow deeper in coarser soils to access moisture.

5. **Soil temperature** is important for root function. Optimal temperature for root function is 20 to 25 degrees Celsius.

6. **Soil flora and fauna**, including fungi, bacteria, worms, nematodes, and insects can affect root growth either positively or negatively.

7. **Soil nutrient status** also determines where roots grow and is important for root function. Nutrient availability varies with pH; optimum pH is usually between 5.5 and 6.5, but can vary depending on rootstock variety.

3.2.1 Soils

The soil type and structure play a large role in determining the maximum depth of the root zone. Course and medium textured soils usually allow deeper root zone development than fine textured soils. Compacted layers or shallow water tables also limit the expansion of the root zone.

Perry (1998) noted that limited root development of agricultural trees is caused by excessive or inadequate moisture and oxygen. Three common soil limitations to root growth are as follows:

- Fine-textured soils with poor internal drainage throughout the profile;
- Soils with dense, compact or cemented subsoils or layers (e.g. claypans, hardpans, fragipans); and
- Stratified soils with abrupt and significant changes in soil texture which causes wetting-front instability, and results in "fingers" of deep percolation where "sinker" roots grow.

Perry (1998) also states that tile drainage, which is usually set four to five feet deep, has uncertain efficacy in soils with restrictive horizons (e.g., pans) or highly stratified soils.

Schenk and Jackson (2005) modeled and reviewed factors related to deep rooting in natural tree systems and concluded that deep roots occur where deep, unrestrictive, less stratified soils occur, because climate and soil variables related to the soil water balance are strongly related to rooting depth. These authors also note the lack of information available on total tree root depth, citing that less than 10 percent of published data on vertical root distribution include measurements all the way to the maximum rooting depth.

3.2.2 Rootstock/Variety

Root depth and architecture are also influenced by rootstock and tree variety. For example, Parvaneh and Afshari (2013) found that some rootstocks respond to water stress by increasing root length, while others respond by decreasing root length. This ability to adapt root length is an important consideration because rootstocks are selected considering several characteristics, including:

- Tolerance of saturated conditions and heavy soil,
- Tolerance of salinity,
- Tolerance of doughty conditions,
- Propensity to sucker (i.e., fast growing, whip-like, non-productive, vegetative growth),
- Compatibility with almond varieties (scions),
- Anchorage,
- Chlorosis, tolerance to high pH,
- Dwarfing (i.e. root stock dictating the size of the tree),
- Disease resistance, and
- Nematode resistance.

Certain rootstocks are better suited to particular soil conditions. The main rootstock varieties and their main performance characteristics, summarized from Doll and Debuse (2011) and Duncan (undated) used in California include:

- Nemaguard (peach) – most common in San Joaquin Valley because of its high vigor, yield potential, and resistance to pests and disease; low tolerance to heavy soils prone to saturation;
- Lovell (peach) – most common in Sacramento Valley because of its relatively higher tolerance to heavier textured soils and wetter conditions;
- Marianna (plum) tolerant of heavy wet soils, however incompatible with nonpareil varietal;
- Peach/almond hybrid – deep rooted and tolerant of drought conditions; and
- Complex hybrids (peach, almond, plum, apricot) – new varieties about which less is known.

While Lovell and Marianna are both relatively more tolerant of heavy wet soils, Marianna is not compatible with the most common almond varietal, nonpareil (Doll and DeBuse, 2011) unless an inter-stock is used (another rootstock grafted in between the main rootstock and scion). Consequently, Lovell might be a rootstock commonly selected for wet conditions. Conversely, some hybrids are poorly suited to saturated conditions because they have roots designed for drought conditions that search out moisture by increasing root length (Duncan, undated).

3.2.3 The Problem of Phytopthora

The problem of Phytopthora disease in almonds is discussed here because it is a significant and increasing problem in California almond orchards, and because its occurrence is highly influenced by west soil conditions. This information is condensed from Flint (2002), Doll (2009), and Doll (2015).

Phytophthora causes root and crown rot throughout the San Joaquin and Sacramento valleys. The problem tends to be more severe in areas of clay to clay-loam series soils, which can be attributed to the higher water holding capacity and poor drainage of these soils in comparison to sandier soils. Conditions that favor disease include excessive periods of saturated soils and cooler temperatures, which are common in the late winter and early spring. Optimal temperature for most Phytopthora. species is between 72 and 82 degrees F, but some species thrive in higher temps (eg. *P. nicotianae*, 81-90 degrees F) or lower temperature ranges (eg. *P. syringae*, 59-68 degrees F). Periods of rainfall or water standing for over 24 hours can provide enough moisture for Phytophthora infection, regardless of the season.

By the time most growers recognize the symptoms in the above ground parts of the tree, several trees are in a declining state due to a long period of infection (several years). Trees suffering from root rot will have black, mushy roots which can be observed upon excavation. Roots and soil may have a “rotten egg” smell. This smell, however, is not from the disease itself, but from the anaerobic conditions caused by excessive soil moisture.

Irrigation sets should not exceed 24 hours. Over-watering should be avoided, especially during periods of low water use by the tree. Within almond and peach, in comparison to Nemaguard and Lovell, Peach/Almond Hybrid rootstocks are more susceptible to Phytophthora, while Marianna 2624 is less susceptible towards the disease. Viking and Atlas have the same level of resistance as Nemaguard and Lovell. Since not all Phytophthora species are the same, the performance of resistant rootstocks will vary by which species is present. The occurrence of Phytophthora has becoming more common over the past few years. This trend is likely the result of lower quality soils in which orchards are now being planted, poor selection of rootstocks for these soils, and mismatched irrigation scheduling for the soil type and tree size, and poor water infiltration associated with poor quality irrigation water (Doll).

3.2.4 Salinity

Sanden (2010) noted that most studies on almond salt tolerance in California are more than 50 years old. Sanden reasons that there are orchards that should be in much worse condition based on soil and water analyses, resulting in much lower yields than they actually have. These scenarios may indicate that there are rootstock, soil, sodium/calcium ratio and chloride/boron/bicarbonate/sulfate interactions that can mitigate or exacerbate the damage beyond the limited data we have at hand.

> *“The most recent almond salinity field study was conducted on the UC Westside Field Station in western Fresno County (an area of prime concern for this issue) from 1980 to 1987. But even the best control treatments and resulting tree performance was far below 21st century industry standards and offered little in the way of management thresholds and guidelines.”* (Sanden, 2010)

Therefore, almond tree variety, and in turn root stock selection both influence root architecture, depth and length in different soil and moisture environments. Many combinations of rootstocks and scions are possible, and some of these combinations may be more probable in certain soil environments because of their suitability and because of grower preference.

3.3 Root Depth

The studies reviewed below indicate that:

1. There is likely no static or distinct boundary between an active and non-active root zone; root function decreases gradually as depth increases, rather than in discrete steps.

2. The depth of the effective and/or active root zone can change in response to changing environmental conditions, such as moisture, temperature and nutrient status.

The Almond Board of California (undated) cites almond root depth at 2.5 feet. This determination may be from observations of uprooted trees in orchards during orchard removal. It is important to note that these uprooted roots likely do not include fine roots which are likely broken off during uprooting.

Koumanov et al. (1997) applied micro-sprinkler irrigation to wet almond orchard soil to a depth of 15 inches (1.25 feet), and found that roots were active in this zone, but not active at greater depths (as determined by soil water flux measurements made to a depth of 90 inches [7.5 feet]). The root excavations found roots down to a depth of 40 inches (3.3 feet). Koumanov suggested that these roots may be active after winter rains in the early part of the growing season before irrigation has commenced.

UCCE Advisor Joe Connell advised that the soil of an almond orchard needs to be wetted to four feet to prevent water stress (Connell, 2012). The California Department of Food and Agriculture's (CDFA) Almond Fertilization Guidelines (2011) reference almond rooting depth at five to seven feet. Other anecdotal resources cite observations of almond roots down to nine feet (Brummer, 2014). Catlin (1996) cited maximum root depth at 13 feet, which is possible in certain soil and moisture regimes.

The Food and Agriculture Organization (FAO) of the United Nations (Allen, 1998) recommends using an assumed root depth of 3.3 to 6.6 feet. The FAO documentation implies that this depth is the maximum root depth. However it is likely that this depth is closer to effective root depth, not the maximum root depth, depending on irrigation method, considering the root investigations in California cited above.

Phogat et al. (2012) determined that the greatest almond root density occurred in the upper 30 cm (1 foot), which implies that this is also an important part of the active or effective root zone. However, the information on root function summarized below suggests that root density may not be a good indicator of the effective root zone, because different types of roots have different functions, and because trees can change preferential root function in response to changing environments.

3.4 Methods of Studying Root Depth

Complete root systems are difficult to observe and describe. Both non-invasive and invasive methods have been used to study roots, and each method has advantages and disadvantages. Study objectives should be considered when selecting a method for studying roots as well as anticipated site conditions, accuracy, cost and time required. Table 3-1 summarizes the methods described below together with advantages and disadvantages.

3.4.1 Non-invasive Methods for Studying Root Depth

Ground Penetrating Radar

Ground penetrating radar (GPR) has been used successfully to measure root biomass in three dimensions under particular site conditions. In this method, electromagnetic radiation reflects signals from subsurface structures. Measurement can be performed through impermeable materials such as concrete or asphalt layers or beneath water or a river-bed. Distances are detected with about 50 mm error and roots can be detected down to a depth of about 2.5 m.

In general, the radar has an accuracy of about 80 percent (Nadeshdina and Čermák 2003). An advantage of this method is the possibility of characterizing root dynamics by repeating measurements over time. However, this method is limited in that radar can only distinguish roots with a diameter greater than 10 to 20 mm. Thus, thin conductive roots or fine absorption roots (with a diameter of 0.1 to 1 mm) and other smaller structures are not visible. Additionally, Butnor et al. (2001) concluded that the utility of current GPR technology for estimating root biomass is site-specific, and that GPR is ineffective in soils with high clay or water content.

Differential Electric Conductance

Several systems for the measurement of electric conductivity have been routinely used for geophysical studies in soils. A similar approach, combining conductivity measurements of tree stems or coarse roots, and soils, has been used to estimate the area of conducting root surface (in square-meters per tree), irrespective of their morphological parameters. This measurement may or may not be related to root depth. This method is based on differences in the conductivity of the materials and the fact that the zones in which roots absorb soil water are practically identical to the zones through which the electric current passes when the tree becomes part of an electric circuit, supplied from an external voltage source. The first results obtained with this method on seedlings and large trees of a range of species are promising; however, no alternative method providing similar data was available against which to compare the results. Therefore, more experience is needed before recommending this method for more general use (Nadeshdina and Čermák 2003).

3.4.2 Invasive Methods for Studying Root Depth

Whole Root Excavation and/or Observation Using Pits and Trenches

The traditional method of studying tree roots involves digging a large pit or trench with excavation equipment to provide a cross-section of soil, on which tree roots and their characteristics can be directly observed and/or excavated throughout the entire depth of the soil profile, and potentially the entire depth of the root zone. Though this method is thorough, it is labor intensive, time-consuming and potentially hazardous if safety precautions are not properly observed. Because of these limitations, fewer trees can be included in root studies. Trees are necessarily damaged and potentially destroyed with this method, and within densely planted orchards, more than one tree may be damaged per pit.

Root Excavation by Supersonic Airstream

Whole root excavation can be performed by a method that uses a laser-like thin supersonic air stream. The air stream is delivered from an above-ground tool held by the operator. When the air stream touches a smooth object (such as a stone or root) it will slip over roots without causing damage. However, when the stream hits any tiny pore, air is compressed within it causing it to "explode." During the "explosion" of the pore spaces, soil is dislodged and the roots and other smooth objects (without small pores) remain untouched. Commercial airstream tools can only excavate down to about a two-foot depth. The soil removed from the ground by the air stream must be removed during observation of roots, then can be replaced.

Dr. Alison Berry (Berry, 2015) and other UC Davis plant scientists have developed a method of excavating tree root depths to six feet below ground surface (bgs) using a high powered AirSpade™ (as opposed to the two foot depth of commercial airstream tools). The UC Davis work was done on native trees situated near San Joaquin River levees. UC Davis staff successfully excavated tree roots to be able to map them using Terrestrial Light Detection and Ranging (T-LiDAR) with high accuracy. T-LiDAR technology utilizes reflected laser pulses sent from a tripod-mounted scanning instrument to determine distances to targets of interest. The resulting dataset is a three dimensional model or "point cloud" of millions of data points, spaced only a few millimeters apart. This highly detailed dataset is used to create topographic models, make detailed measurements, and quantify geomorphic and vegetative changes on the earth's surface. Though in some cases UC Davis staff cut parts of large trees for safety reasons, the trees were not destroyed in the process of using the AirSpade™. This method was particularly useful for accurately imaging and mapping the architecture of the root system in three dimensions. The main advantages of this technique are:

1. It can be carried out with minimal destruction; and
2. The entire tree root system can be mapped accurately.

This method is highly labor intensive, requires specialized equipment, and can be costly. In the above-mentioned levee work, it took about three days to excavate the roots of a large tree down to six feet (Berry, 2015).

Hand-Operated Sampling Tubes and Augers

As an alternative to larger efforts involving soil excavation, the depth of the root zone can be established by using a hand-operated soil sampling tube or auger. These are pushed or twisted by hand into the soil to a maximum depth of five or six feet. The soil samples removed from various depths of the soil profile can be examined for roots and compared. It may be difficult to see roots in a sample of soil, especially if it is course-textured.

Soil sampling tubes are typically small in diameter (e.g., two inches) and do not provide a large sample. Therefore, many samples would be needed to represent on tree root system accurately. Though augers are wider in diameter, the auger process can destroy roots, therefore, making them indistinguishable in the sample. Soil sampling tube or auger "refusal" (i.e., inability to advance the probe deeper) once encountering larger roots or cobbles/stones/gravels is also common and can limit deeper exploration of the root extent. Usually, multiple borings are required per tree root system because samples are so small. This method is labor intensive and unlikely to work in the full range of soils expected within the areas of interest.

Hydraulic Soil Core Sampling

In this method, a hydraulic device mounted on a truck, tractor or all-terrain vehicle pushes a cylinder (typically two inches, but larger diameter (eight-inch diameter) cores have been used at shallower depths) into the ground and extracts an intact soil core that can be immediately observed and discarded, or encased in clear acetate tube for storage/preservation.. The soil core devices can be used to sample a depth of over 10 to 15 feet as long as restrictive layers (large cobbles or thick hardpan) are not encountered. The equipment typically includes a hydraulic hammer mechanism that can penetrate dense soils and thin hardpans. The main advantage of this method is that soil cores can be extracted from all types of soils quickly. The main disadvantage to this method is that the location of roots as they extend laterally from the tree (on the horizontal plain) is unknown, especially at depth. Therefore, several cores may have to be sampled to ensure that roots are not missed at greater depths. Special equipment is required for this method.

Table 3-1.
Methods of Studying Tree Root Depth

Study Option	Description	Advantages	Disadvantages
Non-invasive methods			
Ground Penetrating Radar (GPR)	• Roots can be detected down to a depth of about 8.3 feet • Electromagnetic radiation reflects signals from subsurface structures.	• Measurement can be performed through impermeable materials such as concrete or asphalt layers or beneath water or a river-bed • Can characterize root dynamics by repeating measurements over time	• Can only distinguish roots with a diameter greater than 10-20 mm • Ineffective in soils with high clay or water content.
Differential Electric Conductance	• Based on differences in the conductivity of the materials; the zones in which roots absorb water are practically identical to the zones through which the electric current passes when the tree becomes part of an electric circuit, supplied from an external voltage source	• Used to estimate the area of conducting root surface (in square-meters per tree), irrespective of their morphological parameters	• More experience is needed before recommending this method for more general use

Table 3-1.
Methods of Studying Tree Root Depth

Study Option	Description	Advantages	Disadvantages
Invasive Methods			
Whole Root Excavation with Pits or Trenches	• Digging a large pit or trench to provide a cross-section of soil, on which tree roots and their characteristics can be directly observed	• Entire root system throughout soil profile can be excavated/observed	• Major safety concerns associated with excavating a pit large enough to sample roots at maximum potential root depth (10 feet) • Very time and labor intensive • Destroys whole tree, and in high density orchards, may destroy more than one tree per pit • Requires special equipment and operator
Excavation by Super-Sonic Airstream	• Soil around tree roots is "blasted" with a high-pressure, concentrated air stream directed at soil by an operator	• Trees need not be damaged or destroyed	• Need special equipment • Need operator training • Requires removal and replacement of soil • Time and labor intensive • Excavation to likely maximum depth of roots is impractical

Table 3-1.
Methods of Studying Tree Root Depth

Study Option	Description	Advantages	Disadvantages
Hand-Operated Sampling Tubes and Augers	• Hand pushed sampling tubes (one to two inches in diameter) or hand operated augers (3 to 4 inches in diameter) typically used to sample soil or shallow roots are used to excavate soil samples in which roots can be observed.	• Suited for sampling and observing root systems in upper one to three feet • Does not require special equipment • No major safety concerns	• Sampling tubes may miss roots because diameter is very small; many samples would need to be taken • Can only go to certain depth (five foot maximum) • May be difficult to see roots in a sample of soil, especially if it is course-textured • Augers destroy/damage roots • May not be able to penetrate soils that are dense, panned, etc.
Hydraulic Soil Core Sampling	• Hydraulic device mounted on a truck or all-terrain vehicle (ATV) pushes a cylinder (typically 2-3 inches, but larger diameter (8-inch diameter) cores have been used at shallower depths) into the ground and extracts core; core can be described and samples, or encased in clear acetate tube for storage/preservation if necessary	• Can penetrate all soils • Can reach deeper depths (10 to 20 feet) relatively quickly • Several cores can be completed in a short timeframe • Less labor intensive • Less invasive than other excavation methods • No major safety concerns	• Sampling tubes may miss roots because diameter is small; many samples would need to be taken; the location of roots as they extend laterally from the tree (on the horizontal plain) is unknown, therefore, several cores may have to be sampled at depth • May be difficult to see roots in a sample of soil, especially if it is course-textured • May not be able to penetrate soils with large cobbles or thick hardpan

4.0 Soil Characterization for Selected Parcel Groups

4.1 Preliminary Soil Investigations

Over two hundred groundwater monitoring wells have been installed by Reclamation since 2009. The geologic information developed during the installation of these wells was useful in identifying soil types present in areas where almond orchards are (or may be) planted. The well installations are documented in Groundwater Monitoring Well Installation Geologic Reports (Reclamation, 2012). This information, where available, is helpful in refining the information provided by soil survey, summarized in the next section. Information from those reports includes the following descriptions:

> *Reach 2 is dominated by sand deposits. Geologic investigations performed along this reach encountered mostly silty sand and poorly graded sand with silt. Reach 3 is dominated by sand deposits. Geologic investigations performed along this reach encountered mostly silty sand, and poorly graded sand with silt.*
>
> *Reclamation conducted four previous phases (prior to 2012) of groundwater monitoring installations, installing 42 groundwater monitoring wells at 32 locations in 2009; 22 groundwater monitoring wells in the spring of 2010; 18 groundwater monitoring wells in the fall of 2010; and 18 groundwater monitoring wells in the spring of 2011. The State of California, Department of Water Resources conducted geotechnical investigations in Reach 2 during March 2010, in which Cone Penetrometer Tests 8 (CPT) were conducted along potential alignments for setback levees on the south-side of the San Joaquin River.*
>
> *The soils encountered were generally dominated by sandy deposits in Reaches 2 and 3. Wells installed near the San Joaquin River were likely to encounter thick beds of subsurface sand. The left bank of the Mendota Pool area in Reach 2B (MW-11-164) was dominated by a thick subsurface bed of clean sand, which was also observed downstream on the left bank in wells close to the river in Reach 3 at MW-11-160, and on the right bank in Reach 4A at MW-11-162.*
>
> *The six wells installed downstream in Reach 3 showed similar geology consisting of lean clays with sand interbedded with silty sands overlying silty sands and subsurface layers of clean sand near the SJR.*

The descriptions of soils in the general vicinities of Reaches 2 and 3 generally confirm the presence and dominance of coarse textured soils. However, fine soils are also mapped along with sodic and saline soils in various combinations with textures. Field reconnaissance and sampling is especially recommended for this type of work to validate and refine soil survey information.

4.2 Interpretation of Soil Survey Information and Soil Boring Logs

Reclamation has prioritized the PGs along the river to identify those areas that are more likely to be influenced by the presence of Restoration Flow in the San Joaquin River. Several of these PGs are planted in almonds. Figure 4-1 shows the locations of the PGs that may be candidates for field investigations of almond root zone characteristics. These PGs provide good examples of sites where seepage projects may be necessary, but may not be entirely inclusive of all sites where seepage projects may be necessary.

The soils at each of these locations were reviewed and are described in Table 4-1. In general, the following soil texture profile types are represented by these sites:

- Coarse soils underlain by coarse soils,
- Coarse soils underlain by fine soils,
- Fine soils underlain by fine soils,
- Fine soils underlain by coarse soils (fairly uncommon), and
- Stratified soils and/or restricted soils (soils of various textures underlain by hardpan).

Some of these soil types, according to information presented in the literature review, would be expected to limit root growth. Site conditions that limit root growth include:

- Elevated salinity,
- Stratified soils, restricted soils (with hardpans) and deep fine soils, and
- High water tables

Fields with one or more of these conditions likely have less than potential effective and maximum almond root depths. However, how the effects of the root growth interacting factors interact to influence rooting depth is likely site-specific and is unknown without field investigation. Field studies would be needed to compare sites that differ by soils and how root growth is affected.

Table 4-1 is a summary of the soils found in the PGs in question, their properties expected to influence root growth, and expected relative root depth.

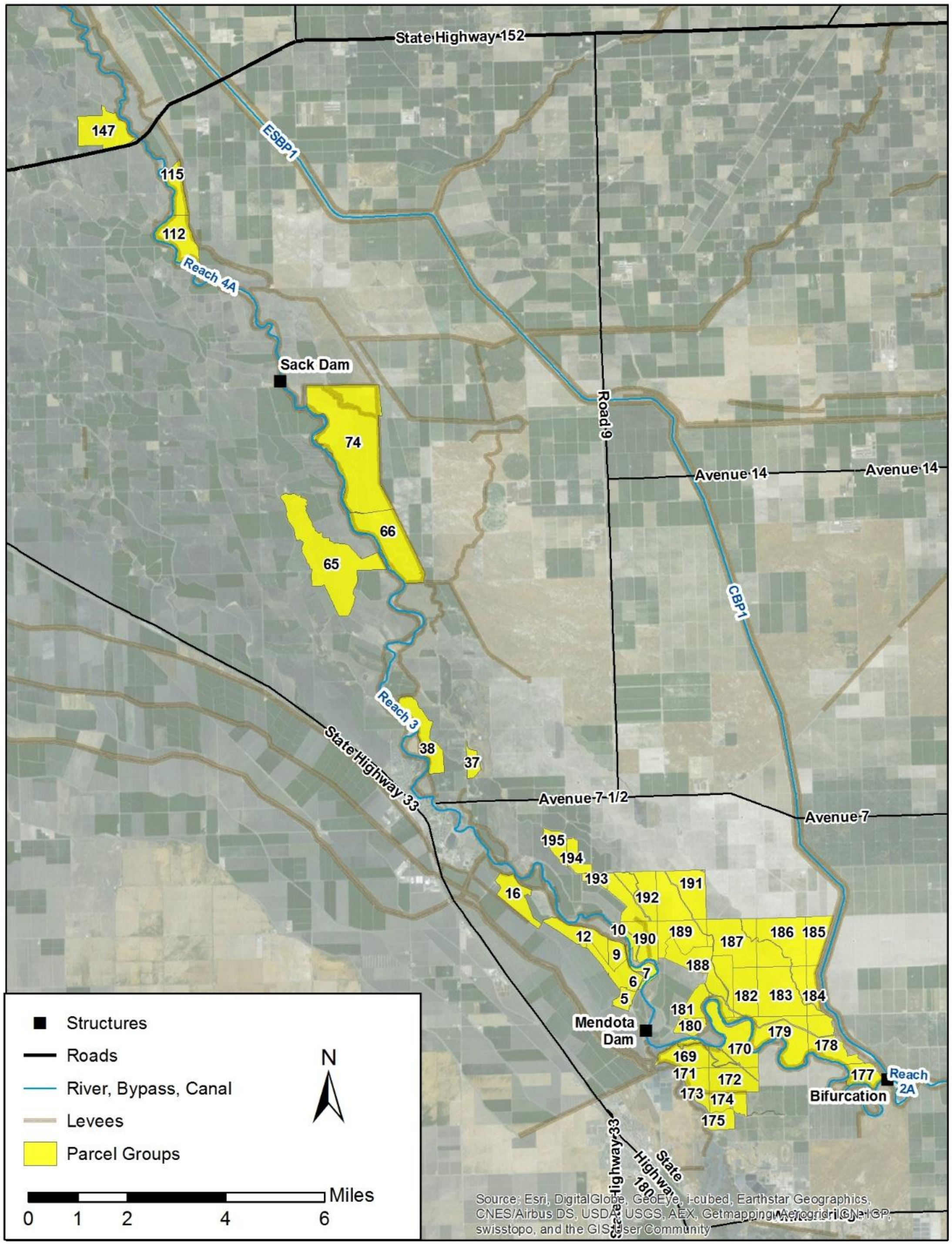

Figure 4-1.
Location of Properties for Potential Almond Root Zone Field Investigations

Table 4-1.
Root Growth Influencing Site Conditions on Properties Considered for Potential Almond Root Zone Field Investigations

Parcel Groups	Predominant Soil Series and Textures	Salinity1	Depth to Water Table	Expected Relative Root Growth
169 through 195	Loams that are largely represented by the Traver, Chino, Foster and Grangeville soil series. These include loams, silt loams and fine sandy loams. Chino and Grangeville coarse loams are underlain by finer soils, such as silty clay loams and clays.	Many areas are mapped as slightly to strongly saline throughout PGs	Groundwater elevation peaked at 8 ft bgs in one well.	Unlimited (unrestricted horizons and medium to coarse textured soils)
5, 6, 7, 9, and 12	Coarse (sandy) loams. Elnido series underlain by sand; Palazzo series underlain by clay loam.	Soils not mapped as saline	PG 7: groundwater elevation peaked at 1 ft bgs (CCID 371)	Unlimited (coarse textured soils). Potentially limited in Palazzo soils.
16	95 % of parcel is Tachi clay down to 60 in bgs (5 ft bgs), becoming sodic at 14 in bgs (2 ft bgs)	May be slightly saline.	Wells 355 and 359 indicate water levels at 10-13 ft bgs, peaking at 8 ft bgs. Water table mapped in soil survey at 40-60 inches (3.3-5 ft bgs)	Limited by deep fine-textured soil and potential salinity. Likely high capillary fringe.
37 and 38	Temple clay and Temple clay loam; Grangeville fine sandy loam underlain by clay.	Majority of soils not mapped as saline.	Groundwater elevations in monitoring wells on these parcels averages around 12 ft bgs and peak is lower than 10 ft bgs	Limited where fine-textured soils occur throughout profile
65 and 66	Armona loam (underlain by stratified finer textures), Gepford clay, Elnido and Palazzo sandy loams; Temple (some slightly saline) and Pozzo clay loam (underlain by coarse soils); Grangeville fine sandy loam and Grangeville fine sandy loam over clay.	Soils in PG 65 not mapped as saline. Majority of soils in PG 66 not mapped as saline.	PG 65: Groundwater elevation peaked at 4-5 ft bgs (CCID 164, MW-10-76). PG 66: 13-19 ft bgs	Limited where fine-textured soils occur throughout profile and potentially limited in stratified soils

Table 4-1.
Root Growth Influencing Site Conditions on Properties Considered for Potential Almond Root Zone Field Investigations

Parcel Groups	Predominant Soil Series and Textures	Salinity1	Depth to Water Table	Expected Relative Root Growth
74	mixed and stratified soils of various textures	Not mapped as saline.	PG 74: MW-11-163 (north end of field) groundwater elevation peaked at 3-4 ft bgs. MW-13-211 and MW-13-212 in southern end of field: groundwater elevation peaked at 17 ft bgs	Potentially limited in stratified soils
112 and 115	Columbia fine sandy loam, some over hardpans or clays; Rossi clay loam	Soils in PG 112 not mapped as saline. Rossi clay loam in PG 115 mapped as slightly saline, representing about 30-40% of PG 115 area extent	PG 112: Groundwater elevation peaked in MW-12-89 at 2 ft bgs but is normally around 12 ft bgs. No monitoring wells on PG 115	Limited (restrictive layers)
147	Half of parcel is clay loam underlain by loam. About one third of parcel is Palazzo sandy loam (underlain by silty loam)	Soils not mapped as saline	Only well on parcel is CCID 189 and there is not water level data available for it	Likely unlimited, but may be limited on clay loam soils

[1] *Source: United States Department of Agriculture, Natural Resources Conservation Service, Web Soil Survey. http://websoilsurvey.sc.egov.usda.gov/App/HomePage.htm. Accessed January-April, 2015.*
Note:
CCID: Central California Irrigation District
in: inches
ft: feet below ground surface

These site conditions can be categorized as follows, approximately in order of least root growth limiting to most root growth limiting (dependent upon irrigation management):

- Least limiting
  - Non-saline, course-textured soils are dominant in PGs 5, 6, 7, 9, and 12, and also occur in PGs 65 and 74. PGs 7, 65 and 74 have potential high water tables.
  - Saline, course-textured soils are found in PG 74 and the southern portion of the Paramount property.

- Moderately limiting
  - Saline loams, or medium textured soils occur in PG 74 and the northern portion of the Paramount property; however, non-saline loams are not prevalent in any of the parcel groups.
  - Non-saline, fine-textured soils are dominant in PGs 37 and 38 is, and this soil type occurs in PG 65 as well.
- Most limiting
  - Saline fine-textured soils occur in PG 66 (where it is dominant), 112 and 115.
  - Restrictive (including hardpans or clay layers at depth) or stratified soils occur in PGs 65, 112 and 115.

5.0 Potential Additional Root Zone Study

Literature review and expert interviews provided valuable information about almond rooting depths and influencing factors. There are limitations however, to the direct application of this information within properties considered for potential almond root zone field investigations within the SJRRP due to lack of site-specific root depth data here and throughout California. For this reason, the potential for further site specific observations was evaluated. Information obtained through literature reviews and expert interviews was used to develop potential options for collecting site specific rooting depth information for the SJRRP. These options, including different levels of effort, are described in a preliminary study plan in Appendix B. The decision about whether or not to proceed with additional study of rooting depths is dependent on several factors. The potential value of such site-specific information has costs and limitations. Advantages and disadvantages of a field study effort are listed below.

5.1 Advantages

- A customized study would provide actual local field data. Such data are the most credible and likely most influential in negotiating refinements to target rooting depths and approaches in the SMP. Site specific information is difficult to refute and is the only data that stands up to growers' anecdotal observations on rooting depth.

- Local study observations would support and refine estimates suggested by experts. Most literature and expert opinion relates broadly to statewide almond production. It is expected that site specific data would confirm and validate the ranges suggested by experts and further define where almond root depth falls within that range in the specific SJRRP area. It is also possible that SJRRP depth ranges are smaller under certain conditions, which translates to significant cost saving in future design efforts if site specific information can be used.

- A field study would provide data to validate or disprove the almond agricultural threshold that is currently published in the SMP. Roots may be found at deeper depths, but they would be different roots with different function than those found in the active/effective root zone.

- A field study would greatly improve grower/stakeholder confidence and understanding; Reclamation has heard from growers that they that the growers have observed roots at great depth (e.g., nine feet) and conclude that these are important roots that would be affected by salinity/saturation. Observations combined with expert opinion would do much to clarify this lack of understanding of root function. In the absence of other recorded observations, these anecdotal observations are the only site specific information available and carry significant weight.

- A field study would serve the additional purpose of collecting other field data (soil information, for example) that is needed for future seepage project design efforts. Some of this information would be recommended or required before certain design efforts were initiated anyway.

- Study costs are a consideration, but are likely to be far less than costs of overdesigned systems and rooting depth disputes that may arise in the absence of site specific data to support the seepage management plan and implementation.

- A field study may have a public relations benefit showing that the SJRRP shares the concerns of the stakeholders and is willing to work with them to reach a common understanding.

5.2 Disadvantages

- Implementing a study will require time and administrative effort to obtain necessary permits and approvals as well as coordination efforts with vendors and consultants. Recent SJRRP permitting for Section 106 Compliance for similar work has taken over six months could result in significant delays to project design and implementation for high priority seepage projects.

- The study will have a cost, which will depend on the level of effort desired.

- Study duration is expected to take a full season, depending on the level of study effort selected. The availability of final data will be dependent on this study duration and the up-front logistics and approvals required for study implementation.

- Study implementation will require significant grower coordination and communications to ensure adequate participation/access and understanding of the study.

- Field examination of rooting depth, type and abundance doesn’t provide comprehensive root function information and may not resolve all questions surrounding the active, effective, and total root zone.

- There will always be some level of uncertainty associated with even the most carefully designed field study of almond root zone depths. Even the results from a statistically robust study may not increase stakeholder confidence in the resulting SJRRP almond root zone depth used to establish SJRRP SMP thresholds and growers may interpret the field investigation data differently.

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Appendix A. UC Expert Advisory Log

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Gurreet Brar, January 15, 2015	
Depth of almond roots observed in field	On drip irrigated orchards, most roots are in top 4-5 ft. This includes structural roots for anchorage. Effective root zone where most water and nutrient uptake occurs and most fine secondary roots are is top 2 ft.
Methods of root study	Not experienced in root study methods, but referred to Astrid Volder.
Age of peak root development	Not sure when roots reach peak development/depth, but thinks it would coincide with orchard maturity, which would be around year 7.
Effect of orchard density of root depth	Not sure. Referred to Roger Duncan for this topic.
Effect of rootstock	Is not familiar with effect of different rootstocks on root depth. Nemaguard and Hanson 536 should be included to observe most extensive rooting systems (if used in project area). Hanson 536 is more tolerant to salinity. Viking is also one of the more salinity tolerant rootstocks. For high water tables/wet soils, Marianna 3634 is good (used in Sac Valley) but may not have good compatibility with nonpareil scion.

Roger Duncan, January 22, 2015	
Depth of almond roots observed in field	80% in top 2 ft. In areas of high water table roots tend to grow to the same depth but are impacted by salinity. Salinity is bigger factor than saturation, because of lack of leaching. Would not be comfortable planting where water table was at 5 ft. Would be ok if water table was at 10 ft. Water table should be somewhere between 5 and 10 ft, but not sure where.
Methods of root study	Thinks excavation would be better than smaller scale methods. Agrees with Volder's assessment.
Age of peak root development	Doesn't know, but agrees with rationale that orchard should at least be at maturity (7 years after planting) to study max root development.
Effect of orchard density of root depth	Density of orchard does not influence that much. Trees are smaller, so root system could be also, but doesn't know of data that proves that they are shallower.
Effect of rootstock	Rootstock does influence rooting depth, but salinity is driving factor. He used to think that saturation mattered in rootstock selection, but has changed mind because now he thinks salinity is more important. Rootstock selection has only come into "vogue" in last few years (less than 10). Nemaguard prior to 6 yrs. ago made up 90%, but now there are more varieties; peach hybrids root deeper but are also more salt tolerant.

Ted DeJong, January 13, 2015	
General response	Email response: "Basically in irrigated orchards 90+% of the roots are no deeper than 4 ft. However if the grower isn't irrigating to the level required roots can grow deeper and water extraction in almond orchards has been documented below 12 ft. On the other hand if the water table near rivers is above 4 ft it can severely compromise the health and vigor of the trees. Almost all orchard trees need well drained soil. Pear trees are the most resistant to excessive soil moisture."

Bruce Lampinen, January 27, 2015	
General response	Email response: "I listened to your voice message and I think you have already talked to all the right people. I do not have any specific knowledge on almond rooting depth beyond what you would have already received talking to Astrid Volder, Ken Shackel as well as farm advisors. I have observed rooting depth to be highly variable and basically limited by how the irrigation system is operated in summer. If water is only being pushed down to 1 foot between irrigation cycles then that is where the functional roots will be (this is not uncommon). More common would be to have 90% of roots in the top 3 ft."

Ken Shackel, January 23, 2015	
Depth of almond roots observed in field	Some deep roots beyond 10 ft, but most are in top as noted by others. On root activity - deep roots always have a low level of activity. When an environmental stressor occurs in the upper active root zone, the tree has to depend more on the deep roots, but that doesn't mean that they increase their activity significantly. This is because there are not nutrients/minerals down that deep anyway, and because it is so hard for the tree to transport water/nutrients that far. Therefore, seepage impacts (saturation, salinity, etc.) would have less detrimental effects on deep roots than on the very active roots. But, trees are known for taking a long time to die; i.e. harm may be occurring but you may not see it right away. Agrees that you can't just drain to the lowest level of active roots (4-5 ft) because you need some room to leach. But it is likely not realistic to drain to the deepest roots because activity is so low and because the effects of seepage would be small.
Methods of root study	Excavating is the way to study root depth, but what would be the purpose? If we already know that most roots are in upper two ft, most of the rest are within 4-5 ft, and then there are a few deep roots, what is the purpose of digging up roots? Only to validate what we already know? Need to clarify purpose.
Effect of orchard density of root depth	Thinks that trees are smaller in denser orchards, so root systems are also smaller and shallower. Some others, though, theorize that since roots are competing on horizontal plane then they should be deeper, but he doesn't agree with that.

Brent Holtz, January 26, 2015	
Depth of almond roots observed in field	In Madera Co. - high water tables near Firebaugh along river - planted almonds where water table was 4-5 ft and they were ok. In SJ Co. almonds are being planted in Delta with high water tables but that is more like spring water. Depends on water quality.
Methods of root study	Talk to Franz Niederholzer.
Effect of rootstock	Krymsk 86 used in Sac valley on wet soils.

David Doll, January 13, 2015	
General response	Email response: "I am willing to speak with you, but I doubt I can provide much more than what you have read. Most of what we know about roots is based on generalities and old assumptions that somehow has become gospel. Recent work by Astrid Volder is trying to take a modern look at 'the final frontier.' She might be a better person to contact."

Blake Sanden, January 27, 2015	
Depth of almond roots observed in field	Though growers are pushing the limits on almond rooting zone up to only 4-ish ft (because of high almond prices, chasing good water quality, etc.) no farm advisor would recommend it. Farm advisors recommend 6 ft of oxygenated root zone. Would demand an average water table at 6 ft, accounting for capillary fringe, which can be up to 4 ft on some clay soils. Periodic saturation up to 4 ft would probably be OK, but not ok on average. Timing of saturation is also important. If increased flows, and therefore, increased seepage occurs in spring (for fish flows) that is prime temperature/conditions for phytopthera disease. Also, from mid-April to mid-June, "June-drop" occurs in almond trees. This is where they drop some of their developing fruits as a way to balance carbohydrates. During this time, B, P, Mn and Cu nutrition is critical for fruit set, canopy growth, and cell division. Under saturated conditions, nutrient availability and uptake are inhibited. Therefore, timing of saturation (and duration) potentially affects disease occurrence and production. As for the specific effects of duration and frequency of saturation on roots, talk to Patrick Brown. These effects would likely be less pronounced on roots deeper than the primary root zone in the top two ft, but doesn't know for sure because could depend on soil, moisture conditions, etc. Should also consider existing "shelf" of salinity. If seepage is coming from below, could potentially push shelf of salt that was previously ok (lower than roots) up into root zone.
Effect of orchard density of root depth	Likely depends on soil, but knows that irrigation management affects rooting depth. If you irrigate with short duration high frequency irrigations, roots will stay relatively shallow. There is likely not much difference in rooting depth between drip and micro--sprinkler if they are managed well and assuming double-line drip. Single-line drip may potentially result in smaller root structure overall.
Effect of rootstock	Hansen and Viking are both used on saline soils, but they are more susceptible to disease. Roger Duncan is expert on rootstocks.

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Astrid Volder, January 20, 2015	
Depth of almond roots observed in field	Most roots are in top 2 ft - both fine and woody. Since she only studies fine roots that take up water and nutrients, she only samples down to two ft. She agreed that structural roots generally go down to 4-5 ft, and occasionally go down to very deep depths in rare situations such as deficit irrigation. Has only studied pecan roots and one walnut orchard. Architecture likely changes with site and species. In one almond study, finer roots were at top. In walnut study, finer roots increased with depth to a certain depth. Likely influenced by soil moisture conditions.
Methods of root study	She only uses a 2-inch soil core, and only does one core per tree because it is so labor intensive. It is VERY labor intensive to extract roots form soil cores. GPR only works for large roots. Mini-rhizotrons are more for studying root development. Air-spades can be used for in-situ extraction. Suggested that maybe a backhoe would be better suited to our purpose and potentially more accurate. Cores are so small that it is hit or miss if you find roots. Just because you don't find them doesn't mean they aren't there. Referred to Schenk and Jackson for deep root studies.
Age of peak root development	Should study mature orchards. Woody roots (larger structural ones) would likely be less affected by frequent saturation because they have very low respiration rates, since they don't take up nutrients and water. Fine roots that take up nutrients and water have high respiration rates, so they would suffer more from lack of oxygen.
Effect of orchard density of root depth	Doesn't study root depth per se. Soils definitely have an influence. For what we want to know, finding an orchard being pulled out would be valuable.

Franz Niederholzer, January 27, 2015	
Depth of almond roots observed in field	There are more roots in upper foot than in the increment of 1-2 ft. Deep roots can become more active when resources are low in upper root zone. Irrigation dictates where roots will grow. Planting berms is a good option to keep roots viable where there are salinity problems when the water is coming from the top. But when the water is seeping up from the bottom that is a different story. Wicking could end up concentrating salts in berms. The environment in which roots are established may affect how they react to imposed water scenarios. If roots are established in a high water table area, they have adapted. But roots that were established in a low water table scenario might have trouble adapting to a water table that rises. Fine roots cycle annually (die off and regenerate) but woody roots don't.
Methods of root study	Root excavation would be best. Selecting replicates - should try to select trees that have similar light interception. For example, a tree at the end of a row will likely have a different root system than a tree in the middle of a row.
Age of peak root development	Not sure about peak root development, but likely mirrors canopy development.
Effect of orchard density of root depth	Orchard density may or may not affect root depth because - even if tree is smaller, and root system is smaller, that means less biomass but not necessarily less length.

Patrick Brown, January 28, 2015	
Depth of almond roots observed in field	Blake Sanden is correct in that the period from March to May is critical, and if primary root zone is saturated during that time the trees will be harmed. If the soil in the primary root zone is saturated for one to two weeks the trees will likely die. If the saturation is below 3 ft, likely not a big deal. As long as the root zone from 3 ft up stays oxygenated the trees will be fine. However, if there is a salt shelf that is below that 3-foot limit but is still relatively shallow (4-6) it might be pushed upward during seepage events and that should be considered.

Alison Berry, February 24, 2015	
Methods of root study	Most of roots of trees in general are in top 2-4 ft. This is also where they extend the most laterally. So root profile looks like upside down umbrella; lateral extension of roots diminishes with depth. Roots are opportunistic and grow where there are conditions that they need. They only imaged roots to a minimum diameter of 1-inch because roots smaller than this (at any depth) do not play a major role in tree stabilization, which was the purpose of their particular project... Sometimes certain types of trees will extend a taproot, but not all trees do this. So, if you find roots a great depths (beyond 6-8 ft) they are not nearly as functional, either in terms of uptake or structural support, as roots in effective zone, and would therefore not likely be affected by seepage impacts.. Any kind of soil stratification will likely inhibit root growth and/or result in a "perched" root zone. She has an example of a root study on a peach orchard that is illustrated in one of the arboriculture textbooks she uses to teach. It shows that in a fine soil underlain by a coarse soil, the peach roots did not extend into the coarse soil. This is likely because the water in the micro pores in the fine soil cannot flow out of them unless the fine soil is saturated. Similarly, in a coarse soil underlain by a fine soil, these differences in water movement may affect root growth preference.

Alison Berry, February 24, 2015	
Methods of root study	Excavating trees with a backhoe is useful for determining gross measurements of roots like lateral extension and root depth. Alison and Shi-Min Chung (now post-doc) developed method of using a high-powered air-spade with T-LiDAR to excavate tree roots without killing trees so that root systems could be accurately imaged. Did this in levees of SJR, so were likely dealing with similar soils. Most soils were sandy. Clay soils took more time to excavate because they were more compact, but within the range of agricultural soils, difference in ease/time of excavation would likely not vary too much. It took them 3 days to extract roots of one large tree to six ft. You have to have a loader to haul soil away and then put it back (plus compressor, hose, etc.) Very labor intensive process, but got very accurate info without killing trees. They irrigated the night before to try to achieve optimum soil moisture. Too much or too little moisture makes excavation difficult - too muddy or too dusty. Employed consultants to train personnel to use high-powered air-spade (mostly for safety reasons) and to do LiDAR. LiDAR was not the expensive part of project - all the other logistics, labor and time were.
Effect of orchard density of root depth	To her knowledge, trees do not compensate for horizontal constraints by sending roots deeper. Agrees with Shackel and most others that if trees in densely planted orchards are smaller, then their root systems will necessarily be smaller in general. Therefore, roots in densely planted orchards will not be deeper than those in less densely planted orchards.

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Appendix B. Potential Field Programs for Almond Root Depth Investigation

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Appendix B. Potential Field Programs for Almond Root Depth Investigation

This section presents a plan of study for characterizing almond root depth within the project area. It incorporates information gained through detailed literature review and expert interviews specific to the topics driving almond rooting depths in this region. These preliminary efforts both indicated that almond root depth is influenced by soil type, soil moisture regime, salinity, depth of water table, rootstock, and orchard density. Therefore, a field study on almond root depth should be designed to account for multiplicity of these variables found within orchards.

Ideally, the study should primarily include sites that represent contrasting soil textures, soil salinities or soil salinity found at different depths, and water table depths. Orchard density and rootstock are secondary variables, because their influence on root depth is likely overridden by primary factors. Orchard age should be at least eight years to ensure that root systems have reached peak development. This conceptual design would result in a range of site conditions that would provide a good representation of the various responses of root depth to root influencing variables. As this study is exploratory and demonstrative, rather than one that focuses on determining relationships between independent and dependent variables, the particular combinations of these variables that might be found in fields need not necessarily be planned, but should be adequately represented and documented. Replicates (number of trees per site) needed to accurately represent root depth for a given site likely depends on the variability encountered at that site.

This study plan includes discussion of study design, methodology, site selection criteria, and schedule. Three different study approaches that comprise a range of effort, time and cost are presented, assuming partial root excavation with hydraulic core sampling.

It is important to note that observing tree roots at any depth does not provide any other information about the potential seepage impact on those roots. Therefore, a field study would validate the depth of the various root zones, and provide a means of observing if and how much root depths vary in different soil conditions of interest.

It is also important to note that this study plan and accompanying literature review efforts comprise Phase 1 of an almond root depth study effort. Phase 2 has not been completed and would include the implementation of the selected study approach, study site selection and final planning and preparation for study implementation including procurement of equipment, scheduling, landowner coordination, etc.

B.1 Objectives

The objectives of a field investigation would be as follows:

- Validate root zones and their respective root densities and types, as anticipated by UC experts and scientific literature;
- Characterize specific root depths within soil conditions typical of SJRRP area and seepage parcel groups; and
- Provide quantitative support for the almond root zone threshold specified in the SMP.

B.2 Root Depth Evaluation Methodology

A field study on almond root depth should be designed to account for root zone variables found within orchards. The most comprehensive method to observe root zone depth and characteristics is through actual excavation of tree roots, at least partially, to determine their presence or absence. Partial root excavation using hydraulic soil core sampling is the preferred method for the following reasons:

- No major safety concerns;
- Equipment required can operate in densely planted orchards with full canopy;
- Excavation to a depth of 10 to 15 feet depth is feasible and relatively quick;
- Trees need not be destroyed;
- Disadvantage of inability to penetrate hardpans and cobbles is mitigated by approximate sampling locations (specific sampling location can be moved); and
- Disadvantage of small sample size is mitigated by the ability to take several cores at a given tree in a relatively short period of time.

Other methods are either inadequate for certain soil conditions, too costly, too time-consuming, have major safety concerns, are not feasible for densely planted orchards, or are more appropriate for studying small roots and their function.

This type of investigation would be exploratory in nature, rather than statistically robust, but could result in a wealth of information that is impossible to acquire without field study. This will provide the most information with the least cost, time and risk to field staff. Root damage is expected to be limited by utilizing this type of investigation procedure.

Excavated root systems (ideally done with a 3-inch diameter core) would be observed for root type, size, and depth. Several cores would be excavated per tree (e.g. 5 to 10, depending on the variability in characteristics and rooting encountered). Depending on orchard design, cores may be taken along a tree row randomly at varying positions and may not have to be associated with a particular tree. Soils would be characterized in detail to verify conditions represented by the study site. Soil and root characteristics evaluated would include:

- Density of roots in varied size classes by depth;
- Soil physical properties (e.g., texture, structure, density);
- Soil stratification and presence of restrictive layers (e.g., hardpans, claypans, abrupt texture changes);
- Soil moisture parameters (e.g., soil moisture, evidence of seasonal water tables or saturated conditions, texture-based estimated water holding capacity); and
- Soil salinity and nutrient status – Composite soil samples would be collected at depth increments of at least every 18 inches to verify soil salinity and nutrient status. Soil samples will be sealed in re-sealable plastic bags and shipped to a laboratory for analysis of agronomic constituents (Table B-1).

Table B-1.
Soil Analysis Constituents

Constituent	Symbol	Unit
pH	pH	--
Electrical Conductivity	EC	mmhos/cm
Cation Exchange Capacity	CEC	meq/100g
Exch. Sodium Percentage	ESP	percent
Calcium	Ca	ppm
Magnesium	Mg	ppm
Potassium	K	ppm
Sodium	Na	ppm
Nitrogen	NO3-N	ppm
Phosphorus	P	ppm
Sulfate - Sulfur	SO_4-S	ppm
Iron	Fe	ppm
Manganese	Mn	ppm
Zinc	Zn	ppm
Copper	Cu	ppm
Boron	B	ppm
Organic Matter	OM	lb/ac
Sodium Adsorption Ratio	SAR	--
Soluble	Salts	ppm
Chloride	Cl	ppm

Excavation depths will depend on the root depths encountered but are expected to exceed five feet to fully characterize the root systems. In certain areas where access is possible and/or tree damage is less concerning (due to scheduled orchard removal or other reasons) a backhoe may also be considered for some excavations. However, significant limitations will exist with regard to site selection for backhoe excavations due to orchard density and size of excavation needed. If a backhoe is used, protective measures such as benching or sloping (cutting back the trench wall at an angle away from the excavation) would also likely be required.

B.2.1 Equipment

Equipment to be used in study implementation includes the following:

- Field truck – transporting field personnel, soil samples, and other equipment;
- Truck- or All-terrain vehicle (ATV)-mounted hydraulic probe – excavating pits for root observation;
- Appropriate safety and personal protection such as hard hats, safety glasses, etc. – all field personnel;
- Shovels and hand soil excavation equipment – observing soil profile characteristics;
- Munsell soil color evaluation book – determining soil color including indicators of gleying, etc.;
- Sample bags and boxes - collecting and store soil samples; and
- GPS and camera – logging tree locations and recording soil profile and root observations.

B.3 Site Selection and Characterization

Site selection will include two components. Selection of the study sites, and selection of the trees for sampling. The criteria for each are discussed below. As mentioned earlier, actual site selection is to occur in the implementation phase (Phase 2) of this effort, after the preferred study approach has been selected. The specific, individual sites will be selected to meet the scope of the selected study approach and to account for root growth influencing variables. Other factors related to cultural practices and landowner cooperation will also be important. The following factors will be considered in site selection:

- Soil type – representing the range of soil types desired;
- Orchard age – Orchards of at least eight years old will be sought;
- Cultural practices - influence on site selection will depend on study approach selected;
- Site accessibility;

- Landowner cooperation and permission ;
- Specific operations that may be taking place during the time of field investigation that may help or hinder field work (e.g., orchard removal would greatly decrease the level of effort of field work if it were occurring on a potential site); and
- Other operations that may preclude field study at a particular site (such as special pesticide applications).

After each site is selected, tree selection for excavation will be conducted in conjunction with site characterization. Site characterization would include reconnaissance to confirm soil types mapped in soil survey and accessibility, as well as compilation of existing groundwater monitoring water quality and elevation data and information on irrigation practices and other agricultural practices used on the site. This information, paired with input from cooperating growers, will assist in determining where specific excavations occur. Some of these site characteristics may be determined during the site selection process or during a later phase of site selection, depending on the specific objectives of the study and the study design approach.

B.4 Study Design Approach

The study design for this effort is focused on localized, near term objectives of the SJRRP in better understanding rooting depths. To fully understand the range of rooting depth and its interdependencies with site and management conditions, a very broad, replicated study would be required simply due to the number of variables involved and range of variability that exists in almond production. However, the objectives of this effort are more localized and focused on areas where seepage impacts are most likely, which also narrows the variability that must be accounted for.

To address the needs of the SJRRP three potential study approaches were developed that represent different levels of effort and provide varying levels of information. Each of these options take into account some level of variability between almond orchards and spatial variability within orchards, as it affects root depth. The three study options are described below and summarized in Table B-2. All three options assume excavation of roots with a backhoe or similar equipment at a number of sites (almond orchards) located within seepage PGs. All study options also include some level of replication to address variability within each given site. The level of replication recommended was balanced between capturing this variability and a robust, defensible dataset, and the cost associated with higher replication. However, the number of replications may also depend on the level of variability encountered in the field. Likewise, the number of hydraulic core samples at each tree will also depend encountered variability. For planning purposes, a minimum of five cores per tree is recommended, but this number may be adjusted higher or lower based on encountered conditions.

Table B-2.
Potential Study Design Approaches

	Approach A: Site-Specific Study	Approach B: Grouped Study	Approach C: Representative Site Study
Description	Sample each PG to define the full range of variability for the SJRRP, including site-specific management factors	Sample one PG from each site condition category to represent the full range of variability of the SJRRP, but with less specificity	Sample PGs 74 and 65, which have soils representing 5 of 6 site condition categories. Additionally, select one site representing saline fine soils. Gives a survey level sense of rooting depths compared to “typical” literature values
Total Sites	14	6	3
Trees per Site (replications)	2 to 3	3 to 4	4 to 5
Total Trees	28 to 42	18 to 24	12 to 20
Advantages	• Comprehensive information for each PG • All landowner conditions and management practices accounted for • Highly defensible (site-specific)	• Relatively detailed information that is not specific to each PG, but specific to conditions found in them • Realizes efficiencies in time and cost by grouping site conditions	• Represents the least time and cost of all options • Much less coordination with growers required
Disadvantages	• Higher upfront cost (likely mitigated by savings in having specific data on hand for future design purposes) • Longer completion time • More landowner coordination	• Does not represent specific information for each PG • Compromises some defensibility for less time, cost and effort	• Results are not specific to PGs • Includes possibility that an important site condition may be overlooked • Less defensible

B.4.1 Approach A: Site-Specific Study

Ideally, each PG shown in Figure 4-1 would be sampled for root depth at some point in time before seepage projects are carried out, to gather site-specific information about root depth and related soil and site conditions. This approach could be executed in phases or over a longer period of time according to seepage project priorities. Approach A will yield the greatest amount of information and will be the most useful in informing seepage project selection and design.

The advantage to Approach A is that it would capture both environmental and management factors that potentially influence root growth, including soil conditions, water table, irrigation practices, rootstock variety, and orchard density and age. Due to the site-specific nature of the information that would be gained for each site, these advantages likely outweigh the expected disadvantages of time, labor and cost it would require to conduct.

B.4.2 Approach B: Grouped Study

If the level of effort for Approach A is not feasible within the time frame and scope of the current study objectives, a less refined but potentially more efficient approach may be considered to gather representative field data for the range of conditions in the subject PGs**.** This approach would select PG from each of the site condition categories, resulting in six sites to conduct sampling.

The advantage of this approach is that it would represent all of the environmental site condition factors determined to be primary influences on root growth (soil texture, salinity and water table depth) by grouping the PGs into the site condition categories, then selecting only one PG from each category as representative. The disadvantage to this approach is that it would not reflect actual site-specific soil conditions for other PGs, nor would it reflect management factors that might influence root growth such as irrigation practices, rootstock variety, orchard density, and age.

B.4.3 Approach C: Representative Site Study

In Approach C, PGs representing the most prevalent site condition categories would be selected for sampling. In this case, all site condition categories except one are represented in PGs 74 and 65. The remaining site condition category would be represented by an additional site, totaling only three sites. Using this approach, more replicates would be needed to capture the range of conditions on one site.

The advantage to this approach is that it would yield some general information about almond root depth in the project vicinity quickly with little time, effort and cost. The disadvantage to this approach is that the information gleaned would be too general to apply to other sites specifically, may not capture an adequate range of variability among sites to be considered defensible, and would be not be directly applicable for designing site-specific seepage projects in other locations.

B.5 Schedule of Study Tasks

The schedules for the three almond root study approaches include six tasks (Table B-3). The durations of some of these tasks may overlap. For example, Task 2 may begin before Task 1 is completely finished. The timeframes of the Approach B and C studies are assumed to be one year in total, the timeframe of the Approach A is assumed to be longer than one year because of its extended scope. Task descriptions are as follows:

1. **Landowner Coordination** – Includes initial contact with landowner, potentially facilitated/supported by Reclamation staff who have performed previous field

work on site. The purpose of this coordination is to obtain permission to enter and work on land and to collect information on site characteristics such as anecdotal information on field and/or almond orchard growth observations and management practices.

2. **Site Reconnaissance and Selection** – Includes field work planning and initial site visit by field staff and possible other experts. Purpose is to confirm accessibility, identify trees for root sampling and observations, and potentially conduct soil sampling.

3. **Preliminary Data Collection** – Includes compilation of existing field information collected during project activities and information from landowner. Purpose is to review groundwater elevation data, soil boring data, soil salinity sampling, and field management information to guide field sampling efforts.

4. **Field Data Collection** – Includes root sampling. Purpose is to observe almond root depth in various site and soil conditions.

5. **Data Compilation and Interpretation** – Includes compiling preliminary and field data into appropriate databases for documentation. Purpose is to make recommendations on almond root depth from various project sites.

6. **Reporting -** Includes documentation of field work and data analysis as well as input from reviewers. Purpose is to provide official document of almond root study results.

Table B-3.
Schedules of Tasks for Almond Root Depth Study Example Approach Options

Task Number	Task Title	Approach A: Site-Specific Study		Approach B: Grouped Study		Approach C: Representative Site Study	
		Duration[1]	Timeframe	Duration[1]	Timeframe	Duration[1]	Timeframe
1	Landowner Coordination	1-2 months	April-May 2015	1-2 months	April-May 2015	1 month	April 2015
2	Site Reconnaissance and Selection	1 month	May-June 2015	2 weeks	May-June 2015	2 weeks	May 2015
3	Preliminary Data Collection (overlaps with other tasks)	1 month	May-June 2015	1 month	May-June 2015	1 month	May 2015
4	Field Data Collection[2]	3-4 weeks	July 2015	2 weeks	July 2015	2 weeks	June-July2015
5	Data Compilation and Interpretation	1-2 months	August-Sept	1-2 months	August-Sept 2015	1-2 months	July-August 2015
6	Reporting	2 months	Oct-Nov 2015	1-2 months	Oct-Nov 2015	1-2 months	Sept-Oct 2015
Total Expected Duration		**6-9 months**		**5-8 months**		**5-7 months**	

Notes:

[1] Duration may depend on site conditions.

[2] Field data collection should take place in summer or late fall to avoid harvest operations and to potentially catch orchards being removed. Duration of this task might depend on site conditions. Total duration is provided, but does not assume consecutive months.

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