# FINAL REPORT
# VOLUME II
R-PGE-20150427

## Pacific Gas and Electric Company
6121 Bollinger Canyon Road, San Ramon, CA 94583

# Tree Root Interference Assessment
# Attachments

**April 27, 2015**

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***Revision 3***

## Tree Root Interference Assessment Attachments

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# Executive Summary

As part of an ongoing commitment to enhance pipeline safety and integrity, Pacific Gas and Electric Company (PG&E) Gas Operations has undertaken a multi-faceted right-of-way (ROW) maintenance program. It involves a comprehensive survey of PG&E's natural gas transmission pipeline system, enhanced marking of the location of the pipeline, improved management and removal of certain structures, and the assessment and removal of certain vegetation (e.g., trees) along the ROWs. This program was initiated in 2011, involved excavations of tree roots during 2012 and through several initiatives evolved into the Pipeline Pathways program, which formally began in 2013.

Dynamic Risk Assessment Systems, Inc. (Dynamic Risk) was retained by PG&E in late 2012 to provide an assessment of the potential pipeline integrity related threats which could be elevated due to the presence of tree roots and to offer technical support during the tree root excavations. Findings were presented to PG&E in the report "Tree Root Interference Threat Analysis", published on April 29, 2013.

Later in 2013, PG&E retained Dynamic Risk to conduct tree root assessments that further targeted the investigation of trees that could affect buried pipelines. Findings in this report were initially published in the "Tree Root Interference Assessment" dated February 19, 2014, and subsequently revised on April 27, 2015. The study findings supported the conclusion in the April 2013 report that the presence of tree roots adversely affect the risk profile of the pipeline as it relates to certain threats, however the study produced no evidence that tree roots caused deformation or direct damage to the pipe steel. It was noted, however, that the possibility could exist for trees and root systems located over the pipeline to induce bending strains on the pipe.

Upon identification of the possibility of induced bending strains, PG&E requested that Dynamic Risk undertake an additional study to investigate the potential for upward movement of the local ground when the mass of a tree located directly adjacent to or over the pipeline was removed. Findings to this study were presented in the report, "Tree Cutting – Vertical Displacement Study", published on April 27, 2015.

Within this volume are eleven (11) references that are cited within the three (3) reports. It should be noted that this work has advanced over several years. In some cases the references contained here identified issues that were subsequently resolved within the scope of the work or were dismissed through increased understanding of the conditions with regard to tree root interaction with buried pipelines.

# Attachments

1. Frizzell and Associates. "Tree Root Interactions with Natural Gas Transmission Pipelines". April, 2012.
2. Dynamic Risk Assessment Systems, "Tree Root Interference Threat Analysis". April 29, 2013.
3. Pacific Gas and Electric. "Utility Standard: TD-4490S, 11/26/2014 Rev: 2, Gas Pipeline Rights-of-Way Management".
4. Dynamic Risk Assessment Systems, "Tree Root Interference Pipeline Threat Analysis (Draft)", Dynamic Risk Power Point Presentation. October 29, 2013.
5. Det Norske Veritas, "Effects Of Tree Roots on External Corrosion Control". March 25, 2015.
6. Frizzell and Associates. "Tree Root Interactions with Natural Gas Transmission Pipelines: An Arborist Field Study". March 27, 2015.
7. California State University Fresno Center for Irrigation Technology (CSUF-CIT). "Ground Penetrating Radar as a method of evaluating orchard root development near pipelines". December 20, 2013.
8. Mears Group, Inc and GE Energy DE Technicians. "Completed PG&E External Corrosion Direct Examination Data Sheet, Form H (modified)". Rev. 10. (38 Total)
9. Mears Group, Inc. "PGE 2013 Tree Root Inv DE Summary (2) xlsx". December 17, 2013.
10. Tulsa and Canus - NACE Certified Inspectors. "Completed Leak Repair, Inspection, and Gas Quarterly Incident Report (A-Form)". (Rev 03/11). (47 Total)
11. Dynamic Risk, Inc. "PG&E Tree Root Matrix Spreadsheet". December 20, 2013.

# Attachment 1:

**Frizzell and Associates. "Tree Root Interactions with Natural Gas Transmission Pipelines". April, 2012.**

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**RANDALL FRIZZELL & ASSOCIATES**

*Tree & Vegetation Consultants*

# Tree Root Interactions with Natural Gas Transmission Pipelines

Prepared for:

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**Executive Summary**

This White Paper addresses the interactions between tree roots and natural gas transmission pipelines that could affect the integrity and safety of the pipes. It contains a review and analysis of known and potential root–pipeline interactions, an assessment of the risks posed by tree roots for the safe operation and maintenance of pipelines, recommendations for management of trees in proximity to underground pipelines, and suggestions for future research. To prepare this report, we pooled our collective knowledge and relevant texts, communicated with other subject-matter experts, and conducted an extensive search and review of published documents that spanned six continents.

The potential for damage to pipelines does not appear to be associated with particular tree species. Instead, the characteristics of the root system of any tree depend on a complex set of interactions between tree genetics, soil conditions, and tree age and health. It is not possible to predict the exact location and extent of tree roots, but several important general characteristics about tree roots can help to guide management practices along underground gas pipelines. Large roots are usually located within 10 feet of the tree trunk, but small roots may extend more than three times the dripline of a tree. Most roots occur in the upper 20 inches of soil, and 90% or more of the total tree root system usually is in the upper 3 feet. A tree's root system typically has small roots that extend as much as three times the tree's dripline.

The soil in filled trenches around underground pipelines often provides excellent conditions for root growth and proliferation, so it is not surprising that roots are found in proximity to buried pipes. However, only a few types of interactions between tree roots and gas pipelines are likely to pose a hazard. The pressures generated by elongation or radial growth of roots are not sufficient to damage gas pipelines. However, a large root that is in direct contact with a pipeline may exert a pressure sufficient to damage a pipe when the root is pulled as a result of wind-induced rocking or toppling of the tree. This type of damage appears to be extremely rare, and it occurs only in cases where a pipeline passes over or between large-diameter roots, usually within 10 feet of the trunk.

In addition to the uncommon occurrence of roots causing direct damage to pipelines, there is the somewhat greater likelihood of indirect damage. We found a small number of cases in which roots grew through the pipe coating, caused the coating to separate from the pipe surface, and exposed the unprotected portion of the pipe to corrosion. This type of damage is not confined to the effects of large roots. Since smaller roots extend far beyond a tree's dripline, this damage could occur as much as 100 feet or more from the trunk.

Subsidence in expansive clay soils associated with soil water extraction by roots is another potential source of indirect damage to pipelines. Although we found no reports of damage to pipelines caused by subsidence, subsidence caused by differential shrinkage in expansive clay soils as tree roots take up water has damaged other types of infrastructure.

In light of the potential hazards associated with tree roots near pipelines, we provide five recommendations:

1. Tree occurrence near gas transmission pipelines should be limited, based on distance from pipelines and mature size of the tree. In most cases, this distance would be 10 to 14 feet, depending on trunk diameter of the tree.
2. If tree removal is not an option, consider either frequent root pruning or root pruning and root barrier installation.
3. Tree planting should be limited around pipelines, based on the mature size of the tree species and distance from the pipeline.

4. When installing pipe or repairing pipe sections in areas where root intrusion is likely, consider root protection strategies. However, since little is known about the efficacy of root protection strategies for pipelines, field testing would be required.
5. Where pipes are laid in expansive clay soils, construct pipe to withstand subsidence that may result from water extraction by tree roots.

Our research confirmed that there is scant information directly relating tree roots to pipeline integrity. Both the assessment of risks associated with tree roots near pipelines and the recommended actions are based largely on research related to root damage to other types of infrastructure. We believe there is a need for more study of root interactions with buried pipelines, from both field studies of pipe failures close to trees and controlled studies of root growth into utility trenches. We hope this White Paper marks the beginning of a process to increase and disseminate knowledge of tree roots and their effects on natural gas pipelines.

**Introduction**

The Pacific Gas & Electric Company (PG&E) engaged the services of Randall Frizzell and Associates to prepare a White Paper addressing interactions between tree roots and natural gas transmission pipelines that could affect the integrity and safety of the pipes. A team consisting of Laurence R. Costello, Richard Y. Evans, ,Mark A. Frizzell, John M. Lichter, and Randall E. Frizzell produced this document which contains a review and analysis of known and potential root–pipeline interactions, an assessment of the risks posed by tree roots for the safe operation and maintenance of pipelines, and recommendations for management of trees in proximity to underground pipelines. It addresses the following questions posed by PG&E:

- To what extent can tree roots adversely affect underground pipelines?
- What are the risks involved with tree root interactions with pipelines?
- How does tree weight affect underground pipelines?
- What tree species in California are invasive, or not invasive, in relation to underground pipelines?
- How does the disturbed area around an underground pipeline affect root growth?
- What is known about the compatibility of tree roots with pipeline materials?
- What industry standards exist that mitigate impacts of tree roots on underground pipelines?
- What federal or state laws relate to interactions of tree roots on underground pipelines?
- How should trees be managed to reduce the risk of tree root damage to underground gas transmission pipelines?
- What is a safe depth of pipelines as it relates to root impacts?
- When can trees remain near an underground pipeline?

We also pose and address another question:

- What information are we lacking and how can we improve our knowledge of the interaction and management of tree roots and gas transmission pipelines?

Note: The White Paper does not address vegetation removal required for maintenance access to pipelines or for aerial inspection of pipelines.

The body of the document is divided into five sections. The first section, "Tree Roots and Root Systems," provides an overview of collected information about tree roots and their growth and development, with an emphasis on characteristics that are likely to affect underground pipelines. The second section, "Potential Root–Pipeline Interactions," describes the potential for root impacts on buried pipelines. The third section, "Recommendations and Rationale," presents our recommendations for management of trees growing near underground pipelines. In light of the scant information directly relating tree roots to pipeline integrity, we envision a need for more study of root interactions with buried pipelines. Therefore, in the fourth section of this document, "The Future: Research to Minimize the Potential for Pipeline and Tree Root Interactions," we suggest additional lines of research to address questions related to the identification and management of tree root impacts on gas transmission pipelines that are not adequately answered, based on our present knowledge. The fifth section is an appendix, "Laws, Regulations, and Industry Standards," that presents existing policies.

In addition to pooling our collective knowledge, experience, and libraries, we used extensive searches of scientific and trade literature, as well as communications with other subject matter experts. Our literature search used several sources:

- Thompson-Reuters's Web of Knowledge, whose database includes over 12,000 high-impact journals and more than 150,000 conference proceedings extending back to 1900;
- CABI's CAB Abstracts, which includes over 6.3 million records since 1973;
- Google Scholar, which provides extensive coverage of scholarly literature;
- SciFinder Scholar, which contains over 29 million citations and indexes over 10,000 scholarly journals;
- American Society of Civil Engineers' Civil Engineering Database, which contains over 97,000 records of ASCE publications, including journals, proceedings, and standards;
- Google Search.

In order to ensure a comprehensive search regarding knowledge of the interactions between tree roots and pipelines, we developed a list of respected tree root experts from around the world. An email inquiry was sent to the following 14 experts, asking if they were aware of cases or published research or reports concerning root damage to gas transmission pipelines: Alison Berry (University of California, Davis); Kim Coder (University of Georgia); David Cutler (Kew Gardens); Susan Day (Virginia Tech); Ed Gilman (University of Florida); Jason Grabosky (Rutgers University); Jitze Kopinga (Research Institute for Forestry and Landscape Planning, Netherlands); Dealga O'Callaghan (Dealga's Tree Consultancy, United Kingdom); Claus Mattheck (Karlsruhe University, Germany); Greg McPherson and Paula Peper (Pacific Southwest Research Station, U.S. Forest Service, Davis, CA); Kaj Rolf and Orjan Stal (Swedish University of Agricultural Sciences, Sweden); and Gary Watson (Morton Arboretum, Lisle, IL).

We received replies from nine of these experts. Five indicated that they were unaware of any research or incidents concerning roots and natural gas pipelines. Two provided us with papers concerning root intrusion into sewer lines. Jitze Kopinga provided a summary of his personal experience regarding the interactions between tree roots and gas pipeline coatings, which is included in this document. Claus Mattheck indicated that he was aware of two cases in Germany (Viersen and Frankfurt) where tree roots were implicated in natural gas pipeline explosions.

**Tree Roots and Root Systems**

Trees rely on roots for absorption of water and mineral nutrients, synthesis of materials needed for tree growth and development, structural support, anchorage, and storage of starch and oils. The ability to predict the potential for damage to infrastructure caused by roots depends on an understanding of root forms, functions, and interactions with the soil environment.

***Types of Roots***

Tree roots are generally divided into five types: tap, lateral, oblique (also called heart), sinker, and fine (Harris et al. 2004) (see Figure 1). The taproot, which develops from the radicle that emerges when a seed germinates, develops quickly in young plants. It grows vertically downward and provides the axis from which other roots originate. The taproot may have a large diameter immediately below the surface, but it tapers dramatically with depth, especially if many secondary roots emerge from it. In some cases the taproot reaches considerable depths, but deep taproots rarely persist in mature trees.

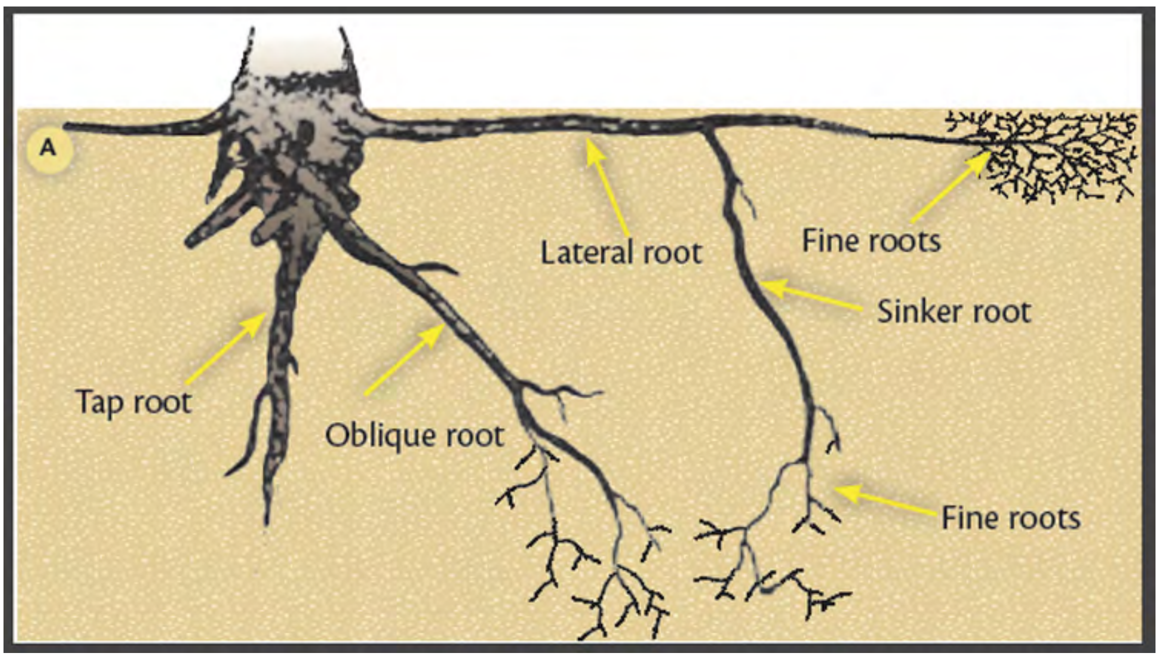


Figure 1. There are five types of roots in the root system of most tree species. From Costello et al. (2011), used with permission.

Lateral roots develop from the taproot near the soil surface and spread horizontally, forming a major part of the total root system. Lateral roots near the base of the tree provide anchorage and support. They branch as they grow away from the tree, forming a network of roots that serve as a conduit for water and minerals. The diameter of lateral roots decreases sharply with distance from the tree (Fayle 1968), and it is rarely more than 4 inches at a distance of 3 feet from the trunk (Cutler et al. 1990). The zone in which lateral root diameter changes rapidly with distance is called the zone of rapid taper (Costello et al. 2011).

Soil conditions, especially moisture content, oxygen concentration, and temperature, play a major role in determining the direction and extent of lateral root growth (Roberts et al. 2006).

Trees usually have 4 to 11 lateral roots (Perry 1994), and the largest five laterals typically represent about 75% of the total root system (Gilman 1997).

Oblique roots emerge at a downward angle from the base of the trunk (known as the root collar), or sometimes from lateral roots. They have been reported to have high wood strength (Drexhage et al. 1999). Oblique roots confer stability to the tree (Harris et al. 2004) and contribute to water absorption (Gilman 1997).

Sinker roots arise from lateral roots and grow vertically downward. They usually occur close to the trunk (Harris et al. 2004, Costello et al. 2011). They provide stability and enable trees to exploit resources deeper in soil (Harris et al. 2004).

Fine roots develop mainly on lateral roots, but they also grow on oblique and sinker roots. They typically are about 0.002 to 0.080 inch in diameter. Depending on soil conditions, they may be distributed uniformly or concentrated in regions favorable for growth (Costello et al. 2011). Typically they occur near the soil surface, where they branch and proliferate, forming thousands of roots in small volumes of soil. Most of a tree's root surface area is associated with fine roots (Millikin and Bledsoe 1999).

***Types of Root Systems***

Three general types of root systems have been described: the heart root system, in which structural roots emerge diagonally from the trunk in all directions; the taproot system, in which the taproot dominates the root architecture; and the surface root system, in which large lateral roots extend near the surface, with sinker roots branching downward (Roberts et al. 2006). Although these three types can be used to classify root systems, they represent general characteristics and not rigidly defined classes. The root system type can change over time, and soil conditions act to alter the form of the root system of individual trees. For example, one study found that about half of the Scots pines (*Pinus sylvestris*) in a mixed forest stand had pronounced taproots, while the rest had lateral and sinker roots (Kalliokoski et al. 2008).

***Root Distribution***

Root distribution is determined by a combination of tree genetics and soil conditions (Costello et al. 2011). As trees mature, deep roots comprise a smaller proportion of the total root system and are usually located within the dripline of the tree. (Gilman 1990b). In well-drained soil, lateral roots are more or less evenly distributed. They taper rapidly away from the trunk to a diameter of about 1 inch and extend beyond the dripline (Fayle 1968). Sinker roots reach a depth of about 3 to 6 feet and almost always occur within the dripline of the tree. Kalliokoski et al. (2008), in a study that focused on three tree species, found that Scots pine (*Pinus sylvestris*) roots tapered sharply with distance from the trunk center, such that roots at a distance of about 3 feet from the trunk were about one-fifth the diameter of roots at the base of the trunk; in contrast, roots of birch (*Betula pendula*) and Norway spruce (*Picea abies*) tapered more gradually, to about half the diameter of those at the trunk base. However, some studies have found that root distribution varied more within a species than across species (Lundstrom et al. 2007).

***Root Depth***

Tree roots primarily grow in the upper 3 feet of soil (Harris et al. 2004), and the amount of root mass decreases exponentially with depth (Roberts et al. 2006). A broad study of northern tree species found that 99% of the root systems of these trees occur within 3 feet of the soil surface (Gale and Grigal 1987), and a number of other studies have reported that 90% of the total root length of trees generally occurs in the upper 3 feet of soil (Roberts et al. 2006). In a survey of the rooting depth of plants around the world, Jackson et al. (1996) reported that 82% of broadleaf tree roots and 70% of conifer roots occur in the upper 20 inches of soil. Rooting depth of trees was measured in England after a severe windstorm, revealing that 96.5% of the fallen trees had root systems shallower than 6.5 feet, and 46.4% had rooting depths of 3 feet or less (Roberts et al. 2006).

There appear to be only minor differences in rooting depth of trees in natural and managed landscapes. Soil conditions and climate limit rooting in most natural settings to depths of 3 to 5 feet over large areas of northern Europe and North America (Stone and Kalisz 1991). The authors note that the maximum rooting depth for many species occurs directly below the trunk. Some researchers have found roots at greater depths, especially in relatively dry climates. For example, roots of evergreen oak (*Quercus fusiformis*) were detected over 75 feet below the surface in central Texas (Jackson et al. 1999), and a survey of trees growing in arid and semiarid ecosystems reported the average rooting depth of 76 species to be 19 feet (Schenk and Jackson 2002).

Trees in managed landscapes generally follow a similar pattern, although rooting depths greater than 6 feet have been documented for some urban trees (Day et al. 2010). About 70% of main roots in jack pine (*Pinus banksiana*) were in the top 8 inches of soil in a natural setting; another 15% were found between 8 and 12 inches (Plourde et al. 2009). In plantation jack pine, 97% of the roots occurred in the top 8 inches.

Although there are instances in which roots of trees in managed environments are found at great depth (Gilman 1990a), deep root systems occur only where soil conditions (bulk density, aeration, moisture) are not limiting (Costello et al. 2011). The maximum rooting depth is normally established within the first few years of growth, and the root system of a particular tree usually is shallower with increasing distance from the trunk (Gilman 1990a).

***Root Spread***

Roots usually extend as much as two to three times the radius of the tree’s dripline (Harris et al. 2004). The ratio of root spread to branch spread may decrease as trees age (Gilman 1990a). Maximum root spread for trees in built environments ranges from about 30 feet (for birch, apple, and cherry) to 100 feet (for oak and poplar), with the extreme being 120 feet for willow (Cutler and Richardson 1989). As with rooting depth, root spread depends greatly on the physical and chemical properties of the soil. In arid and semiarid natural environments, the average root spread is 25 feet (Schenk 2005). Roots extending farthest from the trunk are consistently found near the surface (Cutler and Richardson 1989, Gilman 1990a).

Most of the spread is attributable to small lateral roots and fine roots (Harris et al. 2004). The spread of main structural roots is much more confined. The root plate is the intact volume of the central part of the root system and adhering soil, extending from the trunk to the region where rapid root taper ceases (Cutler 1995, Lonsdale 1999). A study in England found that the maximum root plate radius of trees varies from 3 to 13 feet, and 86% of trees have a root plate radius of 6 feet or less (Cutler 1995). Coder (1998) presents a table of root plate radius in relation to trunk diameter at breast height (DBH; about 4.5 feet, or 1.4 m, above the ground). The root plate radius is less than 10 feet for trees up to 36-inch DBH; the maximum root plate radius, 14 feet, was associated with massive trees with a 100-inch DBH (Figure 2). Note that root plates are not necessarily symmetrical around tree trunks. In fact, species are likely to exhibit a high degree

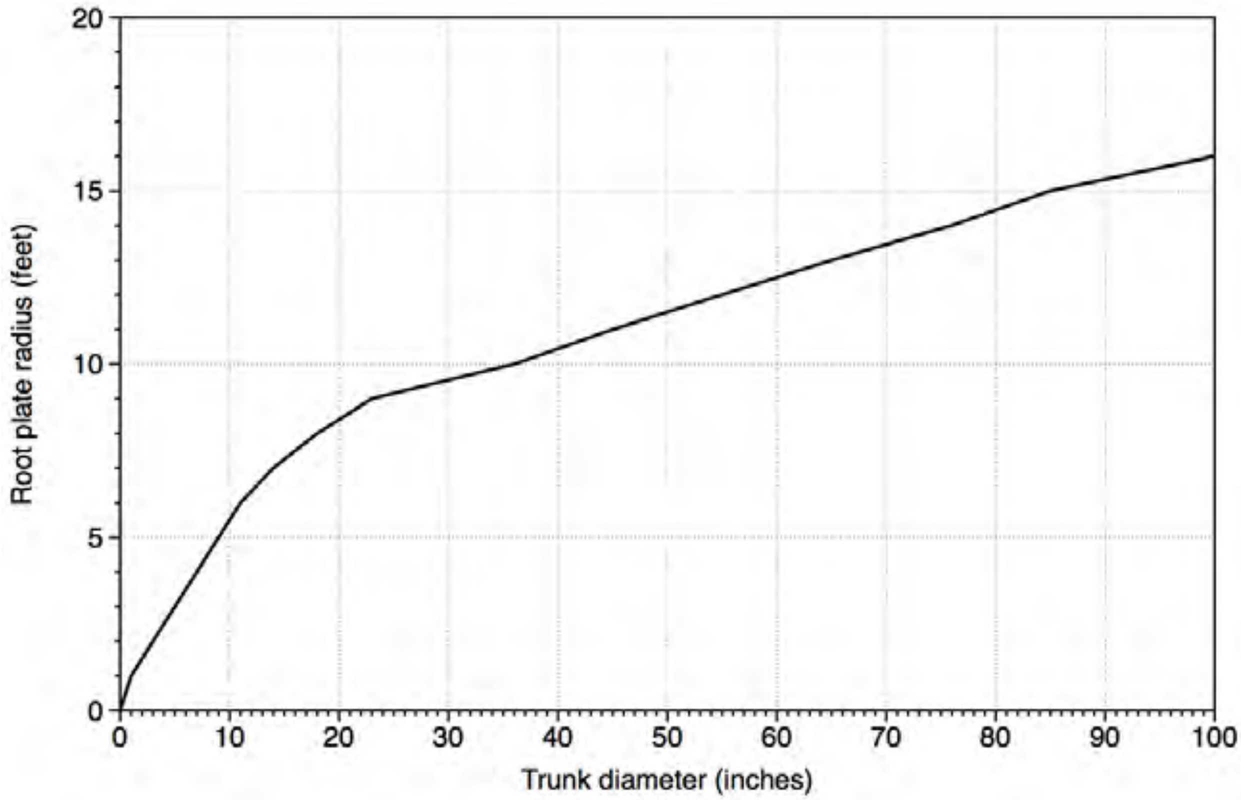


Figure 2. The root plate radius can be estimated from the trunk diameter at breast height (DBH, about 4.5 ft, or 1.4 m, above ground). The data, which are from Mattheck and Breloer (1994) and Coder (1998), are based on measurement of 2,300 coniferous and broadleaf trees.

of asymmetry where root distribution is concentrated in sectors on one side of the trunk or irregularly around the trunk.

Root spread may be irregular, especially when trees lean or are located on slopes (Day et al. 2010). Although individual roots tend to extend symmetrically, variable soil conditions and competition from other plants can cause asymmetrical root growth patterns (Gilman 1990b, Harris et al. 2004). Root growth is greatest where water and nutrients are readily available (Cermák et al. 2000). In addition, physical barriers, such as foundation walls or compacted soil, can block root growth and lead to asymmetrical development of root systems (Costello et al. 2011).

***Tree Species with "Invasive" Roots***

Tree researchers emphasize the dearth of studies of the rooting characteristics of tree species. Beyond the surveys of tree root depth and spread described above, we mainly rely on compilations of reports about tree species that have been associated with infrastructure damage, usually to sidewalks, building foundations, and sewer lines. Such compilations are imperfect and can be misleading. For example, the tree genera most commonly associated with damage to concrete in many American cities are *Liquidambar*, *Fraxinus*, *Zelkova*, *Gleditsia*, and *Prunus*, but these are also the most commonly planted tree genera (McPherson and Peper 1995), so the reports may not indicate a greater propensity to cause damage.

Damage to sidewalks and buildings is most often caused by trees with shallow roots, large root masses, or both (Costello and Jones 2003). Tables that list trees that tend to form shallow root systems or cause infrastructure damage are available (for example, Costello and Jones 2003). However, the rooting characteristics within a tree species are not uniform. For example, in a study of the impact of street trees on curbs and sidewalks in two tropical cities, Francis et al. (1996) note that some tree species were more likely than others to cause damage, but they also observed that distance to infrastructure had a significant effect that was independent of tree species. A British survey of trees and infrastructure damage found that 90% of incidents involved trees within 30 to 40 feet of sidewalks or building foundations (Cutler and Richardson 1989). Reichwein (2002, cited in Costello and Jones 2003) found that tree size and growth rate, not species, determines the potential to cause damage. Burger and Prager (2008) identified both deep-rooted and shallow-rooted individuals of three tree species but found that those characteristics were not usually retained, even in genetically identical trees. The authors observed that soil environment, primarily moisture content, can change rooting characteristics. Gilman (1990a) notes that rooting behavior depends on soil characteristics such as texture, compaction, fertility, depth to water table, and moisture content, as well as on tree genetics.

Tree root invasiveness in relation to sewer lines is almost exclusively associated with shallow-rooted species. The roots of these trees readily intrude through joints or cracks in sewer pipes. Willow (*Salix* spp.), birch (*Betula* spp.), poplar (*Populus* spp.), and elm (*Ulmus* spp.) are widely cited as species known to have invasive roots (Rindels 1995, Stal and Rolf 1998, Randrup 2000, Harris et al. 2004). The government of South Australia has published a list of 100 species that should not be planted within 12 feet of sewer mains (Government of South Australia 2011). However, even species that tend to be deep-rooted when growing in deep, well-drained soils may develop shallow root systems under some urban soil conditions (Roberts et al. 2006). Furthermore, the added soil moisture and nutrients associated with leaky sewer pipes create an environment that promotes root growth and invasion, as described in the following section.

***Growing Conditions in Trenches and Near Pipes***

Fine roots of trees and other plants tend to proliferate around underground utility lines (Krieter 1986, cited in Day et al. 2010). In fact, the National Joint Utilities Group (NJUG) in England states that "root growth is often most prolific within the backfilled trench and in the soil around the services" (NJUG 1995). Schroeder (2005, cited in Day et al. 2010) describes a case where sycamore maple (*Acer psuedoplatanus*) roots penetrated through mortar joints and into an underground utility room. The NJUG (1995) indicates that root growth is prolific in backfilled trenches and around underground utilities due to favorable soil conditions occurring within the trench and near the pipes.

In some cases, larger woody roots develop in proximity to buried pipelines (Figures 3 and 4), although we are not aware of any research that documents the frequency or extent of large root growth along pipelines. One case has been reported in which tree roots grew under and in contact with a natural gas pipeline, and the movement of the roots caused cracks to form in the pipeline (Mattheck and Breloer 1994, Mattheck and Bethge 2000). The diameter of the pipeline was not provided in either document, and it is unclear whether it was a transmission or service line. This incident is described in more detail in the section "Pipe Damage from Roots on Windward Side of Tree."


Figure 3. Tree roots can proliferate in utility trenches. Here, lateral roots of ash (*Fraxinus* sp.) have grown along buried utility lines. Photo by K. S. Jones.

Root distribution is greatly affected by availability of water and nutrients (Mou et al. 1997). A sewer pipeline is the only underground utility that is likely to contribute nutrients, but all underground pipes may alter other aspects of the soil environment. For example, the differential thermal expansion rates of soil and pipelines can introduce pore space along pipelines that are suitable for root growth (Kopinga 1994). Several researchers have reported that a pipeline that is cooler than surrounding soil may condense soil water vapor, which may encourage root growth along the pipeline (Rolf and Stal 1994, Rolf et al. 1995, Coder 1998, Stal and Rolf 1998, Roberts et al. 2006). It has also been argued that soil heating by warm pipelines could accelerate root growth, assuming there is adequate soil moisture (Roberts et al. 2006).

In some cases, roots may grow in proximity to buried pipelines because the soil in the trench is less compacted than surrounding soil (Rolf et al. 1995, Gilman and Sadowski 2007). The compaction rates typically used for infrastructure elements prevent root growth by reducing the amount of oxygen, water, and pore space and increasing mechanical impedance (Coder 1998).

***Forces Exerted by Radial Growth of Tree Roots***

As tree roots mature, they may thicken because of the formation of secondary tissues (Fayle 1968, Harris et al. 2004). The radial expansion of roots can exert a substantial force. This force has not been measured directly, but some researchers have estimated it from indirect measurements. One of the earliest indirect measurements was made on seedling roots of pea, cotton, and sunflower rather than on tree roots. All three species had root radial growth pressures of about 0.25 to 0.5 MPa (35 to 79 psi) (Misra et al. 1986). These pressures are probably

Figure 4. Roots in proximity to buried utility lines (note proximity of trunk to pipes). Pipe diameter is unknown, but appears to be approximately 6 inches. Photo from PIPA (2010).

sufficient, in some cases, to lift and cause damage to concrete structures (Grabosky and Gucunski 2011).

Subsequent indirect measurements of radial growth pressures exerted by tree roots have yielded similar values. Mattheck and Bethge (2000) calculated the pressure exerted by a tree root found growing through the mouth of a broken bottle. They estimated that the pressure was between 0.4 and 0.7 MPa (60 to 100 psi). Grabosky et al. (2011) indirectly measured deformation of foam underlayment by Norway maple (*Acer platanoides*) roots growing under a section of pavement. They inspected and measured the roots and foam, then determined that a pressure of 0.35 to 0.4 MPa (50 to 60 psi) was needed to cause the observed deformation.

Tree roots cannot exert enough pressure to push into pipes (Coder 1998). An expanding root growing between a pipe and an immovable object may be able to rupture or deform a thin-walled plastic pipe, but the pressure involved would be insufficient to affect underground utility lines (Mattheck and Bethge 2000). This topic is discussed in more detail in a subsequent section of this report.

## Potential Root–Pipeline Interactions

### *Root Intrusion*

We found no reported cases of root intrusion into natural gas pipelines. Root intrusion into natural gas pipelines is extremely unlikely because roots cannot exert enough pressure to penetrate pipes (Coder 1998). Furthermore, natural gas released in the root zone from a breach in the pipe would kill tree roots (Harris et al. 2004, Urban 2008). In fact, dead plants occurring near gas pipelines can be an indication of a pipeline leak.

Root intrusion into sewer pipes is common, with an annual occurrence of one case of root blockage for every 2 miles of pipe in the United States (Randrup et al. 2001). There is general agreement among researchers that root intrusion into sewer or drain lines is preceded by pipe failure or leaking joints or connections (Cutler 1995, Roberts et al. 2006, Ridgers et al. 2008).

### *Pipe Deformation or Collapse Due to Radial Growth of Roots*

Roots can exert a considerable amount of pressure, which commonly results in damage to sidewalks and curbs. The maximum instantaneous root tip growth pressures, generated as root tips push through soil pore spaces, are in the range of 1,300 to 2,175 psi (Coder 1998). However, this pressure cannot be sustained by roots for more than a brief instant, so roots cannot generate sufficient pressure to push into pipeline materials (Coder 1998). In contrast, root radial growth pressures can be sustained longer but are probably less than 100 psi (Misra et al. 1986, Mattheck and Bethge 2000, Grabosky et al. 2011). Root diameter growth is greatest within 10 feet of a tree's trunk (Fayle 1968, NJUG 1995). As indicated in the section on radial growth of roots, the pressure generated as roots grow in diameter is too low to deform or break most pipe materials. We found no examples of cases where the radial growth of roots damaged utility pipelines. Mattheck and Bethge (2000) suggest that a plastic pipeline could be compressed laterally by thickness growth of a root, especially if there is a structure or object such as a rock on the opposite side of the root from pipeline (Figure 5). However, they also note that pressure exerted by confined roots is not a significant cause of pipeline rupture. Other authors indicate that service lines are rarely compressed or broken as a result of root growth (NJUG 1995, Brennan et al. 1997).

### *Pipe Damage from Roots on Lee Side of Tree*

Brennan et al. (1997) state that some sewer and pipe displacement may occur as a result of root movement with wind load. When roots on the leeward (compression) side of a tree contact a pipe, root growth will spread out over the pipe, forming a "pressure cushion" (Figure 6). In this scenario, compressive forces may be transferred to a pipeline, which could possibly lead to cracks on the lower surface of the pipe (Mattheck and Bethge 2000). However, the movement created by compressive forces may not be great. Coutts (1986) found that the soil was depressed only 0.4 inches on the compression side of 35-year-old Sitka spruce (*Picea sitchensis*) trees that had been pulled over with a winch. Mattheck and Bethge (2000) calculate that a root on the compression side of a tree must have a radius five times greater than that of a root on the tension side to create the same hazard potential for a pipeline. We were unable to find any reported cases of pipeline damage fitting this scenario.

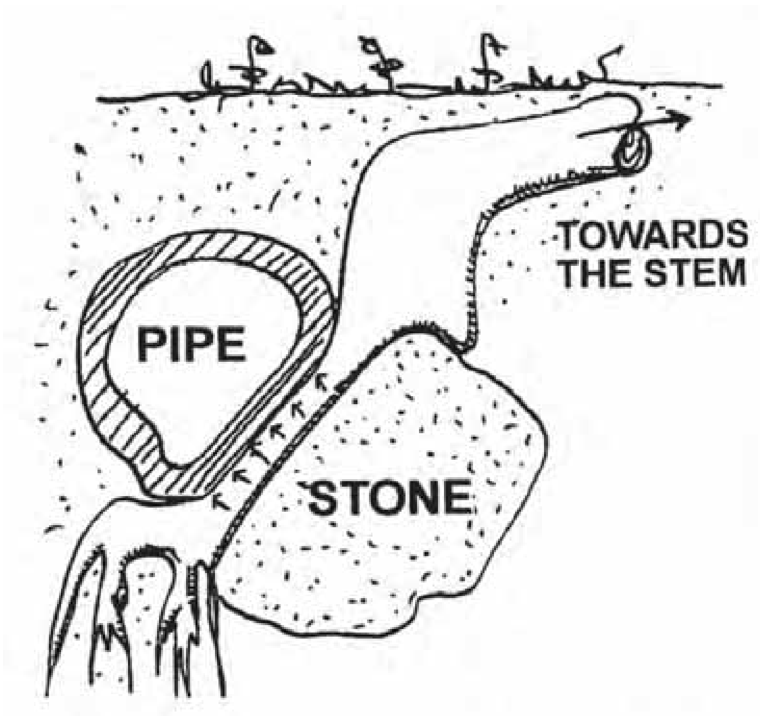


Figure 5. A plastic or thin-walled pipe may be compressed if radial growth occurs in a root supported by a large object, such as a rock. From Mattheck and Bethge (2000), used with permission.

***Pipe Damage from Roots on Windward Side of Tree***

If a tree uproots and topples, the movement of the root plate could damage a pipe passing over or through it. However, the only documented case of natural gas pipeline failure caused by tree roots that we found was that described in two publications by Mattheck (Mattheck and Breloer 1994, Mattheck and Bethge 2000). As reported by Mattheck, the pipeline that failed was on the windward side of the tree, and roots were growing under the pipe (Figures 7 and 8). Another incident in Frankfurt, Germany, in which tree roots apparently caused damage to a buried gas service pipeline was reported (C. Mattheck, personal communication). However, we obtained no documentation or further description of this incident.

Mattheck and Bethge (2000) indicate that within the root plate, mechanical fatigue damage to pipes can be caused by roots alternately sagging and tightening with the force of the wind. Cracks can then start on the upper side of the pipe at "notches, inhomogeneities, welds or surface defects." In trees that lean, the roots may introduce an additional torsional force, which could result in a bending load applied to a pipe. In addition, tensional and levering transverse forces can damage pipes if root wedges or knots form between pipes laid on top of one another (Mattheck and Bethge 2000, Roberts et al. 2006) (Figure 9). Significant movement has been observed in roots on the windward side of trees that have been subjected to transverse forces. For example, roots near the trunk on the windward side of trees have been found to rise vertically when force is applied perpendicular to the trunk axis (Lundstrom et al. 2007). Coutts (1986), who used a winch to apply such forces to Sitka spruce (*Picea sitchensis*) trees, reported a 2.5-inch rise in roots at a distance of 30 inches from the trunk.

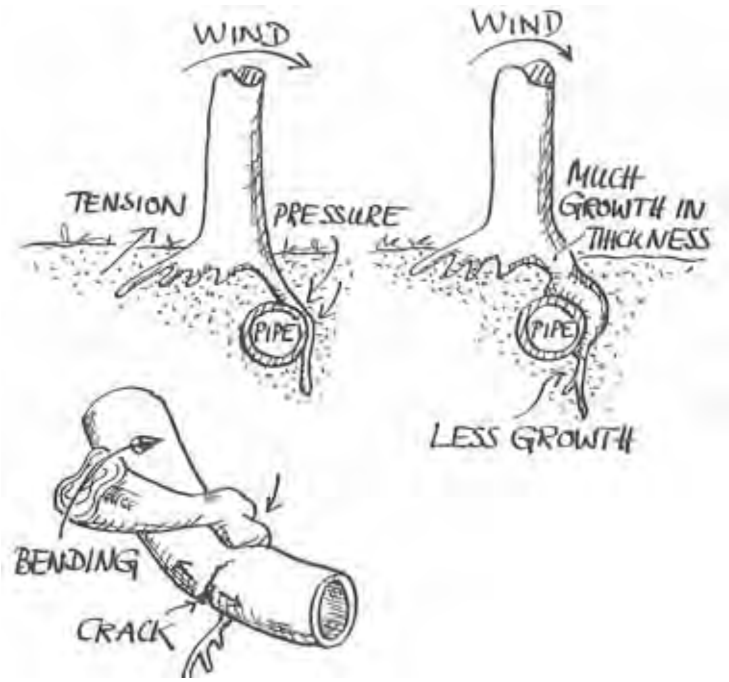


Figure 6. A root in contact with a pipe on the lee (compression) side of a tree may form a "pressure cushion" over the pipe. The risk of damage to the pipe in this scenario is considerably less than if the roots were located under the pipe on the windward (tension) side of the tree. From Mattheck and Breloer (1994), used with permission.

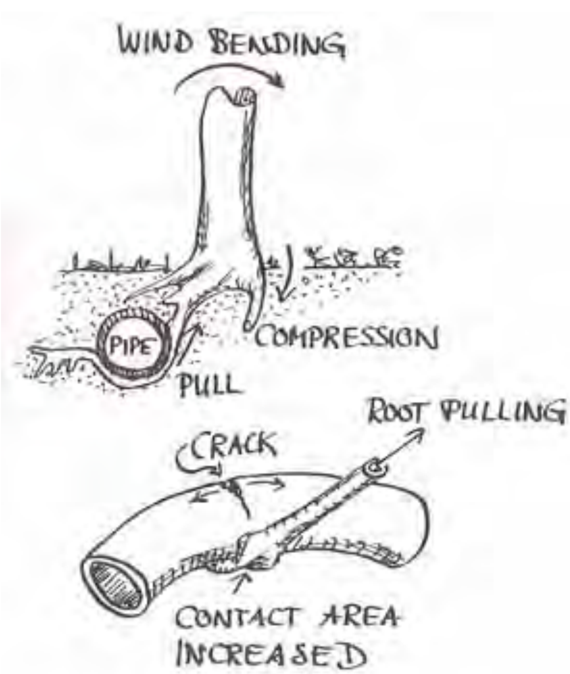


Figure 7. A root in contact with the underside of a pipe on the windward (tension) side of a tree may cause fatigue damage to the pipe due to alternating tightening and sagging of the root as wind sways the tree. From Mattheck and Breloer (1994), used with permission.

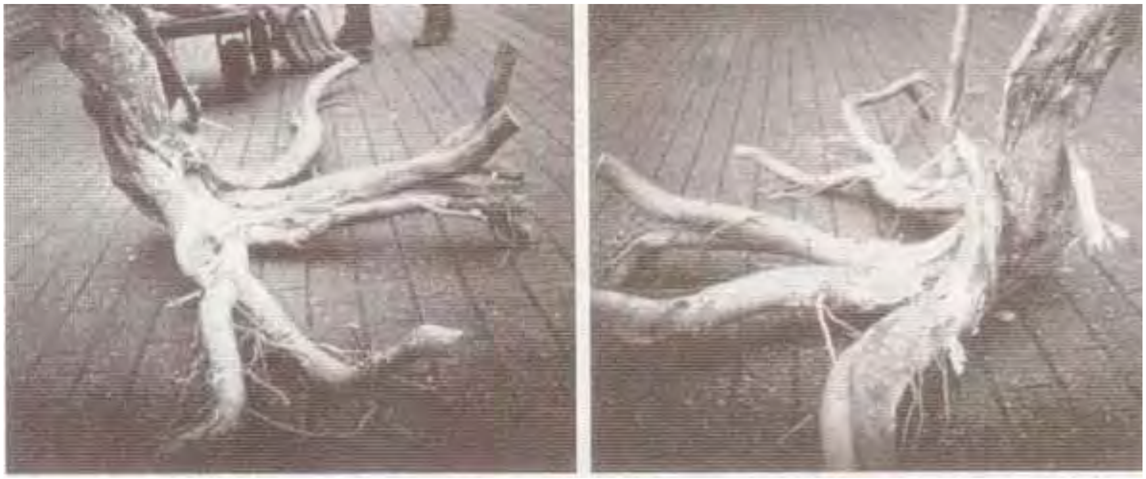

Figure 8. Lateral roots near the base of a tree formed a cradle under a gas pipeline in a situation similar to that depicted in Figure 7. Eventually, movement of the roots caused fatigue in the pipe, which failed at a faulty welded joint. From Mattheck and Breloer (1994), used with permission.

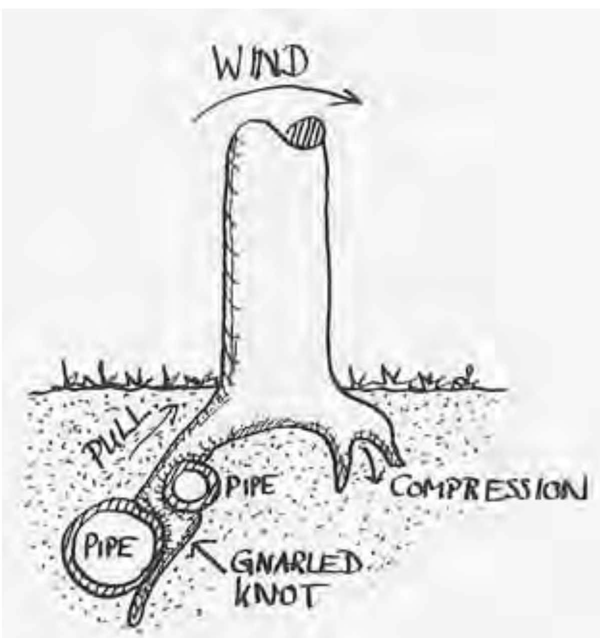


Figure 9. Knots in roots between buried pipelines may act as wedges. From Mattheck and Breloer (1994), used with permission.

***Pipe Damage from Roots Directly Above Pipeline***

If a pipe is located directly below a tree and the prevailing wind is perpendicular to the pipeline, the pipeline is near the neutral pivoting point and damage is unlikely (Biddle 1998), assuming the tree does not have a taproot. Bending stresses to a pipeline directly under a tree would be possible if the tree has a taproot or if the pipeline is oriented in the direction of the prevailing wind (Mattheck and Bethge 2000). However, we found no reported cases of pipeline damage where trees were located directly above pipelines.

Although large trees can weigh over 20 tons, their weight does not pose a problem for underground pipelines. Trees distribute stress evenly along their surfaces as they grow (Mattheck and Breloer 1994, Harris et al. 2004), so a tree's mass tends to be evenly supported by its root system. The pressure exerted by a large tree's weight, spread over the area of its root plate, normally would be less than 1 psi. This pressure is easily resisted by the mechanical strength of soils or pipelines.

***Pipe Damage from Subsidence Influenced by Root Growth***

The roots of vegetation, including trees, can dry soils and lead to soil subsidence or differential soil shrinkage that can damage buildings (Cutler and Richardson 1989, Roberts et al. 2006). Several authors have used English building damage survey findings of over 8,000 trees to rank species according to their likelihood of indirectly causing building damage (Driscoll 1983, Cutler and Richardson 1989, McCombie 1993). Cutler and Richardson (1989) found that all damage claims involved trees located within 65 feet of structures, and 90% involved trees within 40 feet of structures. The relationship between tree roots and soil conditions is complex, and there is no simple relationship between tree species, water demand, and damage (O'Callaghan and Lawson 1995). The majority of tree species are thought to have similar water demands (Roberts et al. 2006). Cutler and Richardson (1989) attribute the differences in damage to tree size rather than species. However, considering tree size alone ignores the substantial effects of a tree's age and vigor on its water use (Roberts et al. 2006).

Even in the absence of trees, underground utilities may be damaged in shrinkable clay soils that undergo differential wetting and drying, especially during drought periods, if the utility lines are not adequately designed (Craul 1992, McCombie 1995, Stewart and Sands 1996, Coder 1998). However, we found no published reports of damage to natural gas or other pipelines due to subsidence. This may indicate that the stresses on pipes caused by the drying of shrinkable clay soils are within the range of tolerance for all buried utility pipe systems except those with short segments (NJUG 1995).

***Damage to Pipe Coatings and Cathodic Protection by Roots***

There is evidence that tree roots can damage pipe coatings (Figures 10 and 11). The number of incidents appears to be relatively small, but the extent of damage is unknown. Pipes coated with nontoxic compounds, including bitumen, can be damaged when roots grow into the coating and it lifts off (NJUG 1995; J. Kopinga, personal communication). The amount of corrosion that occurs as a result of this damage may be acceptable if the pipes are provided with cathodic protection (J. Kopinga, personal communication). However, Kopinga reports that a higher current is required to maintain cathodic protection after the damage. According to Stedman and Brockbank (2012), who report on a conference presentation by Nowak et al. (2002), the speakers stated that roots can damage coal tar and asphalt coatings. The roots can grow along the coating surface, embed themselves in the coating, and cause deep grooves in it. Pipe damage is associated with coating that has lost adhesion to the pipe surface due to damage inflicted by tree roots. Polyethylene-coated pipes are not damaged by root growth (J. Kopinga, personal communication). We found no other documented reports of damage to pipe coatings caused by tree roots.


Figure 10. Oblique roots of a tree planted in proximity to a buried pipeline have come in contact with the pipe coating, causing damage. Photo from PIPA (2010).

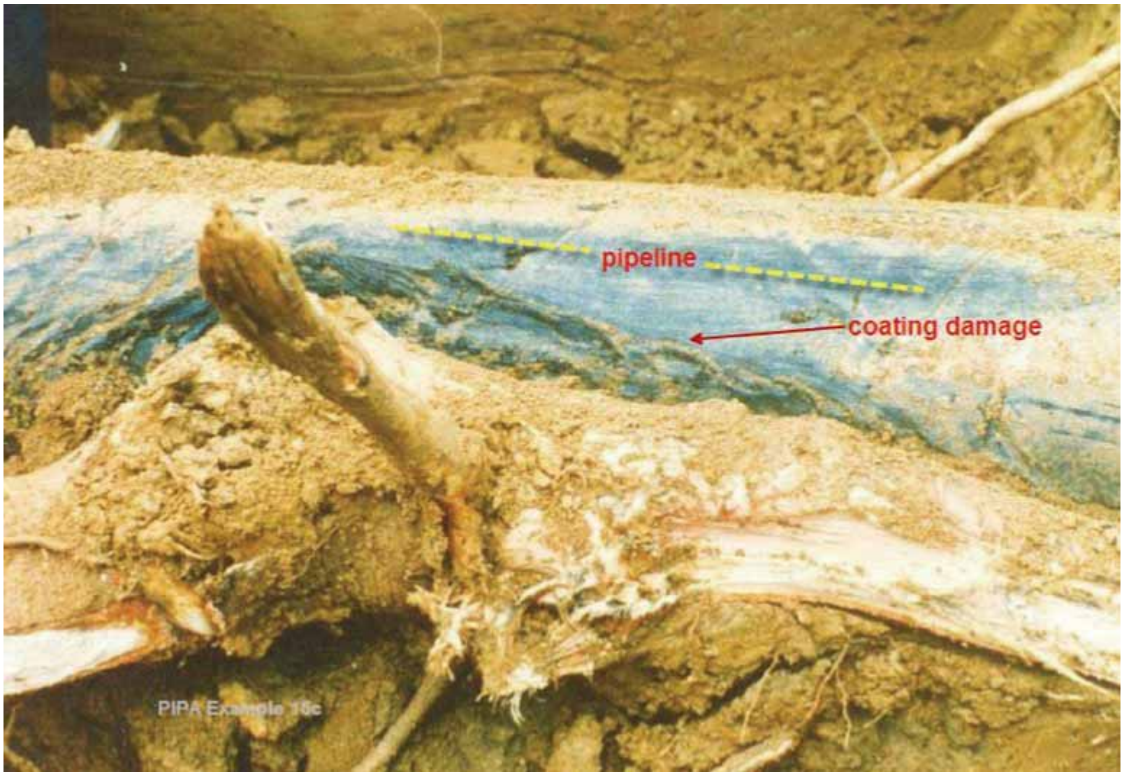

Figure 11. A lateral root growing along a buried pipeline caused damage to the pipe's coating. Photo from PIPA (2010).

There is also the possibility that lightning strikes in trees near pipelines may cause pipe deformation, cracking of welded joints, or damage to the cathodic protection. However, we found no reports of this type of damage to natural gas pipelines other than photographs (Figures 12 to 14) and their accompanying caption in a report by the Pipelines and Informed Planning Alliance (PIPA 2010).

Figure 12. A tree growing close to a buried pipeline was struck by lightning. The electric current passed through the roots to the wet soil, causing soil moisture to vaporize. The resulting rapid expansion of the soil created a crater and damaged the pipe. Photo from PIPA (2010).

Figure 13. Apparently, the top of this pipe was dented by the explosive expansion of soil after a tree was struck by lightning, as described in Figure 12. Photo from PIPA (2010).

Figure 14. Tension in the pipeline caused by the lightning strike described in Figure 13 resulted in the formation of a crack in a girth weld in the pipe. Photo from PIPA (2010).

**Recommendations and Rationale**

1. Tree occurrence near gas transmission pipelines should be limited, based on distance from pipelines and mature size of the tree. Within 5 feet of pipelines, no trees should occur. Between 5 and 10 feet, trees that achieve a DBH (trunk diameter at 4.5 ft from ground) of less than 8 inches at maturity can be retained, while trees with a DBH larger than 8 inches should be removed. Between 10 and 14 feet, retain trees with a DBH less than 36 inches and remove trees with a DBH larger than 36 inches. Beyond 14 feet, all trees can be retained.

   Rationale: The distances recommended for trees from pipelines (above) are based on published reports of root plate size and root growth characteristics (see the section "Root Spread" and Figure 2). Limiting tree occurrence based on these distances will reduce the potential for root damage to pipelines from wind stresses, as described in Mattheck and Bethge (2000) (see the section "Pipe Damage from Roots on Windward Side of Tree"); windthrow, as described by Cutler (1995) (see the section "Pipe Damage from Roots on Windward Side of Tree"); and radial growth of roots (NJUG 1995) (see the section "Pipe Deformation or Collapse Due to Radial Growth of Roots"). Note, however, that these distances may not be adequate to protect pipelines from root damage to pipeline coatings or cathodic protection (see Recommendation 4).

2. If tree removal is not an option, consider either frequent root pruning or root pruning and root barrier installation.

   Rationale: Root pruning will temporarily reduce the likelihood of root damage to gas pipelines. Note, however, that root pruning can injure and destabilize trees, depending on the extent of root removal (Costello and Jones 2003). In addition, roots typically regrow following root pruning (Coder 1998, McPherson and Peper 1996). Installing a root barrier after root pruning may reduce the amount of root growth adjacent to the pipe. However, the results of studies have been mixed regarding the effectiveness of root barriers (Roberts et al. 2006).

3. Tree planting should be limited around pipelines, based on the mature size of the tree species and distance from the pipeline. Avoid planting trees within 10 feet of pipelines. From 10 to 14 feet, do not plant trees that will achieve a DBH greater than 36 inches. Beyond 14 feet, no restrictions on tree planting are suggested.

   Rationale: These recommended distances for trees from pipelines are based on published reports of root plate size and root growth characteristics (see the section "Root Spread" and Figure 2). Limiting tree occurrence based on these distances will reduce the potential for root damage to pipelines from: wind stresses, as described in Mattheck and Bethge (2000) (see the section "Pipe Damage from Roots on Windward Side of Tree"); windthrow, as described by Cutler (1995) (see the section "Pipe Damage from Roots on Windward Side of Tree"); and radial growth of roots (NJUG 1995) (see the section "Pipe Deformation or Collapse Due to Radial Growth of Roots"). Note, however, that these distances may not be adequate to protect pipelines from root damage to pipeline coatings or cathodic protection (see Recommendation 4).

4. When installing pipe or repairing pipe sections in areas where root intrusion is likely (e.g., forested areas), consider root protection strategies. These include protecting pipelines by

backfilling the trench around the pipeline with structural soil and lining the trench with a root barrier that physically deflects or chemically inhibits roots as they grow toward pipelines. Alternatively, pipes can be painted or wrapped with a product that may reduce the likelihood of root development adjacent to pipes. This strategy will require efficacy testing, however.

Rationale: Root protection strategies may reduce the likelihood of root growth adjacent to pipelines. Products for trench lining include polyethylene sheeting and geotextile fabrics with or without slow-release root inhibitors (van der Werken 1982, cited in Coder 1998). These fabrics or copper screen could be used to wrap pipe, or pipe could be painted with root growth inhibitor (Ely 2010, Roberts et al. 2006), such as cupric carbonate mixed with white acrylic paint (Arnold and Struve 1989). Pipe trenches in the United Kingdom are typically lined with root barriers (O'Callaghan, personal communication, 2012).

5. Where pipes are laid in expansive clay soils, construct pipelines to withstand subsidence that may result from water extraction by tree roots.

   Rationale: It is not realistic to expect that roots of trees and other plants will not be growing in utility trenches. Therefore, as trees (or other vegetation types) extract water, some subsidence can be expected where expansive clay soils are present.

**The Future: Research to Minimize the Potential for Pipeline and Tree Root Interactions**

This White Paper represents the beginning of a process to expand our knowledge of tree roots and their potential effects on natural gas pipelines. We hope it will lead to a ongoing cycle of information gathering from research and field experiences, followed by application of the information to refine industry guidelines, standards, and best management practices.

We believe there is much to learn from research conducted in the field as pipelines are uncovered around the state for maintenance and/or inspections, or when new transmission pipelines are constructed in the vicinity of trees. Field studies of pipeline failures close to trees and of root systems close to pipelines would add immensely to our understanding of root and pipeline interactions. In addition, controlled studies investigating root growth into utility trenches would contribute substantially to the development of management strategies. Following are lines of research that could be followed and questions that could be addressed by such investigations.

1. Field studies:

*a. Forensic examination of pipeline failures from leaks, cracks, ruptures, or deformations near trees.*

Where pipelines have failed close to trees, observation, measurement, and documentation of the following information should help us to more fully understand the interactions between tree roots and pipelines.

- Were roots present? If so, what was the species, size, depth, and distance from trunk(s)?
- What was the root proximity to the pipeline?
- What side of the tree(s) was the pipe on (windward, leeward, above)?
- Was pipe movement implicated in the failure?
- Were roots adjacent to the pipe of a size capable of moving the pipe?
- Was corrosion implicated in the failure?
- Were roots damaging the pipe coating?
- Was there evidence of pipe deformation?
- What size was the pipe?
- What pipe materials were used?
- How was the utility constructed?
- Were pipe defects implicated in the failure?

*b. Examination of root systems of trees near pipelines.*

Careful exposure of roots near pipelines and subsequent observation and testing can provide valuable information regarding tree roots and pipelines. Mechanical, pneumatic, and/or hydraulic excavation can help us understand the extent of root development and whether roots deform pipes or damage pipe coatings. In addition, it is possible to install equipment on roots and pipes to quantify forces from roots acting on pipes during wind events.

2. Controlled studies to investigate root development in utility trenches and pipeline interactions.

   One or more test sites could be developed where pipelines are installed adjacent to trees or trees are installed adjacent to simulated or abandoned pipelines. Studies at such sites may include the following:

   - characterizing root development into utility trenches;
   - comparing root development of different species;
   - quantifying the forces from roots acting on pipelines;
   - determining the susceptibility of various pipe coatings to root damage; and
   - testing the efficacy of root barriers, root inhibiting products and pipeline wraps.

**Conclusions**

Although there is little evidence that roots cause direct damage to pipelines, there is some potential (albeit small) for such damage to occur. Excluding trees from a zone along pipelines that is as wide as a large tree root plate radius should be sufficient to prevent direct damage.

We found only one documented case (and unverified mention of one other case) in which an underground gas pipeline failed due to direct damage inflicted by tree roots. That incident, which occurred in Germany in the early 1990s, involved a pipeline that apparently passed very near the base of a tree. Neither elongation nor radial growth of roots develops sufficient force to damage gas pipelines. In the rare case that force sufficient to damage a pipe can be applied by roots as a result of wind-caused rocking or toppling of trees, only a pipeline that passes through the tree's root plate would be affected.

There is a somewhat greater likelihood of roots causing indirect damage to pipelines. We found a small number of cases in which roots grew into the pipe coating, caused the coating to separate from the pipe surface, and exposed the unprotected portion of the pipe to corrosion. The potential for indirect damage to pipelines does not appear to be associated with particular tree species. Tree genetics contribute to rooting behavior, but soil characteristics such as texture, compaction, fertility, depth to water table, and moisture content play a greater role. The trenches in which pipelines are buried can provide a favorable soil environment for root growth. Conceivably, damage of this type could occur 100 feet or more from the base of trees, since small roots can extend as much as three times the radius of a tree's dripline. The risk of this hazard could be reduced by backfilling trenches around buried pipelines with engineered soil, installing barriers that deflect roots, or covering pipes with a material that excludes roots.

Another potential source of indirect damage to pipelines by tree roots is subsidence in expansive clay soils. We found no reports of damage to pipelines caused by subsidence, but soil drying as tree roots take up water causes differential shrinkage in expansive clay soils, and this type of subsidence has damaged some types of infrastructure. Pipelines should be designed to withstand the force imposed by such subsidence.

***Appendix: Laws, Regulations, and Industry Standards***

Transmission pipeline operators are required by law, and by pipeline safety regulations, to develop and implement programs and processes that focus specifically on safe operating and maintenance activities. In our review of the federal and state laws and regulations, only one mention of tree roots was found: by FERC, which is discussed below. Instead, the government departments and agencies provide only safety standards and programs that cover any condition that would impact pipeline integrity and safety.

The U.S. Department of Transportation (DOT) Office of Pipeline Safety (OPS) is responsible for regulating the safety of natural gas transportation pipelines, including the safety requirement prescribed by the U.S. Code of Federal Regulations Title 49, Part 192 (49 CFR 192), "Transportation of Natural and other Gas by Pipeline: Minimum Federal Safety Standards." This part prescribes minimum safety requirements for pipeline facilities and the transport of gas.

In 2003, OPS issued a rule requiring natural gas operators to develop integrity management programs (IMPs) for gas transmission pipelines located where a leak or rupture could do the most harm (Folga 2007). An IMP, among other things, establishes procedures for performing risk and integrity assessments and applying prevention, mitigation, and remediation measures. Operators must assess conditions that might affect the safety or operation of the pipeline and make continual improvements to the IMP.

The Federal Energy Regulatory Commission (FERC) regulates the interstate transmission of natural gas. In one document they state, "Trees with roots that may damage the pipeline or its coating and other obstructions that prevent observation from aircraft during maintenance are usually not allowed." (Wellinghoff 2010).

The federal OPS and the state of California, through its California Public Utilities Commission (CPUC), have a cooperative agreement to share regulatory responsibilities. OPS regulates and enforces interstate gas and liquid pipeline safety requirements in California. OPS also inspects interstate gas pipeline safety requirements. Through certification by OPS, the state of California regulates, inspects, and enforces intrastate gas and liquid pipeline safety requirements.

At least one CPUC regulation has bearing on transmission operators in California: CPUC General Order 112-E: "Rules Governing Design, Construction, Testing, Maintenance, and Operation of Utility Gas Gathering, Transmission, and Distribution Piping Systems." These rules are incorporated in addition to the 49 CFR 192 regulations. The purpose of these rules is to establish, in addition to the federal pipeline safety regulations, minimum requirements for, among other things, operations and maintenance of facilities used in transmission of natural gas to safeguard life or limb, health, property and public welfare and to provide that adequate service will be maintained by gas utilities operating under the jurisdiction of the commission.

At least one municipal agency speaks to tree roots in their policies. The San Francisco Public Utilities Commission (SFPUC) has stated, "It is our experience that roots can impact transmission pipelines by causing corrosion to the outer casements" (SFPUC 2007).

Industrial organizations and alliances have concluded that roots can impact pipelines. Two of these industry-based groups are Pipelines and Informed Planning Alliance (PIPA) and the Transportation Research Board (TRB). PIPA is a stakeholder initiative led and supported by the U.S. Department of Transportation's Pipeline and Hazardous Materials Safety Administration (PHMSA). PIPA has developed recommended practices that are not mandated but are intended to provide guidance to pipeline operators, local officials, property owners, and developers to provide for the safe use of land near transmission pipelines (PIPA 2010). These include recommended practices relevant to risk from trees and tree roots:

> ND 15—Plan and Locate Vegetation to Prevent Interference with Transmission Pipeline Activities. Trees and other vegetation should be planned and located to reduce the potential of interference with transmission pipeline operations, maintenance, and inspections. Additionally, trees and other vegetation adjacent to transmission pipeline ROW with root systems that may reach down to the pipeline should also be avoided, since contact from their root systems may physically impact the pipe or its protective coating. The landowner/developer and transmission pipeline operator should work together using local land use planners and landscape and forestry professionals to make landscape choices that are acceptable.

> ND 17—Reduce Transmission Pipeline Risk in New Development for Residential, Mixed-Use, and Commercial Land Use. New development within a transmission pipeline planning area should be designed and buildings located to reduce the consequences that could result from a transmission incident and provide adequate access to the pipeline. Landscaping should be planned to ensure adequate access to the transmission ROW to avoid interference with pipeline operations and maintenance activities.

The Transportation Research Board (TRB) of the National Academies published Special Report 281, in which they state, “Tree roots can also be a source of outside damage to pipelines, so allowing mature trees in the rights-of-way poses a safety hazard.” (Transportation Research Board 2004). Recommendation 3 in the report states, “The federal government should develop guidance about appropriate vegetation and environmental management practices that would provide habitat for some species, avoid threats to pipeline integrity, and allow for aerial inspection” (page 10).

In summary, it appears that, if natural gas transmission operators apply what is known about root and pipeline interactions to vegetation management practices, they would fulfill federal and state laws regarding pipeline integrity programs and the safe maintenance of facilities.

**Glossary**

**cathodic protection.** The process of arresting corrosion on a buried or submerged metallic structure by electrically reversing the natural chemical reaction. This includes, but is not limited to, installation of a sacrificial anode bed, use of a rectifier based system, or any combination of these or other similar systems.

**coatings.** Many types of materials and processes to protect the surface of pipe have evolved over the past 90 years, including hot tar asphaltic, somastic, fusion bonded epoxy, and polyken tape. PG&E's Gas Standard & Specifications E section describes current pipe coatings and their selection and application.

**diameter at breast height (DBH).** The diameter of a tree trunk, measured 4.5 ft, or 1.4 m, above ground.

**dripline.** The width of a tree's lateral foliage extension.

**fine root.** A small-diameter root that develops mainly on lateral roots but can also be found on oblique and sinker roots.

**lateral root.** A root that develops from the taproot near the soil surface and spreads horizontally, forming a major part of the total root system.

**oblique root.** A root that emerges at a downward angle from the base of the trunk, or sometimes from a lateral root.

**pipe.** Tube or hollow body for conducting liquid or gas. Pipe material for natural gas transmission has always been carbon steel, according to PG&E Corrosion Engineering.

**right-of-way (ROW).** (1) Property, usually consisting of a narrow, unobstructed strip or corridor of land of a specific width, that a pipeline company and the fee simple landowners have legal rights to use and occupy; a string of contiguous properties on which easements have been acquired along which a pipeline operator has rights to construct, operate, and maintain a pipeline. (2) A defined strip of land on which an operator has the right to construct, operate and maintain a pipeline.

**root plate.** The intact volume of the central part of the root system and adhering soil, extending from the trunk to the region where rapid root taper ceases.

**sinker root.** A root that arises from a lateral root and grows vertically downward.

**taproot.** A root that grows vertically downward and provides the axis from which other roots originate.

**transmission pipeline.** A pipeline, other than a gathering line, that transports natural gas or hazardous liquids from producing areas to refineries and processing facilities, and then to consumer areas and local distribution systems.

**windthrow.** Tree failure associated with uplifting of the entire root plate in response to wind.

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# Attachment 2:

**Dynamic Risk Assessment Systems, "Tree Root Interference Threat Analysis". April 29, 2013.**

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# FINAL REPORT

R-PGE-20130429

# Pacific Gas and Electric Company

# Tree Root Interference Threat Analysis

## April 29, 2013

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*Rev. 2*

Dynamic Risk

# Tree Root Interference Threat Analysis

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**Dynamic Risk Assessment Systems Inc.**
**APEGGA Permit #P08193**

# Executive Summary

Pacific Gas and Electric Company (PG&E) has commenced a right-of-way (ROW) management project to enhance public safety through better management of structures and vegetation (e.g., trees) along their ROW's. The study presented herein addresses the interaction between tree roots and buried pipelines. This study concluded that the presence of trees along the buried pipeline ROW adversely affects the risk profile by increasing the susceptibility to threats, decreasing the ability to monitor and protect the buried pipeline, and decreasing the ability to respond to emergencies as required by federal safety regulations for integrity assessments.

This study also concluded there is no obvious means to predict the interaction between the tree root and the buried pipeline prior to performing an excavation. It is not yet known, for instance, whether the same species of tree affects the pipeline and coating the same way in each instance, to what extent each variable may or may not contribute, and/or whether the variables will be repeatable or predictable for assessing tree root interaction.

While a complete understanding of all factors and their influence on pipeline integrity continues to evolve, the following recommendations are made at this time:

- To reduce the pipeline integrity risk profile for segments where trees are in proximity to the pipeline, a tree removal program is recommended with the following governing criteria:
  - All trees within 5 feet of the pipeline edge should be removed.
  - Trees with a DBH* 8 inches or larger located between 5 and 10 feet of the pipeline edge, should be removed.
  - Trees with a DBH larger than 36 inch located between 10 and 14 feet of the pipeline edge, should be removed.
  - Trees of a species likely to grow to a size that would require their future removal under these guidelines should also be removed.
- In cases where tree removal cannot be accomplished, alternative monitoring and mitigation strategies should be further developed and integrated into PG&E's integrity management program. This includes identifying and monitoring mitigative actions and their effect on the risk profile including threat susceptibility, ability to monitor, and ability to respond.
- Tree root investigations on the pipeline system should be continued in order to advance the knowledge base of tree root and pipeline interactions. Recommendations are made regarding refinement of the reports that are generated subsequent to these investigations.
- ILI and ECDA data should be correlated to the presence of tree roots to help establish the potential for corrosion influenced by presence of tree roots.
- Pipeline corrosion specialists should evaluate the potential for above-ground surveys (CIS, ECDA) to be adversely influenced by the presence of tree roots, and to evaluate the potential for cathodic shielding to occur as a result of the presence of tree roots.

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* DBH (Diameter at Breast Height) is the tree diameter at a height of 54-inches (4.5 feet)

- The PG&E Transmission Integrity Team should integrate the findings of this report into its integrity management program and consider all aspects of assessment, monitoring, and mitigation.
- Collaboration with industry is recommended in order to develop consensus standards and guidelines related to tree setback distances and their effect on pipeline integrity management and risk management.

Dynamic Risk

# Table of Contents

# 1. Introduction

As part of an ongoing commitment to pipeline integrity, Pacific Gas and Electric Company (PG&E) has commenced a right-of-way (ROW) management project to enhance public safety through better management of structures and vegetation (e.g., trees) along their ROW's. PG&E has retained Dynamic Risk Assessment Systems, Inc. (Dynamic Risk) to provide an assessment of the potential threats to pipeline integrity management, created by the presence of tree roots to PG&E's buried natural gas pipelines.

# 2. Background

In 2011, PG&E retained arborists (Randall Frizzell & Associates) to provide expertise and provide support for a number of excavations to evaluate the interaction between the tree roots and their buried pipelines as part of a vegetation management program. In 2012, PG&E commenced a 'Pilot Program' on a 10-mile section of Line 132 and a 10-mile section of Line 153 in order to improve their ROW management program. As part of this Pilot Program, PG&E identified structures and large trees on top of and/or in close proximity to the pipe centerline. The arborists were then retained to provide additional support in these matters.

PG&E commenced the Pilot Program to gather the necessary data, knowledge and experience to develop guidelines that will be used to identify and address encroachments and vegetation issues throughout their system. Ultimately, the guidelines resulting from this Pilot Program will be used to develop protocols that will be implemented throughout the entire PG&E pipeline transmission system.

The arborists retained by PG&E developed a 'white paper' on the interaction of tree roots with buried pipelines based upon publically available information. As a result, it was recommended that a number of pipeline excavations involving a representative sample of tree root systems should be performed and the results used to further determine how tree roots systems interact with buried pipelines.

As of the date of the writing of this report, 18 locations (excavations that are planned, underway or completed) have been considered within this evaluation.

# 3. Objective

Identify and assess potential pipeline integrity threats and provide recommendations that will mitigate the risks related to vegetation management, specifically trees, along PG&E's ROW.

# 4. Approach

The objectives of this analysis have been achieved through the successful execution of the following activities:

- Literature Review
- Review of Completed and Planned Excavations
- Pipeline Integrity Management Considerations

- Risk Assessment
- Conclusions
- Recommendations

Each is described below.

# 5. Literature Review

## 5.1. Review of the White Paper

In April 2012, PG&E commissioned a study to investigate the interaction of tree roots with natural gas transmission pipelines[1] ('white paper'). The white paper collated information regarding then-available industry experience on tree root interaction and expert commentary regarding the behavior of tree roots. The report recognizes it was the beginning of a process to further expand industry knowledge of tree roots and their potential effects on natural gas pipelines and calls for further study of the issues. The report also puts forward recommendations regarding the reduction of tree root interference based on botanical considerations. These recommendations include:

- Increased distance between tree and pipeline.
- Root pruning and installation of root barriers.
- Limiting the presence of trees in proximity to pipelines.

The white paper states that while tree roots can emanate from the base of a tree to a radius of up to several hundred feet, or several times the radius of a tree's drip-line, the majority (90%) of the total tree root system is usually within 3 feet of the surface. While large and medium size roots are less likely to reach such distances, the same research shows that the presence of pipelines can affect the path of root systems as they provide channels for water to collect, creating a preferred path for tree roots. This interaction between pipelines and tree root growth patterns means that the normal assumptions regarding the directionality and depth of tree roots is difficult to rely upon for determining safe distances between trees and pipelines. In this work, the potential for tree roots to enhance and interact with other pipeline threats was characterized as a function of distance. Accordingly the authors provided "distance category" guidelines to characterize tree proximity based on tree diameter.

## 5.2. Pipelines and Informed Planning Alliance (PIPA)

Pipelines and Informed Planning Alliance (PIPA) was established to improve the safety and reduce risks related to land use near buried natural gas transmission pipelines. PIPA is comprised of 130 stakeholders (local governments, regulators, property developers, property owners, real estate boards, and transmission pipeline operators) and is sponsored by the U.S. Department of Transportation (DOT) Pipeline and Hazardous Materials Safety Administration (PHMSA). A guiding principle in PIPA's work is that to be successful in reducing risk related to land use near natural gas transmission pipelines, all stakeholders need to be committed to the risk management of buried pipelines. PIPA provides a mechanism to achieve this goal by providing recommended practices.

PIPA has established that transmission pipeline operators need to protect their pipelines from potential damage by activities on or near pipeline ROW's. PIPA created a recommended practice[2] that states that trees, crops and orchards are not acceptable on the pipeline ROW, since tree root structures may be deep and extend beyond tree canopies. In cases of significant tree root encroachment, damage to transmission pipeline coatings can occur, leading to the potential for corrosion.

These guidelines have also established the need for pipeline operators to have unrestricted access to the pipeline ROW for maintenance and emergency response[2]. In some cases, the presence of trees on the ROW could affect the ability of operators to comply with federal pipeline safety regulations. For instance, federal safety regulations stipulate:[3]

> *"Each operator shall have a patrol program to observe surface conditions on and adjacent to the transmission line right-of-way for indications of leaks, construction activity, and other factors affecting safety and operation."*

Additionally, the following recommended practice was made by PIPA:[2]

> *"After a transmission pipeline is installed, the pipeline right-of-way (ROW) must be maintained by the pipeline operator to allow for inspection of surface conditions as required by federal law. The transmission pipeline operator must maintain the ROW vegetation so that it will not hinder pipeline inspection and maintenance activities. Extensive landscaping or other obstructions can block the view of and impede the operator's access to the pipeline."*

## 5.3. Review of Industry Best Practices

The development and implementation of comprehensive ROW vegetation management programs is considered as a best-practice approach across the pipeline industry. A sample review of a few selected programs is as follows:

- Duke Energy has an established program noting 'vegetation harmful to the integrity of the pipeline will be removed'.*
- Columbia Pipeline Group does not permit trees on the ROW.†
- Questar has developed a brochure that explains why 'planting deep-rooted vegetation, specifically trees, in pipeline rights-of-way is not permitted'.‡
- NorthWestern Energy describes how tree roots can damage coating and may have a detrimental effect on cathodic protection of the buried pipeline.§
- Louisville Gas & Electric describes right-of-way encroachment and through their public awareness program indicates that "access to the right-of-way is inhibited by trees and other vegetation, fences, buildings, and other structures".**

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* http://www.duke-energy.com/safety/right-of-way-management/pipeline-clearance-faqs.asp
† http://columbiapipelinegroup.com/en/landowners/maintenance.aspx
‡ www.questargas.com/brochures/59090.pdf
§ http://www.northwesternenergy.com/display.aspx?Page=Planting_Trees_Natural_Gas&Item=265
** http://www.lgeenergy.com/rsc/lge/LGE_IN_2012_Public_Awareness.pdf

- Local government, in conjunction with Atmos Energy, explains that 'keeping trees, shrubs, buildings, fences, and other structures and encroachments well away from the pipelines promotes maintenance of pipeline integrity and safety'.*

In all of these cases, there is a consistent message that clear ROW's are required for effective integrity management of buried pipelines.

## 5.4. Pipeline Failure Data

A review of publicly available PHMSA Gas Transmission incident data (2002 – current)† was completed to determine whether or not tree roots have been identified as root cause or contributing factor to natural gas pipeline failures. While, this review did not specifically identify tree roots as a direct or contributing cause of pipeline failure, there are several reasons for this deficiency, including reporting guidelines and reporting forms. For example, a pipeline failure cause may be reported as 'external corrosion' but there is no clear means to report whether the presence of tree roots, contributed to the external corrosion. The PHMSA incident reporting requirements over this time period are quite rigorous, but the forms are not set up to consistently report whether or not a tree and/or tree root system was a contributing cause or direct cause to a failure. In addition, there are certain limiting criteria for reporting a pipeline incident (e.g., injury/fatality, property damage, ignition, etc.), so not all failures are captured. Furthermore, the majority of transmission pipelines maintain cleared pipeline ROW corridors between 25-feet and 50-feet wide and therefore, the incident rate due to the encroachment of trees may not be well represented.

Transmission pipeline environments, where pipelines are typically located on dedicated ROW's or within road allowances, differ significantly from distribution environments, which are characteristically much more congested in terms of adjacent land use. Therefore, a similar review was conducted on PHMSA Gas Distribution incident data (2004 – present)‡‡. This review revealed five (5) incidents related to tree roots. Three (3) of those five (5) incidents involved service lines or meter sets and are summarized as follows:

1. Uprooted tree damaged above ground meter set (2005 #20050026 Central Indiana Gas Company). Release ignited and produced $700,000 in property damage.
2. Tree root cracked 0.75-inch diameter PE service tee (2012, South Jersey Gas Co). Release ignited and produced an explosion and produced $320,000 in property damage.
3. Uprooted tree pulled out 1.25-inch PE service line from foundation (2012 #20120094, Keyspan Energy). Release ignited, produced an explosion, resulted in one (1) injury, and produced $750,000 in property damage.

Two (2) of those five (5) incidents involved mains; in both cases, the mains were small-diameter, non-steel, as summarized below:

* http://www.wellingtonhoa.net/picture/faq_s_-_r-o-w_maintenance_102012.pdf

† http://phmsa.dot.gov/portal/site/PHMSA/menuitem.ebdc7a8a7e39f2e55cf2031050248a0c/?vgnextoid=fdd2dfa122a1d110VgnVCM1000009ed07898RCRD&vgnextchannel=3430fb649a2dc110VgnVCM1000009ed07898RCRD&vgnextfmt=print

4. Tree root loading caused rupture of 2-inch cast iron main operating at 60 psig, resulting in gas ignition and evacuation (2005 20060021, Centerpoint Energy). Release ignited, produced an explosion, resulted in one (1) injury, and produced $140,000 in property damage.

5. Tornado uprooted tree and pulled up 2-inch PE main, operating at 25 psig, resulting in release of gas (2011 20110161, City of Mapleton, IA).

The above evidence suggests that pipelines located in close enough proximity to tree roots that are sufficiently large to cause either high root loading forces, or significant entanglements, are susceptible to failures related to tree root damage. The evidence suggests that this susceptibility may be particularly enhanced for small-diameter (≤2-inch), non-steel pipelines.

# 6. Review of Completed and Planned Excavations

PG&E is performing a series of pipeline excavations to better characterize the interaction between tree roots and buried pipelines. It began this effort in 2012 and is continuing through 2013. A summary of these excavations is provided in Table 1 for the 2012 excavations and the 2013 excavations (completed and in-progress).

The pipeline excavations performed in 2012 produced baseline knowledge that was relied upon to enhance aspects of the excavation program for 2013 and to develop an encroachment specific detailed and consistent reporting mechanism. As a result of this evolving process, the information available from the 2013 excavations is more comprehensive than that obtained from the 2012 excavations. In addition, four (4) of the 2013 pipeline excavation sites were visited by Dynamic Risk personnel.

Based upon a review of these excavations results, discussions and observations during the field visit, it is evident tree roots do cause damage to the pipeline coatings. It is also clear there are numerous variables that affect the interaction of tree roots on pipelines, including the following:

- Species of tree (e.g., type and size of root system)
- Size of the tree (e.g., DBH, age)
- Proximity of tree to pipeline centerline (e.g., distance)
- Depth of Cover
- Local Environment (e.g., irrigation, sidewalks, land use, water table depth, etc.)
- Soil (e.g., native backfill, etc.)
- Type of Coating (pipeline and girth weld)
- Pipe Diameter.

Based upon these findings and observations, there is no obvious means to predict the interaction between the tree root and the buried pipeline prior to performing an excavation. Moreover, it is not yet known:

- whether the same species of tree affects the pipeline and coating the same way in each instance,
- to what extent each variable may or may not contribute, and/or

- whether the variables will be repeatable or predictable for assessing tree root interaction.

There is a high potential for tree roots to compromise the two (2) primary barriers that protect buried pipelines from external corrosion - external coating and cathodic protection. While in many cases tree roots are in contact with the pipe have not yet resulted in damaged coating, there is the potential for tree root growth to eventually damage the coating as the tree grows. Moreover, while the data from excavations show no active corrosion resulting from the damaged coating, there remains the potential for corrosion to occur in these locations over time.

# 7. Pipeline Integrity Management Considerations

The presence of tree roots on or near the ROW adversely affects the risk profile for a pipeline system. Vegetation, including trees in proximity to buried pipeline systems, can adversely affect several aspects of pipeline integrity management including:

- Increased susceptibility to threats
- Decreased ability to monitor
- Decreased ability to respond.

## 7.1. Increased susceptibility to Threats

### 7.1.1 External Corrosion/Cracking

Buried pipelines rely upon external coating and cathodic protection (CP), to protect the pipe and mitigate external corrosion, stress corrosion cracking, and hydrogen induced cracking. Tree roots can damage external protective coatings by creating coating holidays (coating voids or gaps), growing against the pipe, and penetrating between the coating and the pipe surface.

Depending upon the tree root system and/or coating systems, disbonded (but still intact) coating can also prevent CP from adequately protecting the pipe surface in a phenomenon known as CP shielding. Shielding can be exacerbated by the presence of tree root entanglements surrounding the pipe surface. Additionally, the presence of tree roots may affect the ability to measure CP effectiveness using above ground measurements.

Therefore, tree roots can negatively affect two barriers used to protect the external pipe surface – external coatings and cathodic protection.

### 7.1.2 Lightning

Lightning is also a threat to pipelines and the likelihood of this threat is increased when trees are in proximity to the buried pipeline. Since lightning strikes often involve trees, the tree roots can provide the mechanism for increasing the susceptibility of lightning damage to the buried pipeline. Lightning can strike a tree and propagate through the roots to the soil surrounding a pipeline:[2]

> *"The lightning passed down the tree and through the wet clay. The moisture in the clay instantly vaporized. In the region where the current passed through the soil, an instant and violent*

*expansion of the moisture in the soil occurred creating the crater in the ground around the perfectly smooth dent in the top of the pipe. The resulting tension in the pipeline initiated a crack in a girth weld a few feet away."*

### 7.1.3 Weather and Outside Force

Wind and flooding are also factors to consider where tree roots affect buried pipelines. When a tree is uprooted by wind or flooding, large tree roots entangled around a pipeline can potentially pull on, or even extract a pipeline from the ground.

### 7.1.4 Fatigue

Metal fatigue can occur if the tree roots are affecting a pipeline. Over time, wind can create movement of the pipeline where the movement can produce a fatigue environment that can negatively impact the structural integrity of girth welds or other discontinuities that may exist.

## 7.2. Decreased Ability To Monitor

### 7.2.1 Damage Prevention

A clear and designated ROW is required to adequately monitor the threats and hazards that may affect a pipeline. A clear ROW will provide the opportunity to detect encroachments before they occur and/or cause damage to the pipeline.

Independent study has identified that one of the most significant factors contributing to the threat of someone inadvertently striking and damaging a pipeline (referred to as 3rd Party Damage and includes anyone knowingly or unknowingly performing an excavation along the ROW) is the ability of the public to identify and recognize a pipeline ROW[4]. Heavy vegetation within the ROW prevents corridor recognition and contributes to the potential for inadvertent impact of a pipeline by a 3rd party excavator.

### 7.2.2 Cathodic Protection Surveys

Pipeline operators perform CP surveys to evaluate the effectiveness of CP systems. These above ground surveys include, but are not limited to, close interval surveys (CIS) and direct current voltage gradient survey (DCVG). In cases where access to the ROW is limited due to vegetation overgrowth and the presence of structures, such CP surveys are not possible. In addition, the validity of such surveys when performed, can be in question due to the presence of potential shielding by root systems.

External Corrosion Direct Assessment (ECDA) is an assessment method used to determine whether external corrosion is a potential integrity concern. Since ECDA relies upon above ground surveys such as CIS and DCVG, the results from the integrity assessment may be inaccurate if there is limited confidence in the above ground surveys due to the presence of tree roots.

## 7.3. Decreased ability to respond.

A clear pipeline ROW and access along the ROW is critical for timely emergency response and effective reaction to the presence of threats discovered through integrity assessments [e.g., ECDA, in line inspection (ILI), etc.]. During emergency situations, any obstructions in the ROW will impact the ability to respond in a timely manner.

# 8. Risk Assessment

Pipeline operators perform risk assessments in order to develop a consistent and defensible methodology for the evaluation of potential threats and consequences across their pipeline infrastructure. The risk assessment results then become part of an overall risk management program that consider viable monitoring and mitigation strategies used to manage enterprise risk and to comply with federal safety requirements. An integral part of an effective risk management program is to incorporate lessons learned from either internal programs or from external stakeholders.

As part of this tree root interference analysis, a model has been developed to consider variables that have been identified through work performed to date. Based upon this model, a threat assessment has been performed to characterize the degree of interaction with each of the relevant threats identified. Based upon the risk assessment results, examples of monitoring and mitigative activities that can be considered in developing a comprehensive integrity management and risk management program are presented.

Each is described below.

## 8.1. Tree Root 'Interaction Model'

In order to perform a high-level risk assessment, definitions are required to evaluate the interaction between the trees and the buried pipeline. As described above, the potential interaction between trees and pipelines is a function of many factors including, but not limited to:

- Species of tree (e.g., type of root system)
- Size of the tree (e.g., age)
- Proximity of tree to pipeline centerline (e.g., distance)
- Depth of Cover
- Local Environment (e.g., irrigation, sidewalks, land use, etc.)
- Soil (e.g., native backfill, etc.)
- Type of Coating (pipeline and girth weld).

Since it is not yet possible to establish and validate a model that predicts all tree root interactions ('interaction model'), a simplified interaction model has been relied upon for the purpose of this assessment. It is recognized that this interaction model may evolve as more information becomes available.

The interaction model proposed herein is based upon the information and knowledge developed to date and establishes a correlation between a tree's proximity to the pipe centerline and the tree diameter. The proximity of the tree to the pipeline is characterized by immediate, adjacent, and distal defined as follows:

Immediate Proximity. Tree trunks are considered to be in Immediate Proximity if any portion of the trunk is either directly above the centerline or close enough that the size of roots in contact with the pipeline are expected to be of the same size as roots directly below the tree. Trees in Immediate Proximity are most likely to interfere due to the presence of large roots including tap roots, and oblique roots. Threats that are related to the presence of large roots are most affected by trees in immediate proximity, and the potential and severity of the threat interaction should consider the likelihood of substantial roots with a large surface of contact between the root and the pipeline.

Adjacent Proximity. Adjacent Proximity trees are defined as those likely to cause interference with lateral roots. Such roots may grow along pipelines for considerable distances so the effect of lateral roots may interact with other threats along significant portions of the pipeline. Determination of the severity of influence for trees in Adjacent Proximity should consider the likelihood of lateral roots coming in contact with pipelines and growing along their length.

Distal Proximity. Distal Proximity trees are not likely to contact the pipeline with large roots, but may still interfere with fine roots and far-reaching lateral roots.

Based upon these definitions, the table below provides guidance (provided in white paper), to characterize tree root interaction for the purpose of this assessment:

***Tree Root Interaction Categories**** 

| DBH† | Immediate | Adjacent | Distal |
|---|---|---|---|
| **< 8 inches** | < 5 ft. | 5-10 ft. | > 10 ft. |
| **> 8 inches** | < 10 ft. | 10-14 ft. | > 14 ft. |
| **> 36 inches** | < 14 ft. | > 14 ft. | > 14 ft. |

## 8.2. Threat-Based Risk Assessment

ASME B31.8S provides guidance on the threat assessment to pipelines. The threats provided in B31.8S have been used as guidance in this assessment and the attribute of each threat has been considered as they relate to tree root interaction with the pipe.

Table 2 characterizes the degree of interaction with each relevant threat based on the proximity categories defined above. The threat interaction severities (‘high’, ‘medium’, and ‘low’), reflect the perceived severity for tree root interaction only, and do not necessarily denote absolute threat levels from the perspective of pipeline failure, defined as loss of containment. For example, the descriptor ‘high’ found

* These distances should therefore be considered a guideline, which is subject to re-evaluation as more information is gathered. Larger zones of influence than those provided below are possible, and consideration of the factors discussed above should be given with respect to the potential for larger zones of influence to exist.

† DBH (Diameter at Breast Height) is the tree diameter at a height of 54-inches (4.5 feet).

in Table 2, represents the greatest interaction potential for tree roots, however this does not suggest an absolute level of elevated threat.

This threat-based risk assessment has assumed that the tree roots are alive and in proximity to the buried pipeline. One factor not considered in this assessment, and also requires consideration as part of the development of a tree root removal program, is the effect of tree roots that are not alive and have the potential to decompose. It is recognized that the decomposition of organic matter will produce carbon dioxide ($CO_2$) and this has the potential to increase the susceptibility to cracking of the outside diameter pipe surface. Further study, assessment and consideration for this phenomenon is required.

## 8.3. Risk Mitigation and Monitoring

The removal of trees will reduce the risk profile but on a case-by-case basis, alternative monitoring and/or mitigation strategies may also provide required risk reductions. A listing of example actions and their perceived effect on threat management are provided in Table 2. The further development of Table 2 as part of a comprehensive integrity management program will provide further guidance on mitigation strategies and their effect on risk management.

Similar mitigative measures can also be undertaken to reduce the risk profile related to their effect on ability to monitor and ability to respond. For example, tree trimming will provide a better visual along the right of way that will increase the likelihood to identify encroachments and will better identify a designated corridor. Similar to the development of mitigation strategies related to the threats presented in Table 2, all monitoring and mitigative activities should be identified that will reduce the risk profile for ROW monitoring and response.

# 9. Conclusions

1. Trees located in close proximity (< 5 ft) from the pipeline centerline damage the external coating and therefore have the potential to cause direct damage to the pipe's pressure-retaining capacity. This may be particularly true for small-diameter (≤ 2 inch), non-steel pipelines that have burial depths of less than 3 ft.
2. Trees located within the pipeline ROW and adjacent to the pipeline ROW adversely affect the risk profile for a pipeline system in the following ways:
    - Increased threat susceptibility
    - Degradation in barriers designed to protect the pipeline
    - Reduction in damage prevention capabilities
    - Reduction of recognizable ROW
    - Impact on ability to perform routine maintenance and monitoring
    - Increase in time frame required for emergency response and pipeline integrity investigations.
3. Tree root interaction with pipelines is difficult to predict based upon study results produced to date.

- o Numerous variables (e.g., tree species, local environment, proximity to pipeline, etc.) require more knowledge in order to develop and validate an interaction model.
- o It is not yet known, whether the same species of tree affects the pipeline and coating the same way in each instance, to what extent each variable may or may not contribute, and/or whether the variables will be repeatable or predictable for assessing tree root interaction

4. Cathodic protection surveys, including ECDA used for performing integrity assessments may be affected by the root system between the surface of the ground and the pipe and the roots in proximity to the pipe.
5. Removal of trees in close proximity (< 5 ft) to the pipeline will reduce the risk profile related to:
   - o Pipeline threats
   - o Damage prevention
   - o Emergency response.

# 10. Recommendations

1. Tree removal as follows will reduce the risk profile:
   - o All trees within 5 feet of the pipeline centerline should be removed.
   - o Trees within between 5 feet and 10 feet of pipeline centerline and DBH 8 inches and greater should be removed.
   - o Trees within 10 feet and 14 feet of pipeline centerline and DBH greater than 36 inches should be removed.
   - o Trees that will likely affect the buried pipeline in the future should also be removed.
2. Refine reports for Tree Root Investigations produced for the Pilot Program.
   - o Further develop a consistent and concise fact-based report to document field findings related to the interaction between the trees and the buried pipelines.
   - o Develop definitions and/or comparators to describe the classifications and observations (e.g., moderate, significant, etc.)
3. Develop procedure for tree removal. Consideration for the procedure may include the following.
   - o Training programs, in conjunction with Operator Qualification requirements, should be implemented as part of the procedure implementation.
   - o Decomposition and CO2 production could increase susceptibility to cracking. Further study, assessment and consideration for this phenomenon is required.
   - o The effects of leaving tree root systems in place and how they could affect future pipeline integrity and/or future integrity surveys that may be required.
   - o Cautionary guidance while removing trees that may already be affecting a pipeline.
   - o Consistent procedures for excavation, non-destructive examination, remediation, documentation, etc.

4. Continue to perform tree root excavations to develop the knowledge related to all of the variables affecting the interaction between tree roots and buried pipelines.
    - This should include diverse species of trees and environments that could potentially affect the interaction.
    - Integrate available ILI data and ECDA data with potential tree root excavation locations and consider excavating where corrosion may be coincident with a tree root system.
5. Develop better understanding of the effects of tree roots on external protective coatings and cathodic protection of the buried pipeline.
    - Consider the impact of tree roots on effectively protecting the buried pipeline including the possibility of shielding.
    - Pipeline corrosion specialists should be retained to evaluate the potential for the presence of tree roots to affect above ground cathodic protection measurements (e.g., CIS, DCVG, etc.).
6. Further develop monitoring and mitigation strategies that can be used for effective risk management in cases where tree removal is not a viable option.
    - Identify all mitigative actions and their effect on the threat susceptibility, ability to monitor, and ability to respond (e.g., root barrier systems).
    - Quantify the effect of the monitoring and mitigative strategies on the risk profile.
7. Work with industry to develop consensus standards and guidelines related to tree setback distances and their effect on pipeline integrity management and risk management.

*Table 1. Severity of Threat Interaction Attributed to Tree Roots*

| Threat Description | Potential for Interaction between Tree Roots and Buried Pipeline | | | |
|---|---|---|---|---|
| **Threat**[*] | **Threat Attribute** | **Immediate** | **Adjacent** | **Distal** |
| **External Corrosion** | Monitoring Accessibility (CIS, DCVG, etc.) | High | N/A | N/A |
| | ECDA Accessibility | High | N/A | N/A |
| | Cathodic Protection Interference | High | Med | N/A |
| | Coating Damage to Susceptible Coatings | High | Med | Med |
| **Internal Corrosion** | ICDA Accessibility Interference | Med | Low | N/A |
| **Environmentally Assisted Cracking** | Accessibility for Monitoring and Patrol | High | N/A | N/A |
| | Cathodic Protection Interference | High | Med | N/A |
| | Coating Damage to Susceptible Coatings | High | Med | Med |
| **Third Party Damage** | Increased Activity from Landscaping / Tree Crops | High | Med | N/A |
| | Depth of Cover Survey Access Interference | Med | N/A | N/A |
| **Weather Related and Outside Forces** | Lightning Strikes | High | N/A | N/A |
| | Uprooting During a Hurricane, Flood, or Tornado | High | Low | N/A |
| **Manufacturing and Construction Related Defects** | Stresses Due to Radial Growth | High | Med | N/A |

[*] Threat categories established by B31.8S.

*Table 2. Examples of Monitoring and/or Mitigation Actions and Effect on the Risk Profile.*

| | Will 'action' reduce the threat likelihood? | | | |
|---|---|---|---|---|
| **Monitoring and/or Mitigation Action** | External Corrosion/ Cracking | Lightning[*] | Weather/ Outside Force | Fatigue |
| **Tree and Root Removal** | Yes | Yes | Yes | Yes |
| **Tree Removal** | Maybe | Yes | Yes | Yes |
| **Root Barrier System (e.g., barriers, sever between tree and pipe)** | Maybe | Yes | Yes | Yes |
| **Tree Trimming** | No | Maybe | Yes | Maybe |

[*] For lightning, methods may identify prior damage versus simply protecting from the initial damage.

*Table 3. Summary of Tree Root Excavations*

| DIG ID | Documentation* | Species |
|---|---|---|
| **2012 Examinations** | | |
| **Orville[5]** | Report | California Sycamores |
| | Report | American Ash |
| **Yuba City[6]** | Report | Walnut Orchard |
| **Kiefer Road[7]** | Report / Photos | Liquid Amber |
| **2013 Excavations (Reports Completed)** | | |
| **132-8[8] (734 Manzanita)** | Report/Photos | Incense Cedar |
| **153-1[9] (15633 Wicks)** | Report/Photos | Old Monterey Pine |
| **153-3A[10] (15667 Wicks)** | Report | Monterey Cypress |
| **153-4[11] (15685 Wicks)** | Report/Photos | Italian Stone Pine |
| **2013 Excavations (In Progress - Preliminary Information)** | | |
| **132-1[12,13] (1963 Rock Street)** | Photos/DR Field Visit | Redwood |
| **132-2[13] (891 San Lucas)** | Photos | Magnolia |
| **132-7[12,13] (735 Madrone)** | Photos/DR Field Visit | Privet |
| **132-9A[12,13] (741 Santa Christina)** | Photos/DR Field Visit | Black Walnut |
| **132-9B[12,13] (749 Santa Christina)** | Photos/DR Field Visit | Elm |
| **132-10[13] (798 Carolina)** | Photos | Juniper (multi-stem) |
| **153-7[12,13] (15747 Via Sorrento)** | DR Field Visit | Palm |
| **153-9.1[13] (15787 Via Sorrento)** | Photos | Poplar |
| **153-10[13] (15803 Via Hornitos)** | Photos | Willow (dead) |
| **153-12[13] (2193 Corte Hornitos)** | Photos | Mulberry |

* Report (Excavation Report completed by Frizzell), Photos (Site photos and/or excavation photos available), DR Field Visit (locations visited by Dynamic Risk).

*Table 4. Summary of Selected Results from Tree Root Excavations*

| ID | 153-1 | 153-3A | 132-8 | 153-4 | Oroville | | Yuba City | Kiefer Road |
|---|---|---|---|---|---|---|---|---|
| **Species** | Monterey Pine | Monterey Cypress | Incense Cedar | Italian Stonepine | California Sycamore | American Ash | Walnut (orchard) | Liquid Amber |
| **Tree Diameter (base)** | 28” | 36” | 26” | 36” | 34” | | | |
| **Tree Diameter at DBH** | 34.5”/19.1” | 17”/17”/16” 12”/6 | 20” | 35” | 18” | 35” | | |
| **Tree edge to Pipe Centerline** | 2.5’ | < 0.5’ | 7’ | 0’ | | | | 27.8’ |
| **Depth of cover** | 4’ | 4’ | 6’ | 4’ | | 3’10” | | |
| **Visual tree root interaction with pipe? (subjective)** | Moderate | Insignificant | Moderate / Extensive | Extensive | No | | | Yes |
| **Coating Impression** | Yes | No | Yes | Yes | No | | Yes | Yes |
| **Coating Holiday? (intact visually)** | No | No | Yes | Yes | No | | Yes | |
| **Visual evidence of External Corrosion?** | No | No | No | No | No | | No | |

Dynamic Risk

# 11. References


[1] Frizzell, Randall, Tree Root Interactions with Natural Gas Transmission Pipelines. Prepared for Pacific Gas & Electric Company by Randal Frizzell and Associates, Nevada City, CA (April, 2012)

[2] "Partnering to Further Enhance Pipeline Safety In Communities Through Risk-Informed Land Use Planning", Pipelines and Informed Planning Alliance (November 2010), Final Report

[3] CFR 192.705(a) Transmission Lines: Patrolling

[4] Fuglem, M.K., Chen, Q., and Stephens, M.J., "Pipeline Design for Mechanical Damage", PRCI Report No. PR-244-9910, October, 2001.

[5] Randall Frizzell & Associates, Oroville, June 2012 Tree Root Interactions With Natural Gas Transmission Pipelines (June, 2012).

[6] Randall Frizzell & Associates, Yuba City, June 2012 Tree Root Interactions With Natural Gas Transmission Pipelines (June, 2012).

[7] Randall Frizzell & Associates, Photos, Kiefer Road (June, 2012).

[8] Randall Frizzell & Associates, Tree Root Excavation Gas Transmission Line 132 734 Manzanita Avenue, Sunnyvale, California (January, 2013).

[9] Frizzell & Associates, Tree Root Excavation Gas Transmission Line 153 15633 Wicks Blvd, San Leandro, (January, 2013).

[10] Frizzell, Randall and Frizzell, Mark. Tree Root Excavation – 15667 Wicks Blvd, San Leandro, CA. Prepared for Pacific Gas & Electric Company by Randal Frizzell and Associates, Nevada City, CA (February, 2013).

[11] Randall Frizzell & Associates, Tree Root Excavation Gas Transmission Line 153 15685 Wicks Blvd., San Leandro, California (January 2013).

[12] Field Visit Photo-documentation by Dynamic Risk Personnel, February 27, 2013.

[13] Photo documentation provided by Randall Frizzell & Associates.

# Attachment 3:

**Pacific Gas and Electric. "Utility Standard: TD-4490S, 11/26/2014 Rev: 2, Gas Pipeline Rights - of-Way Management".**

# Gas Pipeline Rights-of-Way Management

## SUMMARY

This utility standard establishes the requirement for vegetation and structures when managing rights-of-way (ROW) for Pacific Gas and Electric Company (Company or PG&E) natural gas transmission pipelines and distribution mains including all equipment and physical facilities that transport gas, such as pipe, valves, compressor units, metering stations, regulator stations, delivery stations, and fabricated assemblies.

## TARGET AUDIENCE

All personnel involved with patrolling, surveying, operations and maintenance (O&M), pipeline engineering and design, land rights management, and legal.

## SAFETY

Always consider employee and public safety in the application of this utility standard, consistent and pursuant to Utility Standard SAFE-1001S, "Safety and Health Program."

## TABLE OF CONTENTS



## REQUIREMENTS

### 1 General

1.1 This gas pipeline ROW management utility standard extends PG&E's continued commitment to public safety and safe operational practices to manage vegetation and structures on the ROW. This commitment includes the following points:

- Reducing risk to pipeline integrity that can occur from the presence of vegetation and structural intrusions in the ROW.

  

# Gas Pipeline Rights-of-Way Management

1.1 (continued)

- Providing safe access to Company natural gas pipeline facilities to conduct pipeline O&M activities required by regulatory code, which include the following:
    - Leak surveys
    - Patrolling
    - Inspections
    - Testing
    - Pipeline repairs and/or replacements
    - Keeping ROW clear of obstructions to allow access to safely operate, maintain, and respond in the event of an emergency
- Creating a line-of-sight corridor of the ROW
- Emphasizing the marking of the pipeline
- Increasing public awareness of the location and presence of PG&E's pipeline facilities
- Reducing the likelihood of damage to the pipeline from any excavation on or near the pipeline
- Enhancing the ability of emergency responders to identify and access the pipeline facilities
- Eliminating or mitigating the negative impact of vegetation (e.g., roots) and structures (e.g., buildings and carports) on underground natural gas pipelines, as well as managing safe and reliable pipeline accessibility
- Ensuring that all vegetation management operations are done in a safe, effective manner and in conformity with all federal and state laws, regulations, and permit conditions, with special attention to addressing any environmental concerns

# Gas Pipeline Rights-of-Way Management

## 2 Vegetation Control Standards

2.1 **Vegetation zone design:** The vegetation zone design allows for the landscape to incorporate an environmentally balanced “feather cut” from the pipe zone as it moves outward to the border zone. A hard cut is the severe change from one zone to another without a natural transition between the two zones. The vegetation zone design avoids “hard cuts” on ROW that begin from the area over the pipeline (defined as the “pipe zone”), and expands to the outer edges beyond the pipe zone called “border zones.”

2.2 **Pipe zone:** The pipe zone extends from the edge of the pipe to the border zone.

A pipeline may not always be located in the center of the easement. Figure 1, “Illustration of the Pipe Zone and Border Zone,” below shows the relationship of the trees and foliage in the pipe zone and border zone, and the manner prescribed to create a “feather cut” to the edge of the ROW.

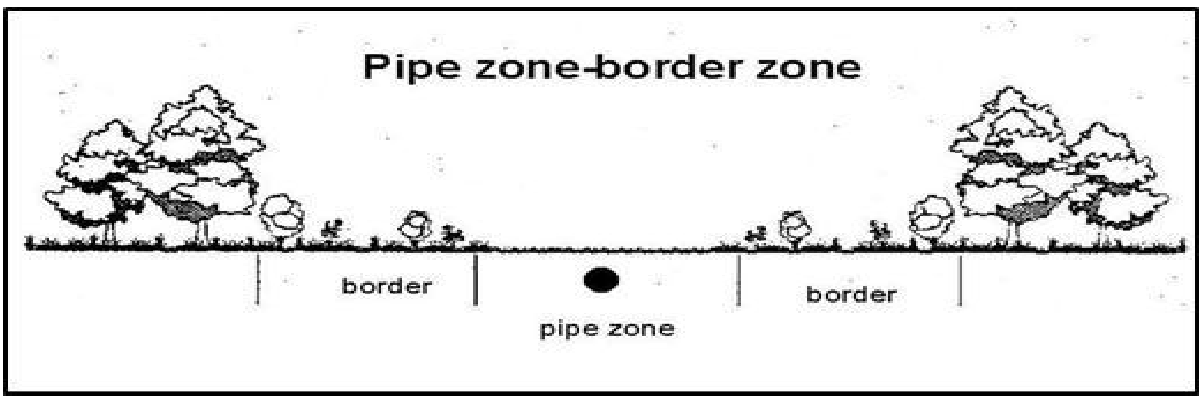


**Figure 1. Illustration of the Pipe Zone and Border Zone**

Subject to the criteria described in Section 2.4, trees, woody shrubs, and woody vegetation must be removed and are not permitted to be planted in the pipe zone.

Lawns, flowers, low-profile grasses, and low-growing herbaceous plants are permitted within the pipe zone.

2.3 **Border zone:** The border zone extends from the edge of the pipe zone to the edge of the ROW.

1. Impermissible Vegetation Found in the Border Zone:

    a. Trees, woody shrubs, or woody vegetation exceeding 8 in. in diameter, or of a species likely to exceed 8 in. in diameter at 4.5 ft above ground diameter at breast height (DBH) at maturity, and the trunk or main branch is 5 to 10 ft from the outer edge of the pipeline, must be removed and not permitted to be planted in the border zone. See Figure 2. Typical DBH Measurement.

## Gas Pipeline Rights-of-Way Management

**Figure 2. Typical DBH Measurement**

b. Trees, exceeding 36 in. in DBH or of a species likely to grow to and exceed 36 in. in DBH at maturity, and the trunk or main branch is 10 to 14 ft from the outer edge of the pipeline, must be removed and not permitted to be planted in the border zone.

2.4 Tree Management

- In those circumstances in which application of the standard in Sections 2.2 and 2.3 above are not possible, the Company will conduct an evaluation of the risk posed to the safety of the pipeline and the public by leaving the tree in place per Utility Procedure TD-4490P-03, "Detailed Risk Analysis Process for Vegetation Removal."

### 3 Structures Control Standards

3.1 All structures located in the ROW are considered an encroachment. If the Company determines that the encroachment does not interfere with O&M, does not endanger the facilities, and does not compromise the safety of the public, the Company may enter into an encroachment agreement with the land owner. The agreement must comply with California Public Utility Code (CPUC), Section 851 and General Order 69-C.

- General Order 69-C Summary

  CPUC General Order 69-C sets forth the type and nature of real property rights a public utility may convey without further approval of the CPUC. Specifically, it authorizes public utilities to grant easements, licenses, and permits for the use or occupancy of operating property.

  

## Gas Pipeline Rights-of-Way Management

3.2 Permissible Structures Found in the Border Zone

Generally, construction of buildings and other structures is restricted by the terms of the easements creating the ROW; however, there are times when some types of structures may be acceptable.

- Contact land department personnel for assistance in determining if a structure or other use is acceptable within the Border Zone.

### 4 Generally Permissible Uses of ROW

The following uses are typically permitted within ROW boundaries:

- Some patios or concrete slabs (subject to limits)
- Flower beds, vegetable gardens, lawns, low shrubbery, and certain crops
- Livestock grazing
- Some sports and game fields, parks, and golf courses (subject to limits)

### 5 Prohibited Uses of ROW

To keep pipelines accessible, the following uses are prohibited within the ROW boundaries (list not all-inclusive):

- Buildings, structures or foundations, overhanging roofs and balconies, garden sheds, and signs
- Wells, swimming pools, or other boreholes
- Storage of flammable materials, heavy equipment, and bulk goods
- Burning materials, such as waste, scrap lumber, and slash
- Pile-driving or blasting

See exemption process as described below in Section 6 and refer to Utility Procedure TD-4490P-03, “Detailed Risk Analysis Process for Vegetation Removal” regarding the detailed site-specific risk analysis process.

### 6 Exemptions Process

6.1 Prior to issuing an exemption for removal of trees or woody vegetation in either the border zone or the pipe zone, a risk analysis must be conducted per Utility Procedure TD-4490P-03, “Detailed Risk Analysis Process for Vegetation Removal.”

  

6.2 Any decision to make an exemption for removal of trees or woody vegetation must be documented in writing and include the following:

- Rationale for the exemption
- Integrity analysis supporting the decision
- Description of alternative mitigation strategies in place to reduce risk

6.3 The exemption document must be reviewed and approved by the Director of Transmission Asset Integrity Management and the Director of Gas Operations.

**7 Exemptions for Environmentally Sensitive Areas**

7.1 Exemptions in environmentally sensitive areas, such as an endangered species habitat or an area of historical or cultural significance, or other similar designations must be determined:

1. On a case-by-case basis, and
2. The distinct environmental demands of the area while balancing safety and operational requirements.

7.2 These exemptions must also follow the exemption process in Section 6.

**8 Outside the ROW**

8.1 The Company must take appropriate action to identify, assess, and mitigate the potential risks of trees and vegetation located outside the ROW that are capable of producing limbs and roots that may adversely impact the pipeline integrity within the easement.

8.2 In some cases, trees in poor health (hazard trees) will be identified because of the risk of falling and potential damage to exposed portions of pipeline (e.g., stream crossings).

8.3 The Company must work with the appropriate property/land owners and occupants to reach a written agreement before the removal or trimming of vegetation, trees, or limbs outside the easement.

**END of Requirements**

**DEFINITIONS**

**Border zone:** An area extending from the edge of the pipe zone to the edge of the ROW.

**Corridor:** A tract of land forming a passageway.

**Diameter at breast height (DBH):** A standard method of expressing the diameter of the trunk or bole of a standing tree.

  

# Gas Pipeline Rights-of-Way Management

**Easement:** The limited right to make use of property owned by another. Pipeline ROW is documented in a written easement. The easement may grant the right to install and maintain a pipeline across another person's property. The rights and restrictions are usually defined in the easement document. The easement is usually recorded to provide notice of the rights and restrictions that apply to the property, even when it transferred or sold.

**Encroachment:** To advance beyond established or proper limits; make gradual inroads or to trespass upon property, domain, or rights of another, especially gradually or stealthily.

**Herbaceous:** A plant with leaves and stems that die down at the end of the growing season to the soil level, which has no persistent woody stem above ground.

**Pipe zone:** An area around the pipeline extending from the edge of the pipe to the border zone. In a ROW with widths equal to or less than 10 ft the width of the pipe zone must be equal to the width of the ROW. In ROW with widths greater than 10 ft the width of the pipe zone must be equal to the width in the ROW that is up to 5 ft on either side of the edge of the pipeline. Any area within the ROW that is outside of the pipe zone will be considered "border zone."

**Rights-of-way (ROW):** The right to cross property to go to and from another parcel. The ROW may be a specific grant of land or an "easement," which is a right to pass across another's land.

**Vegetation:** All the plant life in a particular region taken as a whole.

## IMPLEMENTATION RESPONSIBILITIES

Document owner must set up a session to tailboard this utility standard to the affected integrity management personnel.

Guidance Document Tailboard must be emailed to land management, engineering, O&M, and legal managers.

## GOVERNING DOCUMENT

NA

## COMPLIANCE REQUIREMENT / REGULATORY COMMITMENT

49 CFR Part 192, Subpart O, "Gas Transmission Pipeline Integrity Management"

CPUC, Section 851

CPUC General Order 69-C, "Easements on Property of Public Utilities Resolution No. L-230"

## REFERENCE DOCUMENTS

**Developmental References:**

CPUC, Section 851

CPUC General Order 69-C, "Easements on Property of Public Utilities Resolution No. L-230"

**Supplemental References:**

Utility Procedure TD-4490P-03, "Detailed Risk Analysis Process for Vegetation Removal"

49 CFR Part 192, Subpart O, "Gas Transmission Pipeline Integrity Management"

49 CFR §192.451, "Scope"

49 CFR §192.613, "Continuing Surveillance"

49 CFR §192.614, "Damage Prevention Program"

49 CFR §192.616, "Public Awareness"

49 CFR §192.705, "Transmission Lines: Patrolling"

49 CFR §192.706, "Transmission Lines: Leakage Surveys"

49 CFR §192.707, "Line Markers for Mains and Transmission Lines"

49 CFR §192.933, "What Actions Must be Taken to Address Integrity Issues?"

## APPENDICES

NA

## ATTACHMENTS

NA

## DOCUMENT RECISION

This utility standard supersedes Utility Standard TD-4490S, "Gas Pipeline Rights-of-way Management," Rev. 1, issued 04/2014.

## DOCUMENT APPROVER

Chauna Moreland, Director, Gas Transmission Right of Way

# Gas Pipeline Rights-of-Way Management

**DOCUMENT OWNER**

Jeannette Lindemann, Standards Engineer

**DOCUMENT CONTACT**

Ettore Minor, Manager

  

# Gas Pipeline Rights-of-Way Management

## REVISION NOTES

| Where? | What Changed? |
|---|---|
| Entire document | Updates to incorporate site-specific risk analysis references have been made throughout the document. |
| Section 1 | Updated commitments list. |
| Section 2.4 | Section updated to “Tree Management” and added tree removal criteria and risk-based approach for vegetation in the ROW. |
| Section 2.4.4 | Added reference to TD-4490P-03, which details the site-specific risk analysis process. |
| Section 3 | Updated requirements for permissible structures on the ROW. |
| Section 5 | Added reference to TD-4490P-03. |
| Section 7 | Changed paragraph format. |
| Section 9 | “Easement Safety” section was removed. |
| Section 10 | Renumbered to Section 9. |

# Attachment 4:

**Dynamic Risk Assessment Systems, “Tree Root Interference Pipeline Threat Analysis (Draft)”, Dynamic Risk Power Point Presentation. October 29, 2013.**

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Dynamic Risk Assessment Systems, Inc.

Dynamic Risk USA

Your Integrity Management Partner

From wellhead to burner tip, Dynamic Risk's integrity management solutions provide you the information to make effective decisions for your entire asset base.

# Tree Root Interference Pipeline Threat Analysis (Draft)

October 29, 2013

# Introduction
# PG&E's Pipeline Pathways

- ◊ As part of its commitment to enhance public safety, Pacific Gas and Electric Company (PG&E) is conducting a "Pipeline Pathways Program"
- ◊ This program includes
  - ➢ A comprehensive survey of its natural gas transmission pipeline system
  - ➢ Increased marking of the pipeline in the right-of-way (ROW)
  - ➢ Identifying structures and vegetation (e.g., trees) along the ROW
  - ➢ Working cooperatively with property owners to remove or replace structures or vegetation that interfere with PG&E's ability to maintain, inspect, or safely operate its natural gas transmission pipelines.
- ◊ As part of the Program, PG&E is conducting a Root Study to develop a better understanding of the potential interaction between tree roots and its natural gas transmission pipelines.

# Introduction
# Dynamic Risk's Role

- ◊ To assist in the Root Study, PG&E has retained Dynamic Risk Assessment Systems, Inc. (Dynamic Risk) to:
  - ➢ Continue the assessment of the interaction of tree roots with PG&E's buried natural gas transmission pipelines to identify and understand potential threats tree roots may pose to pipeline integrity.
  - ➢ Provide continued technical support for the development and implementation of the Root Study.
  - ➢ Conduct assessment of the results from the Root Study, including assessing effectiveness of PG&E's current framework for addressing such potential threats.
  - ➢ Develop findings from the Root Study and produce a final report by end of the year for further consideration by PG&E's Transmission Integrity Management team.
- ◊ This Power Point report provides an interim summary of the Tree Root Study and includes objectives, findings to date, preliminary conclusions and additional considerations that may impact on the nature of results in the final report.

# Objectives of Tree Root Study

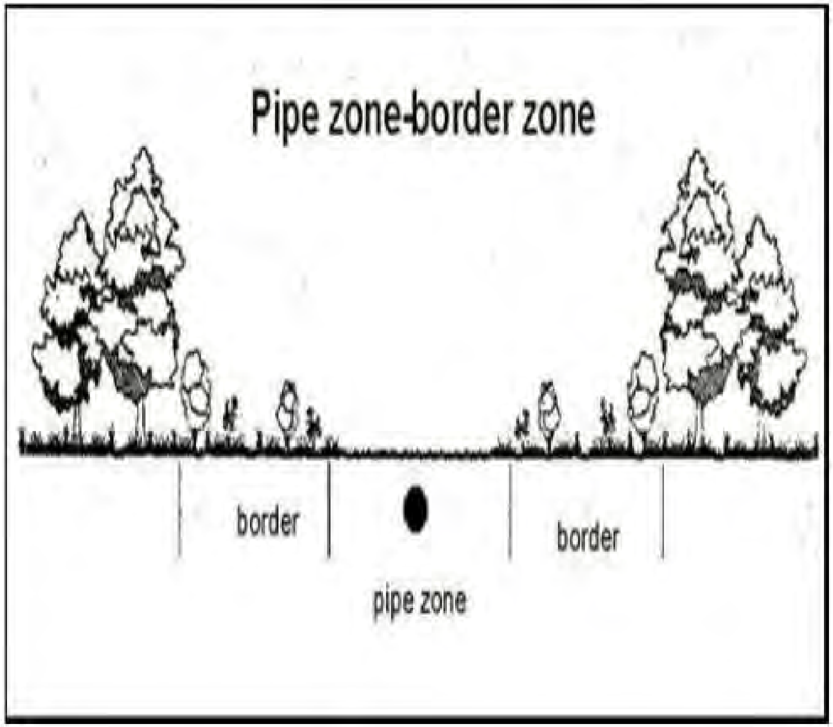
- ◊ To evaluate the interaction of live tree roots with buried pipelines to determine and quantify potential threats to pipeline integrity, including answering the following:
  - ➢ Does pipe contact with tree roots result in coating damage or corrosion initiation?
  - ➢ Does pipe contact with tree roots result in an accelerated corrosion condition?
  - ➢ Does pipe contact with tree roots result in deformation, ovality change or related or other damage to the pipe steel?
  - ➢ What are primary factors that must be accounted for when PG&E assesses the risk arising from the presence of tree roots near/on the pipeline?
  - ➢ If trees remain on the pipeline ROW, what other mitigation efforts could PG&E undertake to manage pipeline integrity?
- ◊ To evaluate whether dead tree roots near or on the pipeline create a chemical or microbiological environment that may be conducive to initiating external corrosion or accelerating corrosion growth, including answering the following:
  - ➢ Does the remaining presence of dead tree roots have any impact on management of pipeline integrity?

# Objectives of Tree Root Study (cont.)

3. To study effectiveness of above ground integrity assessment surveys performed at locations with dense tree root systems, including answering the following:
   - Do tree roots near or around pipelines interfere with pipeline integrity surveys and assessments?
   - Does the presence of the tree roots on/near the pipeline interfere with Cathodic Protection or with testing for the presence and effectiveness of Cathodic Protection?
   - If above ground surveys are determined to be impacted, does removing the tree, but leaving the root base, in accordance with the current PG&E ROW standard* reduce or eliminate this impact?
4. To evaluate the requirement for review and improvements to the present PG&E practices in regards to vegetation control, including answering the following:
   - Is clearing the Pipe Zone and the Border Zone of vegetation in accordance the current PG&E ROW standard sufficient to appropriately managing pipeline integrity?

# PG&E Gas Pipeline Right-Of-Way Utility Standard Vegetation Requirements Summary

- ◊ …… "Lawns, flowers, low-profile grasses and low-growing herbaceous plants are permitted within the Pipe Zone".
- ◊ ………"trees, woody shrubs, and woody vegetation must be removed and are not permitted to be planted in the Pipe Zone"
- ◊ ……."flower beds, vegetable gardens, lawns, low shrubbery, and certain crops" are permitted within the right-of-way boundary "



# PG&E Gas Pipeline Right-Of-Way Utility Standard Vegetation Requirements Summary (cont.)

- ……."trees, woody shrubs or woody vegetation **exceeding 8 inches or of a species likely to exceed 8 inches but less than 36- inches in diameter** at 4.5 feet above ground diameter at breast height (DBH) at maturity, and the trunk or main branch **is 5- to 10-feet from the centerline of the pipeline, must be removed** and not permitted to be planted in the Border Zone"
- …. "Integrity Management personnel may elect to exempt specific trees or woody vegetation for removal from the Border Zone"
- ….."Decisions on the timing of the removal of any specific tree or woody shrubs currently in the Pipe Zone, or those greater than 8 inches in DBH at maturity in the Border Zone, must be made by Integrity Management personnel using risk-based assessment tools"

# Project Roles and Responsibilities

◊ ***Dynamic Risk*** - To provide continued technical support for the development, implementation, and assessment of results related to the 2013 Pacific Gas and Electric (PG&E) tree root program/ To develop findings and produce final report.

◊ ***Det Norske Veritas (DNV)*** - To provide support and direction in regards to assessment of external corrosion conditions, evaluate external corrosion data collected and to produce a supporting report that summarizes corrosion related findings and conclusions.

◊ ***Mears Group, Inc.*** - To collect Direct Assessment inspection/test data as specified on the modified PG&E H-Form (the pipe condition excavation data collection form).

◊ ***NACE Certified Inspectors*** - To collect excavation and data and produce the PG&E A Form (Leak Repair, Inspection, and Gas Quarterly Incident Report).

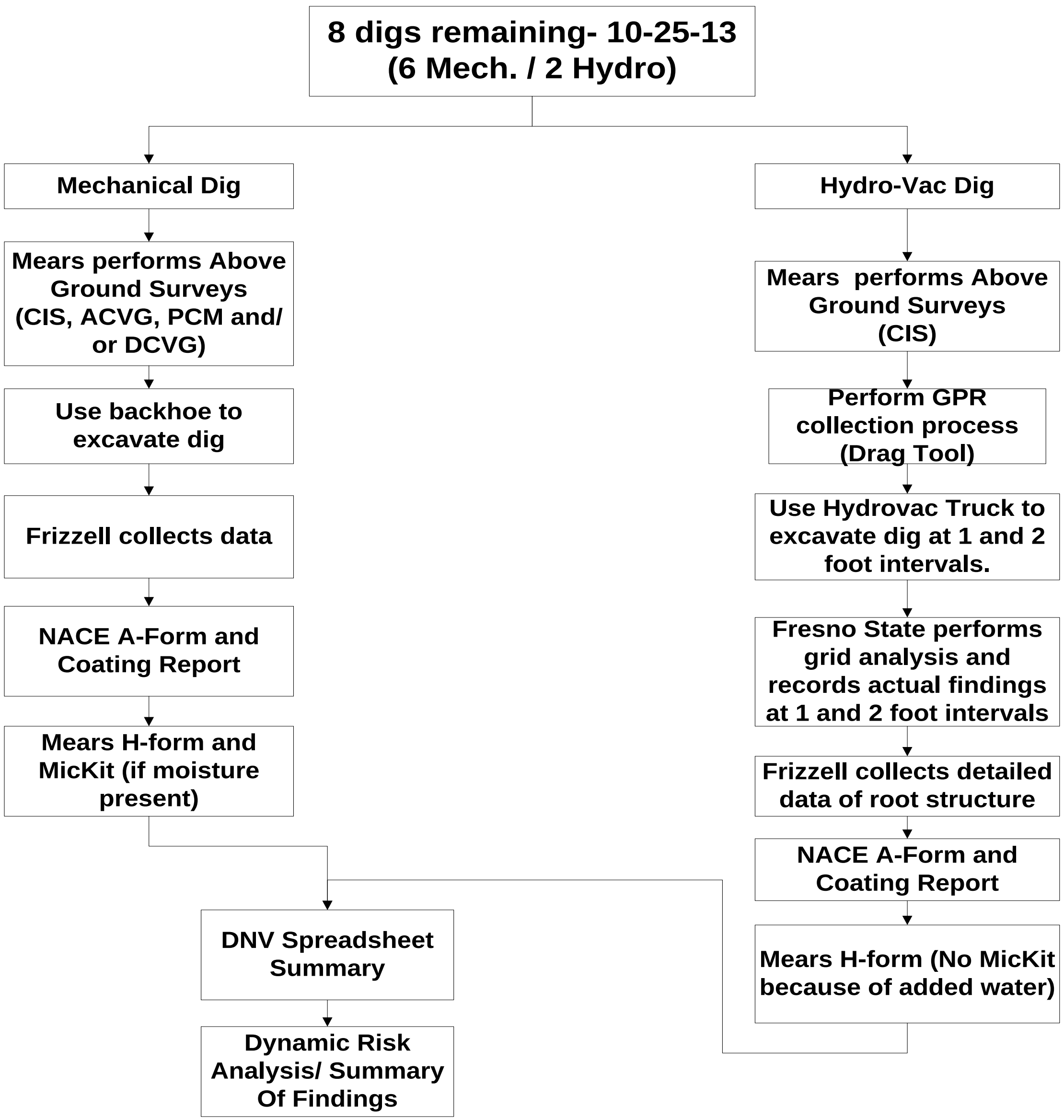
◊ ***Frizzell and Associates (Arborists)*** – To provide analysis in regards to trees and the extent and nature of tree roots impacting on the underground pipeline systems via a compilation of field investigations/ To produce the Field Report Summary.

◊ ***Fresno State University*** – To provide analysis on Ground Penetrating Radar (GPR) compared with actual findings collected in the field to determine the effectiveness of using GPR to locate tree roots, determine aggressive root structure of various orchard and measure impact of soil type on tree root growth.

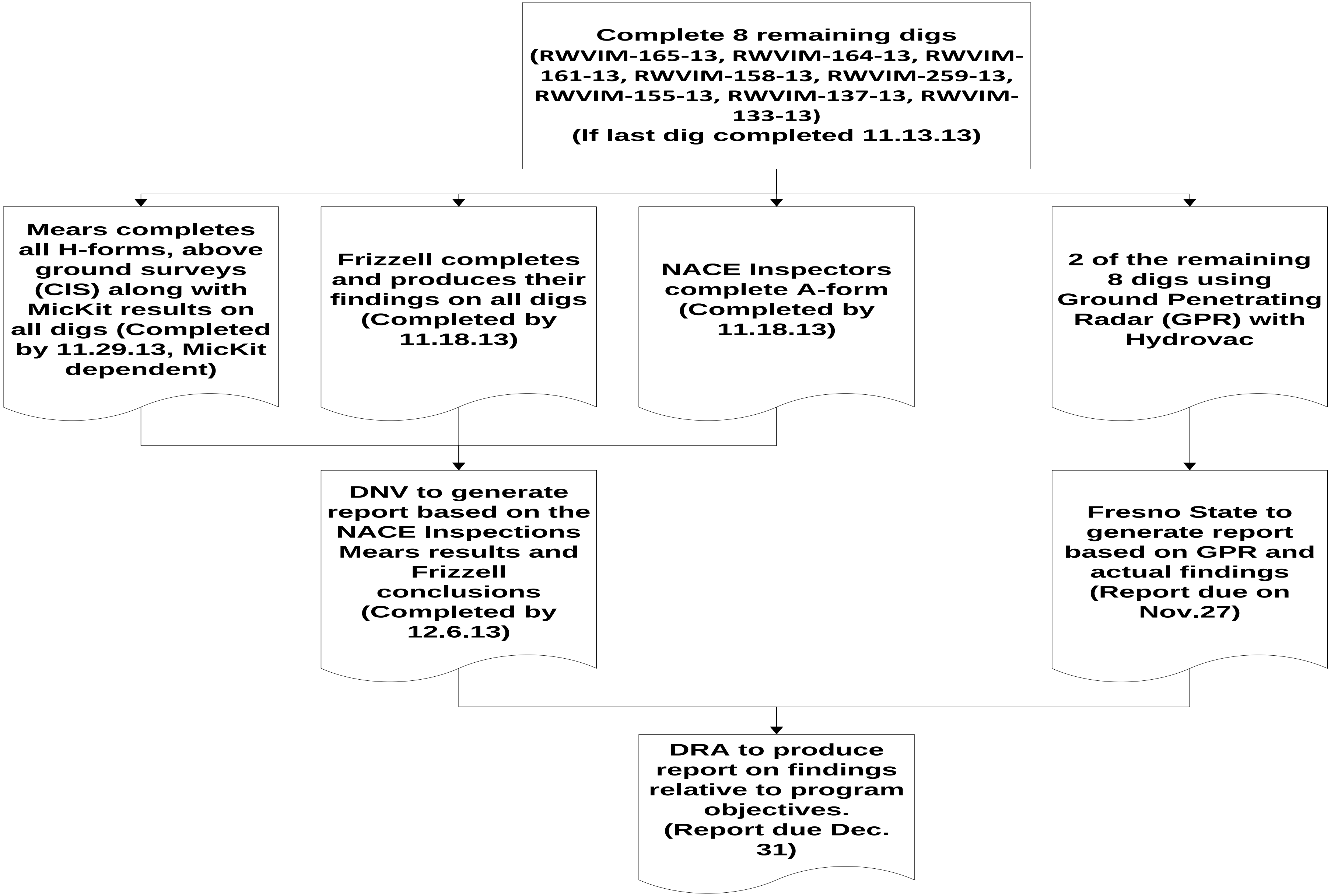
# Tree Root Site Excavation Process
# Two Approaches

- Hydrovac (High Pressure Water)
  - Benefit- Removes ground cover efficiently while leaving root base undamaged and fully exposed for study. Provides for gradient removal of pipe cover as required for Ground Penetrating Radar (GPR) analysis.
  - Disadvantage- Presence of external high pressure water contaminates site and prevents obtainment of in the ditch water sample for analysis.
- Mechanical (Backhoe)
  - Benefit- Eliminates external water contamination of site.
  - Disadvantage(s)- Process is slower.  Potential for damage to roots. Potential for pipe contact and damage.

# EXCAVATION PROCESS/ DATA COLLECTION



# Final Report Completion Process Flowchart



# Summary of Excavations and Completion of Digs
# 49 Completed Excavations/ Sample Spreadsheet

Dynamic Risk

| Project ID | Project Status | Project Type | Address | City | LAT | LON | Line | Dig Completion | H-Form Complete/ Received | A-Form Complete / Receiv | Frizzell Report complete/ Receiv | Mears Above Ground Survey Reports Completed/ Received | Fresno State University/ Findings Review | MicKit Performed/ Report received |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 132-6a (RWVIM-104-13) | Complete | Full Root | 810 San Lucas Court | Mountain View | 37.403288 | -122.071889 | L132 | 2/20/2013 | Y | Y | Y | NOT PERFORMED | | NOT PERFORMED |
| 153-10a (RWVIM-99-13 dig #1) | Complete | Full Root | 15803 Via Hornitos | San Lorenzo | N/A | N/A | L153 | 11/10/2012 | Y | Y | Y | NOT PERFORMED | | NOT PERFORMED |
| 153-10a (RWVIM-99-13 dig #2) | Complete | Stump | 15803 Via Hornitos | San Lorenzo | N/A | N/A | L153 | 11/10/2012 | Y | Y | Y | NOT PERFORMED | | NOT PERFORMED |
| RWVC-36-13 (RWVIM-96-13) | Complete | Full Root | 785 San Lucas Ave. | Mountain View | 37.403756 | -122.072851 | L132 | 2/20/2013 | Y | Y | Y | NOT PERFORMED | | NOT PERFORMED |
| RWVC-38-13 (L109) | Complete | Full Root | 1963 Rock Street | Mountain View | 37.411480 | -122.090139 | L109 | 3/24/2013 | Not Performed | Y | Y | NOT PERFORMED | | NOT PERFORMED |
| RWVC-38-13 (L132) | Complete | Full Root | 1963 Rock Street | Mountain View | 37.411480 | -122.090139 | L132 | 3/24/2013 | Y | Y | Y | NOT PERFORMED | | NOT PERFORMED |
| RWVC-44-13 (RWVIM-100-13) | Complete | Full Root | 15747 Via Sorrento | San Lorenzo | 37.673902 | -122.153557 | L153 | 3/2/2013 | Not Performed | Y | Y | NOT PERFORMED | | NOT PERFORMED |
| RWVC-46-13 (RWVIM-101-13) | Complete | Full Root | 741 Santa Christina Court | Sunnyvale | 37.39508676 | -122.022912 | L132 | 4/18/2013 | Y | Y | Y | NOT PERFORMED | | NOT PERFORMED |
| RWVC-47-13 (RWVIM-102-13) | Complete | Full Root | 735 Madrone Ave | Sunnyvale | 37.395265 | -122.025526 | L132 | 4/26/2013 | Y | Y | Y | NOT PERFORMED | | NOT PERFORMED |
| RWVC-49-13 (RWVIM-103-13) | Complete | Full Root | 811 San Lucas Court | Mountain View | 37.403068 | -122.071449 | L132 | 2/20/2013 | Y | Y | Y | NOT PERFORMED | | NOT PERFORMED |
| RWVC-55-13 (RWVIM-105-13) | Complete | Full Root | 2194 Corte Hornitos | San Lorenzo | 37.671056 | -122.150934 | L153 | 2/28/2013 | Not Performed | Y | Y | NOT PERFORMED | | NOT PERFORMED |

# Summary of Excavations and Completion of Digs (cont.)

Dynamic Risk

◊ As of 10/25/13:
  - 8 Remaining Excavations
  - 2 In progress
  - 49 Complete Excavations- Includes excavations performed in 2012 and 2013.

◊ Remaining Excavations

| Project ID | Project Status | Project Type | Address | City | Dig Completion |
|---|---|---|---|---|---|
| RWVIM-133-13 | 18-Nov | Full Root | Hwy 124 Charles Hwd Park | Ione | 12/4/2013 |
| RWVIM-137-13 | 18-Nov | Full Root | Hwy 124 Charles Hwd Park | Ione | 12/4/2013 |
| RWVIM-165-13 | 8-Nov | Orchard | 2254 Sunset Ave | Los Banos | 11/10/2013 |
| RWVIM-158-13 | 4-Nov | Orchard | Hwy 45 South of Dodge Rd | Princeton | 11/11/2013 |
| RWVIM-164-13 | 31-Oct | Orchard | E. Whitmore | Hughson | 11/8/2013 |
| RWVIM-259-13 | 26-Oct | Orchard | Hwy 12 (PDVG-5) Walnut Tree | Lockeford | 11/2/2013 |
| RWVIM-155-13 | 26-Oct | Grape | Hwy 12 | Lockeford | 11/2/2013 |
| RWVIM-161-13 | 24-Oct | Orchard | I-5 and Vernalis Road | Tracy | 10/30/2013 |
| RWVIM-159-13 | 17-Oct | Orchard | Pennington & Schroeder Rd | Live Oak | 10/26/2013 |
| RWVIM-160-13 | 14-Oct | Orchard | Pennington & Schroeder Rd | Live Oak | 10/26/2013 |

# Status of Final Reporting
# DR Final report status

Dynamic Risk

- ◊ Report Structure completed/ Approved
- ◊ To be completed in parallel with excavations/ Analysis
- ◊ On-going – Findings/ Conclusions - To be completed after analysis of all the dig site reports and conclusions currently being finalized by Mears, Frizzell, DNV and NACE Inspectors

| | 1st Draft | 2nd Draft | Final |
|---|---|---|---|
| Frizzell Summary Report | 15-Nov | - | 13-Dec |
| Fresno State Orchard Report | 15-Nov | 6-Dec | Prior To 31-Dec |
| DRA Overall Report | 29-Oct | | 31-Dec |

# Analysis Approach

- Step 1- Literature Review
- Step 2- Excavation site selection process
- Step 3- Excavation site data collection process
- Step 4- Pipeline threat susceptibility and interaction studies
- Step 5- Determine applied variables - Listed in table below

| Pipe | Tree | Soil Type |
|---|---|---|
| Depth of Cover | Species | Clay |
| Coating Type | Condition | Sand |
| Age of Pipe | DBH | Loam |
| Diameter | Height | Wet |
| Distance to tree | Age of Tree | Rock |

Dynamic Risk

# Analysis Approach (cont.)

- Step 6- Ensure procedures in place and undertaken for above ground surveys, excavation, pipe examination and condition profiling, tree root examinations, tree profiling and site reporting
- Step 7- Development of “Matrix Spreadsheet” findings summary accounting for excavation findings relative to all variables as a basis for predictive assessment
- Step 8- Application of findings to determine pattern conditions for predictive assessment and high level review of PG&E Gas Pipeline Right-Of-Way Management Utility Standard: TD-4490S
- Step 9- Completion of Final Dynamic Risk report

# Findings to Date
# Matrix Spreadsheet/ Sample

- ◊ Developed by Dynamic Risk to collect and track all variable findings for each excavation site as a basis for condition predictive analysis.

| Excavation Number | Consequence | | | Pipe | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Depth of cover, inches | | Coating type | | | | Age, years | | Diameter, inches | | Distance to Tree, feet | | | | |
| | Presence of External Corrosio | Tree root in contact with pip | Presence of coating damage | ≤50 | >50 | HAA | Polyken Tape | CTE | Cold Tar | ≤65 | >65 | ≤25 | >25 | <5 | >5 | Avocado | Black Wal | Coast Redwood |
| 132-8 | | | Y | | Y | Y | | | | | Y | Y | | | Y | | | |
| 153-1 | | Y | Y | Y | | Y | | | | Y | | | Y | | Y | | | |
| 153-12 | | Y | Y | | Y | Y | | | | Y | | | Y | Y | | | | |
| 153-3 | | | | Y | | Y | | | | Y | | | Y | Y | | | | |
| 153-4 | | Y | Y | | Y | Y | | | | Y | | | Y | | | | | |
| RWVC-38-13 (L132) | Y | Y | Y | Y | | Y | | | | | Y | Y | | | Y | | Y | |
| RWVIM-101-13 | Y | Y | Y | Y | | Y | | | | | Y | Y | | | Y | | | |
| RWVIM-102-13 | Y | Y | Y | Y | | Y | | | | | Y | Y | | Y | | | | |
| RWVIM-103-13 | Y | Y | Y | | Y | Y | | | | | Y | Y | | | Y | Y | | |
| RWVIM-104-13 | Y | Y | Y | | Y | Y | | | | | Y | Y | | | | | | Y |
| RWVIM-89-13 | Y | Y | Y | Y | | Y | | | | | Y | Y | | Y | | | | |
| RWVIM-90-13 | | Y | Y | Y | | | | Y | | | Y | Y | | Y | | | | |
| RWVIM-96-13 | Y | Y | Y | Y | | Y | | | | | Y | Y | | Y | | | | |
| RWVIM-98-13 | Y | Y | Y | Y | | Y | | | | | Y | Y | | Y | | | | Y |
| RWVIM-99-13 #1 | | | Y | Y | | Y | | | | Y | | | Y | | Y | | | |
| RWVIM-99-13 #2 | | | Y | Y | | Y | | | | Y | | | Y | NA | NA | Y | | |

# Findings to Date (cont.)

| Excavation Number | Consequence | | |
|---|---|---|---|
| | Presence of External Corrosio | Tree root in contact with pip | Presence of coating damage |
| 132-8 | | | Y |
| 153-1 | | Y | Y |
| 153-12 | | Y | Y |
| 153-3 | | | |
| 153-4 | | Y | Y |
| RWVC-38-13 (L132) | Y | Y | Y |
| RWVIM-101-13 | Y | Y | Y |
| RWVIM-102-13 | Y | Y | Y |
| RWVIM-103-13 | Y | Y | Y |
| RWVIM-104-13 | Y | Y | Y |
| RWVIM-89-13 | Y | Y | Y |
| RWVIM-90-13 | | Y | Y |
| RWVIM-96-13 | Y | Y | Y |
| RWVIM-98-13 | Y | Y | Y |
| RWVIM-99-13 #1 | | | Y |
| RWVIM-99-13 #2 | | | Y |

- Based on information analyzed to date:
  - 8 out of 16 - Presence of External Corrosion
  - 12 out of 16 - Roots Contact Pipe
  - 15 out of 16 - Coating Damage
- Note:
  - The matrix is currently missing information from some H-Form and from some Frizzell reports still to be completed.
  - Currently 16 out of 49 Excavations have both reports.

*Note: Findings will evolve as increased data becomes available and further evaluation is undertaken*

# Preliminary Conclusions

| Program Objectives | Preliminary Conclusions Based on Analysis to Date |
|---|---|
| 1. To evaluate the interaction of live tree roots with buried pipelines to determine and quantify potential threats to pipeline integrity. | |
| • Does pipe contact with tree roots result in coating damage or corrosion initiation? | • Tree roots utilize the pipeline as a preferential pathway and in some cases can completely envelop the pipe circumference for a distance of 20 feet or greater.<br>• All coating types examined; Tape Wrap; Hot Applied Asphalt; Cold Tar Enamel were found to be susceptible to tree root damage/ Vintage Coating type may not be a factor in resistance to tree root damage.<br>• Not targeting newer pipe coatings; i.e.; FBE, as application of this coating is relatively recent within the PG&E system and the trees have not progressed to sufficient DBH to qualify for the study. |
| • Does pipe contact with tree roots result in an accelerated corrosion condition? | • The presence of tree roots does not appear to result in accelerated site specific corrosion, as adjacent pipe not affected by tree roots exhibited corrosion of similar geometry and depth.<br>• Analysis of water samples and other data related to the presence of external corrosion under continuing analysis by DNV. |

# Preliminary Conclusions (cont.)

Dynamic Risk

| Program Objectives | Preliminary Conclusions Based on Analysis to Date |
|---|---|
| • **Does pipe contact with tree roots result in deformation, ovality change or related or other damage to the pipe steel?** | • The presence of tree roots does not appear to result in pipe deformation, ovality change or pipe damage other than external corrosion. |
| • **If trees remain on the pipeline ROW, what other mitigation efforts could PG&E undertake to manage pipeline integrity?** | • Analysis not completed/ Final report will address. |
| • **Is clearing the Pipe Zone and the Border Zone of vegetation in accordance the current PG&E ROW standard sufficient to appropriately managing pipeline integrity?** | • Analysis not completed/ Final report will address. |
| • **What are primary factors that must be accounted for when PG&E assesses the risk arising from the presence of tree roots near/on the pipeline?** | • Pipe and Tree factors; i.e. Pipe diameter; Tree species; tree height; Tree DBH; Tree age have not exhibited significant patterns relative to the presence of corrosion.<br>• Pipe depth relative to tree location (hypotenuse distance) may be a factor- Analysis not completed/ Final report will address. |

# Preliminary Conclusions (cont.)

| Program Objectives | Conclusions |
| --- | --- |
| **2. To evaluate whether dead tree roots near or on the pipeline create a chemical or microbiological environment that may be conducive to initiating external corrosion or accelerating corrosion growth.** | |
| • **Does the remaining presence of dead tree roots have any impact on management of pipeline integrity?** | • Targeting primarily live trees; previously cut trees (stumps) have been difficult to locate.<br>A continued program may be required. |

# Preliminary Conclusions (cont.)

| Program Objectives | Conclusions |
|---|---|
| 3. To determine effectiveness of above ground integrity assessment surveys performed at locations with dense tree root systems. | |
| • Do tree roots near or around pipelines interfere with pipeline integrity surveys and assessments? | • Analysis not completed/ Final report will address. |
| • Does the presence of the tree roots on/near the pipeline interfere with Cathodic Protection or with testing for the presence and effectiveness of Cathodic Protection? | • Analysis not completed/ Final report will address. |
| 4. To evaluate the requirement for review and improvements to the present PG&E practices in regards to vegetation control. | • Analysis not completed/ Final report will address. |

# Additional Considerations
# Limitations of Root Study

- ◊ Targeting only vintage pipe coatings (Tape Wrap, Asphalt, Coal Tar) as these coatings form the basis for the majority of PG&E system pipelines where older and larger trees exist in the right-of-way.
- ◊ May be able to conclude based upon the data that such coatings as a group are susceptible to root damage, however difficult to quantify the degree of susceptibility for each coating type or associated pipe diameter.
- ◊ Not targeting newer pipe coatings; i.e.; FBE, as application of this coating is relatively recent within the PG&E system and the trees have not progressed to sufficient DBH to qualify for the study.
- ◊ Targeting primarily live trees; very few previously cut trees (stumps) have been targeted for excavation.
- ◊ Targeting many species of trees and may be able to quantify significance in terms of DBH and the relationship between pipe depth and tree location distance from pipe.
- ◊ Significance of specific tree species or even DBH alone, difficult to quantify due to the number of variables involved such as historic climatic conditions, irrigation approach, soil type.

Dynamic Risk

# Additional Considerations (cont.)

- Data collection inconsistencies
  - Recent data collected is more detailed and complete than the data collected previously; i.e., there are gaps where water samples were not collected/ H-Forms not performed.
  - Recognize and document knowledge gaps and inconsistencies within final report

| Documents | Received | Comments |
|---|---|---|
| A-Forms Received | 42/49 | 7 missing performed / Remain outstanding |
| H-Forms Received | 32/49 | 17 not performed on sites |
| Frizzell Reports Received | 26/49 | 23 performed / Remain outstanding |
| Above ground Survey Reports Received | 13/49 | 36 not performed on sites |
| Mic Kits Received | 4/49 | 45 not performed- Due to no water present or due to procedure not undertaken |

# Preliminary Conclusions
# Based on Data collected and analyzed to date

Dynamic Risk

- There is a correlation between the presence of tree roots and damage to nearby pipelines
- There is no current correlation between damage to the pipeline and other variables (e.g., tree size, vintage, coating type)
- There is no evidence that the presence of tree roots accelerates corrosion or causes pipe deformation

# Next Steps

- ◊ Complete Root Study
  - ➢ Complete planned excavations
  - ➢ Gather and analyze remaining data
  - ➢ Develop findings and recommendations to PG&E
  - ➢ Prepare and deliver report to PG&E Management and Integrity Management Team

# Attachment 5:

**Det Norske Veritas, "Effects Of Tree Roots on External Corrosion Control". March 25, 2015.**

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DET NORSKE VERITAS™

# Final Report

# Effects of Tree Roots on External Corrosion Control

Pacific Gas and Electric Company
Walnut Creek, California

**For Distribution by Pacific Gas and Electric Company**

Report No./DNV Reg No.: TAOUS813KKRA (PP082694)
March 25, 2015

| Title of Report: Effects of Tree Roots on External Corrosion Control | DET NORSKE VERITAS (U.S.A.), INC.<br>Materials & Corrosion Technology Center<br>5777 Frantz Road<br>Dublin, OH 43017-1886, United States<br>Tel: (614) 761-1214<br>Fax: (614) 761-1633<br>http://www.dnv.com<br>http://www.dnvusa.com |
|---|---|
| For:<br><br>Pacific Gas and Electric Company<br>375 North Wiget Lane, Suite 200<br>Walnut Creek, CA 94598 | |
| Account Ref.: | |

| Date of First Issue: | December 19, 2013 | Project No. | PP082694 |
|---|---|---|---|
| Report No.: | | Organization Unit: | Materials & Corrosion Technology Ctr. |
| Revision No.: 4 | Revised Final 03-25-15 | Subject Group: | |
| Summary: | Please see Executive Summary. | | |
| Prepared by: | Katherine M. Krajewski, Ph.D.<br>Senior Engineer | *Signature* Katherine M Krajewski | |
| Verified by: | John A. Beavers, Ph.D., FNACE<br>Director – Forensic Investigation | *Signature* John A Beavers | |
| Approved by: | Oliver C. Moghissi, Ph.D.<br>Technology Manager – North America | *Signature* Oliver C. Moghissi | |

## Executive Summary

Pacific Gas and Electric Company (PG&E) retained Det Norske Veritas (U.S.A.), Inc. (DNV) to support PG&E's Integrity Management Group with their on-going efforts to assess the potential effects of tree roots on buried pipelines. Specifically, DNV was tasked to support PG&E in determining whether root systems can affect the susceptibility of buried pipelines to external corrosion and whether the root systems can impact aboveground CP and coating survey measurements used to assess cathodic protection (CP).

The specific technical questions that DNV was retained to address included:

- Whether the presence of tree roots (dead or alive) affect the likelihood or severity of external corrosion and/or stress corrosion cracking (SCC)
- Whether the presence of tree roots alter the effectiveness of CP to mitigate external corrosion on a pipeline, and
- Whether the presence of tree roots affect aboveground CP and coating survey measurements.

The work performed by DNV was divided into two main tasks. The first task was to develop an expert opinion or hypothesis regarding the effects of tree roots on external corrosion control of buried pipelines. The second task was to provide guidance on data collection and to assess the data collected at excavation sites in order to support or better develop the opinion. This report summarizes the opinions developed by DNV regarding the effects of tree roots on external corrosion control based upon findings from a literature review, industry experience, and field data collected at 53 excavation sites.

Based upon the dig results, it was found that living tree roots could cause coating damage, which is a prerequisite for external corrosion and SCC of buried pipelines. Thus, tree roots could increase the potential for external corrosion and SCC. In this study, there was evidence of external corrosion in some locations where the tree roots caused coating damage. On the other hand, the inspection crews did not identify SCC in the areas of coating damage caused by the tree roots or at any other locations on the excavated pipe. In response to the second question posed to DNV, the impact of tree roots on the effectiveness of CP to mitigate external corrosion was determined to be low. Finally, the findings from the study indicate that the presence of tree roots do not significantly hinder aboveground CP and coating surveys. Thus, these surveys should be valid for evaluating the effectiveness of CP mitigation and for external corrosion direct assessments for buried pipelines when tree roots are present.

Based upon the findings from the literature review, industry experience, and field data collected at 53 excavation sites, DNV's conclusions regarding the effects of tree roots on external corrosion control are as follows:

1. Tree roots can promote coating damage. The extent of damage observed varied by coating type.
2. The presence of living tree roots can increase the likelihood of external corrosion and SCC, primarily by causing coating damage (i.e. which is a prerequisite for external corrosion of buried pipelines).
3. The presence of dead tree roots can increase the likelihood of SCC, when coating damage is present, by promoting the generation of potent cracking environments.
4. There was no clear evidence from this study to indicate that tree roots, living or dead, promoted SCC in areas of coating damage.
5. There was not enough data from this study to indicate whether dead tree roots increase the likelihood of external corrosion and SCC.
6. Trends in the measured corrosion at areas of damaged coating and parameters such as pipe-to-soil potential and soil pH are consistent with current understanding on CP and soil corrosivity.
7. There was no evidence from this study to indicate that tree roots alter the effectiveness of CP to mitigate external corrosion on a pipeline.
8. There was no evidence from this study that tree roots deleteriously affect aboveground CP and coating surveys.

## Table of Contents

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## List of Figures (continued)

# 1.0 BACKGROUND

Pacific Gas and Electric Company (PG&E) retained Det Norske Veritas (U.S.A.), Inc. (DNV) to support PG&E's Integrity Management Group with their on-going efforts to assess the potential effects of tree roots on buried pipelines. Specifically, DNV was tasked to support PG&E in determining whether root systems can affect the susceptibility of buried pipelines to external corrosion and whether the root systems can impact aboveground CP and coating survey measurements used to assess cathodic protection (CP).

The specific technical questions that DNV was retained to address included:

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# 2.0 LITERATURE REVIEW

## 2.1 Summary

The affinity of tree roots to grow towards and around buried pipelines, especially concrete sewer lines, is well documented in the literature.[1] Tree roots need water, oxygen, and nutrients to sustain life and grow. Tree roots will grow via the path of least resistance to reach these essential elements. In general, tree roots are found within the first 3 feet of soil; however, if tree roots have access to oxygen, they will propagate deeper to reach water and nutrients.[Ref 1-6] It is these roots, which advance deeper into the soil that can interact with buried pipelines and are the concern of this study. According to Reference 2, trees that exhibit the most aggressive root systems and are of the greatest concern include figs, maples, elms, willows, birch, mulberry, ash, poplar, cottonwood, large eucalyptus, and sweet gum.[2]

Any effect that the interaction between tree roots and buried steel pipelines has on external corrosion is not fully documented or understood. The objectives of the literature search were to (1) determine what, if any, information is available regarding how root systems can affect the susceptibility of buried pipelines to external corrosion, and (2) determine what effect, if any, tree roots have on aboveground CP and coating survey techniques.

A review of the literature revealed that it is widely accepted that the interaction between tree roots and buried pipelines can result in coating damage. The extent of the damage is generally related to the root structure and the coating type (i.e. tape, coal tar, and epoxy). Only van Oostendorp et al.,[7] however, considered the effects of tree roots on the external corrosion of pipelines. Their study found a case where minor to moderate damage to the pipe coating was noted due to the interaction of the pipe with tree roots. They observed cracked coating on the pipe, but no corrosion was observed at the areas of coating damage.

Further review of the literature, uncovered an e-mail from the Manager of Forestry, Pest Control & Horticulture Branch in Regina, Saskatchewan in Canada to Canadian Urban Forest Network inquiring about "*how roots of trees/shrubs are decaying/corroding the protective coating on oil and gas pipe lines*." The e-mail was dated November 23, 2011 and arose from a meeting between the Manager of Forestry, Pest Control & Horticulture, and an unnamed high profile oil company. The oil company was requesting that trees and shrubs be removed from a city easement due to concerns that the interaction between the roots of the trees and shrubs would lead to coating damage and corrosion of the pipeline, which, in turn, would lead to leaks or ruptures. Although the resolution was not documented, the existence of this e-mail indicates that the issue of tree roots and pipeline corrosion is a concern to pipeline operators other than PG&E.

The second part of the literature review focused on what, if any, effect tree roots have on aboveground CP and coating surveys. To achieve this, a literature search was performed to determine how tree roots affect the conductivity/resistivity of the surrounding soil. Zanetti et al.[8] performed an investigation on the detection of tree roots using electrical measurements, specifically conductivity. The variables considered by Zanetti et al. included: (1) tree species, (2) root orientation, (3) soil type, and (4) water content. During their study, conductivity was measured using an inverse Wenner configuration. In general, the researchers found that the presence of tree roots increased the measured conductivity of the soil. The magnitude of the increase was dependent on the tree species, root orientation, and soil type. These findings indicate that the presence of tree roots likely will not adversely affect CP aboveground survey techniques. This conclusion is supported by independent findings by van Oostendorp[7] and Ersoy.[9] As previously stated, van Oostendorp published an account in which coating damage was attributed to tree roots. The coating damage was initially identified using aboveground CP and coating surveys, and was attributed to tree roots only after the pipe was excavated. This finding indicates that aboveground survey techniques are effective in identifying coating damage associated with tree roots. Additional findings by Ersoy also support this conclusion.

In 2005, Ersoy gave a presentation on direct assessment activities at a research and development forum in Houston, Texas sponsored by the Department of Transportation. During his presentation, Ersoy reported that the survey techniques utilized by his group (i.e. direct current voltage gradient [DCVG], pipeline current mapper [PCM], and Close Interval Surveys [CIS]) were more sensitive than expected. Of particular note, the survey techniques used were able to detect tree root intrusions under field wrap and coal tar enamel (CTE) coatings. The extent, size, and species of the tree roots associated with the coating holidays were not reported by Ersoy. The fact that the survey techniques were able to detect coating holidays associated with tree roots indicates that the tree roots likely did not significantly affect the performance of the CP and coating survey techniques.

## 2.2 References

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## 3.0 REVIEW OF EXCAVATION DATA

DNV was provided with multiple photographs, forms, and reports from 57 excavations, conducted along various PG&E pipeline segments, for review. The digs were part of a program that was directed by the Integrity Management Group within PG&E in order to assess the potential effects of tree roots on buried pipelines. The majority of the digs were performed in 2013; however, six digs were performed in the fall of 2012.[1] The objectives of the DNV review were to assess:

1. Whether the presence of tree roots affect the likelihood or severity of external corrosion and stress corrosion cracking,
2. Whether the presence of tree roots alter the effectiveness of cathodic protection (CP) to mitigate external corrosion on the pipeline, and
3. Whether the presence of tree roots affect aboveground CP and coating survey measurements.

Although data for 57 digs were provided, data for only 53 digs were used by DNV. The digs that were not used include those identified by PG&E as RWVIM 142-13, 143-13, 161-13, and 164-13. Digs RWVIM 142-13 and 143-13 were not included in the assessment because the data obtained for these digs were associated with casing pipe and not carrier pipe. The digs that were used by DNV were all associated with carrier pipe segments and so the data collected for the casing pipe segments were not comparable. Digs RWVIM 161-13 and 164-13 were not used by DNV due to a lack of data available at the time that this report was prepared (i.e. only aboveground survey data were available).

Table 1 is a summary of the digs that were used by DNV. The table provides information regarding the pipe segments that were excavated and trees with which they interacted. Columns 1 – 3 in Table 1 provide dig identifications for each excavation. As seen in the table, several of the excavations had multiple identifications. The next three columns in the table, Columns 4 - 6, provide information about the pipe segments associated with each excavation. The information listed in these columns includes the nominal pipe size, the pipe vintage, and the coating type. A review of the pipe information presented in the table reveals that the excavations covered a wide range of pipe diameters (i.e. 6 to 34 inch nominal diameters) and pipe vintages (i.e. 1931 - 1987). As seen in Column 6 of the table, three coating types were encountered during the digs. The

1 Digs 132-8, 153-1, 153-3A, 153-4, 153-10A (RWVC41-13A),and 153-12.

coating types include hot applied asphalt (HAA), CTE, and tape.[2] Thirty-five (35) of the pipe segments associated with the excavations were coated with HAA, while 12 and 6 of the pipe segments were coated with CTE and tape, respectively. Finally, Columns 7 and 8 in Table 1 provide information regarding the type and health of the trees encountered during the excavations. As seen in Column 7, a wide range of tree types was encountered during the digs. The health status of these trees ranged from healthy (good) to damaged/diseased (i.e. fair or poor).

The materials reviewed by DNV for the 53 digs included the following:

- Aboveground CP and coating survey reports: These reports including information from DCVG, alternating current voltage gradient (ACVG), CIS, PCM, and depth surveys.
- "A" forms: Generic forms provided by PG&E and completed by representative NACE inspectors that were used to document the condition of the coating once a pipe segment was exposed.
- "H" forms: Forms provided by PG&E and completed by the inspection crew (i.e. Mears or GE personnel) that documented the data collected during the external corrosion direct examinations.
- Daily reports: Reports produced by NACE certified personnel (i.e. Tulsa and Canus) that consisted of written and photographic documentation of the daily activities performed at each dig site.
- Frizzell reports: Reports produced by the on-site arborist and that consisted of written and photographic documentation regarding the condition of the trees associated with each dig site.
- Coating reports: Reports documenting inspections performed on new coatings applied to the excavated pipe sections at the completion of a dig. These forms were not used for the assessment performed by DNV.

It should be noted that the forms, reports, and photographs listed above were not all available for every dig.

DNV considered five topics during the review of the dig data. The topics considered included the following: (1) coating damage, (2) external corrosion, (3) SCC, (4) CP effectiveness, and (5) aboveground CP and coating surveys. Each topic is addressed below individually. The findings

2 Discrepancies were identified between the coating designations of HAA and CTE in the completed "A" and "H" forms for particular digs. Coating designations referenced throughout this report correspond to those provided in the "A" form or as verbally communicated to Dynamic Risk by the NACE certified inspectors. The coating discrepancies did not impact the conclusions within this report.

and assessments presented below are based only on a review of the information contained in the provided materials and the expertise of DNV personnel.

## 3.1 Coating Damage

A review of the data provided to DNV revealed occurrences of coating damage at many of the dig sites.[3] Damage was observed for all coating types (i.e. HAA, CTE, and tape coatings); however, coating damage was not observed at all the dig sites. The extent of the damage varied by coating type with the most significant damage associated with HAA and CTE coated pipes. The damage observed for these coatings included disbondments, root impressions, and root intrusions of the coating. The damage observed for the tape coated pipe segments included tenting[4], root intrusion, and coating discoloration.

Based on the documentation provided to DNV, the majority of the coating defects encountered during the excavations were due to the interactions of the tree roots with pipe segments. Documentation was found within the "H" forms for seven pipe segments[5] that exhibited coating damage that was unrelated to tree roots. The damage observed on these pipe segments was described as stress cracks and coating degradation.

Figure 1 and Figure 2 contain representative photographs of coating damage observed on pipe segments that were coated with HAA, while Figure 3 and Figure 4 contain photographs showing coating damage observed on HAA and CTE coated pipe segments, respectively. As seen in the figures, coating disbondments, root impressions, and root intrusions were observed for both coating types. Figure 5 and Figure 6 contain representative photographs of coating damage observed on pipe segments that were coated with tape. As seen in the photographs, the damage observed for the tape coated pipe segments consisted of tenting and fine root intrusions. A comparison of the damage observed for the three types of coatings revealed that the damage observed on the tape coated pipe segments was not as severe as that observed for the HAA and CTE coated pipe segments.

The coating damage shown in Figure 1 – Figure 6 was associated with interactions of the pipe segments with tree roots. Representative photographs of coating damage that was not attributed to tree roots was not discernable in the data provided to DNV and so are not provided in this report.

In general, buried pipelines have coating holidays and areas of disbondment regardless of root activity. When corrosion or SCC occurs, it generally occurs at a disbonded areas associated with

3 For this report, coating damage is defined as any mechanical damage, disbonding, tenting, or intrusion of roots with respect to the coating.
4 Tenting is a form of coating damage associated with tape coated pipe segments that is characterized by the formation of gaps between the tape and the pipe surface.
5 Digs RWVIM 96-13, 103-13, 107-13, 140-13, 141-13, RWVC 41-13A, and 153-4.

coating holidays. Since root growth has shown to cause coating damage, a pipeline buried in a corrosive environment without mitigation (e.g., CP) is expected to have more locations of corrosion when exposed to growing roots. For these instances, effective corrosion mitigation will reduce the total likelihood of corrosion. In addition, monitoring can help to ensure adequate CP, while assessments (e.g., by ECDA) can gauge the overall corrosion threat.

## 3.2 External Corrosion

A review of the dig data provided to DNV revealed occurrences of metal loss due to external corrosion on 15 of the 53 pipe segments that were examined. Figure 7 contains representative photographs showing examples of the external corrosion that was observed on the 15 pipe segments. Table 2 is a summary of the 15 pipe segments that contained external corrosion with measurable wall loss. As seen in the table, all of the documented occurrences of measurable wall loss were associated with coating damage due to tree root interactions with the pipe. The trees associated with the occurrences were all living and the health of the trees ranged from good to fair.

As seen in Column 4 of Table 2, most of the pipe segments that contained measurable external corrosion were installed between 1931 and 1947. The one exception was the pipe segment from Dig RWVIM 131-13 that was installed in 1965. Further review of the table reveals that the majority of the occurrences were associated with HAA coated pipe segments. Five occurrences of external corrosion were found on pipe segments that were coated with CTE, and no occurrences were documented on pipe segments coated with tape. The fact that no occurrences were found on the tape coated pipe segments was initially surprising. In general, tape coated pipe segments are susceptible to tenting. This form of coating damage can cause the pipe beneath the tape to be shielded from any CP that may be applied to the pipe segment. In addition, the gaps that form between the tape and the pipe due to tenting can allow for the ingress of ground water and/or microorganism, producing a corrosion cell. For this study, however, the majority of the tape coated pipe segments exhibited minor to no evidence of coating damage. Consequently, the lack of any measurable wall loss due to external corrosion observed for the tape coated pipe segments is understandable.

Columns 6 and 7 in Table 2 list the maximum depths and the associated percent of metal loss that was measured for the 15 pipe segments. As seen in the table, the maximum depths of corrosion ranged from 0.015 – 0.109 inches.[6] These depths corresponded to percent wall losses of 5 – 44%, based upon the nominal wall thicknesses of the pipe segments. Comparisons of the measured maximum depth of wall loss to the health of the associated tree revealed no correlation.

In order to better understand why measurable corrosion was present on the 15 pipe segments, soil measurements obtained at the time of the excavations were extracted from the data and compared. Table 3 is a summary of the soil measurements obtained for the 15 pipe segments that contained measurable external corrosion. As seen in the table, the soil measurements considered include: (1) average pipe-to-soil potentials,[7] (2) U/S soil pH values, (3) D/S soil pH values, and (4) soil resistivities. A comparison of the percent wall loss due to external corrosion to soil resistivity revealed no clear correlation (i.e. the data were quite scattered). These findings are not altogether unexpected. While higher corrosion rates generally occur in soils with lower resistivity under freely corroding conditions, the ability to cathodically protect a pipeline, especially regions of disbonded coating, increases with decreasing resistivity. Depending on when the resisitivities were obtained, it is also possible that moisture introduced during hydrovac operations may have impacted the measurements. A similar comparison of the percent wall loss due to external corrosion to the measured pipe-to-soil potentials revealed that the amount of wall loss tends to increase as the pipe-to-soil potential become more noble. In general, more noble potentials near the -850 mV vs. CSE threshold were associated with occurrences of the highest percent metal loss. The occurrences with the least amount of wall loss were typically associated with more negative pipe-to-soil potentials (i.e. < -1000 mV vs. CSE). Finally, a comparison of the amount of external wall loss to measured soil pH revealed that the largest amounts of wall loss were associated with the lowest pH values. Based on the expertise of DNV, the associations observed for the 15 pipe segments regarding percent wall loss due to external corrosion and soil resistivity, pipe-to-soil potentials, and soil pH are consistent with the findings of fundamental corrosion literature for external corrosion of cathodically protected pipelines.

The data were insufficient to assess whether bacteria played a role in the corrosion observed.[8] The majority of the digs were performed prior to the development of the modified "H" form and prior to the data collection requests, including bacteria sampling, posed by DNV. In addition, many of these digs were excavated using a hydro-vac, which would have compromised the integrity of any corrosion product or bacterial sampling.

Chemical analyses of corrosion deposits associated with the region of measurable wall loss were performed at three of the 15 dig sites, i.e. Digs RWVIM 96-13, 103-13 and 104-13. The results of the analysis performed on the pipe segment from RWVIM 96-13 revealed the presence of carbonates, calcium, and ferric iron cations. The pH of the deposits was 6 and there was no

6 The maximum depths reported are the depths measured at the time of excavation. The depths reported do not consider any historical information with respect to the corrosion (i.e. when coating damage occurred, when corrosion initiated, and the time period over which the corrosion grew).

7 Average of U/S and D/S measurements.

8 Bacteria testing was performed on liquids found beneath disbonded coating for 9 pipe segments. These pipe segments were coated with HAA and CTE and had no measurable wall loss. Table 4 is a summary of the results for these pipe segments. A wide range of bacteria was detected for all nine pipe segments that were tested; however, the results were inconclusive on whether MIC played a role in the external corrosion.

evidence of sulfides or ferrous iron cations in the deposits. The results of the analysis performed on the pipe segments from RWVIM 103-13 and 104-13 revealed the presence of carbonates, calcium, ferrous iron cations, and ferric iron cations. The pH of the deposits ranged from 6.5 to 7.0 and there was no evidence of sulfides in the deposits. Although similar analyses were not performed for the other 12 dig sites, documentation within the "H" forms for 12 of the 15 digs noted the presence of calcareous deposits and/or iron oxides associated with the corrosion. The presence of calcareous deposits associated with the regions of metal loss indicates that CP was present on these pipe segments.

External corrosion on pipelines most commonly occurs by mechanisms of differential oxygen cells, microbial activity, or some type of stray current. Based on the experiences of DNV personnel, these mechanisms are not expected to have a significant effect on the likelihood of external corrosion when the pipeline has adequate cathodic protection.

Unmitigated oxygen corrosion can be affected by the presence of live or dead roots due to the formation of a crevice where the cathodic reaction occurs outside of the root area (i.e., where oxygen reaches the bare pipe surface), and the anodic reaction occurs under the root. This mechanism is mitigated by cathodic protection both outside the root (e.g., by removing oxygen) and under an electrically conductive root. The fact that measurable external corrosion was only found on holidays associated with tree roots indicates that tree roots may impact the susceptibility of some pipe segments to external corrosion. Based upon the findings from the dig data, the degree of the impact is not conclusive.

Microbial effects can be enhanced in an occluded geometry that prevents chemical transport. A live root, dead root, rock, disbonded coating, or any other low-permeability material including clay can form the occlusion. A pipeline buried with heterogeneous backfill is likely to have occluded areas from multiple sources. Thus, over and above causing coating damage, the presence of roots do not represent a unique risk. In addition, CP through a conductive root would be expected to mitigate the corrosion influenced by bacteria, so the overall threat is not considered to be affected by the presence of live or dead roots.

Tree roots may increase the risk of stray current corrosion by causing coating damage or providing a low resistivity path to the pipe.

## 3.3 Stress Corrosion Cracking

A review of the dig data provided to DNV revealed that 36 of the 53 pipe segments were examined using magnetic particle inspection (MPI). As standard procedure, MPI was only performed in areas where the pipe was exposed due to damaged/disbonded coating. Three (3) of the 17 pipe segments that were not examined using MPI did not have any documented coating damage. Thus, an examination was not necessary for these pipe segments. H forms were not prepared for the remaining 14 pipe segments. Thus, there is no documentation on whether MPI was performed on these pipe segments.

A review of the information for the pipe segments that were examined using MPI, revealed the presence of linear indications on 13 of the 36 pipe segments. No indications were found on the other 23 pipe segments. Table 5 is a summary of the digs where linear indications were identified using MPI. As seen in Table 5, the number of indications identified for these digs ranged from 3 to 27. The primary coating type for the pipe segments from these digs was HAA, with the exception of four pipe segments that were coated with CTE. The thirteen identified pipe segments that contained linear indications were all noted to be in contact with tree roots. The trees were living and exhibited good to fair health. Trees that were characterized as “fair” primarily contained damage due to poor pruning practices.

Per the excavation reports, none of the linear indications found on any of the 13 pipe segments were attributed to SCC. GE Energy performed the inspections on 11[9] of the 13 pipe segments and concluded that these segments did not contain SCC. In general, SCC occurs in colonies, consisting of several to thousands of cracks. SCC cracks are usually oriented in the longitudinal direction[10] and tend to interlink to form long shallow flaws. Figure 8 and Figure 9 contain representative photographs showing the linear indications identified by GE Energy. Photographs of representative linear indications identified for Dig RWVIM 89-13 are shown in Figure 8. As seen in the photographs, the indications were relatively long, straight, and were not associated with colonies. Based on the morphology, these indications were likely not due to SCC. In contrast, the representative indications shown in Figure 9 appear to occur in colonies. It is not clear from the photographs whether the indications are associated with SCC. The inspection crew on-site, however, did not identify these indications as SCC.

Mears performed the inspections on 2 of the 13 pipe segments[11] that contained linear indications. The indications on one of the pipe segments (i.e. RWVIM 160-13) were attributed to manufacturing defects/mill scale (i.e. not SCC), while the likely cause of the indications identified on the second pipe segment (i.e. from Dig 153-12) was not identified. Figure 10 and Figure 11 contain photographs showing representative linear indications that were identified for Digs RWVIM 160-13 and 153-12, respectively. As seen in the photographs, the indications are relatively straight and were not associated with colonies. Based upon the morphology of these indications, they were likely not due to SCC

In summary, linear indications were identified on 13 of the 36 pipe segments examined by MPI. For these 13 pipe segments, there is no clear evidence that SCC was present.

9 The pipe segments associated with Digs RWVIM 89-13, 96-13, 98-13, 101-13, 102-13, 103-13, 107-13, 126-13,127-13, 128-13, and RWVC-38-13.
10 SCC cracks may exist at other orientations, depending on the direction of tensile stress.
11 The pipe segments associated with Digs RWVIM 160-13 and 153-12.

SCC on pipelines occurs through the combination of material susceptibility, stress, and environment. In general, all pipeline steels are considered to be susceptible to external SCC. Both applied stresses from the internal pressure, and residual stresses from welding, installation, or operation can be sufficient to promote SCC. Finally, the pipe surface must be exposed to the potent cracking environment. An intact coating will therefore prevent all forms of corrosion including SCC. Given the fact that the tree roots were shown to cause coating damage, one must conclude that they also will increase the likelihood of SCC. It also is possible that decaying tree roots could create or increase the potency of an SCC environment at the pipe surface by increasing the amount of $CO_2$ in the soil. No clear evidence of SCC was observed for any of the pipe segments that were examined for this report, irrespective of the cause of any coating damage.

## 3.4 CP Effectiveness

The literature shows that tree roots are electrically conductive. Thus, CP effectiveness is not expected to be significantly affected by the presence of tree roots. This expectation is supported by excavation data that documented the presence of calcareous deposits within coating holidays associated with tree roots. Figure 12 contains representative photographs showing calcareous deposits present at coating holidays. The presence of the calcareous deposits in regions of coating damage due to tree roots indicates that the tree roots did not shield the pipe from CP. Although the resistivity of roots, both live and dead, are expected to differ from the immediately surrounding soil, it is common for pipelines to pass through heterogeneous resistive environments. On that basis, the effect of tree roots on CP is not considered to uniquely differ from what is generally experienced across an infrastructure.

## 3.5 Aboveground CP and Coating Surveys

Aboveground survey data (i.e. PCM, CIS, DCVG, and/or ACVG surveys) were available for 19[12] of the 53 digs that DNV reviewed. The results of the surveys were reviewed by DNV and compared to documentation regarding the presence and/or absence of coating holidays observed during the pipe excavations.

Overall, the results of the surveys were consistent with the presence of coating damage observed during the associated pipe excavations. For example, if the results of a coating survey associated with a particular pipe segment contained no call outs (i.e. no indications of coating holidays), no holidays were generally found on the pipe segment at the time of excavation. If coating holidays were identified for a particular pipe segment during an aboveground coating survey, coating holidays were generally found on the pipe segment at the time of excavation. Figure 13 and Figure 14 are representative plots showing the results of aboveground surveys where: (1) no coating holidays were identified and (2) coating holidays were identified. In many cases, the coating holidays identified using aboveground surveys were found to be associated with damage due to tree root interactions with the pipe. These findings indicate that tree roots likely do not hinder aboveground CP and coating survey techniques.

Of the nineteen surveys provided, five surveys did not spatially align with the direct examination and so correlations to the direct examination data could not be made.[13] The survey data associated with eight digs identified the potential for coating damage. These findings were confirmed during the direct examinations.[14] The survey data associated with six digs did not identify the potential for coating damage.[15] Of these six digs, only one dig, Dig 77-13, did not correlate with the direct examination findings. For this dig, seven areas of coating damage were found during the direct examination. The soil resistivity measured for this dig was 11,490 Ohm/cm. This resistivity was within the range of soil resistivities associated with the surveys that were consistent with the excavation data (i.e. soil resistivities ranged from 5362 - 60,322 Ohm/cm).

The findings presented above are consistent with the expectation that tree roots, both dead and alive, have resistivities within the range of what is generally experienced by pipelines without contact with tree roots. Based upon the findings, the effect of tree roots on aboveground CP and coating surveys is not significant.

## 4.0 CONCLUSIONS

Three basic questions were asked of DNV with respect to the presence of live and/or dead tree roots. The first was whether the presence of tree roots increases the likelihood or severity of corrosion and SCC on a cathodically protected pipeline. The second was whether the presence of tree roots alters the effectiveness of CP to mitigate external corrosion on a pipeline. The third was whether aboveground CP and coating surveys intended to assess the threat of external corrosion are detrimentally affected by the presence of tree roots.

Based upon the dig results, it was found that living tree roots could cause coating damage, which is a prerequisite for external corrosion and SCC of buried pipelines. Thus, tree roots could increase the potential for external corrosion and SCC. In this study, there was evidence of external corrosion in some locations where the tree roots caused coating damage. On the other hand, the inspection crews did not identify SCC in the areas of coating damage caused by the tree roots or at any other locations on the excavated pipe. In response to the second question posed to DNV, the impact of tree roots on the effectiveness of CP to mitigate external corrosion

12 The 19 digs included RWVIM 76-13, 77-13, 78-13, 90-13, 132-13, 133-13, 136-13, 137-13, 138-13, 139-13, 140-13, 141-13, 144-13, 155-13, 158-13, 159-13, 160-13, 165-13, and 259-13.

13 The digs included RWVIM 76-13, 155-13, 158-13, 160-13, and 259-13.

14 The digs included RWVIM 78-13, 90-13, 132-13, 136-13, 140-13, 141-13, 159-13, and 165-13.

was determined to be low. Finally, the findings from the study indicate that the presence of tree roots do not significantly hinder aboveground CP and coating surveys. Thus, these surveys should be valid for evaluating the effectiveness of CP mitigation and for external corrosion direct assessments for buried pipelines when tree roots are present.

Based upon the findings from the literature review, industry experience, and field data collected at 53 excavation sites, DNV's conclusions regarding the effects of tree roots on external corrosion control are as follows:

1. Tree roots can promote coating damage. The extent of damage observed varied by coating type.

2. The presence of living tree roots can increase the likelihood of external corrosion and SCC, primarily by causing coating damage (i.e. which is a prerequisite for external corrosion of buried pipelines).

3. The presence of dead tree roots can increase the likelihood of SCC, when coating damage is present, by promoting the generation of potent cracking environments.

4. There was no clear evidence from this study to indicate that tree roots, living or dead, promoted SCC in areas of coating damage.

5. There was not enough data from this study to indicate whether dead tree roots increase the likelihood of external corrosion and SCC.

6. Trends in the measured corrosion at areas of damaged coating and parameters such as pipe-to-soil potential and soil pH are consistent with current understanding on CP and soil corrosivity.

7. There was no evidence from this study to indicate that tree roots alter the effectiveness of CP to mitigate external corrosion on a pipeline.

8. There was no evidence from this study that tree roots deleteriously affect aboveground CP and coating surveys.

15 The digs included RWVIM 77-13, 138-13, 139-13, 144-13, 133-13, and 137-13.

Table 1. Summary of the 53 digs reviewed by DNV.

| RVIM Dig Identification | RWVC Dig Identification | Alternate Dig Identifications | Nominal Pipe Diameter (inches) | Pipe Vintage | Coating Type * | Tree Type | Tree Health |
|---|---|---|---|---|---|---|---|
| RWVIM-73-13 | – | – | 20 | 1962 | HAA | Afghan pine | Good |
| RWVIM-74-13 | – | – | 20 | 1962 | HAA | Eucalyptus | N/A |
| RWVIM-75-13 | – | – | 20 | 1962 | HAA | Afghan Pine | Good |
| RWVIM-76-13 | – | – | 10 | 1957 | CTE | Coast Redwood | Good |
| RWVIM-77-13 | – | – | 10 | 1957 | CTE | Silver Maple | Good |
| RWVIM-78-13 | – | – | 10 | 1957 | CTE | Deodar Cedar | Good |
| RWVIM-81-13 | – | – | 34 | 1973 | Tape | Monterey Pine | Good |
| RWVIM-82-13 | – | – | 34 | 1973 | Tape | Monterey Pine | Good |
| RWVIM-87-13 | – | – | 30 | 1949 | HAA | Firethorn | Fair |
| RWVIM-88-13 | – | – | 8 | 1931 | HAA | Elm | Poor |
| RWVIM-89-13 | – | – | 8 | 1931 | HAA | Eucalyptus | Good |
| RWVIM-90-13 | – | – | 12 | 1955 | HAA | Valley Oak | Good |
| RWVIM-92-13 | – | – | 8 | 1931 | HAA | Deodar Cedar | Fair |
| RWVIM-96-13 | RWVC -36-13 | – | 24 | 1944 | HAA | Avocado | Good |
| RWVIM-98-13 | | – | 24 | 1944 | HAA | American Elm | Fair |
| RWVIM-100-13 | RWVC-44-13 | – | 30 | 1949 | CTE | Date palm | Good |
| RWVIM-101-13 | RWVC-46-13 | – | 24 | 1944 | HAA | Black walnut | Fair |
| RWVIM-102-13 | RWVC-47-13 | – | 24 | 1944 | HAA | Privet tree | Good |
| RWVIM-103-13 | RWVC-49-13 | – | 24 | 1944 | HAA | Cottonwood | Good |
| RWVIM-104-13 | RWVC-51-13 | 132-6a | 24 | 1944 | HAA | Cottonwood | Good |

| RVIM Dig Identification | RWVC Dig Identification | Alternate Dig Identifications | Nominal Pipe Diameter (inches) | Pipe Vintage | Coating Type * | Tree Type | Tree Health |
|---|---|---|---|---|---|---|---|
| RWVIM-105-13 | RWVC-55-13 | – | 24 | 1949 | HAA | Myoporum | Poor |
| RWVIM-106-13 | – | – | 8 | 1931 | HAA | Silk | Good |
| RWVIM-107-13 | – | – | 8 | 1931 | CTE | Hackberry | Fair |
| RWVIM-126-13 | – | – | 8 | 1931 | CTE | Eucalyptus | Good |
| RWVIM-127-13 | – | – | 8 | 1931 | CTE | Deodar Cedar | Fair |
| RWVIM-128-13 | – | – | 8 | 1931 | CTE | Deodar Cedar | Good |
| RWVIM-129-13 | – | – | 8 | 1931 | CTE | Silk | Poor |
| RWVIM-130-13 | – | – | 8 | 1931 | CTE | Ailanthus | Fair |
| RWVIM-131-13 | – | – | 8 | 1965 | CTE | Interior Live Oak | Good |
| RWVIM-132-13 | – | – | 10 | 1957 | HAA | Black walnut | Good |
| RWVIM-133-13 | – | – | 6 | 1966 | HAA | Interior Live Oak | Poor |
| RWVIM-136-13 | – | – | 10 | 1957 | HAA | Black walnut | Good |
| RWVIM-137-13 | – | – | 6 | 1966 | HAA | Interior Live Oak | Poor |
| RWVIM-138-13 | – | – | 6 | 1987 | Tape | Black walnut | Dead |
| RWVIM-139-13 | – | – | 6 | 1987 | Tape | Valley Oak | Good |
| RWVIM-140-13 | – | – | 12 | 1944 | HAA | Almond | Fair |
| RWVIM-141-13 | – | – | 12 | 1942 | HAA | Almond | Good |
| RWVIM-144-13 | – | – | 6 | 1987 | Tape | Valley Oak | Good |
| RWVIM-155-13 | – | – | 10 | 1957 | HAA | Grape | Good |
| RWVIM-158-13 | – | – | 18 | 1957 | HAA | Black walnut | Good |
| RWVIM-159-13 | – | – | 16 | 1954 | HAA | Walnut | Fair |
| RWVIM-160-13 | – | – | 16 | 1954 | HAA | Plum | Good |

| RVIM Dig Identification | RWVC Dig Identification | Alternate Dig Identifications | Nominal Pipe Diameter (inches) | Pipe Vintage | Coating Type * | Tree Type | Tree Health |
|---|---|---|---|---|---|---|---|
| RWVIM-165-13 | – | – | 6 | 1958 | CTE | Apricot | Fair |
| RWVIM-259-13 | – | – | 10 | 1957 | HAA | Walnut | Poor |
| – | RWVC-38-13 | L109 | 34 | 1973 | Tape | Coast Redwood | Good |
| – | RWVC-38-13 | L132 | 24 | 1944 | HAA | Coast Redwood | Good |
| – | RWVC41-13A | 153-10A | 30 | 1949 | HAA | Weeping Willow | Dead |
| – | RWVC 41-13B | 153-10B | 24 | 1944 | HAA | Avocado | Good |
| – | – | 132-8 | 24 | 1944 | HAA | Incense Cedar | Good |
| – | – | 153-1 | 30 | 1949 | HAA | Monterrey Pine | Good |
| – | – | 153-12 | 30 | 1949 | HAA | Mulberry Tree | Fair |
| – | – | 153-3A | 30 | 1949 | HAA | Monterrey Cypress | Good |
| – | – | 153-4 | 30 | 1949 | HAA | Italian Stone Pine | Good |

* Coating types reflect information provided in "A" form or as verbally communicated to Dynamic Risk by NACE certified inspectors.
HAA = hot applied asphalt
CTE = coal tar enamel

Table 2. Summary of the 15 pipe segments that contained external corrosion with measurable wall loss.

| Dig Identification | Tree Contact with Pipe | Tree Health | Pipe Vintage | Coating Type* | Maximum depth of Corrosion (inches) | Percent Wall Loss |
|---|---|---|---|---|---|---|
| RWVC 38-13 (L132) | Yes | Good | 1944 | HAA | 0.015 | 5 |
| RWVIM 89-13 | Yes | Good | 1931 | HAA | 0.109 | 44 |
| RWVIM 96-13 | Yes | Good | 1944 | HAA | 0.069 | 25 |
| RWVIM 98-13 | Yes | Fair | 1944 | HAA | 0.023 | 8 |
| RWVIM 101-13 | Yes | Good | 1944 | HAA | 0.040 | 14 |
| RWVIM 102-13 | Yes | Good | 1944 | HAA | 0.027 | 10 |
| RWVIM 103-13 | Yes | Good | 1944 | HAA | 0.019 | 7 |
| RWVIM 104-13 | Yes | Good | 1944 | HAA | 0.038 | 14 |
| RWVIM 107-13 | Yes | Fair | 1931 | CTE | 0.076 | 30 |
| RWVIM 126-13 | Yes | Good | 1931 | CTE | 0.109 | 44 |
| RWVIM 127-13 | Yes | Fair | 1931 | CTE | 0.109 | 44 |
| RWVIM 128-13 | Yes | Good | 1931 | CTE | 0.063 | 25 |
| RWVIM 131-13 | Yes | Good | 1965 | CTE | 0.018 | 10 |
| RWVIM 140-13 | Yes | Fair | 1944 | HAA | 0.023 | 11 |
| RWVIM 141-13 | Yes | Good | 1942 | HAA | 0.030 | 15 |

* Coating types reflect information provided in "A" form or as verbally communicated to Dynamic Risk by NACE certified inspectors.
HAA = hot applied asphalt
CTE = coal tar enamel

Table 3. Summary of soil measurements collected for the 15 pipe segments that contained external corrosion with measurable wall loss.

| Dig Identification | Coating Type * | Maximum Depth of Corrosion (inches) | Percent Wall Loss | Average Pipe to Soil Potential (mV) | Soil pH U/S | Soil pH D/S | Resistivity (Ω-cm) | Excavation Method |
|---|---|---|---|---|---|---|---|---|
| RWVC-38-13 (L132) | HAA | 0.015 | 5 | -1130 | 4 | 3.5 | 1130 | Hydrovac |
| RWVIM-89-13 | HAA | 0.109 | 44 | -879 | 4 | 3.5 | 6536 | Backhoe |
| RWVIM-96-13 | HAA | 0.069 | 25 | -719 | 4 | 3.5 | 2834 | Hydrovac |
| RWVIM-98-13 | HAA | 0.023 | 8 | -1003 | 6.5 | 6.5 | 5580 | Hydrovac |
| RWVIM-101-13 | HAA | 0.04 | 14 | -1038 | 6.5 | 6.5 | 1200 | Hydrovac |
| RWVIM-102-13 | HAA | 0.027 | 10 | -1011 | 6 | 6 | 7900 | Hydrovac |
| RWVIM-103-13 | HAA | 0.019 | 7 | -1017 | 6.3 | 6.5 | 1656 | Hydrovac |
| RWVIM-104-13 | HAA | 0.038 | 14 | -960 | 5.5 | 5 | 1327 | Hydrovac |
| RWVIM-107-13 | CTE | 0.076 | 30 | -858 | 5 | 5 | 47645 | Hydrovac |
| RWVIM-126-13 | CTE | 0.109 | 44 | -879 | 4 | 3.5 | 6536 | Backhoe |
| RWVIM-127-13 | CTE | 0.109 | 44 | -879 | 4 | 3.5 | 6536 | Hydrovac |
| RWVIM-128-13 | CTE | 0.063 | 25 | -801 | 4 | 4 | 38492 | Hydrovac |
| RWVIM-131-13 | CTE | 0.018 | 10 | -1138 | 6 | 6 | 710 | Hydrovac |
| RWVIM-140-13 | HAA | 0.023 | 11 | -771 | 5.5 | 6 | 2145 | Hydrovac |
| RWVIM-141-13 | HAA | 0.03 | 15 | -1099 | 6 | 6 | 1436 | Hydrovac |

* Coating types reflect information provided in "A" form or as verbally communicated to Dynamic Risk by NACE certified inspectors.
HAA = hot applied asphalt
CTE = coal tar enamel

Table 4. Summary of bacteria analyses performed on swabs taken of liquids beneath disbonded coating.

| RVWIM Dig Identification | Coating Type [1] | pH of Liquid Beneath Coating | Bacteria Concentration (bacteria per $cm^2$) | | | | |
|---|---|---|---|---|---|---|---|
| | | | Low Nutrient Bacteria | Iron-related Bacteria | Anaerobic Bacteria | Acid-producing Bacteria | Sulfate-reducing Bacteria |
| 76-13 [2] | CTE | 12 | 1 to 10 | 1 to 10 | > 100,000 | > 100,000 | > 100,000 |
| 77-13 [2] | CTE | 12 | > 100,000 | 1 to 10 | Not detected | Not detected | Not detected |
| 78-13 [2] | CTE | 13 | 1,000 to 10,000 | 1 to 10 | Not detected | Not detected | Not detected |
| 90-13 [2] | HAA | 8 | 10 to 100 | 10 to 100 | 10 to 100 | 10 to 100 | 10 to 100 |
| 133-13 | HAA | 8 | 1,000 to 10,000 | > 100,000 | 10 to 100 | 1,000 to 10,000 | 1 to 10 |
| 155-13 [2] | HAA | 8 | 10 to 100 | > 100,000 | 10 to 100 | 1 to 10 | Not detected |
| 158-13 | HAA | 8 | 10 to 100 | > 100,000 | 1,000 to 10,000 | 1,000 to 10,000 | 10 to 100 |
| 159-13 [2] | HAA | 8 | 1 to 10 | > 100,000 | 1,000 to 10,000 | 1,000 to 10,000 | 10 to 100 |
| 165-13 [2] | CTE | 7 | 1,000 to 10,000 | > 100,000 | > 100,000 | 1,000 to 10,000 | 10 to 100 |

1 Coating types reflect information provided in "A" form or as verbally communicated to Dynamic Risk by NACE certified inspectors.
2 These digs contained holidays associated with tree roots.
HAA = hot applied asphalt
CTE = coal tar enamel

Table 5. Summary of linear indications identified on 13 of the excavated pipe segments, using wet fluorescent magnetic particle inspection.

| RVIM Dig Identification | RWVC Dig Identification | Alternate Identifications | Coating Type [1] | Number of Linear Indications found | Tree Health |
|---|---|---|---|---|---|
| RWVIM-89-13 | – | – | HAA | 15 [2] | Good |
| RWVIM-96-13 | RWVC -36-13 | – | HAA | 14 | Good |
| RWVIM-98-13 | – | – | HAA | 16 | Fair, poor pruning |
| RWVIM-101-13 | RWVC-46-13 | – | HAA | 8 | Good |
| RWVIM-102-13 | RWVC-47-13 | – | HAA | 6 | Good |
| RWVIM-103-13 | RWVC-49-13 | – | HAA | 16 | Good |
| RWVIM-107-13 | – | – | CTE | 27 | Fair |
| RWVIM-126-13 | – | – | CTE | 15 [2] | Good |
| RWVIM-127-13 | – | – | CTE | 15 [2] | Fair |
| RWVIM-128-13 | – | – | CTE | 3 | Good |
| RWVIM-160-13 | – | – | HAA | 17 | Good |
| – | RWVC-38-13 | L132 | HAA | 16 | Good |
| – | – | 153-12 | HAA | 13 | Fair, Heart rot in canopy |

1 HAA = hot applied asphalt, CTE = coal tar enamel.

2 Together, the pipe segments associated with Digs RWVIM 89-13, 126-13, and 127-13 had a total of 15 indications. The exact numbers of indications per pipe segment were not provided.

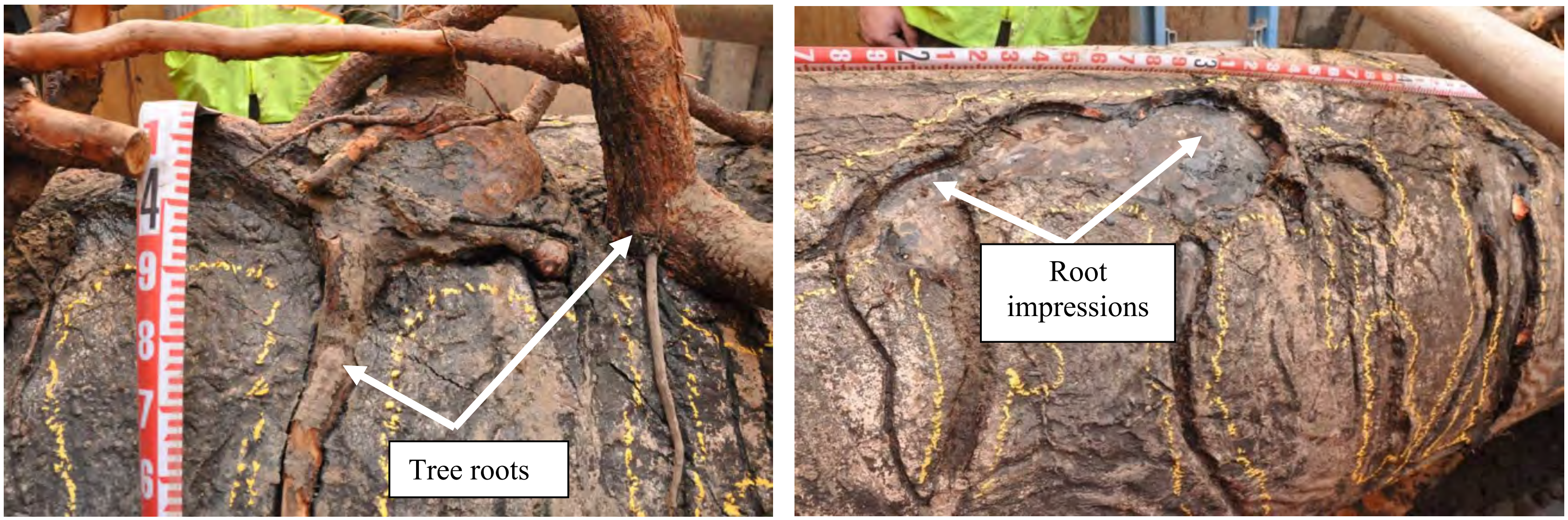


Figure 1. Photographs showing the interaction of tree roots with the pipe section from Dig RWVIM-153 - 4, which was coated with hot applied asphalt: Tree roots in contact with pipe (Left) and coating damage after tree roots were removed (Right).

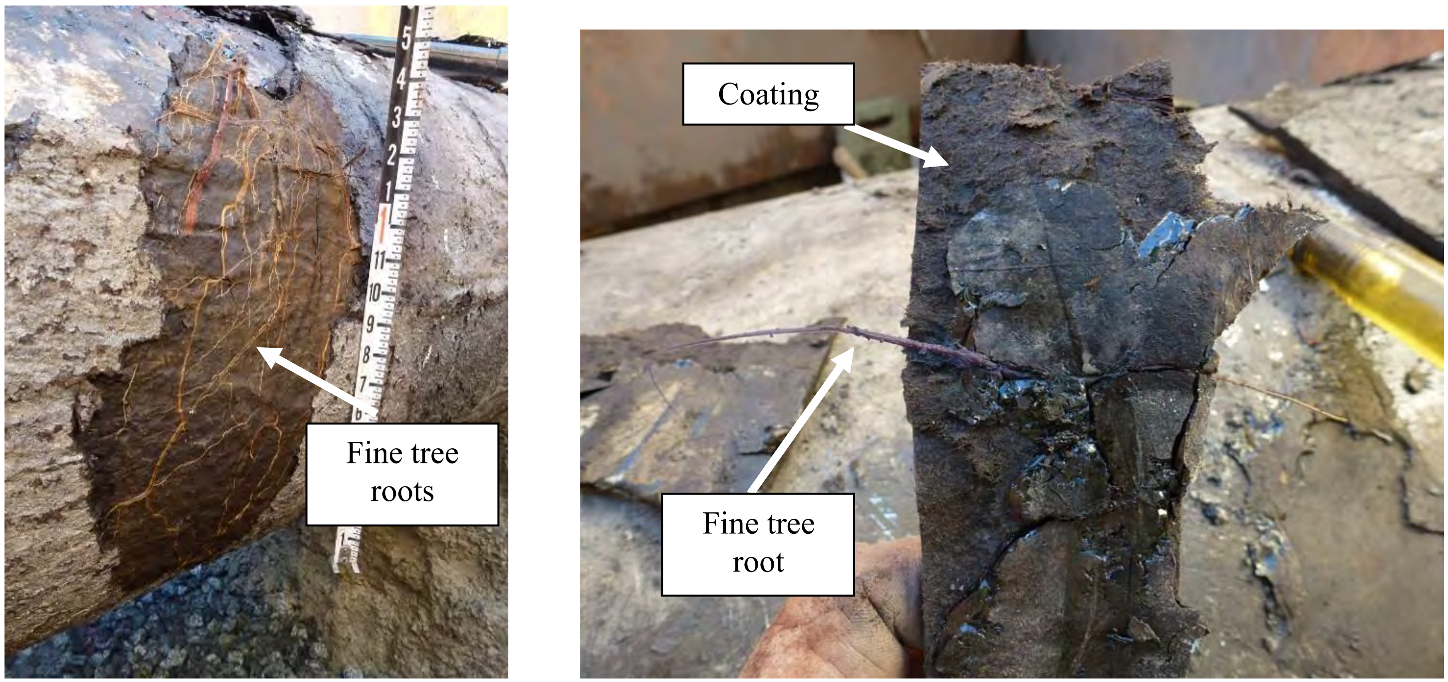


Figure 2. Photographs showing fine roots beneath the hot applied asphalt coating for the pipe section associated with Dig RWVIM 132 -8.


Figure 3. Photographs showing the interaction of a tree root with the pipe section from Dig RWVIM-259-13, which was coated with hot applied asphalt: Tree root in contact with pipe (Left) and coating damage after the tree root was removed (Right).


Figure 4. Photographs from Dig RWVIM 76-13 showing: A root impression in the coal tar enamel coating (Left) and disbonded coating with root intrusions (Right).


Figure 5. Photographs showing coating damage observed on pipe sections coated with tape.

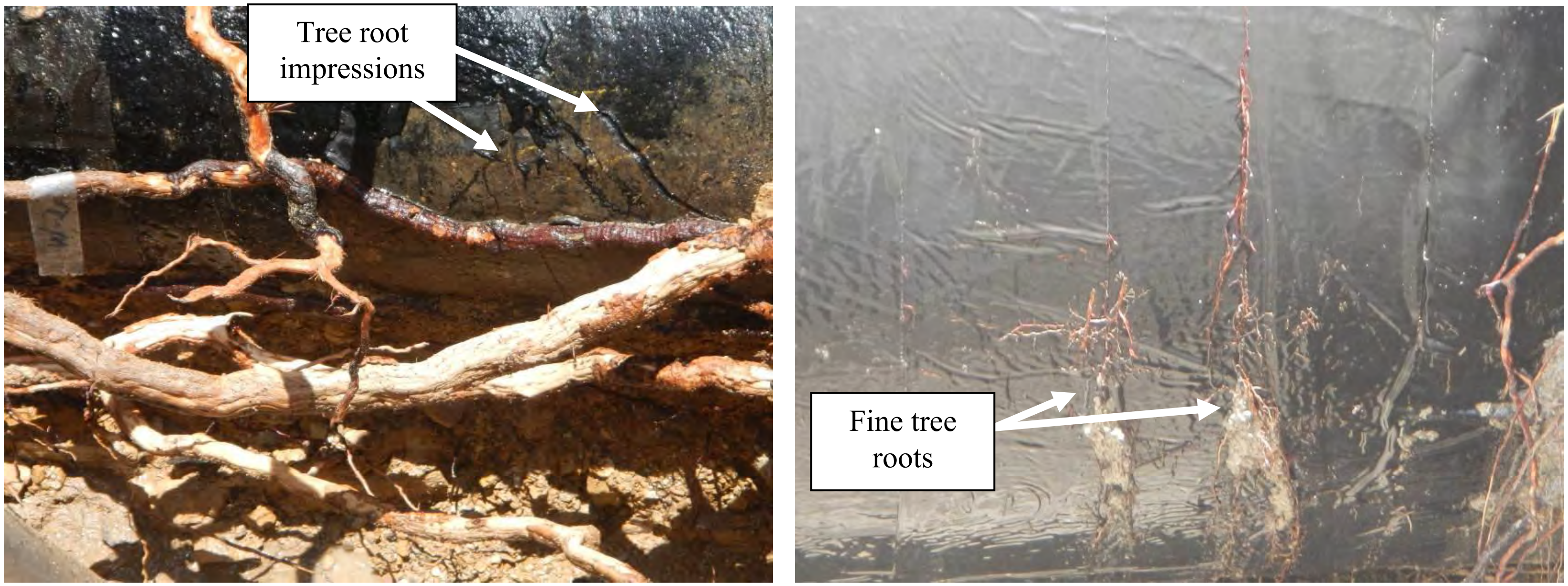


Figure 6. Photographs showing coating damage observed on pipe sections coated with tape.


Figure 7. Representative photographs showing external corrosion on pipe segments.

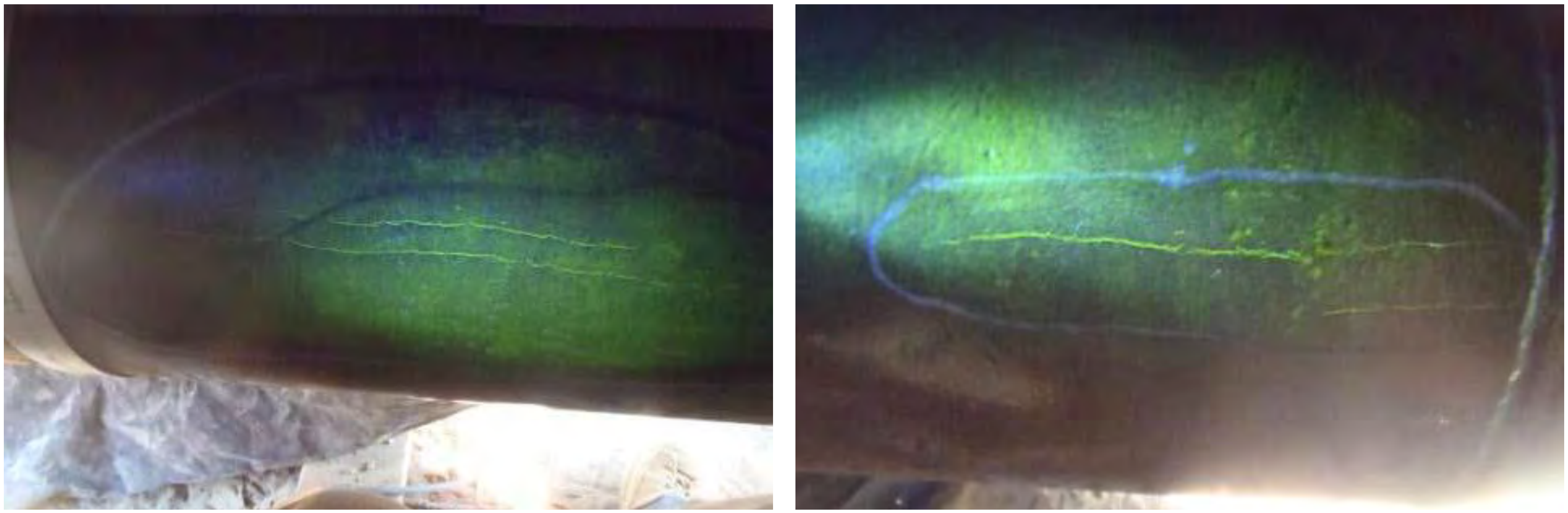

Figure 8. Photographs, provided from Dig RWVIM 89-13, showing representative linear indications identified using wet fluorescent magnetic particle inspection.

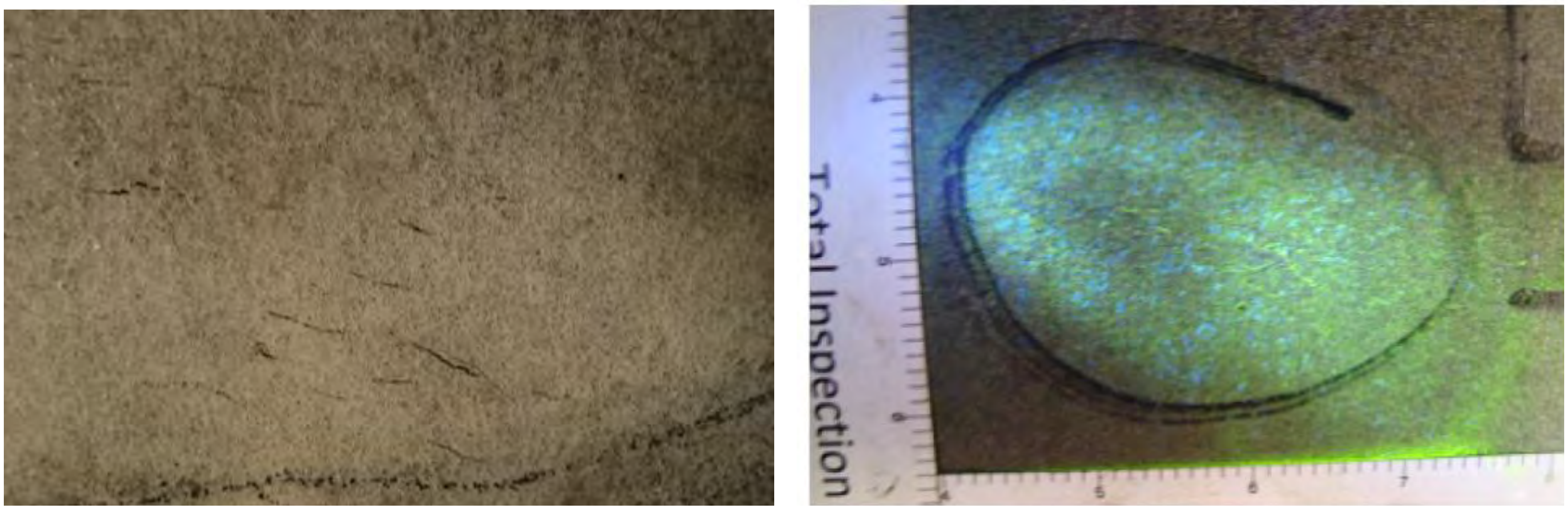


Figure 9. Photographs, provided from Digs RWVC 36-13(Left) and RWVIM 101-13 (Right), showing representative colonies of linear indications identified using magnetic particle inspection.

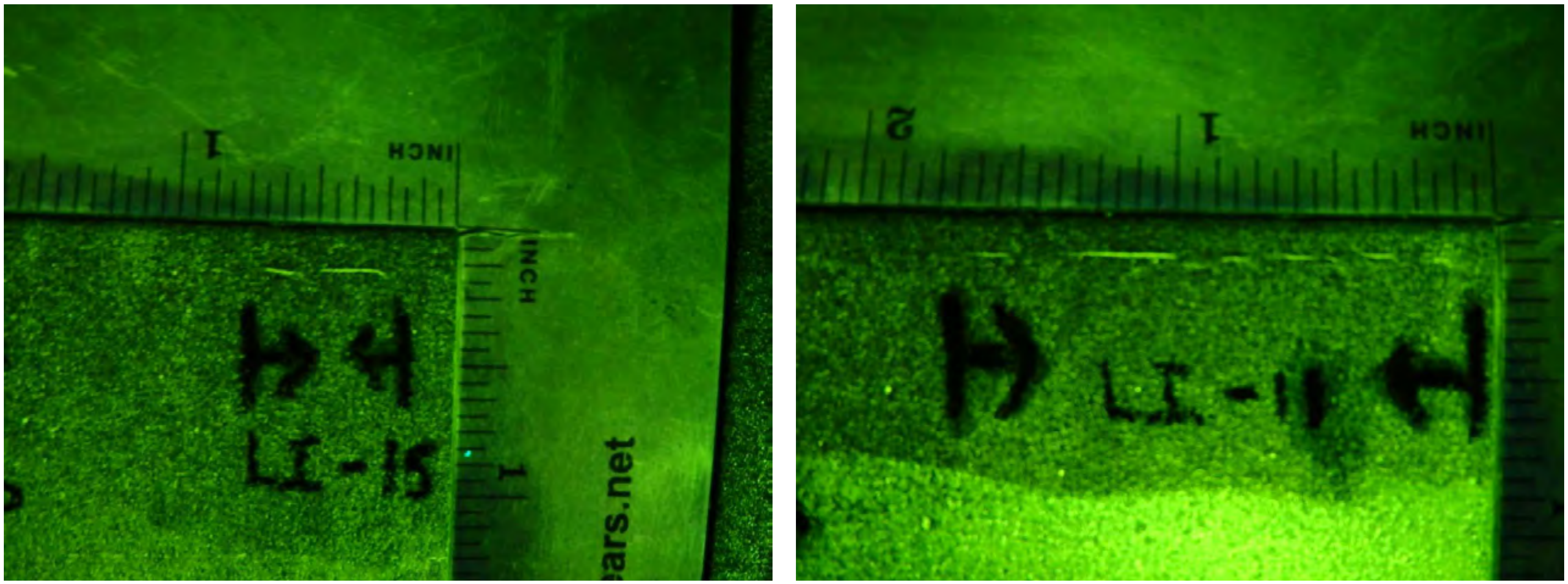


Figure 10. Photographs, provided from Dig RWVIM 160-13, showing representative linear indications identified using wet fluorescent magnetic particle inspection.

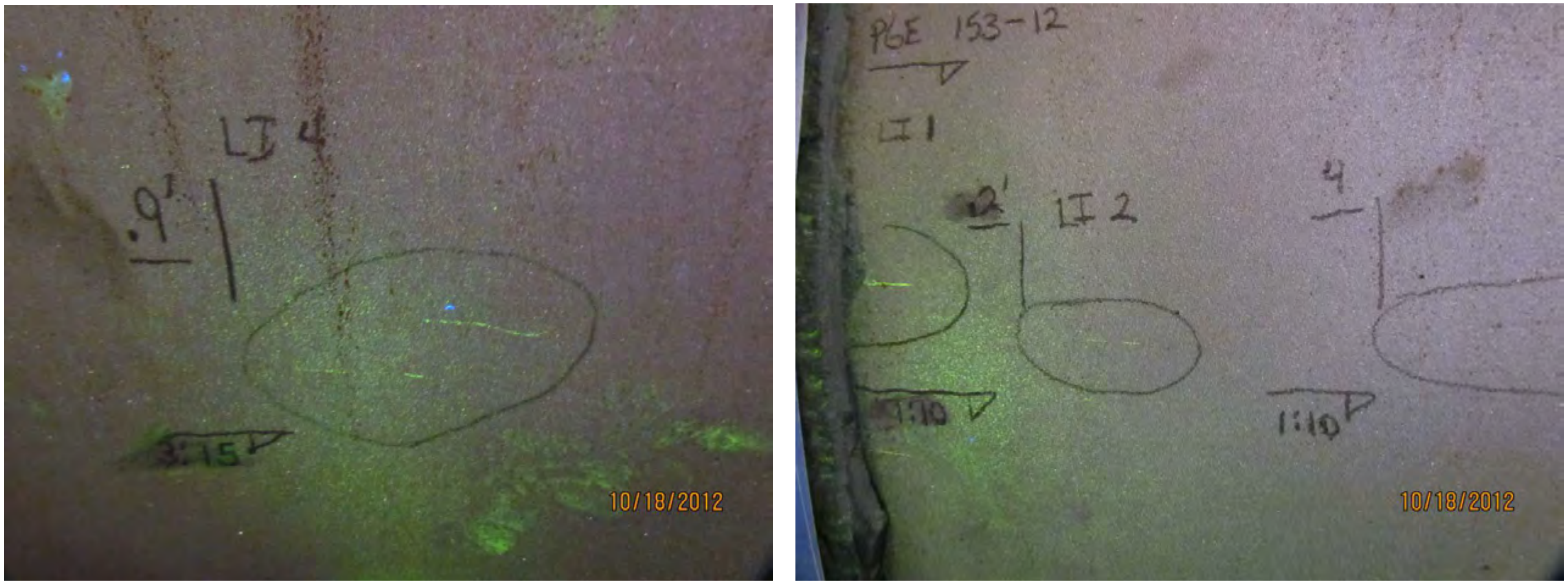


Figure 11. Photographs, provided from Dig 153-12, showing representative linear indications identified using wet fluorescent magnetic particle inspection.


Figure 12. Photographs showing the presence of calcareous deposits in areas where the coating disbonded.

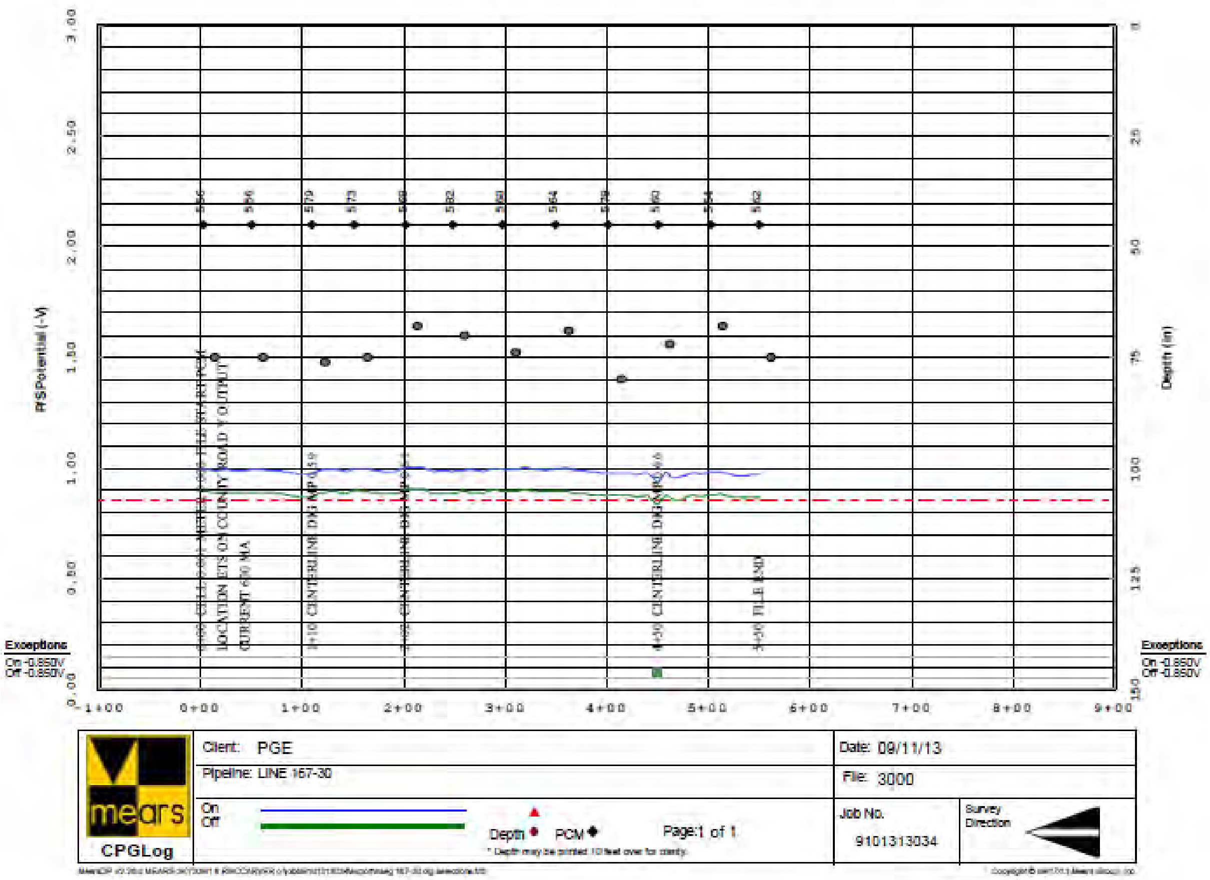


Figure 13. Profile, provided by Mears, showing representative results from an aboveground survey where no coating holidays were identified.

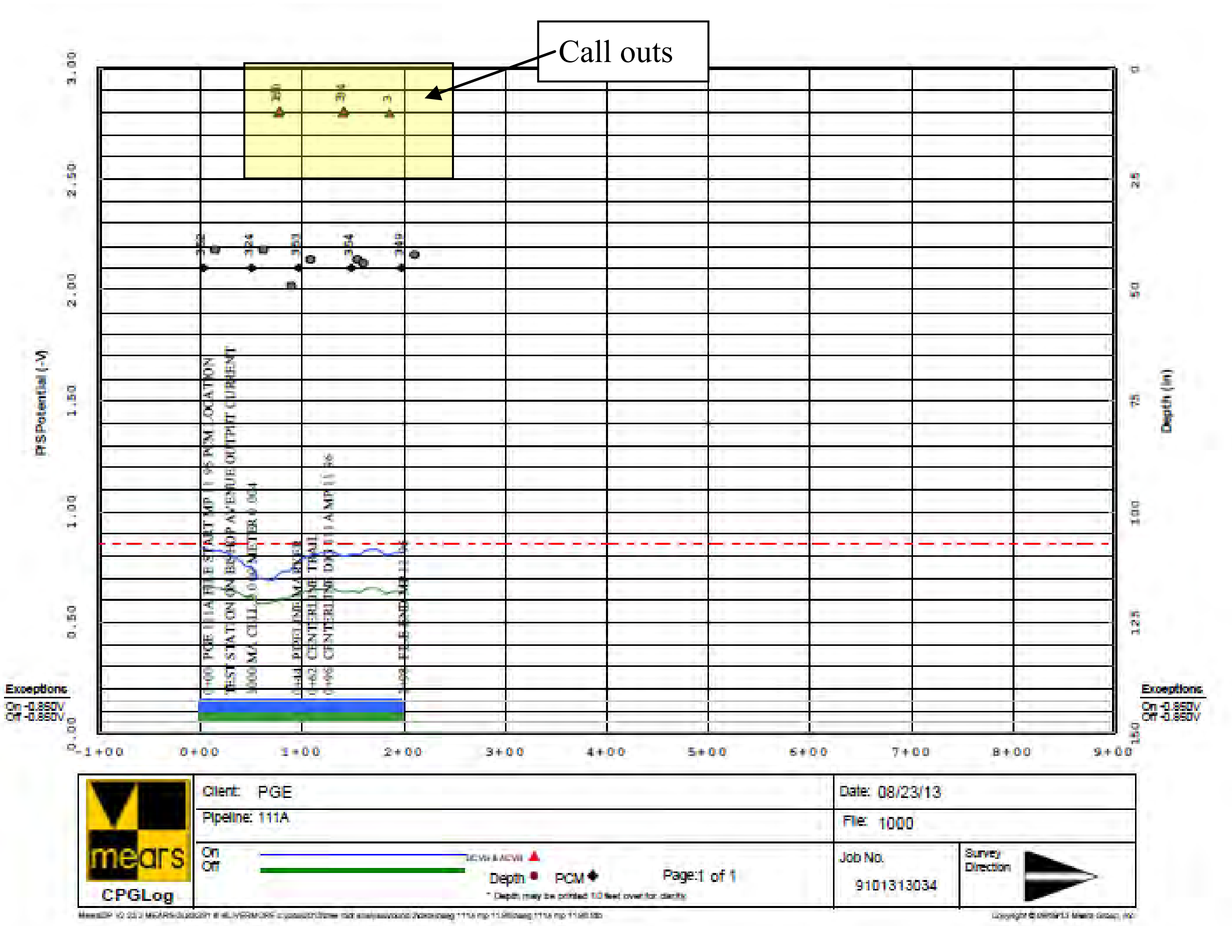


Figure 14. Profile, provided by Mears, showing representative results from an aboveground survey where coating holidays were identified.

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# Attachment 6:

**Frizzell and Associates. "Tree Root Interactions with Natural Gas Transmission Pipelines: An Arborist Field Study". March 27, 2015.**

*Final Report*

*As of*

*December 31, 2013*

# TREE ROOT INTERACTIONS WITH NATURAL GAS TRANSMISSION PIPELINES: AN ARBORIST FIELD STUDY

For

## Pacific Gas and Electric Company

6121 Bollinger Canyon Road, San Ramon, CA  94583

*Revised March 27, 2015*

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## Table of Contents

## 1.0 EXECUTIVE SUMMARY

In September of 2012, PG&E initiated a limited number of excavations for the purpose of assessing, documenting, and reporting roots from a variety of species near gas transmission pipelines. This became the Root Study described herein, which was eventually expanded to a total of 53 sites within PG&E gas transmission pipeline corridors. The excavations (or digs) took place from September 2012 through November 2013.

This report presents an overview of the observations, findings, and conclusions from the root study. A number of recommendations have come out of this and can be found at the end of the report. A secondary objective of this report is to compare the observations and conclusions from the Root Study with the findings in the 2012 White Paper by Randall Frizzell & Associates, titled *Tree Root Interactions with Natural Gas Transmission Pipelines*.

PG&E personnel prepared the 53 sites by removing the trees at each location, leaving a short stump, then in collaboration with arborists from Frizzell & Associates, laid out the excavation pit for the root study. The excavation pits ranged in sizes from 8’ x 8’ to 10’ x 10’ (w x l) and as deep as the bottom of the pipe plus 2-feet. At two dig sites the pit was lengthened to follow roots.

PG&E employed specialized pipeline contractors using different techniques to expose the roots and their interactions with pipelines. The primary technique was hydro-vac excavation, which removes soil while leaving much of the root system intact. The other technique, in a smaller number of digs, used trackhoe excavation equipment and hand digging to remove all soil and roots in the excavation pit. In both types of excavations the arborists (root inspectors) directed the pipeline contractor to remove soil in 1-foot layers. The root inspectors made observations and took various measurements, documenting roots and their interactions with pipes at each interval to the bottom of the excavation pit.

Tree roots are generally divided into five types: tap, lateral, sinker, oblique and fine. Tap roots were not observed during the root study but all other types were evident, to varying degrees, at most of the excavation sites. From 53 dig sites, 23% had lateral roots interacting with pipe coatings, 51% had sinker roots interacting, 34% had oblique roots interacting, and 72% had fine roots interacting with pipe coatings. Fine roots were the most common type of root to interact with pipe coatings. Fine roots are opportunistic, taking advantage of any weakness in the coating and also growing into and through seemingly solid Hot Applied Asphalt (HAA) and Cold Tar Emulsion (CTE) coatings. The tree root interactions with coatings were not restricted to pipes with shallow cover depths. Roots of all types were observed interacting with pipes to depths in excess of 8-feet.

Tree species was observed to be a factor contributing to the severity root-pipe interactions. Species naturally tolerant of dry soils were observed to develop deep root systems that resulted in significant pipe/coating interactions, even without contributing factors such as restrictive soil layers. These species included Eucalyptus, Deodar cedar, Cottonwood, Afghan pine, Italian stone pine, and Date palm. An exception to this was the native Interior live oak, a species growing tin the dry Sierra foothills. While drought tolerant and thriving in dry soils, it has predominantly shallow root systems. Cottonwoods were observed to have roots and interactions far from the tree. There were not enough non-drought tolerant species in the root study to compare average total contact areas between drought tolerant and non-drought tolerant species.

Soil conditions in trenches and near pipes were a factor in root-pipe interactions. Backfill soils often created a favorable environment for root growth near the pipes. At most of the 53 dig sites, the backfill soils around the pipe were native soils. These native soils provided a good growing environment for tree roots and an opportunity for many root-pipe interactions. Restrictive soil layers, such as hardpans/duripans and bedrock were observed to increase the incidence of root/pipe interactions. Roots growing in soils with restrictive layers flourished in the backfill soils. The restrictive soil layers accentuated the interaction of roots with the pipe. At a number of dig sites where restrictive soils were not a factor, roots were observed growing in from various directions and when encountering the pipe, turned and grew along the pipe in continuous contact.

The quantity and severity of tree root interactions, was in part, determined by pipe coating type. Of 47 dig sites with pipe coating comprised of HAA or CTE, all had tree root interactions with pipe coatings. Tape/wrap coating resisted root interaction more effectively than HAA or CTE coating. Of the 6 dig sites having tape/wrap coating, one location had fine roots growing through imperfections in the tape/wrap to reach metal pipe.

There are a number of factors contributing to the wide-ranging variability in the findings. Because the dig site selection process did not result in trees that were always located in the same relative position to the pipe, measurements were often unique to each dig site and often not comparable. Also, because of variables in site factors such as environmental conditions, inherent species characteristics, and individual tree genetics, comparing data from each dig site is complicated and difficult. This variability is prevalent in at least four areas:

- Variability within one species
- Variability in relationships between root-pipe interactions and cover depth
- Variability in relationships between root-pipe interactions and distance from tree to pipe centerline
- Variability of root-pipe interactions and orientation to pipe - trees growing on one side of the pipe can produce root-pipe interactions on the opposite side of the pipe.

In large part, the recommendations in this report are aimed at PG&E vegetation managers. It is hoped these findings may be useful in their planning and practices as it relates to gas transmission pipelines. The recommendations included

- Developing a Prioritization Matrix
- Review current standards and incorporate relevant information
- Prioritize tree removals based on proximity to restrictive soil layers
- Initiate a no-planting campaign
- Continue research with additional species, especially palm trees, fine roots, large trees, decaying roots on pipes, and root growth on pipes.

## 2.0 INTRODUCTION

### 2.1 BACKGROUND

In 2012, Randall Frizzell and Associates wrote a White Paper (WP) for Pacific Gas & Electric (PG&E) titled *Tree Root Interactions with Natural Gas Transmission Pipelines*. The WP was presented to PG&E in April 2012 after an exhaustive literature search and personal communications with several international researchers. In September, 2012, PG&E initiated a limited number of excavations for the purpose of assessing, documenting, and reporting roots near gas transmission pipelines. This became the Root Study described herein, which was eventually expanded to a total of 55 locations within PG&E gas transmission pipeline corridors. The excavations (or digs) took place from September 2012 through November 2013. At the conclusion of the Root Study, only 53 dig sites were reported because two sites mistakenly involved a pipe casing rather than the intended gas transmission pipe sections.

All root study sites (or dig sites) were selected by PG&E staff. These dig sites were initially located in the San Francisco Bay Area along PG&E's gas pipeline encroachment pilot program, Lines 153 and 132. The project eventually moved inland to numerous sites in the San Joaquin valley, Sacramento valley, and the Sierra foothills representing a variety of species, land uses, and site conditions.

## 2.2 OBJECTIVES

The primary objective of the Root Study was to observe and document the extent to which roots of a variety of tree species can adversely impact underground pipelines at various sites. The excavations provided an opportunity to observe and collect data related to (1) the interaction between tree roots and pipes and (2) root growth patterns (root architecture) at the 53 excavation sites. Fundamental to this objective was determining whether root attributes, patterns, and interactions with pipes could be predicted based on tree species, size, health, soil factors, irrigation, proximity to pipelines, pipe diameter, depth of cover, and coating type.

## 2.3 DOCUMENTATION

Observations and measurements from each excavation site in the root study were recorded on a field form that was developed for this study. The field form evolved as the root study protocols developed and changed over the span of the 14-month project. Photographic documentation was also conducted at each dig site. From the data collected at each dig site a report was generated. Initially, extensive narrative reports were developed. In the later half of the root study project the narrative reports were replaced with one-page report summaries. All reports were provided to Dynamic Risk Assessment Systems (DRAS).

Soil samples, both bagged and bulk density, were taken at each dig site and sent to a soils laboratory for analysis. The lab reports are maintained with the field forms in a database. The arborists (tree inspectors) provided preliminary interpretations of the lab results. If needed, the lab reports can be used by soil scientists for further interpretation.

## 2.4 DEFINITIONS

Definitions of terms in this report include:

**Contact**: for the purposes of the root study - refers to a contact between a root and the pipe or its coating. It is a general term that does not refer to the simple touching of roots on pipe coatings but is a measurable interaction between roots and coating that has been severe enough to have either left a coating impression or actually displaced coating to the point of creating a hole or gap (holiday). Measurements of contacts are quantified in this report as square inches of total contact area.

- **Coating Impression:** coating that has had its surface deformed by pressure from a root.
- **Holiday:** a hole or gap in the coating that exposes the metal surface of the pipe. For the purposes of this report, only root-caused holidays are discussed.

- **Approximate Total Contact Area:** the estimated area (sq. in.) of all root-caused coating impressions and holidays combined.

**Dig Site or Dig**: a general description of an excavation site/project. It includes the location of the excavation on residential or commercial property or farmland and can also refer more broadly to project details including identification, notification, customer negotiation, pit excavation and site restoration.

**Excavation Pit or Pit**: refers specifically to the hole in the ground that is created by the removal of soil in the process of exposing roots and pipe (see Figure 2).

**Hydro-Vac Technique of Excavation**: this excavation technique utilizes a Hydro-Vac truck. The truck has a large volume of water on board that is applied to the soil at very high pressure to displace the soil. As the soil is washed away it creates a muddy slurry that is sucked out of the pit by the strong vacuum system that is also a part of the Hydro-Vac truck. This method of excavation allows the majority of the root system to remain intact. This is especially beneficial for the study of root architecture in general and specifically around gas transmission pipelines (Figure 1 and 2).

Figure 1. A typical Hydro-Vac truck.

Figure 2. The hydro-vac process uses high pressure water and a large suction hose to excavate soil leaving the roots intact.

**Root Inspector**: an individual on the dig site responsible for observing and documenting the details of root architecture and root-pipe interaction. Root inspectors were trained by and worked under the direction of Frizzell and Associates. All root inspectors were Certified Arborists who had extensive professional experience and a general understanding of tree physiology, anatomy, and site factors.

**Root Interaction (or Interaction):** for the purposes of the root study - tree roots in contact with the pipe and/or coating in one of three ways: creation of coating impressions or coating holidays and fine root penetrations into pipe coatings.

**Roots - Types of:** (tap, lateral, sinker, oblique, and fine) are defined in the following Section 3.2.

**Trackhoe Technique of Excavation, (or Dry Dig)**: this excavation technique utilizes a trackhoe, which is a mechanical piece of equipment similar to a backhoe but moves on tracks rather than wheels. The trackhoe excavation removes soil (and roots) without the use of water (Figure 3).

Figure 3. This is a dry dig site using track hoe and shovels to excavate soil and roots.

Waterless excavation was implemented for the purpose of collecting samples from the excavated pipe section and testing for the presence of specific microbes. The introduction of water into the pit with Hydro-Vac equipment invalidates the microbe test. Dry digs were implemented by DRAS when they were brought onto the project in 2013.

### 2.5 LIMITING CONDITIONS

All findings and conclusions are based on our knowledge and observations as of December 2013.

The dig site selection process did not choose trees that were always located in the same relative position to the pipe, therefore root patterns were difficult to compare among the 53 sites.

The root inspectors were not trained or qualified to take readings related to Cathodic Protection, assessing coating condition, assessing the effects of chronic stresses on pipes caused by trees in close proximity to pipes, or the effect of trees on pipe function or integrity.

A comparative analysis of all the soil physical characteristics, soil analysis, and bulk density results was not in the scope of this study.

## 3.0 OBSERVATIONS

### 3.1 METHODS

PG&E personnel chose the locations of the dig sites. The criteria for selecting the dig sites was based, in part, on tree species, accessibility, and landowner permission to remove trees and excavate on their property. Early in the project a PG&E forester in collaboration with arborists from Frizzell & Associates laid out the location of the excavation sites for the root study. After the above ground portion of subject trees were removed, leaving short stumps, the excavation pits were laid out with corner stakes. Pit sizes varied but typically were 8’ x 8’ or 10’ x 10’ (w x l) and as deep as the bottom of the pipe plus 2-feet. At two dig sites the pit was lengthened in order to follow roots.

The location of the subject trees and their root systems in relation to the excavation pits varied widely because the pipes were required to be centered in the excavation pits. In some cases this led to tree stumps that were not fully excavated and some stumps that were completely outside the pit. A small number of excavation pits contained roots from more than one tree.

The pipeline contractor, under the direction of the root inspectors, used excavation equipment to remove soil in approximately 1-foot layers. After each incremental layer of soil was removed the root inspectors assessed, measured, and documented the visible roots. After several feet of excavation, roots were cut out of the way so the excavation process could continue downward. As sections of pipe were uncovered and exposed during the excavation process they were tested and recoated in accordance with PG&E protocol.

To conduct the root study excavations at the 53 dig sites, PG&E employed specialized pipeline contractors utilizing either hydro-vac techniques to remove soil while leaving the root system intact or, in a smaller number of digs, using trackhoe excavation equipment and hand digging (called dry digs) to remove all soil and expose roots within the excavation pit. Over the course of the root study, a total of 41 digs were completed using hydro-vac excavation and 12 were done using the dry dig techniques.

Once the roots were exposed, the roots around the pipe were measured and photographed for analysis. Where dry dig techniques were used, root architecture was difficult to observe or quantify because the trackhoe excavator had to remove many roots with the soil during the excavation to proceed to its specified depth. Dry digs were employed later in the project to enable the collection of important microbial samples from the pipe’s surface without the introduction of water from outside sources.

## 3.2 ROOTS AND ROOT INTERACTION ANALYSIS

Tree roots are generally divided into five types: tap, lateral, sinker, oblique and fine. Tap roots were not observed during the root study but the other types were evident to varying degrees at most of the excavation sites.

### 3.2.1 Lateral Roots

Lateral roots typically develop from a taproot early in the life of a tree seedling, near the soil surface and spreading horizontally, forming a major part of the total root system. In most mature trees the tap root is outgrown by the lateral roots and is difficult to find. Lateral roots branch as they grow away from the tree, providing stability for the tree as well as forming a network of roots that serve as conduit for water and minerals (Figure 4).

Figure 4. A lateral root system at 153-1.

The following 12 digs in this study (23%) had lateral roots interacting with the pipe coating (Figure 5):

**Lateral Root Interactions**

| DIG SITE | SPECIES | COVER DEPTH (in.) | APPROX. TOTAL CONTACT AREA (sq. in.) |
|---|---|---|---|
| RWVIM-90-13 | Valley oak | 48 | 2937 |
| RWVC-38-13-L132 | Coast redwood | 36 | 195 |
| RWVIM-159-13 | Walnut | 38 | 133 |
| RWVIM-160-13 | Plum | 42 | 101 |
| RWVIM-106-13 | Silk | 33 | 81 |
| RWVIM-128-13 | Deodar cedar | 36 | 78 |
| RWVIM-132-13 | Black walnut | 52 | 78 |
| RWVIM-89-13 | Eucalyptus | 39 | 62 |
| RWVIM-127-13 | Deodar cedar | 38 | 47 |
| RWVIM-136-13 | Black walnut | 40 | 33 |
| RWVIM-92-13 | Deodar cedar | 30 | 32 |
| RWVIM-137-13 | Interior live oak | 61 | 2 |

Figure 5

For the most part, the diameter of lateral roots decreases rapidly as they divide within several feet from the trunk depending upon tree size. This is called the zone of rapid taper. This zone of rapid taper was observed on root systems at many dig sites, but it must be noted that not all trees exhibited a zone of rapid taper. Exceptions to this characteristic were documented in Cottonwood, Hackberry, Ailanthus, and Eucalyptus trees, which were located many feet from the pipe yet had large diameter roots interacting with pipe coatings. There was a zone rapid of taper with the Hackberry, Ailanthus and Eucalyptus trees but they also had a small number of uncharacteristic lateral roots that did not taper much as they grew great distances along and in contact with pipes. On the other hand, the two Cottonwoods in the root study produced lateral roots that did not decrease rapidly in diameter near the tree. A root was discovered on one Cottonwood that may have increased in diameter as the distance from the tree increased.

During the root study we observed numerous examples of lateral roots growing in downward directions. Seven (7) trees formed horizontal lateral roots that turned downward a short distance from the base of the tree and contacted pipe and or coating (Figure 6).

**Downward Growing Lateral Roots**
**Contacting Pipe and/or Coating**

| DIG SITE | SPECIES | APPROX. TOTAL CONTACT AREA (sq. in.) |
|---|---|---|
| RWVIM-126-13 | Eucalyptus | 551 |
| RWVIM-128-13 | Deodar cedar | 78 |
| RWVIM-132-13 | Black walnut | 78 |
| RWVIM-89-13 | Eucalyptus | 62 |
| RWVIM-127-13 | Deodar cedar | 47 |
| RWVIM-136-13 | Black walnut | 33 |
| RWVIM-92-13 | Deodar cedar | 32 |

Figure 6

### 3.2.2 Sinker Roots

Sinker roots originate primarily from lateral roots and grow downward at a steep angle (Figure 7).

Figure 7. Sinker roots at dig site 153-4.

The following 27 digs in this study (51%) had sinker roots interacting with the pipe coating (Figure 8):

**Sinker Root Interactions**

| DIG SITE | SPECIES | COVER DEPTH (in.) | APPROX. TOTAL CONTACT AREA (sq. in.) |
|---|---|---|---|
| RWVIM-90-13 | Valley oak | 48 | 2937 |
| RWVIM-126-13 | Eucalyptus | 36 | 551 |
| RWVIM-75-13 | Afghan pine | 48 | 250 |
| RWVIM-77-13 | Silver maple | 48 | 123 |
| RWVIM-76-13 | Coast redwood | 48 | 112 |
| RWVIM-73-13 | Afghan pine | 60 | 104 |
| RWVIM-160-13 | Plum | 42 | 101 |
| RWVC-47-13 (RWVIM-102-13) | Privet | 50 | 95 |
| RWVIM-106-13 | Silk | 33 | 81 |
| RWVIM-74-13 | Eucalyptus sp. | 60 | 79 |
| RWVIM-128-13 | Deodar cedar | 36 | 78 |
| RWVIM-132-13 | Black walnut | 52 | 78 |
| RWVIM-107-13 | Hackberry | 36 | 73 |
| RWVIM-78-13 | Deodar cedar | 48 | 73 |
| RWVIM-141-13 | Almond | 44 | 69 |
| RWVIM-89-13 | Eucalyptus | 39 | 62 |
| 153-1 | Monterey pine | 48 | 47 |

| | | | |
|---|---|---|---|
| RWVIM-127-13 | Deodar cedar | 38 | 47 |
| RWVIM-92-13 | Deodar cedar | 30 | 32 |
| RWVC-40-13 (RWVIM-98-13) | Elm | 36 | 29 |
| RWVIM-155-13 | Grape | 58 | 27 |
| RWVC-55-13 (RWVIM-105-13) | Myoporum | 48 | 18 |
| 153-12 | Mulberry | 48 | 11 |
| RWVIM-129-13 | Silk | 33 | 7 |
| RWVC-36-13 (RWVIM-96-13) | Avocado | 48 | 4 |
| RWVIM-81-13 | Monterey pine | 60 | Fine roots |
| RWVIM-82-13 | Monterey pine | 60 | Fine roots |

Figure 8

### 3.2.3 Oblique Roots

Oblique roots, unlike lateral roots, emerge at a downward angle from the base of the trunk (known as the root collar), or sometimes from lateral roots. It is the oblique and sinker roots that are most likely to interact with gas transmission pipes as they divide and grow to greater depths (Figure 9).

Figure 9. These are oblique roots at dig site 128-13.

The following 18 digs in this study (34%) had oblique roots interacting with the pipe coating (Figure 10):

**Oblique Root Interactions**

| DIG SITE | SPECIES | COVER DEPTH (in.) | APPROX. TOTAL CONTACT AREA (sq. in.) |
|---|---|---|---|
| RWVIM-90-13 | Valley oak | 48 | 2937 |
| RWVIM-126-13 | Eucalyptus | 36 | 551 |
| 153-4 | Italian stone pine | 48 | 437 |
| RWVIM-75-13 | Afghan pine | 48 | 250 |
| RWVIM-77-13 | Silver maple | 48 | 123 |
| RWVIM-76-13 | Coast redwood | 48 | 112 |
| RWVIM-73-13 | Afghan pine | 60 | 104 |
| RWVIM-160-13 | Plum | 42 | 101 |
| RWVIM-106-13 | Silk | 33 | 81 |
| RWVIM-74-13 | Eucalyptus sp. | 60 | 79 |
| RWVIM-128-13 | Deodar cedar | 36 | 78 |
| RWVIM-132-13 | Black walnut | 52 | 78 |
| RWVIM-107-13 | Hackberry | 36 | 73 |
| RWVIM-89-13 | Eucalyptus | 39 | 62 |
| RWVIM-136-13 | Black walnut | 40 | 33 |
| RWVC-40-13 (RWVIM-98-13) | Elm | 36 | 29 |
| RWVIM-129-13 | Silk | 33 | 7 |
| RWVIM-137-13 | Interior live oak | 61 | 2 |

Figure 10

**3.2.4 Fine Roots**

Fine roots, for the purpose of this root study, are less than 0.1-inch in diameter. It was observed that fine roots interacted with the pipe coatings at most of the 53 dig sites. Of the 53 dig sites, 38 digs (72%) had observable fine root interactions with pipe coatings; 8 digs had no observable fine roots associated with the pipe/coating; 3 digs involved dead trees where fine roots may have rotted away, and 1 dig had inconclusive results. It should be noted that the excavation process, including hydro-vac, can destroy small roots. Fine root interaction with coatings was not restricted to pipes with shallow cover depths. Fine roots were present on pipes in excess of 8-feet.

Figure 11. Dig site 132-8 fine roots are growing between the layers of the HAA coating.

Fine roots can be of two different types. First, many fine roots live only a short time (perhaps a year); existing for the primary function of absorbing water and mineral nutrients. Genetically they do not have the ability to develop into larger root structures that would displace coating enough to create holidays. Secondly, if a root is destined (genetically) to become a lateral (or oblique or sinker) root, then it will continue to live well beyond the lifetime of fine absorbing roots. It will increase in length and girth over time. Most, if not all, the roots the inspection team discovered that caused coating impressions or holidays were once a fine root that came in contact with the pipe and then grew in girth as it matured. Fine roots were not quantified in this root study because of various constraints (Figure 11).

## 3.3 ROOT DEPTH

At most of the dig sites it was common to observe roots interacting with pipe/coatings - creating impressions and holidays at depths greater than 3-feet. It has already been mentioned earlier in the report that fine root interaction was observed at a majority of dig sites. In many instances coating impressions or holidays were evident without the presence of the causal root. This is due to the excavation process destroying small roots. In a few cases, the digs involved dead trees in which the roots had long rotted away leaving only impressions and holidays as evidence of their existence.

The depth of roots and root interactions was observed and measured by two methods: (1) the measurement of total approximate area of contacts on pipes with a cover depth of 3-feet or more (Figure 12) and (2) the area measurement (in square inches) of roots that exist at the pit perimeter walls (Figure 13).

The first method, which was used at all dig sites simply measured root caused impressions and holidays. In many cases the roots had to be removed from the surface of the coating/pipe in order to take the simple area measurements. The following table lists the digs where measureable contacts occurred and at what depths.

**Dig Sites with Measurable Contacts at Cover Depths 3-feet and Greater**

| DIG SITE | TOTAL APPROX. CONTACT AREA (sq. in.) | COVER DEPTH |
|---|---|---|
| RWVC-40-13 (RWVIM-98-13) | 29 | 36 |
| RWVIM-107-13 | 73 | 36 |
| RWVIM-128-13 | 78 | 36 |
| RWVC-38-13-L132 | 195 | 36 |
| RWVIM-126-13 | 551 | 36 |
| RWVIM-127-13 | 47 | 38 |
| RWVIM-159-13 | 133 | 38 |
| RWVIM-89-13 | 62 | 39 |
| RWVIM-136-13 | 33 | 40 |
| RWVIM-140-13 | 3 | 41 |
| RWVIM-160-13 | 101 | 42 |
| RWVIM-141-13 | 69 | 44 |
| RWVC-36-13 (RWVIM-96-13) | 4 | 48 |
| 153-12 | 11 | 48 |
| RWVC-55-13 (RWVIM-105-13) | 18 | 48 |
| RWVC-46-13 (RWVIM-101-13) | 38 | 48 |
| 153-1 | 47 | 48 |
| RWVIM-78-13 | 73 | 48 |
| RWVIM-76-13 | 112 | 48 |
| RWVIM-77-13 | 123 | 48 |
| RWVC-51-13 (RWVIM-104-13) | 197 | 48 |
| RWVIM-75-13 | 250 | 48 |
| 153-4 | 437 | 48 |
| RWVC-44-13 (RWVIM-100-13) | * | 48 |
| RWVIM-90-13 | 2937 | 48 |
| RWVIM-259-13 | 23 | 50 |
| RWVC-47-13 (RWVIM-102-13) | 95 | 50 |
| RWVIM-131-13 | 4 | 52 |
| RWVIM-132-13 | 78 | 52 |
| RWVIM-165-13 | 16 | 54 |

| | | |
|---|---|---|
| RWVC-49-13 (RWVIM-103-13) | 57 | 54 |
| RWVIM-155-13 | 27 | 58 |
| RWVIM-74-13 | 79 | 60 |
| RWVIM-73-13 | 104 | 60 |
| RWVC-41-13A (RWVIM-99-13) | 118 | 60 |
| RWVIM-137-13 | 2 | 61 |
| RWVIM-87-13 | 6 | 84 |

Figure 12

** Given the unique nature of dig RWVC-44-13 (RWVIM-100-13) (palm), there was no attempt to quantify the roots in contact with pipe and coating.*

Early in the root study a method was devised to measure root growth at the perimeter of the pit. The cut ends of roots were measured and converted to an area measurement (in square inches) of the roots that exist at the pit perimeter walls. These measurements were taken on roots at various levels on the pit wall (0-1', 1-2', 2-3', and 3-4'). The sum of area measurements in a specific layer of soil is considered the Root Area for that layer. Of the 33 sites from which we collected root area data, the following 7 sites exhibited >10% root mass below 3-feet depth:

**Root Area (sq. in.) Percentages at Pit Perimeter Wall**

| | | DEPTH | | | |
|---|---|---|---|---|---|
| DIG SITE | SPECIES | 0" - 12" | 12" - 24" | 24" - 36" | 36" - 48" |
| RWVIM-92-13 | Deodar cedar | 16% | 60% | 12% | 12% |
| RWVIM-106-13 | Silk | 19% | 47% | 23% | 11% |
| RWVIM-126-13 | Eucalyptus | 51% | 0% | 38% | 12% |
| RWVIM-130-13 | Ailanthus | 0% | 28% | 0% | 72% |
| RWVIM-132-13 | Black walnut | 29% | 7% | 48% | 17% |
| RWVIM-133-13 | Interior live oak | 60% | 27% | 4% | 10% |
| RWVIM-136-13 | Black walnut | 14% | 16% | 60% | 11% |

Figure 13

## 3.4 TREE SPECIES FACTORS

During the course of the root study a number of observations were made concerning the role of species in root/pipe interactions.

### 3.4.1 Predictability Within a Species

Not all species in the root study were represented by more than one individual tree. Several species, though, notably Deodar cedar and Eucalyptus had more than one individual in the species and these individuals shared similar root patterns. It should be noted that there were also multiple digs of some species that proved to be less predictable. See section 3.4.2 for this discussion.

### 3.4.2 Variability Within a Species

In some cases there were great differences between individual trees of the same species, even when located adjacent to one another with similar site conditions. Examples of this were observed at the following dig sites:

- Monterey pines (RWVIM-81-13 and RWVIM-82-13): These two trees were the same age and growing only a few yards apart and yet had very different root system architecture. Tree RWVIM-81-13 had approximately four times the root area (the total area measurement of all roots in the 4 pit walls) than tree RWVIM-82-13.
- Cottonwoods (RWVC-49-13/RWVIM-103-13 and RWVC-51-13/RWVIM-104-13): These two trees were approximately the same age, growing near each other in very similar conditions and yet had very different root systems and root-pipe interactions. RWVC-49-13 (RWVIM-103-13) was located 96-inches from the pipe and had 57 sq. in. of approximate total contact area of roots with pipe/coating. RWVC-51-13 (RWVIM-104-13) was located 126-inches from the pipe and had 197 sq. in. of approximate total contact area of roots with pipe/coating. The tree furthest from the pipe had more root-pipe interactions.

**3.4.3 Drought Tolerant Trees Growing Near Pipes**

Deodar cedar, Afghan pine, Italian stone pine, Eucalyptus, Cottonwood, Date palm, and Valley oak are all native to Mediterranean climates in which many months of summer are without rainfall (Figure 14).

Figure 14. Eucalyptus root system in un-irrigated soils at dig site RWVIM-126-13

Eleven (11) drought tolerant trees growing on dry sites were observed to develop deep root systems that resulted in significant pipe/coating interactions (Figure 15):

**Species on Dry Sites with Deep Root Systems**

| DIG SITE | SPECIES | APPROX. TOTAL CONTACT AREA (sq. in.) | COVER DEPTH (in.) |
|---|---|---|---|
| RWVIM-126-13 | Eucalyptus | 551 | 36 |
| 153-4 | Italian stone pine | 437 | 48 |
| RWVIM-75-13 | Afghan pine | 250 | 48 |
| RWVC 51-13 (RWVIM-104-13) | Cottonwood | 197 | 48 |
| RWVIM-73-13 | Afghan pine | 104 | 60 |
| RWVIM-128-13 | Deodar cedar | 78 | 36 |
| RWVIM-74-13 | Eucalyptus | 78 | 60 |
| RWVIM-127-13 | Deodar cedar | 47 | 38 |
| RWVIM-89-13 | Eucalyptus | 61 | 39 |
| RWVC-49-13 (RWVIM-103-13) | Cottonwood | 56 | 54 |
| RWVIM-92-13 | Deodar cedar | 32 | 30 |

Figure 15

The native Interior live oak was the one exception for drought tolerant tree species root systems. It has produced shallow root systems unlike the other drought tolerant trees. The following table illustrates these observations (Figure 16):

**Interior Live Oaks and Root Area (Sq. In.)* Percentages by Depth**

| | | DEPTH | | | | |
|---|---|---|---|---|---|---|
| DIG SITE | SPECIES | 0" - 12" | 12" - 24" | 24" - 36" | 36" - 48" | APPROX. TOTAL CONTACT AREA (sq. in.) |
| RWVIM-133-13 | Interior live oak | 60% | 27% | 4% | 10% | 0 |
| RWVIM-137-13 | Interior live oak | 42% | 51% | 3% | 4% | 2 |

Figure 16

*The area measurement (in square inches) of roots that exist at the pit perimeter walls. These measurements were taken on roots at various levels on the pit wall (0-1', 1-2', 2-3', and 3-4'). The sum of area measurements in a specific layer of soil is considered the 'Root Mass' for that layer.

### 3.4.4 Species Interacting with Pipes/Coating at Great Distances from Pipes

Two species growing in un-irrigated, deep clay soils, were observed to contact pipe coatings at great distances from the trees (Figures 17and 18).

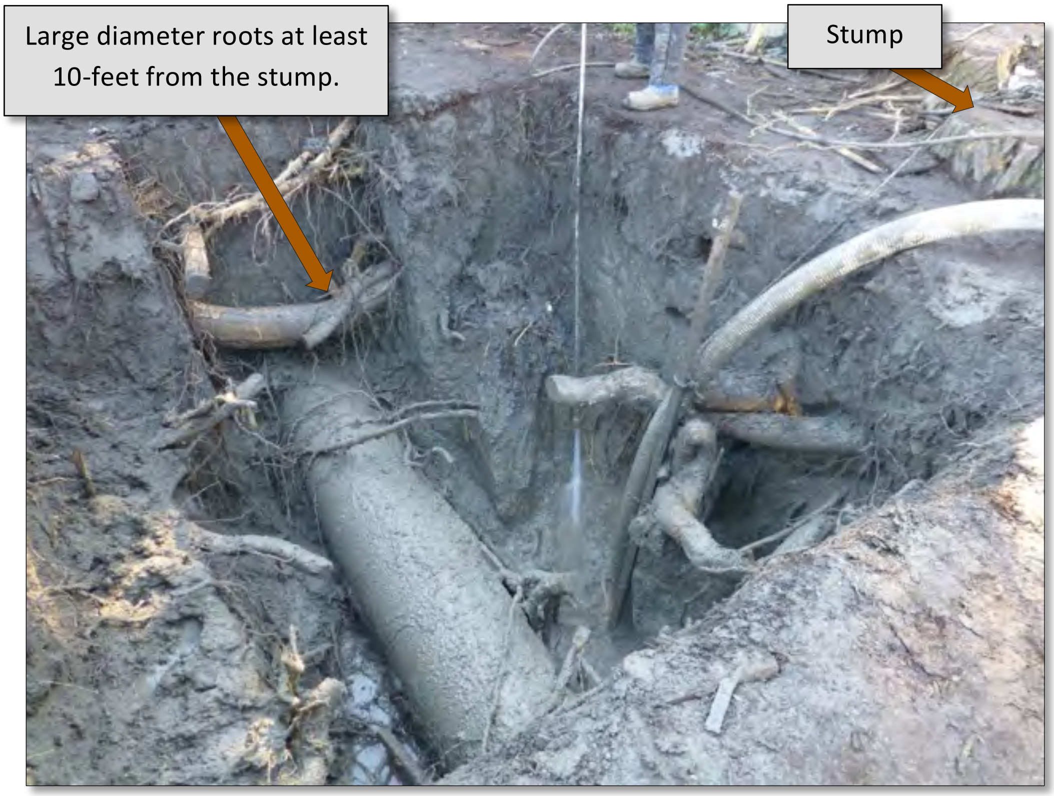


Figure 17. Dig site RWVC-51-13 (RWVIM-104-13)

**High Contact Sites at More Than 10-Feet from Pipe**

| DIG SITE | SPECIES | PROXIMITY TO PIPE (in.) | APPROX. TOTAL CONTACT AREA (sq. in.) |
|---|---|---|---|
| RWCV-44-13 | Palm | 180+ | Not Available |
| RWCV-51-13 | Cottonwood | 126 | 197 |
| RWVC-38-13-L132 | Coast redwood | 131 | 195 |

Figure 18

## 3.5 GROWING CONDITIONS IN TRENCHES AND NEAR PIPES

At most of the dig sites, native soils were used to backfill trenches during pipeline construction. That being said, the physical characteristics of the backfill soils had observable effects on root interactions on pipe/coatings when the soils were sandy or had restrictive layers. On the other hand, it was observed that soils consisting of deep clay, common in the Bay Area, root interactions were less consistently in close proximity to pipes or in creating coating contacts.

### 3.5.1 Trench Environment Effects on Root/Pipe Interactions

Restrictive soil layers, such as hardpans/duripans and bedrock, increased the incidence of root/pipe interactions. Trenching through or into these restrictive layers either (1) provided a pathway for roots to access the soil below this hardpan layer or (2) limited their growth to the backfill soils surrounding the pipe. Roots growing in the restrictive environment flourished in the trench backfill soils. It was observed that restrictive soil layers accentuated the interaction of roots with the pipe. This phenomenon was observed in the following sites (Figure 19):

**Sites With Restrictive Soil Layers**

| DIG SITE | SPECIES |
|---|---|
| RWVIM-90-13 | Valley oak |
| RWVIM-75-13 | Afghan pine |
| RWVIM-160-13 | Plum |
| RWVIM-141-13 | Almond |
| RWVIM-140-13 | Almond |

Figure 19

At these five dig sites roots were utilizing the trench to go into and/or below the hardpan layer. In the case of the Valley oak (RWVIM-90-13) the hardpan actually created a confined area that concentrated the growth of the massive root system near the pipe and, as a result, root and pipe/coating interaction was extensive (Figure 20).

Figure 20. Dig site RWVIM-90-13.

At dig site RWVIM 75-13, the pipe was laid on bedrock. The roots of the Afghan pine ceased downward growth, turned horizontal at the bedrock layer and grew along the pipe, resulting in many root/pipe contacts.

### 3.5.2 Pipe Environment Effects on Root/Pipe Interactions

At several dig sites, roots growing from various directions, came into contact with the pipe then turned and maintained contact with the pipe for great distances. At two dig sites the pit was enlarged in order to follow the roots in contact: Eucalyptus (RWVIM-126-13) roots were found to grow at least 15 feet along the pipe and Hackberry (RWVIM-106-13) roots were found to grow at least 16 feet along the pipe. In both cases, the roots were parallel to and in contact with the pipe as they exited the extended pit wall. It was not determined how far these roots stayed in contact with the pipe (Figure 21).

Figure 21. Dig site RWVIM-106-13.

## 3.6 FORCES FROM LARGE TREES NEAR PIPES

Five trees (Figures 14, 20, 22, 23), all less than 50-years old, had large (>3-inches) roots over, under, and in contact with the pipe. The close proximity of large roots near the pipe, in combination with tall trunks and large tree crowns, which act as levers, was of interest because the trees were relatively young. It is unknown what the implications are for these pipelines as the trees grow to maturity in another 50 to 100 years. The root study did not attempt to measure forces exerted during wind loading from trees in close proximity to pipes.

Figure 22. A young Deodar cedar at dig site RWVIM-92-13 interacting with an 8-inch pipe.

**Large Trees in Close Proximity to Pipes**

| DIG SITE | SPECIES | COVER DEPTH (in.) | APPROX. TOTAL CONTACT AREA (sq. in.) |
|---|---|---|---|
| RWVIM-90-13 | Valley Oak | 48 | 2937 |
| RWVIM-126-13 | Eucalyptus | 36 | 551 |
| RWVIM-128-13 | Deodar cedar | 36 | 78 |
| RWVIM-127-13 | Deodar cedar | 38 | 47 |
| RWVIM-92-13 | Deodar cedar | 30 | 32 |

Figure 23

### 3.7 IMPACT TO PIPE COATINGS BY ROOTS

At many dig sites, roots were observed in close proximity or touching pipes but not yet having any visible effect on coatings, yet. For the purposes of this root study, interactions are tree roots in contact with the pipe/coating in one of three ways: 1) coating impressions, 2) coating holidays, and 3) fine root penetrations into pipe coatings.

1) 'Coating Impression' is coating that has had its surface deformed by pressure from a root. Most commonly, coating impressions were discovered in this investigation by removing roots in contact with the pipe coating. Occasionally impressions were observed with no associated root present because (a) the root had died and decayed leaving no trace of the root that caused the impression or (b) the root was dislodged by the excavation process (Figure 24).

Figure 24. At dig site RWVIM-165-13 some impressions still had roots imbedded while other impressions were vacant.

2) 'Holiday' is a hole or gap in the coating that exposes the metal surface of the pipe. For the purposes of this report, only root-caused holidays are discussed. Many pipe sections excavated in the root study had other holidays that could not be positively identified as root-caused and therefore were not measured during our investigation (Figure 25).


Figure 25. Holidays at dig site 153-4.

3) The nature of these fine root interactions included (Figure 11):

- Fine roots impressed into the coating
- Fine roots growing inside cracks on coating surfaces
- Fine roots penetrating the upper layer of coating and proliferating into web-like complexes within the coating layers
- Fine roots penetrating all coating layers and populating thin spaces between coating and pipe surface
- Fine roots growing into and through apparently solid HAA and CTE coating.

### 3.7.1 Coating Types and Root/Pipe Interactions

Of 47 dig sites with pipe coating comprised of HAA/CTE, all had contacts and/or fine root interactions (Figure 26). 'Approximate Total Contact Area' is the estimated area (sq. in.) of all root-caused coating impressions and holidays combined.

The following table lists, in descending order, the area (sq. in.) of contacts in relation to coating type:

**Coating Type and Approximate Total Contact Area**

| DIG SITE | SPECIES | COATING TYPE | APPROX. TOTAL CONTACT AREA (sq. in.) | FINE ROOT INTERACTION ** |
|---|---|---|---|---|
| RWVC-44-13 (RWVIM-100-13) | Date palm | CTE | * | Yes |
| RWVIM-90-13 | Valley oak | HAA | 2937 | Yes |
| RWVIM-126-13 | Eucalyptus | CTE | 551 | Yes |
| 153-4 | Italian stone pine | HAA | 437 | Yes |
| RWVIM-75-13 | Afghan pine | HAA | 250 | Yes |
| RWVC-51-13 (RWVIM-104-13) | Cottonwood | HAA | 197 | Yes |
| RWVC-38-13-L132 | Coast redwood | HAA | 195 | Yes |
| RWVIM-130-13 | Ailanthus | CTE | 144 | No |
| RWVIM-159-13 | Walnut | HAA | 133 | Yes |
| RWVIM-77-13 | Silver maple | CTE | 123 | Yes |
| RWVC-41-13A (RWVIM-99-13) | Willow | HAA | 118 | No |
| RWVIM-76-13 | Coast redwood | CTE | 112 | Yes |
| RWVIM-73-13 | Afghan pine | HAA | 104 | Yes |
| RWVIM-160-13 | Plum | HAA | 101 | Yes |
| RWVC-47-13 (RWVIM-102-13) | Privet | HAA | 95 | No |
| RWVIM-106-13 | Silk | HAA | 81 | Yes |
| RWVIM-74-13 | Eucalyptus sp. | HAA | 79 | Yes |
| RWVIM-128-13 | Deodar cedar | CTE | 78 | No |
| RWVIM-132-13 | Black walnut | HAA | 78 | Yes |
| RWVIM-107-13 | Hackberry | CTE | 73 | No |
| RWVIM-78-13 | Deodar cedar | CTE | 73 | Yes |
| RWVIM-141-13 | Almond | HAA | 69 | Yes |

| | | | | |
|---|---|---|---|---|
| RWVIM-89-13 | Eucalyptus | HAA | 62 | Yes |
| RWVC-49-13 (RWVIM-103-13) | Cottonwood | HAA | 57 | Yes |
| 153-1 | Monterey pine | HAA | 47 | Yes |
| RWVIM-127-13 | Deodar cedar | CTE | 47 | No |
| RWVC-46-13 (RWVIM-101-13) | Black walnut | HAA | 38 | Yes |
| RWVIM-136-13 | Black walnut | HAA | 33 | Yes |
| RWVIM-92-13 | Deodar cedar | CTE | 32 | No |
| RWVC-40-13 (RWVIM-98-13) | Elm | HAA | 29 | No |
| RWVIM-155-13 | Grape | HAA | 27 | Yes |
| RWVIM-259-13 | Walnut | HAA | 23 | Yes |
| RWVC-55-13 (RWVIM-105-13) | Myoporum | HAA | 18 | No |
| RWVIM-165-13 | Apricot | CTE | 16 | Yes |
| 153-12 | Mulberry | HAA | 11 | Yes |
| RWVIM-129-13 | Silk | CTE | 7 | Yes |
| RWVIM-87-13 | Pyracantha | HAA | 6 | Yes |
| RWVC-36-13 (RWVIM-96-13) | Avocado | HAA | 4 | No |
| RWVIM-131-13 | Interior live oak | CTE | 4 | Yes |
| RWVIM-140-13 | Almond | HAA | 3 | Yes |
| RWVIM-137-13 | Interior live oak | HAA | 2 | Yes |
| 132-8 | Incense cedar | HAA | 0 | Yes |
| 153-3 (RWVIM-153-3A) | Monterey cypress | HAA | 0 | Yes |
| RWVC-38-13-L109 | Coast redwood | Tape/wrap | 0 | No |
| RWVC-41-13B (RWVIM-99-13) | Avocado | HAA | 0 | Yes |
| RWVIM-133-13 | Interior live oak | HAA | 0 | Yes |
| RWVIM-138-13 | Black walnut | Tape/wrap | 0 | No |
| RWVIM-139-13 | Valley oak | Tape/wrap | 0 | No |
| RWVIM-144-13 | Valley oak | Tape/wrap | 0 | No |
| RWVIM-158-13 | Black walnut | HAA | 0 | Yes |
| RWVIM-81-13 | Monterey pine | Tape/wrap | 0 | No |
| RWVIM-82-13 | Monterey pine | Tape/wrap | 0 | Yes |
| RWVIM-88-13 | Elm | HAA | 0 | Yes |

Figure 26

** Given the unique nature of dig RWVC-44-1 (RWVIM-100-13), (palm) there was no attempt to quantify or qualify the roots in contact with the coating.*

*** Fine roots often are destroyed and therefore not visible from hydro-vac excavation.*

Tape/wrap coating resists root interaction much more effectively than HAA or CTE coating. As illustrated in figure 27 , out of the 6 digs with tape/wrap coatings, none (0%) had root-caused coating impressions or holidays and only one had fine root interaction. Of the 47 digs w/ HAA or CTE coating, all (100%) had root-caused coating impressions, holidays, and/or fine root interactions. The data suggests that tape/wrap coating is less likely to be affected by any type of root (Figure 27). Of the six dig sites having tape/wrap coating, one location had fine roots growing through imperfections in the tape/wrap to reach metal pipe. Though these appear to be small root interactions, the implications are unknown.

**Locations with Tape/Wrap Coating**

| DIG SITE | SPECIES | COATING TYPE | FINE ROOT INTERACTION |
|---|---|---|---|
| RWVC-38-13-L109 | Coast redwood | Tape/wrap | None |
| RWVIM-138-13 | Black walnut | Tape/wrap | None |
| RWVIM-139-13 | Valley oak | Tape/wrap | None |
| RWVIM-144-13 | Valley oak | Tape/wrap | None |
| RWVIM-81-13 | Monterey pine | Tape/wrap | None |
| RWVIM-82-13 | Monterey pine | Tape/wrap | Yes |

Figure 27

## 4.0 CONCLUSIONS

Despite much variability in the findings, roots consistently interacted with pipes and coatings at most of the dig sites. All but five dig sites had tree roots interacting (impressions, holidays, and/or fine roots) with pipe coatings.

Variability is the best word to describe the findings gathered from observations made at 53 dig sites. There are a number of factors contributing to this phenomenon. The dig site selection process may be the primary factor with the variability in the findings. Because trees were not always located in the same relative position to the pipe, measurements were often unique to each dig site and not often comparable. Being able to predict tree root interactions with natural gas pipelines is complicated and difficult because of these variables: site factors, environmental factors, inherent species characteristics, and individual tree genetics.

### 4.1 ROOTS

The root types - lateral, sinker, oblique, and fine - all interacted with pipes and affected the pipe coatings. Tap roots, though, were not observed in the root study. There were a number of excavation pits in which lateral roots did not taper rapidly; trees many feet from the pipe had large roots interacting with the pipe. Variability in root growth was evident with all types of roots. Even the lateral roots, which are typically described as horizontal in nature were observed growing in downward directions and contacting pipes/coatings at 7 dig sites.

At most of the dig sites it was common to observe roots contacting pipes/coatings, creating impressions and holidays at depths greater than 3-feet. It was the sinker and oblique roots that were most likely to create contacts with pipe coatings, as they divide and grow to greater depths. Of the 53 dig sites, 36 sites (68%) created contacts on pipe coatings at depths below 3-feet (Figure 12). Of the 33 sites from which we collected root area data, 7 sites exhibited >10% root area below 3-feet depth (Figure 13).

Fine roots were observed interacting in a number of ways with the pipe coatings at most of the 53 dig sites. Of the 53 dig sites, 38 digs (72%) had observable fine root interactions. Fine roots are opportunistic, taking advantage of any weakness in the coating, but also growing into and through, seemingly, solid HAA coatings. These interactions with coatings were not restricted to pipes with shallow cover depths. Fine roots were present on pipes in excess of 8-feet.

## 4.2 SPECIES

Significant root/pipe interaction occurred when drought tolerant species were growing near pipes. Species native to dry Mediterranean climates such as Northern California tend to have root systems capable of reaching great depths, presumably to access water.

There were not enough non-drought tolerant species in the root study to compare average total contact areas between drought tolerant and non-drought tolerant and exotic species.

## 4.3 SOILS

Backfill soils create a favorable environment for root growth near the pipes. At most of the 53 dig sites, the backfill soils around the pipe were native soils. These native soils provided a good growing environment for tree roots and an opportunity for many root-pipe interactions. Roots growing in soils with restrictive layers flourished in the backfill soils. The restrictive soil layers accentuated the interaction of roots with the pipe. There were few differences between backfill soils in the trench and the surrounding native soils in deep clay soils. These soils were common in the Bay Area.

Roots, growing from various directions coming into contact with the pipe would often maintain contact with the pipe for great distances. It was not clear what factors contributed to an environment that favored root growth on the pipe. These conditions may have included:

- Improved soil aeration around the pipe surface
- Favorable pipe and/or soil temperatures near pipe surfaces
- Condensation (moisture) generated around pipe/coating surfaces

## 4.4 VARIABILITY

### 4.4.1 Variability of Root/Pipe Interactions Within Species

Predicting root interactions with gas transmission lines is difficult. Site characteristics, including the layout of the excavation pit, and complex environmental factors as well as growth variability within species and individual trees (due to genetics), are thought to play a role in this unpredictability. The most notable examples include:

- Monterey pines (RWVIM-81-13 and RWVIM-82-13
- Cottonwoods (RWVC-49-13/RWVIM-103-13 and RWVC-51-13/RWVIM-104-13)

### 4.4.2 Variability of Root/Pipe Interactions and Cover Depth

The following chart illustrates the unpredictable relationship between root-pipe interactions and cover depth. The chart depicts a general trend that deeper cover depth corresponds with less root/pipe interactions. However, it is important to note that there are many exceptions, as the red line indicates, which make the ability to predict these interactions difficult (Figure 28):

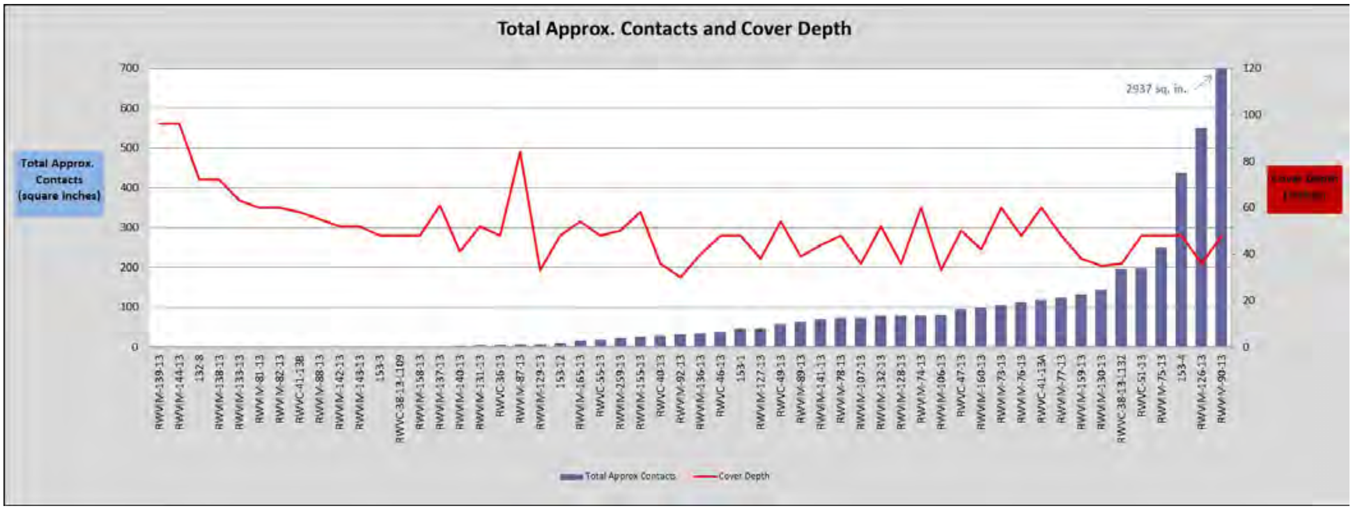


Figure 28

### 4.4.3 Variability of Root-Pipe Interactions and Horizontal Distance From Tree to Pipe Centerline

The following chart illustrates the unpredictable relationship between root/pipe interactions and horizontal distance from tree to pipe. The chart below indicates a trend or relationship between interactions and distance from tree to pipe centerline. Other factors, such as species, size of tree, and soil type affect interactions as much or more than distances between trees and pipe centerlines (Figure 29).

When analyzing the results of this study the following must be kept in mind:

- Analyzing the total contact area of root/pipe interactions can be challenging due to differences in the tree's proximity to the pipe. Because the dig site selection process did not choose trees that were always located in the same relative position to the pipe, root architectures from dig site to dig site were difficult to compare. The variations in tree-to-pipe proximity exacerbated the variability of observations and measurements and further reduced the predictability of root-pipe interactions. The benefit, however, of this variability is it allowed the root inspectors to observe tree roots' capacity to interact with pipes/coatings from a variety of distances from the pipe. Though trends and patterns were observable during this study, it is difficult to compare exact results from the 53 excavation pits.
- Pit sizes varied but typically were 9' x 9' or 10' x 10' (w x l) and as deep as the bottom of the pipe plus 2-feet. Because the excavation pits were limited in size, the excavation revealed only a portion of a tree's root system – not the whole root system, therefore the root inspectors could not predict what root patterns were outside the pit

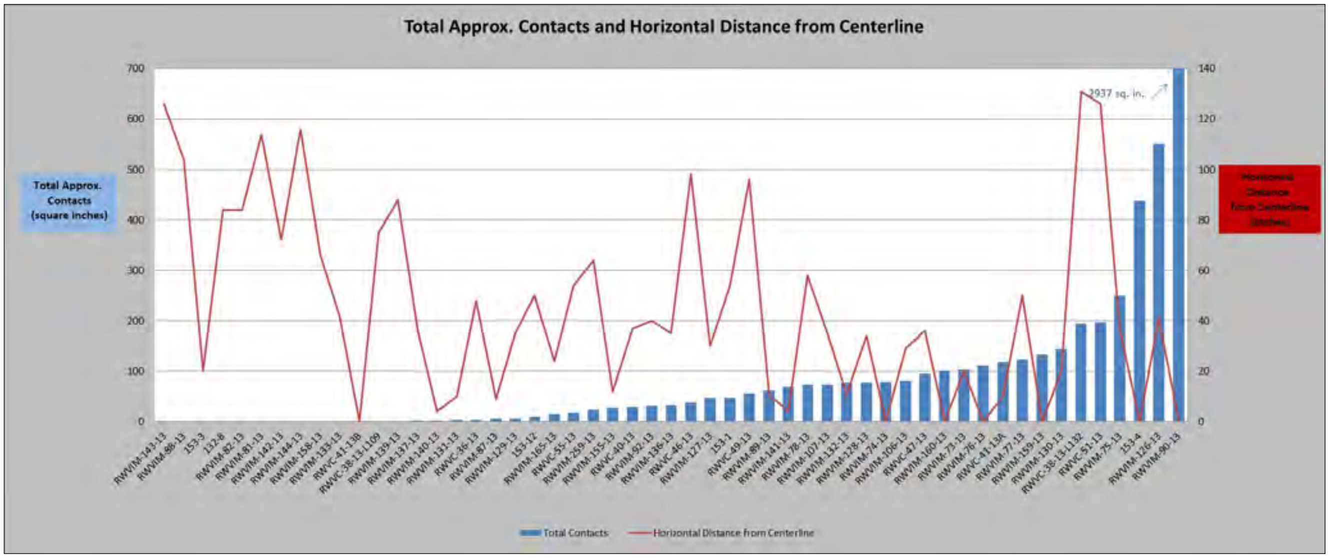


Figure 29

### 4.4.4 Variability of Root/Pipe Interactions and Orientation to Pipe

At two dig sites, trees growing on one side of the pipe produced a majority of root-pipe interactions on the opposite side of the pipe. For trees growing on one side of pipe centerline, it cannot be assumed that coating/pipe interactions will occur on the tree side of the pipe. For example

- Privet (RWVC 47-13): Shallow rooted tree (90% in upper two feet), but had 95 sq. in. of approximate total contact area, most of which were on the opposite side of the pipe from the tree.
- Afghan pine (RWVIM 73-13): Though the tree was on the 3 o'clock side of the pipe, the majority of damage to the coating was on the 9 o'clock side.

## 4.5 PALM TREES AND ROOT-PIPE INTERACTIONS

The only palm tree (RWVC-44-13/RWVIM-100-13), a Date palm, in the root study had more contact with the pipe coating than any other tree, even at great distances and depths. This was evident in all three of the small excavation pits on this site. The non-woody palm roots grew into and through the coating and on the pipe. The roots were unlike any other tree in the root study in that they did not impress or displace the coating. At the time, it was not possible to quantify our observations. Palm trees are sometimes planted in rows of multiple trees. If a condition exists where a row of palms is located near the pipeline, significant root-pipe interactions are possible (Figure 30).

Figure 30. At dig site RWVC-44-13 (RWVIM-100-13) (Palm tree) a 6-inch square sample of coating was removed.

## 4.6 WHITE PAPER AND ROOT STUDY CONCLUSIONS COMPARED

One objective of the root study is to compare observations and conclusions from the field study with the findings put forth in the White Paper (2012). The following table (Figure 31) is a side by side comparison:

| WHITE PAPER FINDINGS | ROOT STUDY OBSERVATION/ CONCLUSIONS |
|---|---|
| **Tree roots are generally divided into five types: tap, lateral, oblique, sinker, and fine. Pg. 5** | All but tap roots were observed during the root study, and all types interacted with pipe/coatings. |
| **The diameter of lateral roots decreases sharply with distance from the tree and is called the zone of rapid taper. Pg. 5** | This was a common anatomical characteristic in the root study but not all trees exhibited the zone of rapid taper. |
| **Lateral roots develop from the taproot near the soil surface and spread horizontally. Pg. 5** | This was observed at many dig sites but a number of trees formed horizontal lateral roots that angled downward a short distance from the base of the tree. |
| **Fine roots typically occur near the soil surface but they also grow from oblique and sinker roots. Pg. 6** | Shallow growth was common but at most dig sites there were fine roots interacting with pipes, even at depths in excess of 8-feet. |

| | |
|---|---|
| **In a broad study of northern tree species, 99% of the root systems occur within 3-feet of soil. Pg. 6** | Because most dig sites had pipes with cover depths exceeding 3-feet, most root-pipe interactions were below 3-feet in depth. 37 of the 53 dig sites (70%) had roots deeper than 3 feet. |
| **Compilations of reports about tree species are imperfect and can be misleading. Rooting characteristics within a tree species are not uniform. At least one report found that tree size and growth rate, not species, determines the potential to cause damage. Pgs. 5-6** | Trees were not always located in the same relative position to the pipe measurements were often unique to each dig site and not often comparable. Also, because of variables in site factors and environmental factors, being able to predict tree root interactions based on species is complicated. |
| **There appear to be only minor differences in rooting depth of trees in natural and managed landscapes. Soil conditions and climate limit rooting in most natural settings to depths of 3 to 5 feet. Some researchers found roots at greater depths, especially in dry climates. Pg.7** | Date palm, Deodar cedar, Afghan pine, Italian stone pine, Eucalyptus, and Valley oak are all native to Mediterranean climates. They were observed to have the ability to develop deep root systems that, when growing on dry sites, resulted in significant pipe/coating interactions at depths greater than 3-feet. |
| **Root growth is prolific in backfilled trenches and around underground utilities due to favorable soil conditions occurring within the trench and near the pipes. Pg.9** | The physical characteristics of the backfill soils had observable effects on root interactions on pipe/coatings when the soils were sandy or had restrictive layers. |
| **Pipes may alter other aspects of the soil environment. For example the differential thermal expansion rates of soil and pipelines can introduce pore spaces, which are suitable for root growth. Temperature variations between soil and pipes may also accelerate root growth. Pg. 10** | At several dig sites, roots growing from various directions, came into contact with the pipe then turn and maintain contact with the pipe (run with the pipe) for great distances. This topic proved a far more complex issue than this study addresses. |
| **The pressure of radial root growth on underground utility lines is not enough to deform or rupture them. Pgs. 11 and 12** | The root study did not attempt to measure the effect of radial pressures on pipes. |
| **There are possibilities of gas pipelines located on the windward side of a tree being stressed by forces that constantly move the tree. Pgs. 13-15** | The root study did not attempt to measure pipe stresses from adjacent trees though the topic is recommended for further research. |
| **There were no reported cases of pipeline damage from the weight of a tree where trees were located directly above pipelines. Pg. 15** | This root study did not attempt to study the potential of pipe damage from the weight of the trees directly above the pipelines nor did it attempt to measure the effect of removing trees located over pipes. |

| | |
|---|---|
| **No pipe damage from subsiding soils was reported. Pg. 16** | The root study did not attempt to measure the effect of subsiding soil on pipes. |
| **The only reference to Polyethylene type coatings reported pipes with these coatings were not damaged by root growth.** | Tape/wrap coating resists root interaction much more effectively that HAA or CTE coating. |
| **The WP does not discuss the effect of tree roots on Cathodic Protection (CP)** | The root inspectors were not qualified to assess or measure the effect of roots on CP. |

Figure 31

## 5.0 RECOMMENDATIONS AND RATIONALE

In large part, the recommendations in this report are aimed at PG&E vegetation managers. It is hoped these findings may be useful in their planning and practices as it relates to gas transmission pipelines. Based on observations and conclusions from the root study the following recommendations are proposed:

### 5.1 DEVELOP A PRIORITIZATION MATRIX

It is recommended that PG&E consider utilizing a prioritization matrix to integrate the findings from the root study into a tool that can help managers prioritize vegetation work within the natural gas transmission corridors. An example of a prioritization matrix can be found in *PG&E Gas Transmission Vegetation Management Assessment,* Garcia and Associates (May 2012). This matrix is found in the Appendix G, *Prioritization Matrix Calculator Algorithms,* of that report. Factors such as soil characteristics, species, tree size, tree age and longevity, and coating type could be weighted components in a prioritization matrix.

It should be noted, though, the limitations associated with using a matrix include the inherent subjectivity associated with the selection of the numerical value (or weight) for each factor. Primarily for this reason, we recommend using a team approach to developing the matrix. The team should include input from researchers, vegetation management staff, and pipeline engineering personnel. The logic behind the development of the subjective values for each category should be documented so the values can evolve over time as more research and data comes available.

### 5.2 REVIEW THE CURRENT PG&E MAINTENANCE STANDARD

Given the unpredictability of root growth and their interactions with pipelines, a conservative approach should be taken in establishing the vegetation standard for natural gas transmission pipelines. For instance, the current PG&E maintenance standard does not allow large trees within 10-feet of pipe centerline. The root study indicates that this minimum distance may need to be reconsidered. Some trees had an impact on pipe coatings at distances greater than 10-feet from pipe centerline as Figure 18 indicates.

## 5.3 PRIORITIZE TREE REMOVAL BASED ON PROZIMITY TO RESTRICTIVE SOIL LAYERS

Restrictive soil layers (hardpans/duripans and bedrock) lead to conditions that increase root/pipe interaction. Utilizing Natural Resource Conservation Service (NRCS) data and soil maps to locate where gas transmission lines are located in these soils could aid in the prioritization of tree removals. The NRCS data may also alert PG&E managers to other soil hazards. For example, the NRCS soils report for the area where RWVIM-140-13 and RWVIM-141-13 were located, describes the soils as having a "*Risk of corrosion pertaining to potential soil-induced electrochemical or chemical action that corrodes or weakens uncoated steel or concrete*."

## 5.4 INITIATE AN EFFECTIVE NO-PLANTING CAMPAIGN

It is recommended that PG&E initiate an effective no-planting campaign for trees within the gas transmission corridors. The most cost-effective tree to remove is the one that was never planted. PG&E has been highly successful in this type of effort on their overhead electrical facilities (e.g., SelecTree: the joint effort between PG&E and Cal Poly, San Luis Obispo).

## 5.5 RESEARCH

Continue research to increase understanding of root-pipe interactions. Although much has been learned during 14 months of field investigations at 53 excavation sites, a number of questions and concerns have surfaced. The following are topics recommended for further research:

### 5.5.1 Additional Palm Studies

Because of the invasive nature of palm roots on the coating at RWVC-44-13 (RWVIM-100-13), further research is recommended for a number of reasons, including but not limited to the following:

- How far do palm roots extend and affect pipe coatings?
- How do palm roots affect other types of pipe coatings?
- How do the roots of other palm species grow and affect pipe coatings?
- With such a large volume of root penetrations, why is there no displacement of coating material?
- What will happen when the large volumes of roots occupying the HAA and CTE coatings all die?

### 5.5.2 Additional Investigation Into Root/Pipe Interactions With Other Species

PG&E could use their vegetation management database to investigate the most common species in their gas transmission rights-of-way and conduct research to determine possible threats to pipelines. Examples of other species:

- Coast live oak (*Quercus agrifolia*), a common native tree growing on droughty soils in the coastal hills throughout California
- Liquidambar (*Liquidambar styraciflua*), a commonly planted landscape tree
- Ash (*Fraxinus spp*.), one ash was excavated but this is a common tree with several species
- Maple (*Acer spp*.), one maple was excavated at Woodbridge Golf course but this is a common tree, with several species, throughout the service territory
- Coast redwood (*Sequoia sempervirens),* only two of this species were excavated yet this is probably one of the most commonly planted species in PG&E's system
- Sycamore or Plane tree (*Platanus*), a California native and also commonly planted landscape tree

#### 5.5.3 Additional Research on Fine Root interactions

Fine roots have been documented growing into, within, and under pipe coatings. A number of questions arose during the root study, which warrant further investigation:

- Do fine root interactions cause disbondment of coating from pipes?
- Do fine roots growing between the coating and pipe create an environment favorable to corrosion (e.g., sulfur reducing bacteria)?

#### 5.5.4 Large Trees and Pipe Structure

Evaluate the effect of large trees growing near pipes, especially small and shallow pipes. In section 3.5, this report discusses long-lived trees. At maturity their large and deep roots may act as levers on the pipe under certain conditions.

#### 5.5.5 The Chemistry of Living and Decaying Roots and Their Effect on Pipe Corrosion

The chemistry of tree roots, alive and dead, is a complex topic. For instance, it is known that live roots can induce a pH change in the rhizosphere by the process of (1) accumulation and degradation of organic acids and (2) extrusion of H+ or OH- into the rhizosphere. Roots are complicated in their reactions with the matrix of substances, and with the myriad organisms that surround them. With the Pathways Project underway there will be vast amounts of dead roots decomposing and in many cases, contacting the pipe.

#### 5.5.6 Root Growth on Pipes

Conduct studies to determine what factors and/or conditions contribute most to the growth of roots on pipes, especially roots that, once encountering a pipe, continue to grow along it for undetermined distances. Some of these contributing conditions could include:

- Aeration
- Soil and Pipe Temperatures
- Soil Texture
- Condensation

# Attachment 7:

**California State University Fresno Center for Irrigation Technology (CSUF-CIT). "Ground Penetrating Radar as a method of evaluating orchard root development near pipelines". December 20, 2013.**

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# Evaluation of Horticultural Factors and Soil Conditions Related to Root System Development of Orchard Trees Planted Near Gas Transmission Lines

# An Interim Report, December 20, 2013

A project conducted as part of a Contract Work Authorization to MSA No. 2500753431 by the CSU Fresno - Center for Irrigation Technology within the overall project entitled:
**Horticultural and Soil Factors Related to Root System Development for Trees Planted Near Gas Transmission Lines**

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## Summary

The California State University Fresno Center for Irrigation Technology was contacted by PG&E in April, 2013 to discuss the potential for crop roots to grow around gas transmission lines. The primary factors that were assumed to affect root development near pipelines were determined to be the particular crop species, soil conditions and agricultural factors primarily, but not limited to, the irrigation method. The CSUF-CIT designed a project to collect data related to the crop and soil factors and to combine them with pipeline location data from PG&E to construct a geographic information system (RGIS) for the root growth potential of agricultural crops in the central valley of California. During the preparation of the proposal to PG&E, the CSUF-CIT staff conducted a literature search but found very little previous work related to root growth near pipelines. Consequently, a number of field studies were included in the project to verify the assumptions regarding the root growth potential of different crops, primarily orchard trees, and the effect of various soil conditions such as profile layers, for preferential root development near a pipeline. Identification of test sites where pipelines occurred under orchard trees in soils that were expected to encourage root growth near the pipe was the first use of the initial version of the RGIS. A number of possible field sites were provided to PG&E to be included in their overall study of pipelines under various trees. A series of 12 – 15 orchard sites was proposed to be excavated and evaluated by PG&E crews and contractors to validate the factors proposed for the RGIS. Once the factors had been confirmed or modified, the complete RGIS could be built to locate pipelines under orchards and vineyards and rank the crops and soils according to their potential for root development near the pipe.

In addition to the excavation and physical evaluation of the tree root systems, non-destructive alternatives to excavation were to be investigated. The most promising of the alternatives was Ground Penetrating Radar (GPR), an established method for detecting objects below the soil surface. The use of GPR to detect the root system of a tree in sufficient detail to evaluate the development of roots near a pipeline would be a valuable capability. No successful application of GPR for such a purpose could be found in published literature. A GPR system was proposed to be evaluated by comparing its results with the excavation and physical evaluation of the root systems at 6 of the 12-15 orchard sites to be excavated. If the root system map produced by the GPR correlated successfully with that done by the arborist in the excavation, then GPR could be a faster, more economical and non-destructive method of determining the degree of root development near a pipeline.

The initial RGIS results in July identified a number of possible test sites to be excavated. Unfortunately, the PG&E excavation and evaluation of non-agricultural trees continued well beyond the proposed start

date of late August for the first orchard excavations. Only 4 orchards and 1 vineyard have been excavated and physically evaluated of the 15 proposed sites. The GPR system was used at 2 of the orchard sites. Despite the fact that less than half the proposed field sites have been evaluated, it is possible to reach some tentative conclusions:

1. Orchard trees and grape vines are the two most likely crop categories to exhibit potential for root growth near a pipeline. There are 63,986 acres of orchards and vineyards over 2,569 miles of pipelines in the central valley. An additional 24,658 acres of orchards and vineyards appear to be close enough to the pipeline routes that further inspection is warranted. Almonds are the most common crop (57%) followed by grapes (31%), walnuts (6%) and pistachio (4%). The soil factors have only been evaluated for Fresno County where less than 15% of the orchard soils are those that were assumed to substantially increase the potential for root growth around pipelines.

2. Roots from orchard trees and grape vines probably have a lower potential for significant root growth near pipelines compared to trees in mature landscapes, old street plantings and natural vegetation communities. Commercial orchards and vineyards are, with some exceptions, younger compared to the life span of non-commercial trees. Most are smaller in size than non-commercial trees due to both genetics and age. Walnuts are an exception to this general conclusion and there are other orchard species with aggressive root systems that need to be evaluated. Some irrigation methods such as drip and micro-sprinklers may limit the tree root system to a smaller soil volume compared to flood or conventional sprinklers but those factors also remain to be evaluated.

3. Ground Penetrating Radar may be a viable, non-destructive alternative to physical excavation for evaluating root development near pipelines. The primary limitation of GPR is the fact that roots must be greater than about 0.6" in diameter to be detected at pipeline depths. GPR field data must be subjected to extensive signal processing to produce a usable root map. The two sites where GPR was used did not have extensive root growth near the pipe, however the roots that did grow in the pipeline trench were mapped if they were large enough. More field work will be necessary to develop GPR as a usable method to evaluate root development but it does appear to be a viable, though complex process.

The initial phase of this project has been reasonably successful, considering the very limited field work that was accomplished. The CSUF-CIT staff is looking forward to phase 2 of the project where the crop, soil and cultural factors can be validated for the completion of the RGIS and the development of the GPR process can be continued.

## Introduction

The following is an interim report of the activity and progress toward completion of a project undertaken at the request of PG&E by the staff of the California State University Fresno Center for Irrigation Technology (CSUF-CIT) to evaluate the potential for root development near gas transmission pipelines from the root systems of commercial crops, particularly orchard trees. After initial discussions between PG&E and the CSUF-CIT in April, 2013, a proposal was submitted for the project and a contract was executed to begin May 1, 2013, and end July 31, 2014. The work plan in the contract was divided into the first phase of a specific series of tasks to be completed by the end of 2013 and a second phase of work in 2014 that would be determined after the results of phase one had been reviewed and evaluated. The following report is a summary of the first phase of the project. The primary objective of the project was to build a Geographical Information System for root growth factors (RGIS) to match the pipelines located under agricultural fields in the PG&E service area with the crops that are planted in those fields and the soils in the root zones of those crops. Orchard trees were initially presumed to be the most likely crop category to pose a root growth potential problem to pipelines and some soil characteristics, such as the degree and intensity of soil layering, were assumed to increase the root growth potential associated with the presence of a pipeline. After further discussion, vineyards were suggested as the second most likely crop to develop roots near pipelines, though the root growth potential was assumed to be less than for the larger, more vigorous orchard trees. The RGIS to be constructed would identify the locations of the orchards and vineyards that included pipelines and characterize the soil conditions that might affect root growth. Root growth potential factors were proposed to be assigned to the different crops and soils to enable the RGIS to predict the degree of root growth potential for a particular orchard or vineyard associated with a pipeline. PG&E indicated in the preliminary discussions that a number of the orchard sites identified in the RGIS would be excavated and the roots growing around the pipe from a tree in the orchard would be characterized by an arborist. Those excavations not only would provide field data to confirm or modify the root growth potential factors assumed for the various tree types and soil conditions, but they would also enable a field evaluation of Ground Penetrating Radar (GPR) as a non-destructive alternative to physical excavation for assessing the degree of root development near a pipeline. About 70 locations were initially identified in the RGIS as sites where orchards or vineyards coincided with the pipeline route maps from PG&E. This first use of the RGIS was to find a wide range of tree and soil types to propose for excavation and was less than 10% of the total orchard area associated with pipelines. A complete RGIS with all crop and soil types found along the pipeline routes is still under construction. Crop maps and data tables in Appendix A show the acreage of particular crop types along the pipeline routes that have been included in the RGIS to date. Of those identified so far, four orchards and one vineyard were subsequently excavated. Two of the orchards were scanned by GPR prior to excavation.

## Preliminary Results and Conclusions

While definitive conclusions will not be possible until many more tree types and soils are investigated, some tentative conclusions have emerged that appear to be significant, though not statistically valid at this point.

1. **The Root Growth Geographical Information System (RGIS).** Though not complete, the RGIS matches crops from the California Department of Food and Agriculture crop maps with the pipeline maps provided by PG&E. The pipeline maps show the pipeline routes as an estimated centerline with a buffer area of 100m to each side of the presumed centerline. The RGIS, at this point in the project, maps all crops that fall within the 200m wide buffer strip representing the pipeline route. In many cases, more than one crop will occur within a buffer strip. In those instances, the total area of the buffer strip is reported in the RGIS, even though part of the area may be something other than an orchard. The precision of the RGIS for locating pipelines under

orchards and vineyards with a significant potential for root development and soils that would promote root growth in the pipeline trench will improve as more and better data is incorporated into the RGIS. The following has been determined from the RGIS as of December 1, 2013:

a. There is a total of 2,569 miles (4,134km) of gas transmission pipelines associated with orchards and vineyards in the areas of the Central Valley for which pipeline routes were provided to CSU Fresno.

b. There are 63,986 acres of farmland that includes orchards and vineyards with pipelines through them, within the 200m buffer area over the reported pipeline routes

c. There are an additional 22,785 acres of farmland that includes orchards and 2,016 acres of farmland that includes vineyards with pipelines routed along the edges of the fields that should be investigated to determine if the trees or vines are near enough to the pipeline to be of concern.

d. Of the 63,986 acres of farmland where the pipeline appears to pass through the field, 12,792 acres (20.0%) are almonds, 1,470 acres (2.3%) are walnuts, 339 acres (0.5%) are stone fruit, 921 acres (1.4%) are pistachios, 3 acres (0.004%) are citrus, 7,009 acres (11.0%) are grapes and 41,344 (64.6%) are other crops with a lower potential for root growth near pipelines.

e. Of the 22,642 acres of orchards and vineyards within the pipeline buffer strips, 56.8% are almonds, 6.5% are walnuts, 1.5% are stone fruits, 4.1% are pistachios, 0.0% are citrus, and 31.1% are grapes.

f. The soil factors described below were used with soil maps from the federal Natural Resources Conservation Service to match the soil factors with the orchards and vineyards found within the pipeline routes. These NRCS maps are very detailed but are only available for small areas such as counties and partial counties so they must be incorporated, individually into the RGIS from these many, separate maps. To date, East Fresno County and West Fresno County maps have been incorporated into the RGIS. Since the limited field excavation data available to date has not been sufficient to validate the assumed soil factors, the soils part of the project was relegated to a lower priority. With the assumptions that: 1. the proposed soil root growth potential factors are valid and 2. the Fresno county soil maps incorporated to date in the RGIS are representative of the rest of the state, some tentative conclusions can be stated. Soils with no significant layering (root growth potential values = 1) are found under 22.5% of the orchards and vineyards associated with pipelines. Soils with some layers or textural differences (root growth potential values = 2 & 3) are found under 62.7% of the orchards and vineyards associated with pipelines. Soils with high density or cemented layers (root growth potential values = 4 & 5) are found under 14.8 % of the orchards and vineyards associated with pipelines.

2. **Roots from trees and vines in commercial orchards and vineyards are probably less likely to grow to and develop a significant root system around a pipeline, compared to trees found in landscapes, street plantings and natural vegetation communities**. The factors that appear to affect the root growth potential of orchard trees planted over a pipeline are the tree type and age, the presence of irrigation and the soil conditions. Factors such as frequent tree replacement, irrigation, and fertility programs that are generally found in commercial orchards probably reduce the degree that orchard tree roots will grow to a pipeline compared to non-commercial trees but the root growth potential is still present. Orchard trees probably produce fewer and smaller roots around a pipeline compared to street and landscape trees but there will still be root development

near the pipe under the orchard. Grape vines, particularly wine grape varieties may be grown for several decades and approach the life span of old, non-commercial trees but their smaller size and growth pattern produces smaller roots than the average tree. Roots from commercial trees and vines may be less numerous and smaller but their potential to grow roots to the pipeline remains.

a. The number of roots and their size that may reach and grow along a pipeline appears to be correlated with the size and age of the tree. Most orchard trees are replaced after 20 – 35 years, either because the production begins to decline with age or new varieties are available that promise better production. The dominant tree crops in the Central Valley are the nut and stone fruits such as almonds, peaches, nectarines, and plums. These are all relatively short lived trees that are replaced relatively frequently compared to the life span of non-commercial trees. These orchard varieties usually do not have time to develop the deep and extensive roots system found under the older and larger non-commercial trees. There are exceptions such as walnuts that may be as old and as large as mature street and landscape trees. The walnut orchards that were excavated in this investigation did have root development around the pipeline exceeding that found under the almond trees that were excavated. Until more orchard trees are evaluated in the field, the degree to which tree type and age affect the root growth potential to a pipeline cannot be fully described but it appears at this point that the typically smaller, younger orchard trees are not as likely to develop extensive root growth compared to street and landscape trees.

b. An important external factor that may influence the root development of an orchard crop in the Central Valley is the presence and type of irrigation. The water requirements for crops found in central California are higher than for all but a few agricultural areas around the world; so irrigation is vital for orchard production. Without irrigation, trees will not produce enough to be commercially viable. Consequently, a successful orchard will be supplied with sufficient water on a regular schedule to maintain yield. The presence of a properly operated irrigation system will provide sufficient water for the growth of the tree in a relatively smaller volume of soil, compared to that usually found under non-commercial trees where the irrigation, if present at all, is generally less optimized than that found in agriculture. Old, successful trees in non-commercial settings are much more likely to have deeper and wider spreading root systems to tap a large volume of soil for the water supply needed to maintain growth. The recent advent of micro-irrigation techniques such as drip and micro-sprinkler irrigation, are even more likely to result in root systems limited to a smaller soil volume. Plant nutrition is an additional consideration that may affect the differences between orchard trees and their landscape counterparts. Commercial trees are generally provided with fertilizers at much higher rates and a more comprehensive spectrum than the typical street or landscape tree. The concentration of plant nutrients in a smaller volume of soil will, like the irrigation system, reduce the tendency of the tree to develop the deep and wide spread root system found under many non-commercial trees where the nutritional augmentation and water supply are applied with less rigor.

c. The soil conditions in the orchard were assumed to be one of the major factors in determining the degree of root growth potential to the pipeline from root growth. Soils exhibit a wide range of development determined by their parent material, age and other environmental factors. The soil conditions expected to influence the degree of root growth around the pipeline were primarily related to the existence of soil layers. Soils tend to differentiate into layers down through the profile. These layers will often have different density, structure and soil textures that will affect the movement of water and the ability of the tree roots to grow. Soil layers can be so dense and hard that roots and water will be excluded. The term for such a layer is a "duripan" though a more common name is "hardpan". There are several types of duripans but they all will restrict root growth and water movement to some degree. When orchards are planted on such soils, deep tillage practices such as ripping are often required to open passages in the duripan to allow roots and water to penetrate into the deeper soil layers. Presumably, deep tillage will be avoided near the pipeline, if the farmer is aware of its location, so the duripan problems may not be resolved along the pipeline route in the orchard. The only opening in the restrictive soil layer for the trees planted over the pipeline may the trench from the pipeline installation. The assumption that the pipeline trench will encourage root development near the pipe is generally valid but the few examples evaluated this fall were ambiguous. The most prominent duripan was found under the almond orchard southeast of Fresno but the root development around that pipe was less than might have been expected. There were no roots growing below the level of the duripan in this orchard except for the area directly under the tree where a hole had been dug when it was planted and where the pipeline trench had broken through the duripan. This tree root growth pattern was expected but the amount of development was less than anticipated. It is possible that the poor soil conditions due to the duripan in the orchard as a whole produced a smaller, less vigorous tree that failed to develop the expected root system. Conversely, the walnut tree in Lockeford was planted in a soil with very little layering yet there was clear evidence that some tree roots were affected when they grew into the soil over the pipeline. A more detailed description of the tree roots in these two orchards is included below in the GPR section of the report. It is clear that the soil conditions in the orchard will affect the root growth near the pipeline but those effects are complex and cannot be predicted with any confidence until more orchards have been investigated.

3. **The use of Ground Penetrating Radar to evaluate the degree and patterns of root development under a tree and pipeline may be a viable alternative to excavation, within certain limitations.** The basic principle of GPR detection of roots is sound but in practice, a considerable amount of data processing is required to convert the reflected signals received by the instrument in the field into a useable root map. There is also a compromise required with regard to selecting the signal frequency used in the orchard. Detecting roots at pipeline depths limits the resolution to roots larger than 1cm in diameter. Smaller roots can be detected with a higher frequency signal but the depth of penetration is generally shallower than most pipelines. The two trees that were scanned by GPR and then subsequently excavated showed reasonably good correlation between roots detected by GPR and those exposed during the excavation. In both cases, there were roots found near the pipe that did not appear on the GPR scans because they were too small. The presence of these small roots could be inferred by the larger roots that were seen by the GPR but no direct measure of all root growth near the pipeline was possible. The use of GPR in these field trials was limited to comparing the GPR data with excavation and physical root mapping to evaluate a tree that had been previously identified as a problem. The use of GPR for surveying along a pipeline route to find the location of the pipe and detect roots from trees in the orchard would be a very useful capability but it is a much more complex task. The currently available GPR, particularly the existing signal processing software, is not a practical system for surveying. Software that would enable larger areas to be evaluated in a shorter period of time may be available in the second phase of the project and will be tested in further field trials. A more detailed description of the GPR system and the two field trials may be found in the GPR section and Appendixes B, C and D of the report.

## Development of the Root Growth Geographical Information System (RGIS)

The construction of the Root Geographical Information System (RGIS) for this project is primarily a matter of combining location specific information from three different data bases to enable the mapping of orchards and vineyards with gas transmission pipeline routes and characterization of the soil conditions where pipelines coincide with orchards and vineyards. Initially, the Root Growth Geographic Information System was built in the following steps

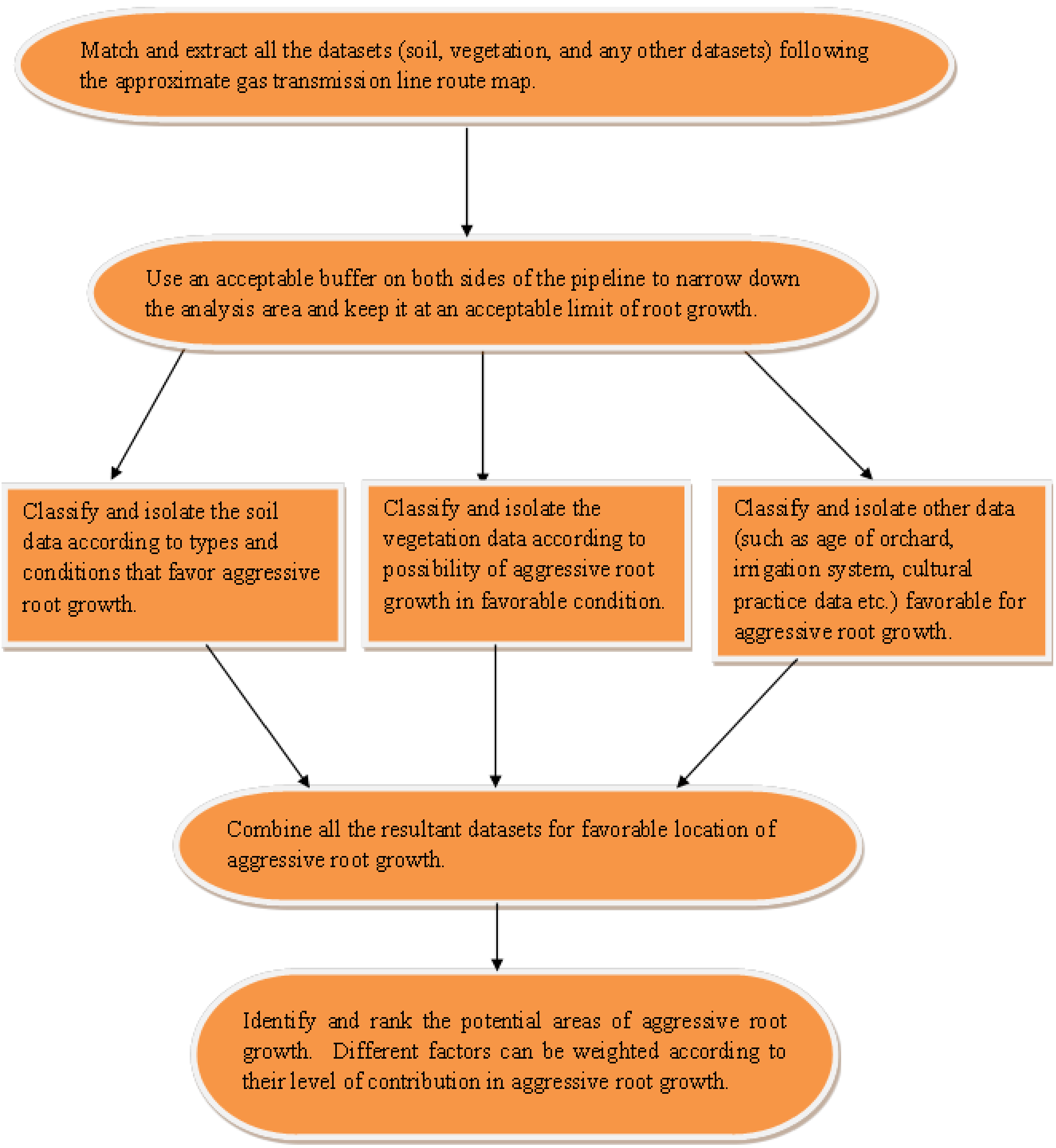


**Figure1: Flow diagram to develop the RGIS**

The first data base required to develop the RGIS was the pipeline location data provided by PG&E. The initial data set was incomplete and some routes were only shown in segments. Subsequent updates provided by PG&E were very helpful in filling in these data gaps. The latest data set received from PG&E, presumably the most recent one though not complete, is PLCL20130930 (line shapefile from centerline survey). Since the precise location of the pipeline was usually uncertain a buffer area of sufficient width was proposed to be sure the pipeline would be found within the buffer strip. After discussion with PG&E staff, it was determined that the pipeline would almost certainly be within 100m of the location reported in the pipeline data base. Therefore, the buffer strip that represents the pipeline route has a width of 200m with the reported centerline of the pipeline in the middle of the strip. Crops and soils that are to be matched with the pipelines would be all those found within the 200m wide buffer strip. Certainly, some crops and soils will be located in the buffer strip but not actually over the pipeline but, until the pipeline location is established more precisely, any crop or soil found within the strip will be assumed to be associated with the pipeline. The most recent pipeline route map is shown in Figure 2.

The factors that were assumed to define the potential for the root systems of trees and vines to develop around pipelines were initially identified as related to crop species, soil conditions and agricultural practices found in a field associated with a pipeline. A statement of those factors, with their assumed levels of influence was prepared at the beginning of the project to enable a Geographical Information System to be constructed. That initial statement of root growth potential factors may be found in Appendix A and is summarized below in Table 1. At the time this interim report was prepared (December, 2013) there was not sufficient field data from the few field investigations to date, to validate the assumptions or to fully justify the division of some root growth potential factors into the categories that were defined below. The soil factors in particular should probably be subdivided into fewer root growth potential categories in the current version of the RGIS, though further field data acquisition should enable a more detailed range of root growth potential factors by the end of the project. Likewise, the crop factors will eventually be refined to differentiate among the various types of trees. Some tree crop species have root systems that are genetically more likely to produce root growth near a pipeline than others. However, until each of the major tree crops has been evaluated in multiple locations and soil conditions, a more specific range of root growth potential factors cannot be postulated.

**Table 1. Initial crop type, soil and cultural factors used to build the RGIS**

**Crop factors used to build the RGIS**

Crop type 1 – Herbaceous crops with a growing season of less than a year.

Crop type 2 – Biennial crops with a growing season of more than one year, but less than two.

Crop type 3 – Perennial herbaceous crops generally grown for at least three years.

Crop type 4 – Perennial vines and shrubs

Crop type 5 – Orchard trees

(a more detailed description of the crop types may be found in Appendix A)

**Soil factors used to build the RGIS**

Category 1 – Soils with no significant changes in texture or density throughout the profile.

Category 2 – Soils with slight changes in texture or density from one layer to another in the profile.

Category 3 – Soils with more significant changes in texture or density increases within the profile

Category 4 – Soils with well developed, but not cemented (indurated) duripans

Category 5 – Soils with very well developed and indurated layers.

(a more detailed description of the soil categories may be found in Appendix A)

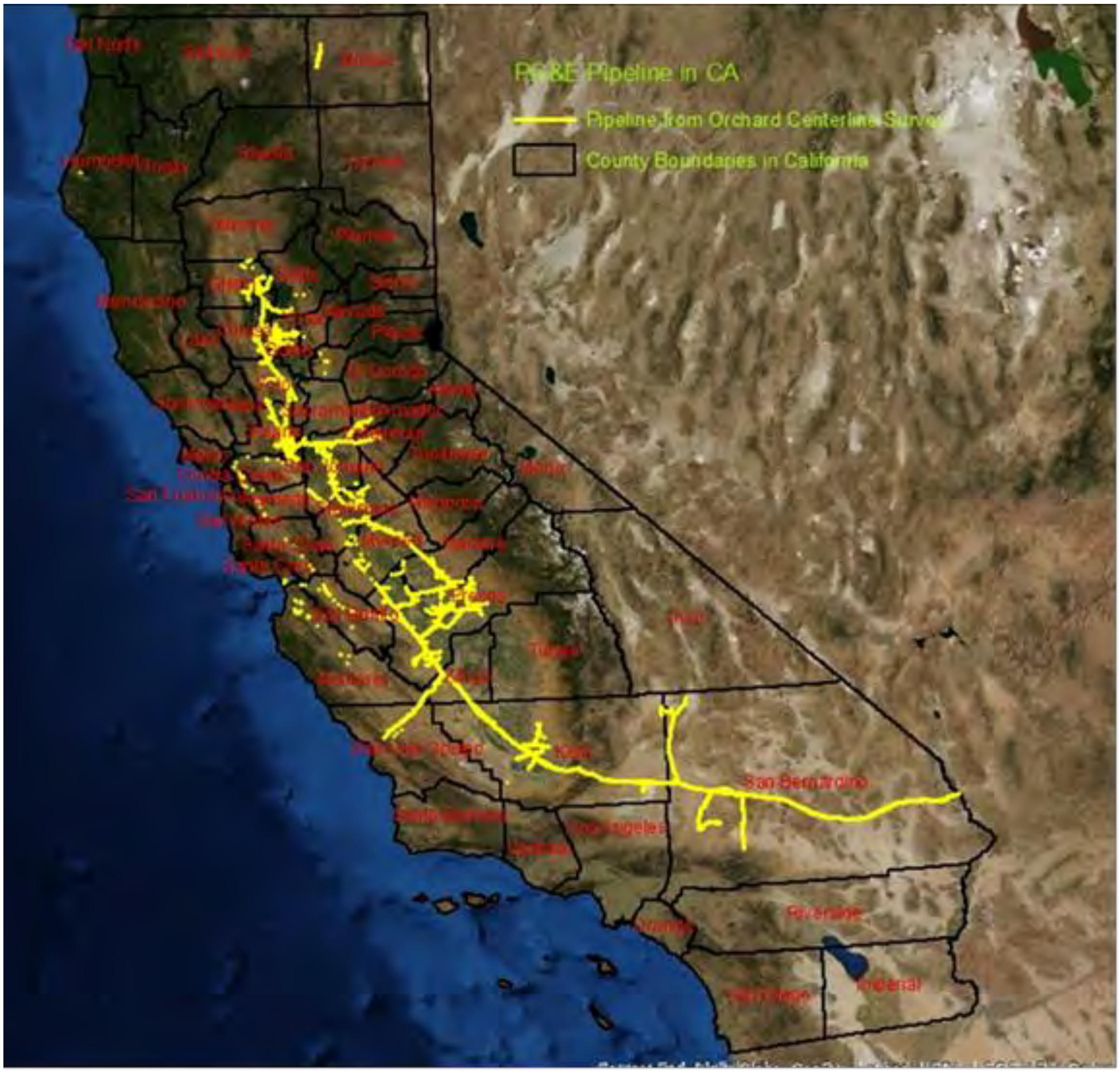


**Figure 2: PG&E pipeline routes in California from the Centerline Survey**

The crop and soil factors listed above and described in more detail in Appendix A are those for which data sets are available to be used to construct the RGIS. Once the crop and soil factors are determined for a specific location, other factors may be added to predict the potential for root growth development around a pipeline at that location. Most of these additional factors will have to be determined by inspection of the specific site or interview with the operator. Probably the most important of those cultural factors would be the presence and type of irrigation system. Irrigation will be necessary for any orchard in California and the particular method may have a significant influence on the potential for root growth around a pipeline. Fertilization of the trees and various tillage practices will also have an effect and would need to be included in any “overall root growth potential” factor that could be developed from the RGIS.

The second data base required for the RGIS was the land cover map from the California Department of Food and Agriculture. That data base shows the locations of major crops in California in a form that, when matched with the pipeline map can be used to find any of the crop types that occur within the pipeline buffer strip. The crops are represented on the CDFA map as a 30 meter x 30 meter resolution raster data set. Since the resolution is 30m, there is some uncertainty associated with it to accurately designate the crop type with its precise spatial location. This data set is the best resource available to use in the RGIS. The crop data set used was from 2012. In phase 2 of the project, the RGIS will include the 2013 land cover data, when it is available, as well as previous land cover data sets for each 10 year increment back to 1980. The current data set used for the RGIS has 66 different crop types, including 15 crop types that are orchards of some type, plus grapes within the buffer strips. Table 2 in Appendix A shows the acreage of each crop type with the orchard and vineyard percentages calculated.

Combining the CDFA crop map with the pipeline route map for the counties in the central valley of the state produced a map of the crops found within the pipeline buffer strips. An example of a pipeline in Fresno County showing the crops that are planted within 100m of the reported pipe centerline is shown in Figure 3. Figure 3 shows that some crops types appear to occur over the reported pipe centerline; some fill the entire 200m buffer strip, some fill most of the buffer strip and some are within the strip but do not occur over the reported pipe centerline. All crops within the buffer strip are listed in Table 2 (Appendix A). The crop types that appear to actually occur over the reported pipe center line are listed in Table 3 (Appendix A). Those that are in the buffer strip but do not appear to have the pipeline running though the planting are listed in Table 4 (Appendix A).


**Figure3: Land Cover within 100 Meter Buffer of Pipeline**

The third data bases to be used in the RGIS are the soil surveys from the federal Natural Resources Conservation Service (formerly the Soil Conservation Service). These are digitized revisions of the soil surveys of agricultural soils that have been mapped by the federal service since the nineteenth century. The updated soil surveys are now available as maps that can be incorporated into a RGIS. The soil surveys were used in two ways for this project. A soil data base was matched with the pipe centerline buffer strips to create a soil map of the pipeline routes in the same manner that the crops were matched with the pipelines. Figure 4 shows a portion of pipeline in Fresno County with the soils mapped for the 200m buffer strip. The NRCS soils data was also used to characterize the soils in the orchards and the vineyard that were identified in the RGIS and subsequently excavated to directly evaluate the root systems. The soil maps and the physical soil characteristics for the sites are in Appendixes C and D.

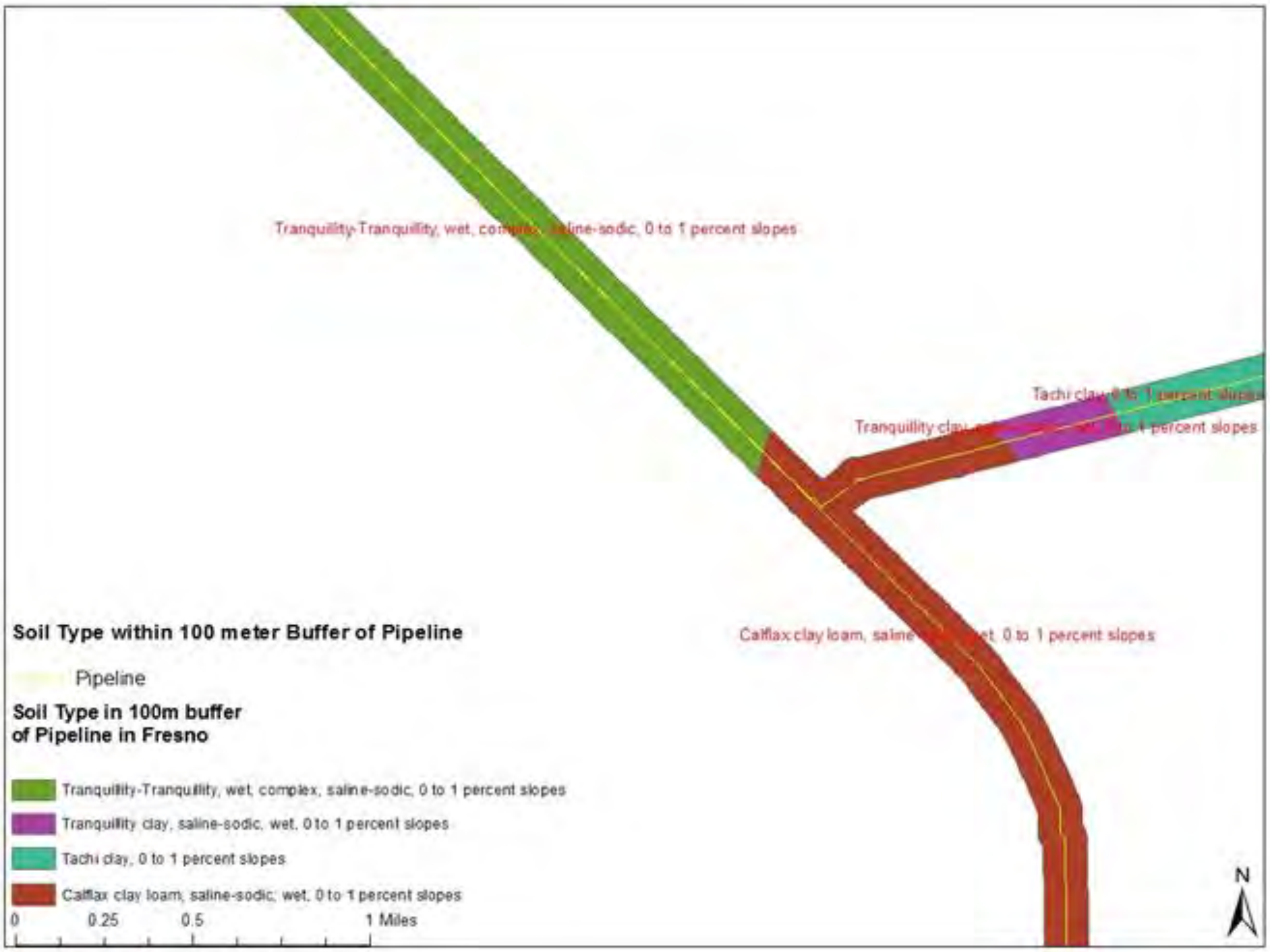


**Figure 4: Soil Types within the 200 meter buffer strip for a section of pipeline in Fresno County**

A complete list of the soils found in the pipeline buffer strips for Fresno County is in Appendix A, Table 5. When the soil conditions that are assumed to affect the possibility of root growth around a pipeline have been validated after additional field excavations, the soils mapped in this fashion will be assigned adjusted rank values and matched with the locations of orchards and vineyards in the RGIS. Currently that work has been done for only a few test areas, completion of the RGIS at that level of detail will require both more field work to validate the soil risk factors and further RGIS revisions to better match the soils with orchards/vineyards and the pipeline routes.

# Evaluating orchard root development near pipelines with GPR

The research agreement between PG&E and the CSUF-CIT has as its primary objective the creation of a Geographic Information System (RGIS) to identify and characterize the commercial orchards and vineyards located along the gas transmission pipeline routes that are of interest to PG&E. A secondary objective in Tasks 4 & 5 of that agreement is the evaluation of Ground Penetrating Radar (GPR) as an alternative to physical excavation and other destructive testing to determine the presence of crop root systems that may be a root growth potential to gas transmission pipelines. In April, 2013, at the time the proposal was prepared and the agreement executed, the CSUF CIT staff had no direct experience with GPR. A search of the scientific literature in horticultural and soil science journals suggested GPR as the most practical method for non-destructive evaluation of root systems so the proposed research plan included time and resources to evaluate the efficacy of GPR for studies of this nature. The objective was to assess the use of GPR for mapping root systems near trees and pipelines that were to be excavated by PG&E as part of their overall project. Root maps produced from the excavations would be compared with those generated by the GPR study that preceded the excavation. If the GPR root mapping correlated sufficiently with the root system documented in the excavation, the use of GPR could then be recommended as an economical and non-destructive alternative to physical excavation that, in most cases, destroys the tree or vine. While a statistically acceptable amount of field work and data processing will be required before a definitive recommendation can be made from this study, it does appear that the use of GPR may be of value in determining the degree of root growth potential from orchard tree root systems planted over gas transmission lines. The potential for GPR as the primary method for locating sites where commercial trees are a pipeline root growth potential may not be valid but GPR does appear to be a usable method for evaluating the degree of tree root development near a pipeline when the tree has been identified as a problem by RGIS or other means.

The three CSU Fresno researchers participating in this project are reluctant to make recommendations regarding the efficacy of GPR for this application based on the limited experience of these two field trials. However, we are aware that it is necessary at this point in the project to reach some conclusions, tentative as they may be. Consequently, we are prepared to make the following recommendations, subject to confirmation or modification after more field work is done. Furthermore, there are some questions and limitations that can be stated, perhaps with more conviction than the positive recommendations that precede them.

1. **Ground Penetrating Radar can be used to map the general development of a tree root system associated with a pipeline within the following constraints:**
   - A. The location and depth of the pipeline should be accurately established by means other than GPR. The pipe may be located by GPR but other features such as animal burrows may be confused with the pipe location unless it is established prior to scanning. The depth of the pipe or some other object in the root zone is necessary in order to accurately calibrate the depths of the roots that are found. The GPR requires at least one known depth to a feature in order to precisely determine the depths to the other objects in the scan.
   - B. A sufficient number of scan lines or profiles must be measured by the GPR to properly characterize the root system of a tree. The circular pattern of scans used at the Lockeford site is a good method of root mapping for this application. The mapping of the entire root system, as was done for the walnut stump, is highly recommended in order to compare the root development in the pipeline trench path with root growth in the native soil.
   - C. The resolution of GPR with the 400 mHz antenna required to penetrate below the pipeline depth is about 1.0 - 1.5cm. The wide bandwidth of the signal may allow some roots

smaller than that to be detected under favorable conditions but only those roots larger than 1cm can be detected with confidence. Therefore, only the large, structural components of a tree's root system will be mapped by GPR. Small roots that reach the pipe may not be seen, though their presence may be inferred from the pattern of growth of the larger roots.

D. Only roots growing in a predominantly horizontal orientation are likely to be detected by GPR. This is a particularly serious limitation for the application to the assessment of pipeline root growth potential where roots may be stimulated to grow deeper when they encounter the backfill of the pipeline trench. Indirect evidence of this type of root growth was seen in the walnut stump excavation where large roots appeared to stop as they reached the edge of the trench but were found in the subsequent excavation to begin to grow vertically at that point. Scanning at a greater density than the 2' increments used in these studies may improve the mapping these radical changes in the direction of root growth but at the expense of more time and effort required to generate the GPR diagrams.

E. The need to scan a number of lines around a tree/pipeline along with the time required to process the data into a comprehensible root map required about the same amount of time as a conventional excavation for these two field studies. The data from the field scans is difficult to interpret until it has been processed. That processing, for these trials, required sending the field data to a consultant (TreeRadar in Silver Spring, MD) to develop the maps and diagrams presented here. While the data processing could be done more quickly if the CSUF-CIT staff had the software available and were properly trained in its use, that will not occur until later in the project. Dr. Mucciardi, the consultant at TreeRadar will be supplying a new version of the software that may enable much of the data processing to be done immediately after the field scans are taken in the field. Should that new software be successful, the time between collection of the field data and the production of the root maps will be considerably reduced. At present, the real value of GPR is the fact that it is non-destructive, not that it is significantly faster than excavation. If the software improvements are realized, GPR will not only be an acceptable alternative with respect to destruction of the subject trees but also much faster than the excavation to evaluate presence of roots near a pipeline.

2. **Ground Penetrating Radar can be used to detect alteration of the native soil in the pipeline trench where the backfill material produced different root growth conditions.** Direct indication of the change in soil structure between the trench and the native soil was not seen in either of the two field data sets reported here but the scientific literature suggests that GPR can detect those changes in soil structure, density and water content. The walnut tree's root growth at Lockeford appeared to be affected by the difference in soil conditions in the trench, though the indications were very subtle. Further consultation with Dr. Mucciardi regarding the detection of soil disturbances such as the pipeline trench assured us that this is very possible with appropriate data processing and training of the GPR operators. The data processing for these two studies was focused on finding and mapping roots near the pipeline location. Further work with the field scan files might enable us to map the altered soil characteristics of the pipeline trench.

The general recommendation by the CSU Fresno CIT research group with regard to the use of GPR to evaluate roots associated with a pipeline is guardedly positive. While none of us were confident at the beginning of the project that GPR would be as successful in mapping roots as a conventional excavation, we now feel that, within its constraints, GPR could replace destructive excavation in many cases. Where the location and depth of the pipe is known and the tree is a species with roots large enough to be detected; GPR properly used with sufficient scan lines and post-field data processing can provide a root system map that would indicate the extent of root growth near the pipe. Small roots, growing closer to the pipe than the large roots, or from trees with small, fibrous root systems may not be completely mapped by GPR. We can recommend the use of GPR to map roots as small as 1cm in diameter and clusters of smaller roots that collectively approach that size.

The two studies done this fall, reported above, were focused on evaluation of orchard trees that were known to be growing over or near pipelines. The location of the pipe and its depth was determined prior to the GPR scanning. The use of GPR for surveying an orchard where the location of the pipe is not know with precision and the presence of the roots of many trees is in question has not yet been investigated. Scanning a long length of pipeline route to find the pipe and indications of tree roots around it would be a very useful application of GPR but the techniques required are different from those of evaluation that were used in these two field studies. The number of closely spaced scans needed for the root maps around those two trees would not be practical for the use of GPR in surveying. The layout of the grid and the scanning required several hours for each tree. A GPR crew might be able to do the field work on 3 or 4 trees in a day, encompassing no more than 50’ - 100’ of pipeline. Different field techniques that would minimize the amount of scanning per tree while maximizing the area of coverage along the pipeline will need to be developed. The field procedures required to find and follow a significant length of pipeline to locate roots along it from a series of trees in an orchard are planned for the later phases of this study but have not yet been investigated. The successful application of new processing software that would enable much of the scan data to be processed immediately in the field (mentioned above in recommendation 1E) would be vital to the development of field survey procedures for the GPR.

## Remaining problems and proposed activities to complete the project

The agreement between PG&E and the CSU Fresno – Center for Irrigation Technology to study root development associated with pipelines is scheduled to continue through August, 2014. The specific tasks listed in that agreement were intended to delineate the phase 1 activities to be accomplished by December, 31, 2013. In the discussions between PG&E and CSUF-CIT, it was recognized that the RGIS would require several more months to be completed. There was very little confidence that the evaluation of the GPR to map root activity could be completed within the 6 field studies that were planned. The original plan called for 6 field evaluations of the GPR to be chosen from 12 – 15 orchards that were to be excavated beginning in late August. In fact, the orchard excavations did not start until early October and only 4 orchards were excavated along with a vineyard. Only two of the orchards were scanned with the GPR prior to excavation.

In order to complete the project and provide PG&E with a sufficiently robust RGIS to enable the prioritization of locations along the pipelines for in-house investigation, the following tasks are proposed:

1. Meet with PG&E staff to discuss the tentative results and conclusions in this interim report. Determine the specific issues to be studied further and assign responsibility for the activities to complete the revised work plan.
2. Determine the additional orchard/soil combinations to be located for field studies to validate the crop and soil factors required to improve the RGIS. In addition to selecting appropriate combinations of crops, soils and cultural conditions, modification of the excavation procedures should be discussed to expedite the process and reduce the time, expense and damage to the orchard from the evaluation.
    i. Identify tree types that have not been sufficiently evaluated and find locations that can be added to the project. Particular emphasis should be placed on

almonds because of their predominance, pistachios because they are reported to have very aggressive root systems and citrus.

ii. Identify additional soils to be studied, particularly under almonds and pistachios since those types are widely planted on a variety of soils.

iii. Select the trees and soils to be studied to include a variety of common irrigation methods to evaluate the effect of the application pattern on tree root development, particularly on soils that appear to have a high potential for root development around a pipeline.

iv. Evaluate each of the sites selected for crop type, soil type and irrigation method for the degree of “root spreading” to establish, if possible a method of evaluating the degree of root development near the pipe as a function of the distance from the tree to the pipeline.

3. Complete the evaluation of the Ground Penetrating Radar system and establish field procedures for its use in determining root development around pipelines

    i. Scan as many as possible of the additional excavated orchards (presumably 15-20 sites) to compare the root maps from GPR with the physical evaluations.

    ii. Acquire the additional signal processing software that will be available next year and develop a procedure that will enable the GPR to be used to survey a significant length of pipeline to locate it precisely and detect significant root development at various points along the pipe.

4. Refine the crop and soil factors used to predict root development in the RGIS. None of the factors used in the incomplete RGIS discussed in this interim report have been validated or could be used with much confidence to predict root development around a pipeline at this point. The field validation of the crop, soil and cultural factors proposed in item 2 will be used to either confirm or modify those factors to increase the accuracy and utility of the RGIS.

    i. Crop factors need to be revised, particularly with respect to the different tree species. The current RGIS crop factor is the same for all trees and that can obviously be improved to reflect different root growth patterns from different orchard species. The field evaluations (item 2) will be the primary method to accomplish this task but a literature search and consultation with other horticulturalists should also occur. Land cover data is available for several years prior to the 2012 data set used in this RGIS. Adding previous years’ crop maps to the RGIS will allow estimates of orchard age as well as identification of orchards that may have existed over pipelines for a significant time but were removed prior to the 2012 year.

    ii. More accurate pipeline route data from the continuing PG&E Center Line study needs to be incorporated to enable the 200m buffer strips to be reduced in size as the pipeline locations are more precisely determined.

    iii. The soil factors will be evaluated in the field studies as well to better establish the effects of different soil conditions. Better soil factors can then be applied to the soil maps beyond the Fresno County soil surveys that the current study was limited to so that the whole RGIS will reflect the different soil conditions for orchards over pipelines.

iv. The crop and soil factors listed above are available as data sets but there are other agricultural factors that need to be evaluated to determine their significance. Irrigation method should be the primary cultural factor but pre planting land preparation and fertility programs may also have an effect. The field studies (item 2) can be used, along with literature searches to determine the magnitude of these cultural factors for the RGIS.

v. Combine the crop, soil and cultural factors into an overall "root development potential value" from the RGIS that will enable PG&E to determine the priority of the orchards in the RGIS with respect to the magnitude of the predicted root development associated with a pipeline. This overall potential value would indicate the order in which the locations should be investigated to most effectively find orchard tree root development issues that might have an effect on a pipeline.

5. The CSUF-CIT staff limited our efforts to the development of the RGIS for orchard trees and other commercial crops. We are aware that a considerable number of non-commercial trees were excavated and evaluated prior to our part of the whole project. While we were able to observe a few of those evaluations of landscape and other trees, there was no provision to compare the results from the 4 orchards we investigated with the many landscape, street and natural vegetation community trees that were evaluated. If PG&E provided the CSUF-CIT staff with the reports and data from those non-agricultural evaluations, a systematic comparison of the differences between agricultural trees and the others could be made.

The original contract between CSUF-CIT and PG&E runs through summer, 2014. The CSUF-CIT staff is applying for matching funding through the CSU Agricultural Research Initiative. This funding would equal the PG&E funding to increase the level of effort, share costs of the field testing and continue the project through 2016. The ARI funding will be confirmed in May and consultation with PG&E to determine shared costs and plan the expansion of the project would begin at that time. The ARI grant would begin in July, 2014 and would require the present contract to remain active through that start date.

# Appendix A

## Rational for the crop and soil factors and data tables for the RGIS

This section is the description and rational behind the root growth potential factors related to soils, crop type and cultural practices that was prepared in June, 2013 and was or will be used to identify the potential in commercial orchards and vineyards for crop root systems to develop around pipelines.

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The root development root growth potential factor assigned to a particular orchard or vineyard is based on the soil type, the type of crop, and cultural factors such as irrigation method and land preparation prior to planting. The soil and crop factors are calculated from various public data bases, primarily available from the federal Natural Resources Conservation Service and the California Department of Food and Agriculture. A root growth potential factor is assigned to each soil and crop type found in fields associated with pipelines. These factors are currently a simple numerical value from 1 to 5 with 1 representing the least assumed root growth potential to a pipeline through 5 for the highest root growth potential. The soil and crop values are then added together for each field associated with a pipeline. A field may include more than one soil type. Where multiple soil types are found, each one is mapped separately with a separate root growth potential factor in the RGIS. The following is a description of the development of the soil and crop root growth potential factors, followed by a description of the cultural root growth potential values that will be used to add further details to the root growth potential values for a specific field, if it is identified as a site that requires additional information.

**Soil Factors**

The following is a description of the soil factors as they were assumed to affect root development near a pipeline, as stated in the proposal prior to the beginning of the project:

Soil conditions influence tree root growth by resisting water movement and root penetration. The range of soil particle sizes, the degree of cementation, the density of the soil and several other soil conditions will affect tree root growth. The most common problem related to installed pipelines occurs where the pipeline trench is a more hospitable soil environment for root growth than a soil with a well developed duripan or other dense, restrictive structure. Water and roots move more easily in the disturbed pipeline trench and so root development can be significantly higher around the pipeline. These soil factors can be identified and quantified with regard to their resistance to root growth. The federal NRCS has been mapping soils for more than a century. Their maps include all of the Central Valley and have recently been digitized so they can be used in a RGIS.

After further investigation and consultation with NRCS soil survey staff, the assumptions in the original proposal are still considered to be the primary factors in assessing the root growth potential to a pipeline. The NRCS soil survey data includes various factors related to the soil particle sizes (texture), density, and induration (cementation) conditions for each layer of soil from the surface down to 60 inches. Those conditions have been used by project staff to assign a root growth potential value to each soil series found in a field associated with a pipeline. The root growth potential value categories are these:

1 – Soils with no significant changes in texture or density throughout the profile.

These are generally new, alluvial soils that produce very little resistance to root or water penetration. These soils would be changed the least by a trench dug to install a pipeline and so plant roots would not be expected to develop preferentially in a trench in these soils.

2 – Soils with slight changes in texture or density from one layer to another in the profile.
Generally, this would be a change from one soil texture class at the surface to another deeper in the profile. Density changes may be more significant and would primarily be identified by an increase in the average soil density of about 0.1 $g/cm^3$ as reported in the soil survey data. These would be slightly restrictive to the growth of roots and the passage of water so any mixing of the layers in the backfilling of a pipeline trench would make it easier for roots to penetrate the soil, though the change would be minor.

3 – Soils with more significant changes in texture or density increases within the profile.
There are 12 specific soil texture classes recognized by the NRCS that range from sand through clay. A change from one texture class such as sandy loam to a closely related texture such as loam would be a reason to assign a soil root growth potential value of "2" as described above. If the change in the texture at the surface was to a much different texture in a lower layer such as sandy loam to silty clay, the effect on root growth would be more significant and the soil root growth potential value would be higher. Some soils in this category may not have a major textural change but could exhibit a significant increase in soil density of 0.2 $g/cm^3$ or greater. Such a compacted layer below the surface would be considered a weak "duripan" and would place the soil series in this root growth potential category. Mixing a soil such as one of these in the backfill of a pipeline trench would produce a significantly different environment for root growth and a considerable increase in root development would be expected in the trench compared to the undisturbed soil.

4 – Soils with well developed, but not cemented duripans.
Soil layers differentiate as the soil ages. Soils with a root growth potential value of 1 in the central valley would generally be less than 500 years old. Centuries of plant growth and seasonal rainfall will eventually change the texture, density and other physical and chemical soil properties in the various soil layers. Often, one soil develops for a period and then more soil is deposited over it by wind or water. These different soils stacked upon each other produce the layer differences that characterize category 3 and 4 soils. When both texture and density differences are significant in the same soil profile, there may be more than one soil layer that restricts growth or a single one that is particularly thick and resistant. Deep tillage practices such as ripping or slip-plowing would be advised prior to planting a crop on soils such as these. The trench opened for a pipeline would be an even better method of mixing these different soil layers to encourage root growth. In some cases, deep tillage operations may have been skipped due to their expense and, in those instances, the pipeline trench would almost certainly cause much of the root system of a tree or vine to proliferate in the trench and around the pipeline.

5 – Soils with very well developed and indurated layers.
Soils that have been in place for more than a hundred thousand years in the central valley will often exhibit indurated or cemented layers. The annual rainfall on these soils slowly weathers soil particles in the upper layers and washes the smaller particles down to a deeper layer. Since the rainfall patterns are relatively similar from year to year the water and materials are left at about the same depth each year. In the dry, hot summer, the water in the deeper layer evaporates precipitating soluble compounds to cement the particles carried down by the rain into a very dense and impenetrable pan. This process is call induration. Typically these cemented duripans occur from 24" to 40" below the surface and are often several inches thick. They are essentially the same as concrete and only allow the passage of water or root growth through cracks and fissures which may be very rare. Deep tillage is strongly advised prior to planting on such soils. Most soils of this type have had some deep tillage though it may have been done only once, long ago. Unless the ripping of such a soil was done several times, in different directions, the large pieces of duripan may still be a significant barrier to root growth. A pipeline trench would generally not be backfilled with these large pieces of duripan and would provide a significantly better root environment.

**Horticultural Factors**

The following is a description of the crop factors as they were assumed to affect root development near a pipeline, as stated in the proposal prior to the beginning of the project:

*Tree root systems are affected by genetics. Some tree or root stock species have significantly more aggressive root systems than others. Classifying crop species by their root development can be done and used with crop maps available from county agricultural commissioner's offices or the CDFA to add tree growth factors to a RGIS that includes soil factors and pipeline routes*.

The database used to identify the crops in the RGIS has 52 different crops, many of which were found in fields associated with pipelines. Some are not agricultural and were assigned a root growth potential value = 0. Herbaceous annual crops are the most common and, since they have a life span of less than a year, were considered the lowest root growth potential (1) with regard to pipeline-root interaction. Biennial herbaceous crops (2) are not common but are occasionally found. The most common is sugar beet and, though it does have an extensive root system, it does not commonly produce many roots at pipeline depths. Root growth potential category 3 includes the perennial herbaceous crops. The most common of these is alfalfa which is generally grown for 4 – 6 years and is known as a deep rooted crop. Permanent pastures are also in this category though they are much less common than alfalfa. Alfalfa roots would be expected to reach pipeline depths in most cases but they would not do so for more than a few years and the roots do not reach diameters of more than a few millimeters. Root growth potential category 4 includes perennial shrubs and vines. Grapes are by far the most common crop in this category and may actually be a greater pipeline hazard than the rest of the category 4 crops due to the fact that they have probably the longest life span of any crop in the valley. Vineyards are often in production for decades and some are known to be over a century old. They grow vigorously and the trunk/branch structure is kept small only by annual pruning. The root system of grapes continues to grow and probably equals most tree species in extent. Other category 4 crops are blueberries, blackberries and pomegranates. Perennial tree crops make up the highest root growth potential category (5) because they are the largest in size and, as a general class, are the longest-lived crop in the valley. Presumably they are the most likely crop to produce root systems that would be a root growth potential to pipelines. Some tree crops are larger in size, walnuts and apricots. Some tree crops are known to have aggressive root systems, almonds and pistachios, because they are native to dry regions. At this point, no further differentiation of tree crops has been done but it is likely that the root growth potential categories will be revised somewhat and, perhaps, expanded after results from the field excavations are evaluated.

**Cultivation Factors**

The following is a description of the additional agricultural factors that were assumed to affect root development near a pipeline, as stated in the proposal prior to the beginning of the project:

*The conditions under which trees are planted and grown can affect tree root development. Deep tillage of the soil by ripping, slip-plowing or backhoe work can significantly affect the soil factors mentioned above. The irrigation method used in an orchard can either increase or decrease the possibility that tree roots will develop around a pipeline. While maps of these cultural practices are not likely to exist, the degree to which they might influence root growth can be determined for specific locations identified in the RGIS and the degree of hazard to the pipeline can be adjusted.*

The soil series and crop in a field associated with a pipeline can be identified from the databases described above to produce the RGIS. However, there are additional factors that could have a significant effect on the root growth potential to a pipeline from the crop growing over it. Most of those additional factors cannot be evaluated without an inspection of the site and, in some cases, a detailed history of the field that can only be obtained by interviewing the owner. The irrigation method employed in a field can be very important, particularly for soils in high root growth potential categories. The type and amount of deep tillage prior to planting an orchard or vineyard could reduce the root growth potential to a pipeline significantly, if it was done thoroughly. At this point in the project, prior to any field excavations or interviews with owners, these additional root growth potential factors can only be postulated. In a few cases, it is possible to identify drip or other micro-irrigation systems from the imagery but even that is of limited value without knowledge of the age and operating parameters of the system. These additional factors will be useful to either increase or decrease the estimated overall root growth potential value for a field when it has been identified as one with a high root growth potential soil and crop. The actual method by which these factors will be applied, and the degree to which they will modify the soil/crop root growth potential, remains to be determined.

**Overall root growth potential value**

Once the soil and crop root growth potential factors have been determined for a field associated with a pipeline, the factors can be used either together or separately to identify sites in the RGIS where pipelines might be most affected. When the RGIS is approaching completion at the end of the project, there may be some value in combining all the factors to create an overall root growth potential factor. Simple addition of the two 1 – 5 values produces an overall range from 2 – 10, however, to this point in the project we continue to use them separately. The sites recommended for excavation have been those with a soil factor of 3 or more and a crop factor of 5. After some discussion, grapes (4) on high root growth potential soils are also being recommended for excavation.

After the assumptions for soil and crop root growth potential factors have been evaluated by comparing the estimated root growth potential to the actual root development found in the excavations, it should be possible to calculate a useable, overall root growth potential value. That overall value could be the current method with 10 as the highest root growth potential. A method of modifying the soil/crop root growth potential value with the cultivation factors is very likely, though the RGIS will only be able to generate the soil/crop value for region.

The above description of the root growth potential factors was prepared as the initial step in the construction of the RGIS that is the primary objective of this project. At the time this interim report was written, the RGIS, as discussed in the following section is not yet complete. There has not been sufficient field validation of either the soil or the crop factors to enable the factors to be applied to the RGIS at the level of detail described above.

**Summary of analysis from land cover datasets for crop type factors are represented in the tables below:**

Table 2 shows the acreage of each crop type from the land cover dataset that occurs within the 200 m pipeline buffer strip with the orchard and vineyard percentages calculated. Table 3 represents Land Cover Classes in 200m buffer strip where pipeline appears to pass through the orchard. Table 4 shows Land Cover Classes within the 200 m buffer strip where the pipeline is not in the orchard but appears at the edge or near to orchard. These tables are generated for the RGIS area.

**Table2: Land Cover in 100 Meter Buffer Area (Each Side) of Pipeline**

| Crop type | Acres | % of total | Crop type | Acres | % of total |
|---|---|---|---|---|---|
| Corn | 2,274.7 | | Grapes | 9,079.7 | 10.22% |
| Cotton | 1,847.4 | | Other Tree Crops | 12.5 | 0.01% |
| Rice | 6,379.6 | | Citrus | 0.2 | 0.00% |
| Sorghum | 84.3 | | Pecans | 10.7 | 0.01% |
| Sunflower | 1,195.4 | | Almonds | 19,772.4 | 22.26% |
| Sweet Corn | 96.3 | | Walnuts | 3,593.5 | 4.04% |
| Barley | 523.3 | | Pears | 13.3 | |
| Durum Wheat | 326.3 | | Pistachios | 1,345.7 | 1.51% |
| Winter Wheat | 5,689.3 | | Triticale | 321.6 | |
| Rye | 10.7 | | Carrots | 122.1 | |
| Oats | 1,335.5 | | Asparagus | 19.6 | |
| Canola | 0.2 | | Garlic | 160.6 | |
| Safflower | 281.6 | | Cantaloupes | 140.3 | |
| Alfalfa | 7,352.8 | | Olives | 240.9 | 0.27% |
| Other Hay/Non Alfalfa | 1,732.9 | | Oranges | 14.2 | 0.02% |
| Camelina | 3.1 | | Honeydew Melons | 36.0 | |
| Dry Beans | 386.3 | | Broccoli | 57.4 | |
| Potatoes | 89.4 | | Peppers | 19.6 | |
| Other Crops | 9.3 | | Pomegranates | 89.4 | 0.10% |
| Sweet Potatoes | 58.7 | | Nectarines | 0.7 | 0.00% |
| Misc Vegs & Fruits | 5.8 | | Greens | 15.1 | |
| Watermelons | 138.8 | | Plums | 829.1 | 0.93% |
| Onions | 401.6 | | Strawberries | 45.1 | |
| Cucumbers | 0.7 | | Squash | 55.6 | |
| Peas | 53.8 | | Apricots | 87.4 | 0.10% |
| Tomatoes | 3,363.7 | | Vetch | 0.2 | |
| Caneberries | 0.4 | | Dbl Crop WinWht/Corn | 749.7 | |
| Herbs | 6.7 | | Dbl Crop Oats/Corn | 774.8 | |
| Clover/Wildflowers | 593.8 | | Lettuce | 143.9 | |
| Sod/Grass Seed | 7.6 | | Dbl Crop Barley/Sorghum | 20.9 | |
| Fallow/Idle Cropland | 16,336.7 | | Dbl Crop WinWht/Sorghum | 83.8 | |
| Cherries | 284.0 | 0.32% | Dbl Crop Barley/Corn | 7.1 | |
| Peaches | 58.7 | 0.07% | Blueberries | 41.6 | |
| Apples | 4.2 | 0.00% | Cabbage | 3.6 | |
| | | | **Total in pipeline buffer strip =** | **88,841.7** | |
| | | | **Orchards in buffer strip =** | **26,343.5** | **29.7%** |
| | | | **Vineyards in buffer strip =** | **9,079.7** | **10.2%** |

**Table3: Land Cover Classes in 100m Buffer of Pipeline where Pipeline Passes through the Orchard**

| Crop Type | Acres | % of total | Crop Type | Acres | % of total |
|---|---|---|---|---|---|
| Corn | 1,857.2 | | Grapes | 7,008.5 | 10.95% |
| Cotton | 1,554.8 | | Pecans | 0.9 | 0.00% |
| Rice | 5,962.2 | | Almonds | 12,792.1 | 19.99% |
| Sorghum | 61.2 | | Walnuts | 1,470.3 | 2.30% |
| Sunflower | 818.9 | | Pears | 5.3 | 0.01% |
| Sweet Corn | 72.9 | | Pistachios | 920.7 | 1.44% |
| Barley | 428.1 | | Triticale | 269.8 | |
| Durum Wheat | 305.3 | | Carrots | 81.6 | |
| Winter Wheat | 4,575.8 | | Asparagus | 1.3 | |
| Rye | 1.6 | | Garlic | 100.7 | |
| Oats | 770.8 | | Cantaloupes | 57.8 | |
| Canola | 0.2 | | Olives | 71.2 | 0.11% |
| Safflower | 132.3 | | Oranges | 2.7 | 0.00% |
| Alfalfa | 5,906.1 | | Honeydew Melons | 21.3 | |
| Other Hay/Non Alfalfa | 1,206.0 | | Broccoli | 49.6 | |
| Camelina | 2.0 | | Peppers | 15.8 | |
| Dry Beans | 239.1 | | Pomegranates | 29.6 | 0.05% |
| Potatoes | 61.8 | | Greens | 15.1 | |
| Other Crops | 3.3 | | Plums | 210.8 | 0.33% |
| Sweet Potatoes | 41.1 | | Strawberries | 25.1 | |
| Misc Vegs & Fruits | 5.3 | | Squash | 32.2 | |
| Watermelons | 115.4 | | Apricots | 15.6 | 0.02% |
| Onions | 321.4 | | Dbl Crop WinWht/Corn | 579.1 | |
| Peas | 33.4 | | Dbl Crop Oats/Corn | 483.9 | |
| Tomatoes | 2,607.6 | | Lettuce | 92.3 | |
| Herbs | 4.2 | | Dbl Crop Barley/Sorghum | 17.6 | |
| Clover/Wildflowers | 463.5 | | Dbl Crop WinWht/Sorghum | 64.0 | |
| Sod/Grass Seed | 0.2 | | Dbl Crop Barley/Corn | 0.2 | |
| Fallow/Idle Cropland | 11,844.1 | | Blueberries | 39.1 | |
| Cherries | 111.2 | 0.17% | Cabbage | 0.9 | |
| Peaches | 1.3 | 0.00% | **Total in pipeline buffer strip =** | **63,986** | |
| Apples | 1.8 | 0.00% | **Orchards over pipelines =** | **15,633** | **24.43%** |
| | | | **Vineyards over pipelines =** | **7,009** | **10.95%** |

**Table4: Land Cover Classes within 100 Meter Buffer of Pipeline Where Pipeline is at the Edge or Near to Orchard**

| Crop Type | Acres | % of total | Crop Type | Acres | % of total |
|---|---|---|---|---|---|
| Corn | 417.4 | | Grapes | 2,071.2 | 8.33% |
| Cotton | 292.7 | | Other Tree Crops | 12.5 | 0.05% |
| Rice | 417.4 | | Citrus | 0.2 | 0.00% |
| Sorghum | 23.1 | | Pecans | 9.8 | 0.04% |
| Sunflower | 376.5 | | Almonds | 6,980.3 | 28.08% |
| Sweet Corn | 23.4 | | Walnuts | 2,123.2 | 8.54% |
| Barley | 95.2 | | Pears | 8.0 | 0.03% |
| Durum Wheat | 20.9 | | Pistachios | 425.0 | 1.71% |
| Winter Wheat | 1,113.5 | | Triticale | 51.8 | |
| Rye | 9.1 | | Carrots | 40.5 | |
| Oats | 564.7 | | Asparagus | 18.2 | |
| Safflower | 149.2 | | Garlic | 59.8 | |
| Alfalfa | 1,446.7 | | Cantaloupes | 82.5 | |
| Other Hay/Non Alfalfa | 526.9 | | Olives | 169.7 | |
| Camelina | 1.1 | | Oranges | 11.6 | 0.05% |
| Dry Beans | 147.2 | | Honeydew Melons | 14.7 | |
| Potatoes | 27.6 | | Broccoli | 7.8 | |
| Other Crops | 6.0 | | Peppers | 3.8 | |
| Sweet Potatoes | 17.6 | | Pomegranates | 59.8 | 0.24% |
| Misc Vegs & Fruits | 0.4 | | Nectarines | 0.7 | 0.00% |
| Watermelons | 23.4 | | Plums | 618.3 | 2.49% |
| Onions | 80.3 | | Strawberries | 20.0 | |
| Cucumbers | 0.7 | | Squash | 23.4 | |
| Peas | 20.5 | | Apricots | 71.8 | 0.29% |
| Tomatoes | 756.1 | | Vetch | 0.2 | |
| Caneberries | 0.4 | | Dbl Crop WinWht/Corn | 170.6 | |
| Herbs | 2.4 | | Dbl Crop Oats/Corn | 290.9 | |
| Clover/Wildflowers | 130.3 | | Lettuce | 51.6 | |
| Sod/Grass Seed | 7.3 | | Dbl Crop Barley/Sorghum | 3.3 | |
| Fallow/Idle Cropland | 4,492.6 | | Dbl Crop WinWht/Sorghum | 19.8 | |
| Cherries | 172.8 | 0.70% | Dbl Crop Barley/Corn | 6.9 | |
| Peaches | 57.4 | 0.23% | Blueberries | 2.4 | |
| Apples | 2.4 | 0.01% | Cabbage | 2.7 | |
| | | | **Total in pipeline buffer strip =** | **24,856** | |
| | | | **Orchards near pipelines =** | **10,723** | **42.5%** |
| | | | **Vineyards near pipelines =** | **2,071** | **8.3%** |

**Summary of Analysis results from soil Datasets for soil type factors in Fresno County are represented in the table below:**

Table 5 The different soils in the buffer strips with their RGIS category, acres and percentage of the total for Fresno County.

| Soil Type | Rank | Acres | % of total |
|---|---|---|---|
| Altaslough clay loam, 0 to 1 percent slopes | 2 | 52.6 | 0.1515 |
| Anela-vernalis association, 0 to 5 percent slopes | 1 | 4.8 | 0.0139 |
| Arburua-Morenogulch association, 15 to 80 percent slopes | 2 | 15.8 | 0.0454 |
| Armona loam, partially drained, 0 to 1 percent slopes | 3 | 173.4 | 0.4990 |
| Atwater loamy sand, 0 to 3 percent slopes | 1 | 64.5 | 0.1857 |
| Atwater loamy sand, 3 to 9 percent slopes | 1 | 26.8 | 0.0772 |
| Atwater loamy sand, moderately deep, 0 to 3 percent slopes | 1 | 0.0 | 0.0000 |
| Atwater sandy loam, 0 to 3 percent slopes | 1 | 452.6 | 1.3029 |
| Atwater sandy loam, moderately deep 0 to 3 percent slopes | 1 | 27.0 | 0.0778 |
| Bisgani sandy loam, drained, 0 to 1 percent slopes | 1 | 1.5 | 0.0044 |
| Borden loam | 2 | 78.7 | 0.2265 |
| Borden loam, moderately deep | 2 | 25.1 | 0.0724 |
| Borden loam, moderately deep, saline alkali | 2 | 36.9 | 0.1061 |
| Cajon coarse sandy loam | 1 | 22.8 | 0.0655 |
| Cajon coarse sandy loam, moderately deep, saline alkali | 1 | 16.3 | 0.0470 |
| Cajon coarse sandy loam, saline alkali | 1 | 3.6 | 0.0103 |
| Cajon loamy coarse sand | 1 | 19.8 | 0.0571 |
| Calflax clay loam, saline-sodic, wet, 0 to 1 percent slopes | 2 | 486.1 | 1.3991 |
| Calhi loamy sand, 0 to 3 percent slopes | 1 | 140.1 | 0.4033 |
| Calhi loamy sand, 3 to 9 percent slopes | 1 | 120.7 | 0.3475 |
| Calhi loamy sand, moderately deep, 0 to 3 percent slopes | 1 | 95.6 | 0.2751 |
| Carranza gravelly sandy loam, 2 to 8 percent slopes | 1 | 56.7 | 0.1632 |
| Cerini clay loam, 0 to 2 percent slopes | 2 | 1995.9 | 5.7453 |
| Cerini clay loam, subsided, 0 to 5 percent slopes | 2 | 476.5 | 1.3715 |
| Cerini sandy loam, 0 to 2 percent slopes | 2 | 525.3 | 1.5121 |
| Cerini sandy loam, subsided, 0 to 5 percent slopes | 2 | 244.0 | 0.7023 |
| Cerini-Anela-Fluvaquents, saline-Sodic, association, 0 to 2 percent slopes | 2 | 11.1 | 0.0318 |
| Chino fine sandy loam | 2 | 9.9 | 0.0284 |
| Chino loam | 2 | 141.4 | 0.4069 |
| Chino loam, saline-alkali | 2 | 2.2 | 0.0064 |
| Ciervo clay, 0 to 2 percent slopes | 2 | 815.7 | 2.3479 |
| Ciervo clay, saline-sodic, wet, 0 to 1 percent slopes | 2 | 41.2 | 0.1187 |
| Ciervo, wet-Ciervo complex, saline-sodic, 0 to 1 percent slopes | 2 | 389.4 | 1.1208 |
| Cometa sandy loam, 3 to 9 percent slopes | 1 | 5.6 | 0.0161 |
| Deldota clay, partially drained, 0 to 1 percent slopes | 2 | 186.1 | 0.5357 |
| Delgado sandy loam, 15 to 30 percent slopes, eroded | 2 | 79.4 | 0.2285 |
| Delgado sandy loam, 5 to 15 percent slopes, eroded | 2 | 14.9 | 0.0429 |
| Delhi loamy sand, 0 to 3 percent slopes | 1 | 869.1 | 2.5018 |
| Delhi loamy sand, 3 to 9 percent slopes | 1 | 345.2 | 0.9938 |
| Delhi loamy sand, moderately deep, 0 to 3 percent slopes | 1 | 47.0 | 0.1352 |
| Delhi sand, 0 to 3 percent slopes | 1 | 166.3 | 0.4787 |
| Delhi sand, 3 to 9 percent slopes | 1 | 37.7 | 0.1086 |
| Dello loamy sand | 1 | 59.5 | 0.1712 |
| Dospalos clay, drained, 0 to 1 percent slopes | 2 | 23.1 | 0.0664 |
| El Peco fine sandy loam | 4 | 348.2 | 1.0024 |
| El Peco loam | 4 | 91.5 | 0.2632 |
| El Peco sandy loam | 4 | 18.3 | 0.0528 |

| | | | |
|---|---|---|---|
| Elnido sandy loam, drained, 0 to 1 percent slopes | 1 | 111.5 | 0.3208 |
| Excelsior sandy loam, 0 to 2 percent slopes | 3 | 807.1 | 2.3233 |
| Excelsior sandy loam, sandy substratum, 0 to 2 percent slopes | 3 | 844.3 | 2.4304 |
| Excelsior, sandy substratum-westhaven association, flooded, 0 to 2 percent slopes | 3 | 61.7 | 0.1776 |
| Exclose-Wisflat-Grazer association, 15 to 65 percent slopes | 2 | 180.1 | 0.5184 |
| Exclose-Wisflat-Rock outcrop association, 30 to 65 percent slopes | 3 | 23.4 | 0.0674 |
| Exeter loam | 4 | 271.9 | 0.7826 |
| Exeter sandy loam | 4 | 434.8 | 1.2514 |
| Exeter sandy loam, shallow | 4 | 45.9 | 0.1321 |
| Foster loam | 3 | 13.1 | 0.0376 |
| Foster sandy loam | 3 | 48.8 | 0.1403 |
| Fresno clay loam | 5 | 111.8 | 0.3217 |
| Fresno fine sandy loam | 5 | 456.2 | 1.3132 |
| Fresno fine sandy loam, shallow | 5 | 563.5 | 1.6220 |
| Fresno sandy loam | 2 | 263.1 | 0.7574 |
| Fresno sandy loam, shallow | 2 | 269.8 | 0.7765 |
| Fresno-Traver complex | 5 | 92.5 | 0.2663 |
| Gepford clay, 0 to 1 percent slopes | 2 | 225.6 | 0.6494 |
| Grangeville fine sandy loam | 2 | 13.7 | 0.0394 |
| Grangeville fine sandy loam, hard substratum, saline-alkali | 3 | 55.8 | 0.1607 |
| Grangeville sandy loam | 2 | 1.1 | 0.0033 |
| Grangeville sandy loam, saline alkali | 2 | 7.4 | 0.0213 |
| Grangeville sandy loam, sandy substratum | 3 | 21.1 | 0.0606 |
| Grazer-Badland-Wisflat association, 15 to 75 percent slopes | 2 | 72.9 | 0.2097 |
| Grazer-Wisflat-Arburua association, 8 to 50 percent slopes | 2 | 23.0 | 0.0661 |
| Greenfield coarse sandy loam, 0 to 3 percent slopes | 1 | 48.3 | 0.1391 |
| Greenfield sandy loam, 0 to 3 percent slopes | 1 | 444.2 | 1.2785 |
| Greenfield sandy loam, moderately deep, 0 to 3 percent slopes | 1 | 295.2 | 0.8496 |
| Guijarral sandy loam, 2 to 5 percent slopes | 1 | 386.5 | 1.1125 |
| Hanford coarse sandy loam | 1 | 176.1 | 0.5071 |
| Hanford fine sandy loam | 1 | 272.1 | 0.7833 |
| Hanford fine sandy loam, silty substratum | 3 | 138.2 | 0.3977 |
| Hanford gravelly sandy loam | 1 | 30.6 | 0.0879 |
| Hanford sandy loam | 1 | 887.7 | 2.5553 |
| Hanford sandy loam, benches | 1 | 16.6 | 0.0477 |
| Hanford sandy loam, clay loam substratum | 3 | 1.3 | 0.0036 |
| Hesperia coarse sandy loam | 1 | 14.2 | 0.0409 |
| Hesperia fine sandy loam | 1 | 577.2 | 1.6616 |
| Hesperia fine sandy loam moderately deep | 2 | 523.1 | 1.5058 |
| Hesperia fine sandy loam, moderately deep, saline-alkali | 2 | 173.0 | 0.4979 |
| Hesperia sandy loam | 1 | 400.1 | 1.1516 |
| Hesperia sandy loam, moderately deep | 2 | 409.7 | 1.1794 |
| Hesperia sandy loam, moderately deep, saline-alkali | 2 | 30.2 | 0.0869 |
| Hesperia sandy loam, saline-alkali | 2 | 47.0 | 0.1353 |
| Hesperia sandy loam, shallow | 1 | 4.9 | 0.0142 |
| Hesperia sandy loam, shallow, saline-alkali | 1 | 27.2 | 0.0783 |
| Hildreth clay | 2 | 3.0 | 0.0086 |
| Kettleman-Delgado-Mercey association, 5 to 15 percent slopes, eroded | 4 | 217.0 | 0.6245 |
| Kimberlina sandy loam, 0 to 2 percent slopes | 1 | 456.3 | 1.3134 |
| Kimberlina sandy loam, 2 to 5 percent slopes | 1 | 84.4 | 0.2431 |
| Lethent clay loam, 0 to 1 percent slopes | 2 | 30.5 | 0.0879 |
| Lethent silt loam, 0 to 1 percent slopes | 2 | 20.2 | 0.0581 |
| Madera clay loam | 5 | 15.5 | 0.0446 |
| Madera loam | 5 | 59.4 | 0.1709 |

| | | | |
|---|---|---|---|
| Madera loam, saline-alkali | 5 | 21.0 | 0.0603 |
| Merced clay | 4 | 49.4 | 0.1423 |
| Merced clay loam | 4 | 178.8 | 0.5148 |
| Merced clay loam, slightly saline | 4 | 74.3 | 0.2140 |
| Merced clay, slightly saline | 4 | 458.4 | 1.3195 |
| Milham sandy loam, 0 to 2 percent slopes | 3 | 722.8 | 2.0806 |
| Milham sandy loam, 2 to 5 percent slopes | 3 | 489.8 | 1.4099 |
| Milham-Guijarral association, 5 to 15 percent slopes | 3 | 148.8 | 0.4284 |
| Milham-Polvadero complex, organic surface, 0 to 5 percent slopes | 3 | 141.0 | 0.4059 |
| Mugatu fine sandy loam, 0 to 5 percent slopes | 2 | 101.8 | 0.2930 |
| Mugatu fine sandy loam, 5 to 30 percent slopes | 2 | 72.6 | 0.2091 |
| Pachappa loam | 3 | 71.6 | 0.2060 |
| Pachappa loam, moderately deep | 3 | 304.9 | 0.8776 |
| Pachappa loam, moderately deep, saline-alkali | 3 | 125.5 | 0.3613 |
| Pachappa loam, saline alkali | 3 | 6.8 | 0.0195 |
| Panoche clay loam, 0 to 2 percent slopes | 3 | 979.1 | 2.8183 |
| Panoche clay loam, subsided, 0 to 5 percent slopes | 3 | 122.9 | 0.3537 |
| Panoche loam, 0 to 2 percent slopes | 3 | 499.2 | 1.4370 |
| Panoche loam, 2 to 5 percent slopes | 3 | 221.2 | 0.6367 |
| Panoche loam, subsided, 0 to 5 percent slopes | 3 | 331.3 | 0.9535 |
| Panoche sandy loam, 0 to 2 percent slopes | 2 | 74.0 | 0.2130 |
| Paver clay loam, 0 to 2 percent slopes | 2 | 455.3 | 1.3105 |
| Piper sandy loam, 0 to 9 percent slopes | 2 | 1.2 | 0.0035 |
| Playas | 2 | 62.9 | 0.1810 |
| Pollasky fine sandy loam, 9 to 15 percent slopes | 1 | 7.6 | 0.0219 |
| Pollasky sandy loam, 2 to 9 percent slopes | 1 | 14.6 | 0.0419 |
| Pollasky-Montpellier complex, 15 to 30 percent slopes | 1 | 0.1 | 0.0003 |
| Pollasky-Montpellier complex, 9 to 15 percent slopes | 1 | 100.3 | 0.2888 |
| Polvadero sandy loam, 0 to 2 percent slopes | 2 | 202.3 | 0.5824 |
| Polvadero sandy loam, 2 to 5 percent slopes | 2 | 303.2 | 0.8729 |
| Polvadero-Guijarral complex, 5 to 15 percent slopes | 2 | 563.9 | 1.6233 |
| Pond fine sandy loam | 3 | 242.5 | 0.6981 |
| Pond fine sandy loam, moderately deep | 3 | 31.1 | 0.0894 |
| Pond loam | 2 | 4.5 | 0.0129 |
| Pond loam, moderately deep | 3 | 118.0 | 0.3396 |
| Pond sandy loam | 2 | 12.9 | 0.0372 |
| Pond sandy loam, moderately deep | 2 | 8.9 | 0.0257 |
| Posochanet clay loam, saline-sodic, 0 to 2 percent slopes | 2 | 32.2 | 0.0927 |
| Posochanet clay loam, saline-sodic, wet, 0 to 1 percent slopes | 2 | 14.9 | 0.0428 |
| Ramona loam | 2 | 102.3 | 0.2946 |
| Ramona loam, hard substratum | 3 | 166.5 | 0.4792 |
| Ramona sandy loam | 2 | 360.1 | 1.0366 |
| Ramona sandy loam, hard substratum | 3 | 245.9 | 0.7077 |
| Rocklin sandy loam, 3 to 9 percent slopes | 2 | 12.4 | 0.0357 |
| Rossi clay loam | 3 | 16.7 | 0.0480 |
| Rossi fine sandy loam | 3 | 71.5 | 0.2058 |
| San Joaquin loam, 0 to 3 percent slopes | 5 | 207.3 | 0.5968 |
| San Joaquin loam, shallow, 0 to 3 percent slopes | 5 | 161.0 | 0.4634 |
| San Joaquin sandy loam, 0 to 3 percent slopes | 5 | 669.2 | 1.9264 |
| San Joaquin sandy loam, shallow, 0 to 3 percent slopes | 5 | 517.2 | 1.4889 |
| San Joaquin sandy loam, shallow, 3 to 9 percent slopes | 5 | 78.6 | 0.2261 |
| Sandy alluvial land, leveled | 1 | 21.1 | 0.0606 |
| Tachi clay, 0 to 1 percent slopes | 3 | 770.6 | 2.2182 |
| Temple clay | 2 | 6.2 | 0.0178 |

| | | | |
|---|---|---|---|
| Temple clay loam | 2 | 113.7 | 0.3273 |
| Temple clay loam, saline | 2 | 10.4 | 0.0299 |
| Temple loam | 2 | 158.7 | 0.4567 |
| Temple loam, saline-alkali | 2 | 3.2 | 0.0092 |
| Tranquillity clay, saline-sodic, wet, 0 to 1 percent slopes | 3 | 869.9 | 2.5040 |
| Tranquillity-Tranquillity, wet, complex, saline-sodic, 0 to 1 percent slopes | 3 | 640.6 | 1.8439 |
| Traver fine sandy loam | 3 | 98.2 | 0.2826 |
| Traver fine sandy loam, moderately deep | 2 | 80.5 | 0.2318 |
| Traver sandy loam | 3 | 59.7 | 0.1717 |
| Traver sandy loam, moderately deep | 2 | 35.6 | 0.1025 |
| Tujunga loamy sand, 0 to 3 percent slopes | 1 | 475.7 | 1.3692 |
| Tujunga loamy sand, 3 to 9 percent slopes | 1 | 4.7 | 0.0135 |
| Tujunga soils, channeled, 0 to 9 percent slopes | 1 | 18.0 | 0.0517 |
| Visalia sandy loam, 0 to 3 percent slopes | 2 | 34.3 | 0.0987 |
| Visalia sandy loam, clay loam substratum, 0 to 3 percent slopes | 2 | 30.0 | 0.0862 |
| Wasco sandy loam, 0 to 2 percent slopes | 1 | 328.1 | 0.9445 |
| Wasco sandy loam, 2 to 5 percent slopes | 1 | 27.4 | 0.0788 |
| Waukena fine sandy loam | 3 | 38.1 | 0.1097 |
| Waukena loam | 3 | 16.9 | 0.0485 |
| Wekoda clay, partially drained, 0 to 1 percent slopes | 2 | 73.9 | 0.2129 |
| Westhaven clay loam, 0 to 2 percent slopes | 3 | 363.5 | 1.0463 |
| Westhaven loam, 0 to 2 percent slopes | 3 | 775.8 | 2.2331 |
| Yribarren clay loam, 0 to 2 percent slopes | 2 | 30.2 | 0.0869 |
| Total (excluding water, pits, riverwash etc.) | | 34740.1 | 100 |

# Appendix B
## Field Evaluation of Ground Penetrating Radar as an alternative to excavation

Ground Penetrating Radar is a method of detecting and discriminating among the various components within a solid, heterogeneous material such as a soil containing roots and other artifacts, i.e. pipelines. A GPR system transmits an electromagnetic signal into the material being studied and a receiver/antenna picks up the reflected signal. Reception of the signal will be affected by differences in the physical characteristics of the various substances in the soil being studied. The dielectric characteristics of the different components of the soil are the primary factors that affect the GPR signal as it is used for this application. The dielectric constant of water is high compared to that of the minerals that make up the soil particles. The high water content of living plant tissue causes roots to reflect the GPR signal in a much different way than the soil particles in which the roots are growing. Conduits filled with vapor such as pipelines or open animal burrows also can be detected due to the distinct differences between the dielectric characteristics of gasses and the surrounding soil particles. Subtle differences in soil water content and structure may be detectable where the native soil layering was disrupted by the trench excavated to install a pipeline. Selection of the specific signal to be use by the GPR is critical for the success of the application. The depth of penetration into the soil is inversely proportional to the frequency used. Lower frequencies (longer $\lambda$) penetrate more deeply. However, the resolution is directly proportional to the frequency. Higher frequencies (shorter $\lambda$) have better resolution and will detect smaller objects. The two frequencies used in the GPR for this study were 900 mHz and 400 mHz. The higher, 900 mHz, signal is the most commonly used for GPR root studies. At that frequency, GPR equipment would be expected to detect roots as small as 0.8cm in diameter to a depth of 1m. This particular study required detection of roots at a deeper depth than the 1m limit of the 900 mHz signal so a 400 mHz antenna that would resolve objects as deep as 3m below the surface was used for most of the field work reported here. The use of the lower frequency decreased the resolution so that only roots larger than 1 - 1.5 cm were expected to be detectable.

**Field Trials**

GPR has been used as a method of detecting objects within soils for many years. However, no previous work was found in the literature related to the use of GPR to document the effects of a pipeline on the degree of root development and the subsequent root growth potential to the pipeline from the expanding root system. Consequently, a trial of GPR was necessary to evaluate its ability to determine root development associated with pipelines. In preliminary discussions with PG&E staff, it was determined that some of the orchard sites identified in the RGIS developed by CSUF-CIT would be excavated by hydro-vacuum and the root systems would be carefully documented by a professional arborist. We proposed to employ a consultant with the appropriate GPR equipment to scan the tree root systems prior to excavation of as many of those orchard sites as possible by November 15. At the time the agreement was executed, in April, we expected to start GPR scans on orchards to be excavated before the beginning of September. Unfortunately, the PG&E excavation schedule was delayed to the point where the first orchard could not be scanned until October 7 and only one additional site could be scanned and excavated a few weeks later. Those two sites, while not sufficient to test the use of GPR for all the tree types and soil conditions that must be investigated to fully evaluate the GPR, were enough to enable the testing of the field techniques and were sufficient to suggest that GPR is a viable method for evaluation of root development around a pipeline.

The initial plan was to use the GPR to scan a rectangular area (10’ x 10’), corresponding to the pit excavated by the hydro-vac system. The GPR scans a profile consisting of a line with the location of objects such as roots indicated along the line and their approximate depths. By scanning lines on a grid of 2', we expected to be able to map the root system of the tree by matching the points along each scanned profile with the adjacent profiles to map the roots by "connecting the dots". The 10'x 10' pit included the tree trunk/root crown and a portion of the pipeline so we expected to see the root system development altered by the presence of the pipeline trench if the roots were, in fact, influenced by the pipeline. The initial field site was an almond orchard in central Fresno County on West Lincoln Ave. about 10 miles south of Kerman. The trees were 12 years old and were planted on a soil with a very distinct restricting layer or duripan. The restricting layer began at a depth of 24"-28" and the pipeline was about 3' deep so the trench with the pipeline was a significant break in the restricting layer of the native soil. The GPR scans indicated an extensive root system in the upper soil layers above the duripan with no roots detected within it. There was some indication of root growth into the pipeline trench but it was not definitive. Subsequent excavation of that tree and a second site in the orchard found the root system to be completely blocked by the restricting layer with some small roots growing down into the trench and along the pipeline. The roots found near the pipe were smaller than the expected resolution limit of the 400 mHz GPR system.

**Figure 5. The almond tree at the W. Lincoln orchard with the GPR grid.** The pipeline runs from under the tree, through the center of the photo at a depth of about 3'.

The second tree that was both scanned by GPR and excavated by hydro-vac was in a walnut orchard near Lockeford, 10 miles east of Lodi in San Joaquin County. The tree was over 50 years old and the soil had very little layering (Category 2). The pipeline was found at about 5'. The difficulties of predicting the root system from the GPR data at the first site, the Fresno almond orchard, were compounded by the small roots of the young trees and the stunting of tree growth due to the significant duripan. In the case of the walnut site, the tree was much older and the roots were expected to be much larger. There did not appear to be any soil conditions that would inhibit root growth in any part of the soil. After discussions with the GPR consultants, the field procedure was altered to scan the root system of the tree in concentric circles with radial increments of 2'. It had been difficult to predict the smaller root system of the almond tree in the limited rectangle that did not include the entire root pattern. It was anticipated that this would be a much more difficult problem with the larger walnut tree so the entire root system was scanned and the 10' x 10' pit location with the pipeline running through it was super-imposed on the larger map of the full root system. The tree was included at the north edge of the excavated pit. The expectation that the roots would be larger and would be more prominent in the GPR scans was realized. There was an extensive root system growing radially from the trunk out to the pipeline and beyond. The circular pattern of GPR scans predicted it quite well. Some roots appeared to stop or disappear as they reached the edge of the pipeline trench. The subsequent excavation showed roots at those locations that abruptly changed direction and grew vertically downward into the area of the old trench. A vertically oriented root is very difficult to detect with the GPR so there was not direct evidence that the roots had followed the trench down toward the pipeline. The roots that were found in the excavation to be growing at the pipeline were near the lower detection limit of the GPR with regard to size so they were not as easily seen as they would have been if they were larger.

**Figure 6. The walnut tree stump at Lockeford.** The circular lines were scanned with GPR to map the entire root system. The trees in the orchard were of varying ages and sizes. The excavated tree stump was similar in size to the largest tree in the background of the photo.

Adjacent to the walnut orchard at Lockeford was an old Zinfandel wine grape vineyard. A vine that was assumed to be over the pipeline was scanned in a few passes to try to identify the pipe but neither it nor a significant number of roots were found. The pipeline was later located, at a deeper depth than had been reported, under an adjacent vine which was then excavated. Several vine roots were found to be growing vertically down to the pipeline but no horizontal root growth was present of the sizes that would be expected to be detected by GPR. The vertical roots from the vine were not large compared to the walnut tree but they were big enough to be seen by the GPR if they had not been vertical.

**Data Processing and Root Maps from Ground Penetrating Radar**

The data from the initial almond orchard in Fresno County was encouraging in that it did predict the root system of the tree quite well. Figure 7 shows the roots detected by the GPR within the grid of the 10' x 10' excavated pit. Figure 8 is a photo of the pit with the tree roots below the 12" depth still in place. The pipeline was not yet exposed at the time the photo was taken but it ran from the corner of the pit at the upper right in the photo, under the tree and across to the left edge of the pit. The trunk of the tree, the root crown and the root system visible in Figure 8 had to be removed prior to further excavation to reach the pipeline.

**Figure 7. The scan grid for the almond tree at W. Lincoln Ave. illustrating the labeled scan lines with the roots detected by the GPR on each line.**

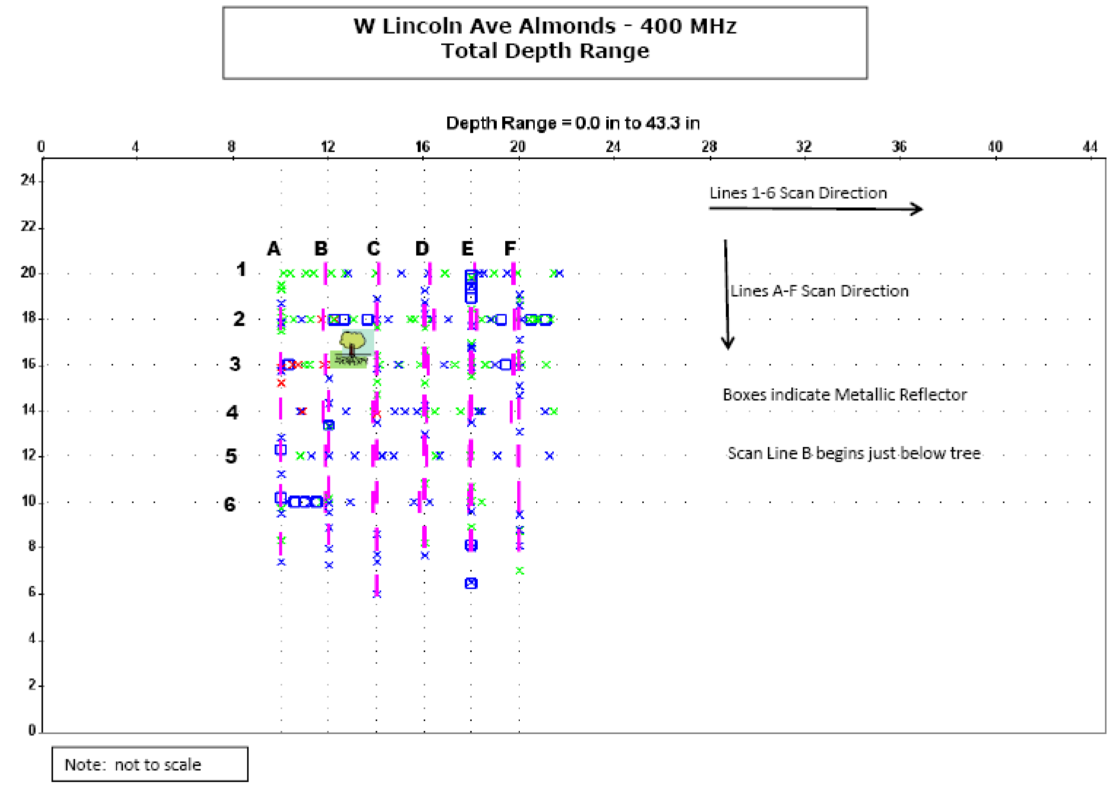
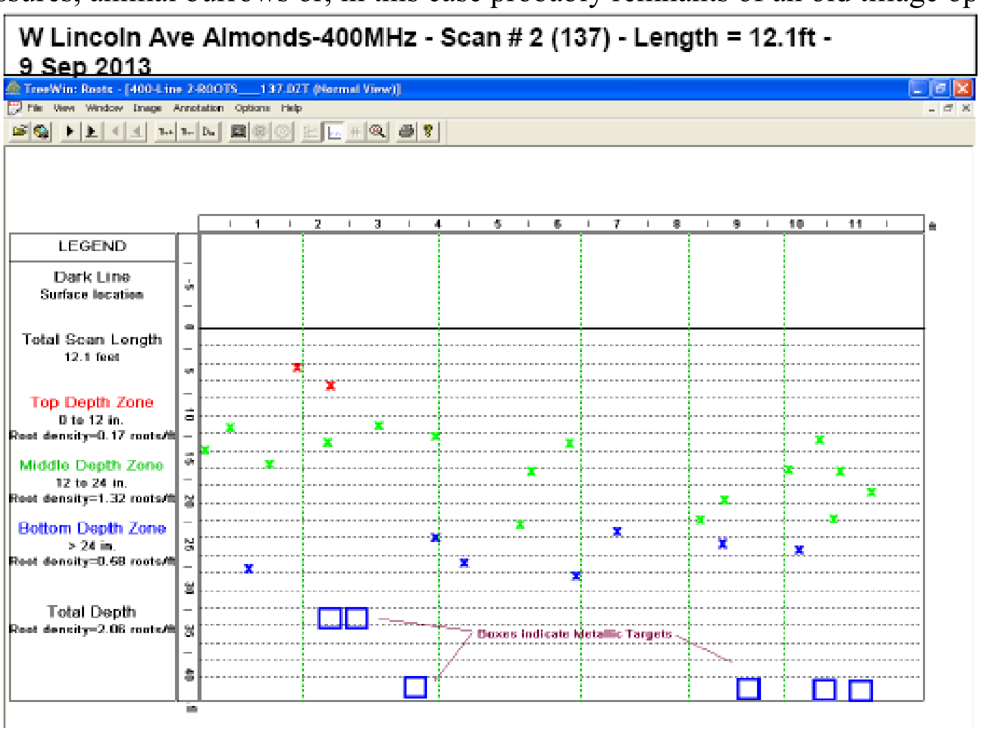


**Figure 8. Photo of the almond tree at W Lincoln Ave. excavated to the top of the duripan (approximately 24”).** The roots found above 12” have been removed for clarity. The photo was taken from point F1 on the grid shown in Fig. 7.

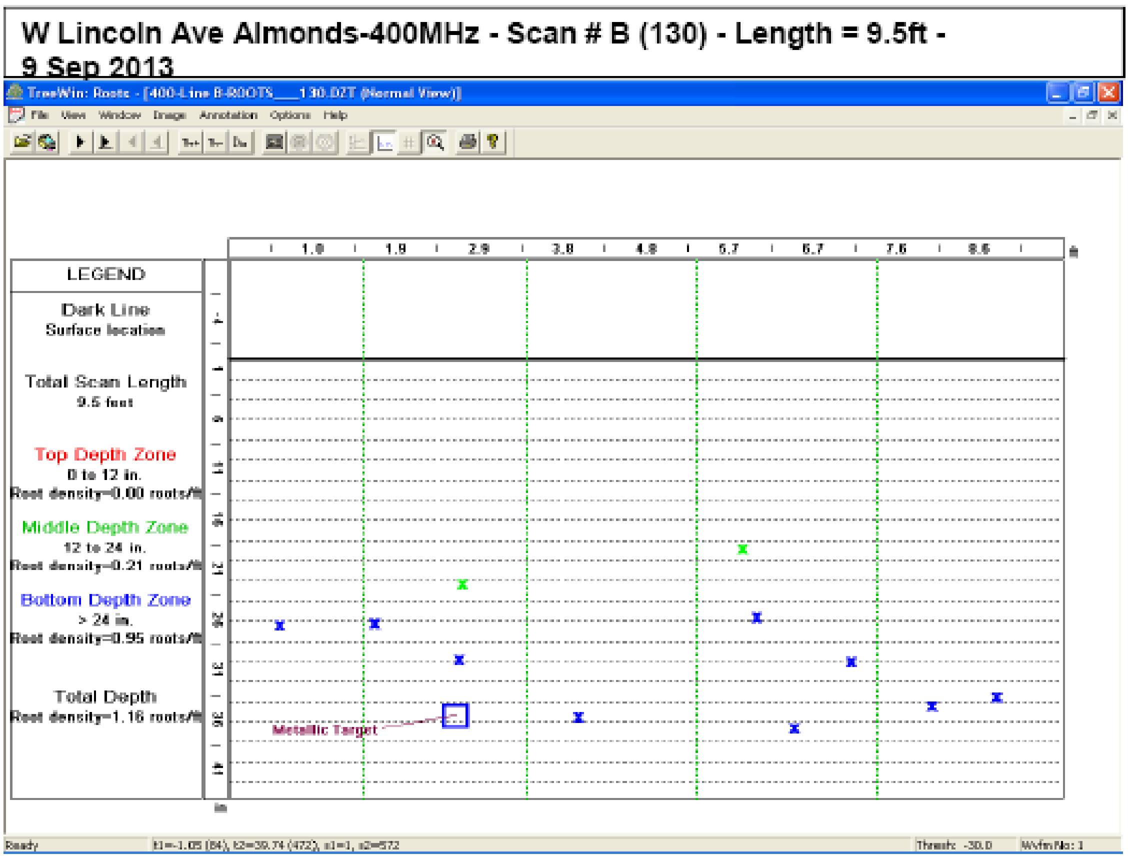
Examples of the scan profiles are shown in Figure 9 (line 2 in Fig. 7) and Figure 10 (line B in Fig. 7). In both scans, the roots are almost exclusively above the top of the duripan layer (28”) except for the area just under the tree in Fig. 10 where there are some roots down at the pipeline depth but not in the pipeline trench. The long roots, seen extending from the tree across to the left side of the photo in Fig. 8, show up well as the green (12-24” depth zone) roots in Fig. 9.

**Figure 9. Profile 2 from the scan grid in Fig. 7 showing roots detected.** The pipeline is the double box at 36” at the 2.5 point of the scan. The boxes at the bottom are voids or openings in the soil structure from cracks, fissures, animal burrows or, in this case probably remnants of an old tillage operation.



Scan profile 2 shown in Fig. 7 is very close to the tree at the beginning of the scan line. The pipeline is shown about where it passes under the tree. The pipeline shows up as a double target when the GPR senses each side of the large pipe and registers them separately. There are other objects that register as "metallic targets". These are most likely open passages where the GPR is detecting an air filled space. Animal burrows, cracks and fissures are the most common feature to occur in this fashion but these appear at a uniform depth and can be seen in Fig. 9 as regularly spaced targets so they are probably channels from a deep tillage operation such as ripping that occurred prior to the installation of the pipe. It is unlikely such channels would persist for so many years except where the soil matrix was as dense and stable as this duripan.

**Figure 10. Profile B from the scan grid in Fig. 7 showing roots detected.** The pipeline is indicated by the box at 36",




The second orchard site that was scanned prior to excavation was the walnut orchard at Lockeford, in San Joaquin County. The tree was cut a year prior to the scanning and excavation but was still living with shoots present around the base of the stump. GPR scanning was done in concentric circles of 2' radial increments. There was some indication that the root system had been influenced by the pipeline trench, probably in the first decade of the tree's growth. The oldest, largest roots grew laterally in the upper part of the root system all around the tree. Figure 11 shows those large, shallow roots (in red on the photo), that were the first roots produced after the tree was planted, extending out from the tree in all directions but stopping at the pipeline. One possible explanation is that the pipeline, laid just a few years before the tree was planted, was backfilled with soil that provided a better environment for root growth so the young tree roots proliferated vertically instead of continuing to grow laterally as they did where the pipeline trench was not a factor. The photo in Figure 11 and the 3d root map in Figure 14 do show some indications of more vertical root growth over the pipeline compared to the roots in the native soil. Most of the roots detected in the GPR scans were well above the pipeline depth but Figure 12, the scan at the 12' radius from the tree shows some evidence of roots at the pipeline depth. The scan is a circle beginning north of the tree. The roots at the pipeline depth are concentrated to the left of the left pipeline box and to the right of the right pipeline box. Those areas are between the pipe and the tree. The space in the center of this graph of the 12" circle would show the soil between the pipe and the 12' radial arc beyond it. The roots in blue are at the pipeline depth, between the pipe and the tree. It would appear from Figure 12 that some roots grew near the pipeline at its depth of 50" and few other roots reached that depth in the native soil. An even more subtle indication of pipeline influence on the root system of this tree can be seen in the 3d root map, Figure 14. The pipeline runs between the 15 and 20 lines of the "Y" axis of the figure. The second, color coded version shows several roots that grow down as they reach the pipeline trench and then grow back toward the surface as they cross it. The significance of these indications was only apparent to us when we knew the location of the pipe and were looking for the influence of the pipe and the trench on the root development of the walnut tree. It appears to us that it would take a knowledgeable GPR operator with considerable experience in orchard tree growth to routinely deduce the effect of the pipeline on the root development of a tree from this evidence. Both the field GPR consultant from Tree Associates and the data processing consultant, Dr. Mucciardi from TreeRadar, suggested that this level of interpretation of the GPR data is possible but only with the experience that comes from the evaluation of numerous examples

**Figure 11. The walnut tree stump at Lockeford excavated to a depth of 4'.** The pipeline is below the yellow "caution" tape on the bottom of the pit.

**Figure 12. The radial scan 12' from the center of the tree stump.** The scan crosses the pipeline in two places, indicated by the boxes.

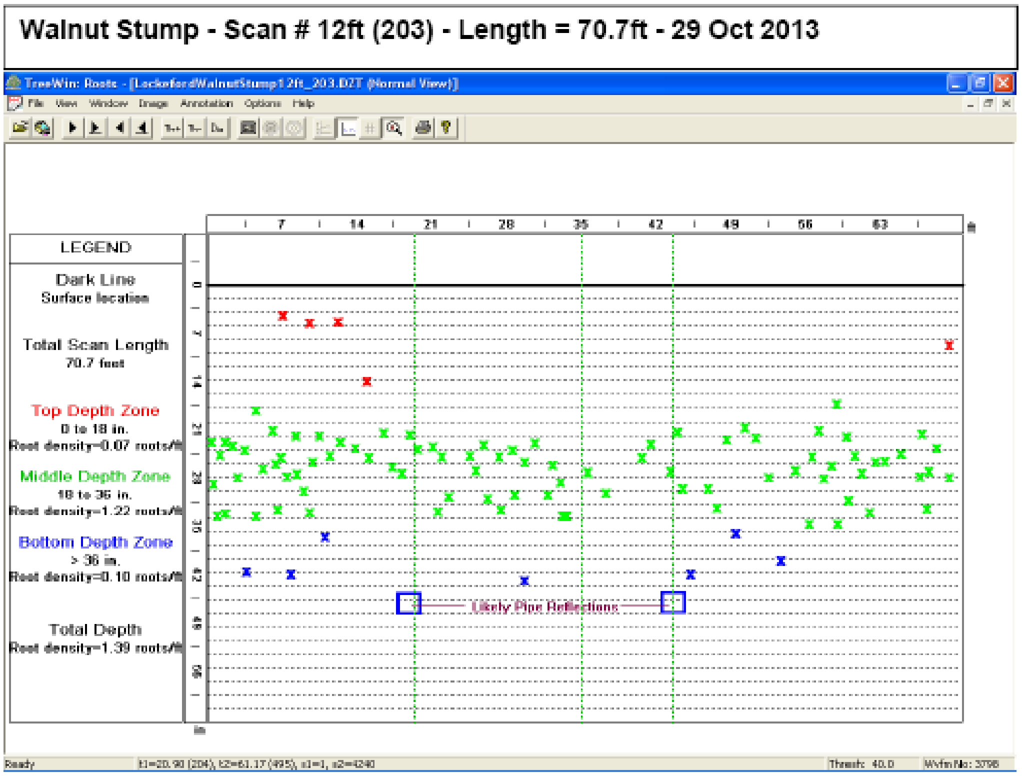



**Figure 13. The root map of the Lockeford walnut stump with the roots indicated by the scan at a depth of 0-18" in red, the 18"-36" roots in green and roots deeper than 36" in blue.**

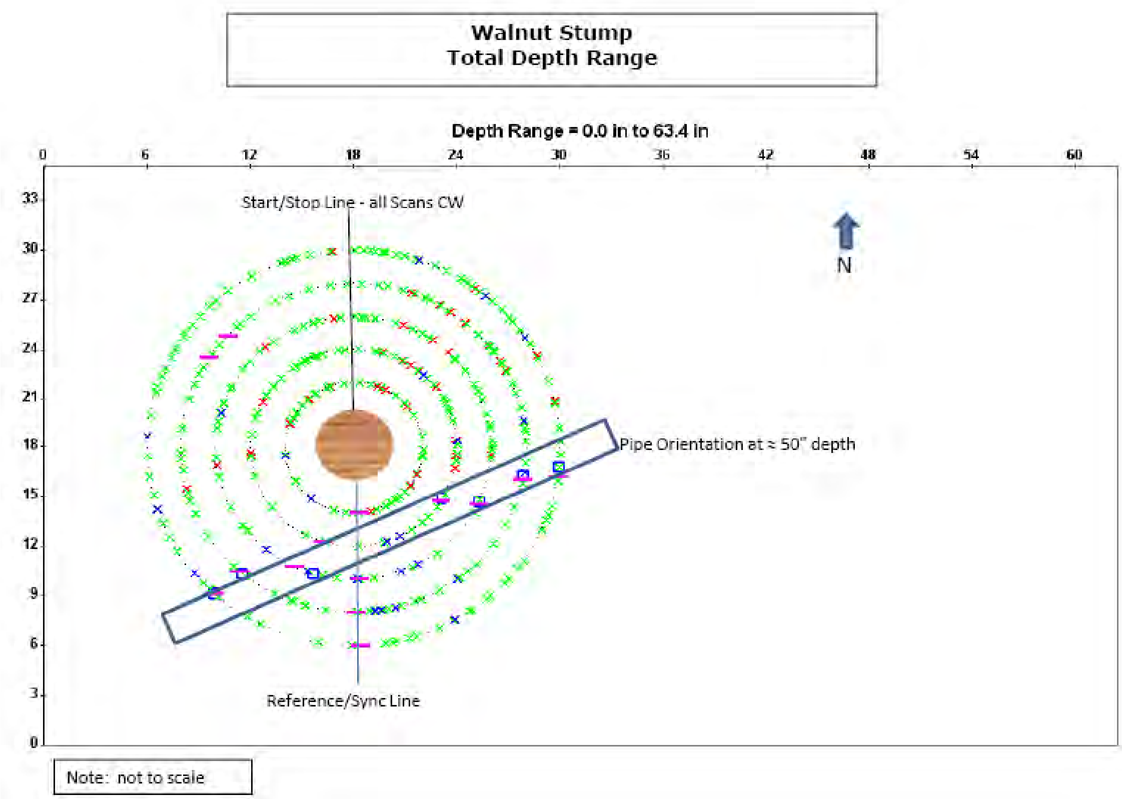
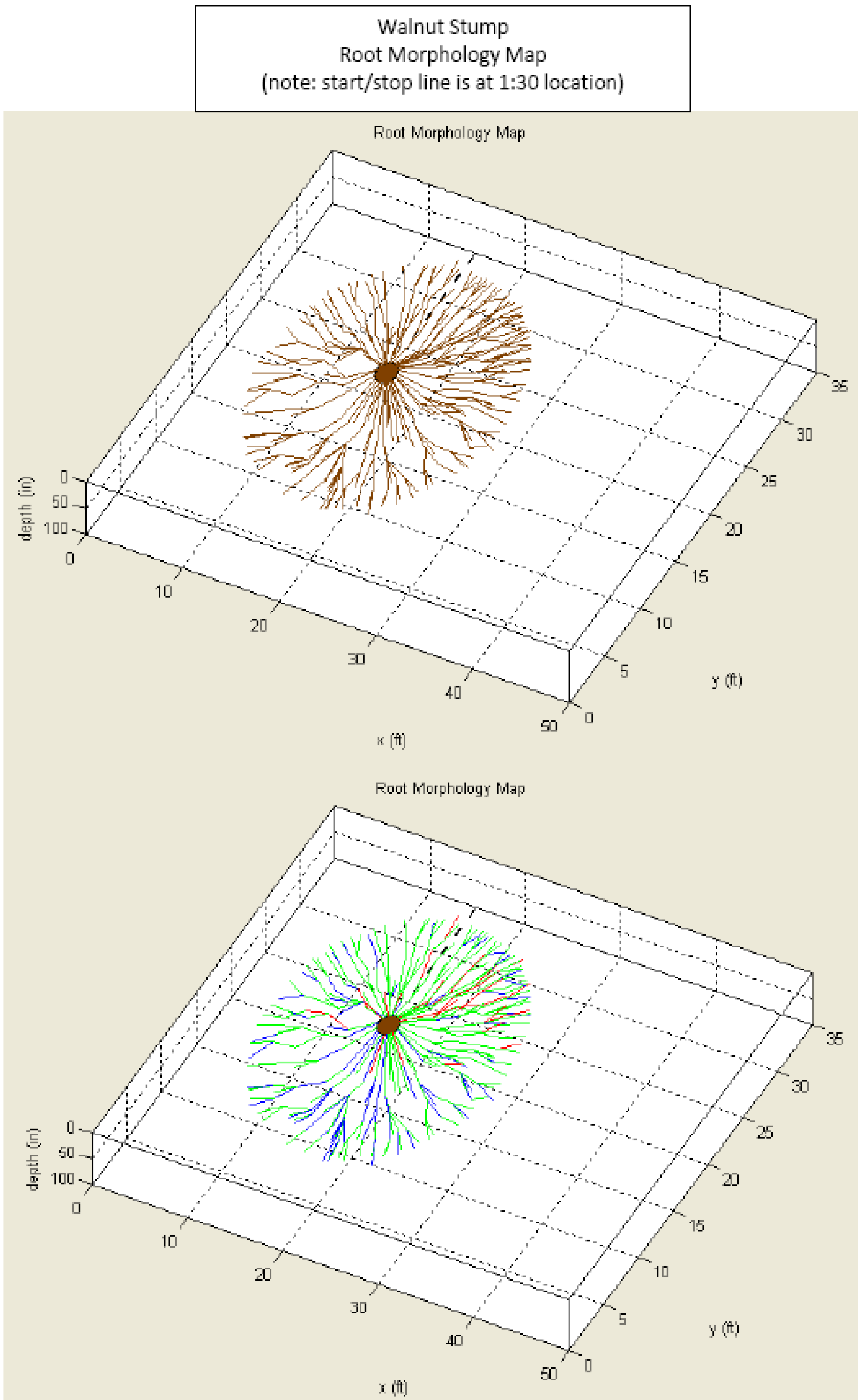


**Figure 14. A 3d representation of the root system of the Lockeford walnut tree.** The pipeline runs between the 15 and 20 values on the “Y” axis. The lower figure is color coded for depth. The top 1/3 is shown in red, the middle 1/3 in green and the deepest roots in blue.



A Zinfandel vine in the wine grape vineyard at Lockeford was also excavated, though not the vine that had been scanned by GPR.  The pipeline changed direction slightly as it exited the orchard and entered the vineyard so the vine it actually ran under was the next one in the row.  A cursory scan with GPR was not able to find it due to the mistake in the estimated location and fact that the reported depth was only half of the 60" where it was eventually found.  The "survey" GPR scan of the vine did not detect any large roots.  Grape vines are smaller plants than most orchard trees and, though they may have grown a deep root system if they are old enough, the roots might not be large enough to readily detect with the GPR.  The vine over the pipeline was excavated by a dry dig so the root system was not preserved as well as with the hydro-vac excavation.  The vine produced several roots that grew straight down into the pipeline trench.  No lateral roots of that size were found in the excavation.  These roots were probably large enough to detect with the GPR but not in their vertical orientation.  Those vine roots did reach the pipeline as shown in Figure 15.  Even if the correct vine had been scanned and the pipeline detected by the GPR, it is likely that these roots would not have been seen.  Their small size and vertical orientation would make it difficult to detect with a GPR scan.

**Figure 15.  The roots from the Zinfandel grape vine at the pipeline level.**

**Recommendations regarding the use of Ground Penetrating Radar to evaluate root development associated with a pipeline.**

The three CSU Fresno researchers participating in this project are reluctant to make recommendations regarding the efficacy of GPR for this application based on the limited experience of these two field trials. However, we are aware that it is necessary at this point in the project to reach some conclusions, tentative as they may be. Consequently, we are prepared to make the following recommendations, subject to confirmation or modification after more field work is done in the next year. Furthermore, there are some questions and limitations that can be stated, perhaps with more conviction than the positive recommendations that precede them.

**1. Ground Penetrating Radar can be used to map the general development of a tree root system associated with a pipeline within the following constraints:**

A. The location and depth of the pipeline should be accurately established by means other than GPR. The pipe may be located by GPR but other features such as animal burrows may be confused with the pipe location unless it is established prior to scanning. The depth of the pipe or some other object in the root zone is necessary in order to accurately calibrate the depths of the roots that are found. The GPR requires at least one known depth to a feature in order to precisely determine the depths to the other objects in the scan.

B. A sufficient number of scan lines or profiles must be measured by the GPR to properly characterize the root system of a tree. The circular pattern of scans used at the Lockeford site is a good method of root mapping for this application. The mapping of the entire root system, as was done for the walnut stump, is highly recommended in order to compare the root development in the pipeline trench path with root growth in the native soil.

C. The resolution of GPR with the 400 mHz antenna required to penetrate below the pipeline depth is about 1.0 - 1.5cm. The wide bandwidth of the signal may allow some roots smaller than that to be detected under favorable conditions but only those roots larger than 1cm can be detected with confidence. Therefore, only the large, structural components of a tree's root system will be mapped by GPR. Small roots that reach the pipe may not be seen, though their presence may be inferred from the pattern of growth of the larger roots.

D. Only roots growing in a predominantly horizontal orientation are likely to be detected by GPR. This is a particularly serious limitation for the application to the assessment of pipeline root growth potential where roots may be stimulated to grow deeper when they encounter the backfill of the pipeline trench. Indirect evidence of this type of root growth was seen in the walnut stump excavation where large roots appeared to stop as they reached the edge of the trench but were found in the subsequent excavation to begin to grow vertically at that point. Scanning at a greater density than the 2' increments used in these studies may improve the mapping these radical changes in the direction of root growth but at the expense of more time and effort required to generate the GPR diagrams.

E. The need to scan a number of lines around a tree/pipeline along with the time required to process the data into a comprehensible root map required about the same amount of time as a conventional excavation for these two field studies. The data from the field scans is difficult to interpret until it has been processed. That processing, for these trials, required sending the field data to a consultant (TreeRadar in Silver Spring, MD) to develop the maps and diagrams presented here. While the data processing could be done more quickly if the CSUF-CIT staff had the software available and were properly trained in its use, that will not occur until later in the project. Dr. Mucciardi, the consultant at TreeRadar will be supplying a new version of the software that may enable much of the data processing to be done immediately after the field scans are taken in the field. Should that new software be successful, the time between collection of the field data and the production of the root maps will be considerably reduced. At present, the real value of GPR is the fact that it is non-destructive, not that it is significantly faster than excavation. If the software improvements are realized, GPR will not only be an acceptable alternative with respect to destruction of the subject trees but also much faster than the excavation to evaluate presence of roots near a pipeline.

2. **Ground Penetrating Radar can be used to detect alteration of the native soil in the pipeline trench where the backfill material produced different root growth conditions.** Direct indication of the change in soil structure between the trench and the native soil was not seen in either of the two field data sets reported here but the scientific literature suggests that GPR can detect those changes in soil structure, density and water content. The walnut tree's root growth at Lockeford appeared to be affected by the difference in soil conditions in the trench, though the indications were very subtle. Further consultation with Dr. Mucciardi regarding the detection of soil disturbances such as the pipeline trench assured us that this is very possible with appropriate data processing and training of the GPR operators. The data processing for these two studies was focused on finding and mapping roots near the pipeline location. Further work with the field scan files might enable us to map the altered soil characteristics of the pipeline trench.

The general recommendation by the CSU Fresno CIT research group with regard to the use of GPR to evaluate roots associated with a pipeline is guardedly positive. While none of us were confident at the beginning of the project that GPR would be as successful in mapping roots as a conventional excavation, we now feel that, within its constraints, GPR could replace destructive excavation in many cases. Where the location and depth of the pipe is known and the tree is a species with roots large enough to be detected; GPR properly used with sufficient scan lines and post-field data processing can provide a root system map that would indicate the extent of root growth near the pipe. Small roots, growing closer to the pipe than the large roots, or from trees with small, fibrous root systems may not be completely mapped by GPR. We can recommend the use of GPR to map roots as small as 1cm in diameter and clusters of smaller roots that collectively approach that size.

The two studies done this fall, reported above, were focused on evaluation of orchard trees that were known to be growing over or near pipelines. The location of the pipe and its depth was determined prior to the GPR scanning. The use of GPR for surveying an orchard where the location of the pipe is not know with precision and the presence of the roots of many trees is in question has not yet been investigated. Scanning a long length of pipeline route to find the pipe and indications of tree roots around it would be a very useful application of GPR but the techniques required are different from those of evaluation that were used in these two field studies. The number of closely spaced scans needed for the root maps around those two trees would not be practical for the use of GPR in surveying. The layout of the grid and the scanning required several hours for each tree. A GPR crew might be able to do the field work on 3 or 4 trees in a day, encompassing no more than 50' - 100' of pipeline. Different field techniques that would minimize the amount of scanning per tree while maximizing the area of coverage along the pipeline will need to be developed. The field procedures required to find and follow a significant length of pipeline to locate roots along it from a series of trees in an orchard are planned for the later phases of this study but have not yet been investigated. The successful application of new processing software that would enable much of the scan data to be processed immediately in the field (mentioned above in recommendation 1E) would be vital to the development of field survey procedures for the GPR.

# Appendix C

# Almond Orchard on West Lincoln Ave. in Fresno County

An almond orchard in central Fresno County about 8 miles south of Kerman was identified in the GIS as having a pipeline routed through it. The soil was mapped as a Fresno sandy loam, shallow phase, a soil known to have a very dense duripan. Two trees were excavated, at each point where the pipeline entered the orchard. One of the trees was scanned with a Ground Penetrating Radar system by Tree Associates on October 7 and the scanned tree was excavated on October 8. The soil survey reports from the Natural Resources Conservation Service and the GPR report from Tree Associates are included in the following appendix

Soil Map—Eastern Fresno Area, California
(Lincoln Ave. Almonds - Flood Irrigated)


Map Scale: 1:6,710 if printed on A portrait (8.5" x 11") sheet.

Meters: 0, 50, 100, 200, 300

N

Feet: 0, 300, 600, 1200, 1800

Map projection: Web Mercator Corner coordinates: WGS84 Edge tics: UTM Zone 10N WGS84

## MAP LEGEND

**Area of Interest (AOI)**
- Area of Interest (AOI)

**Soils**
- Soil Map Unit Polygons
- Soil Map Unit Lines
- Soil Map Unit Points

**Special Point Features**
- Blowout
- Borrow Pit
- Clay Spot
- Closed Depression
- Gravel Pit
- Gravelly Spot
- Landfill
- Lava Flow
- Marsh or swamp
- Mine or Quarry
- Miscellaneous Water
- Perennial Water
- Rock Outcrop
- Saline Spot
- Sandy Spot
- Severely Eroded Spot
- Sinkhole
- Slide or Slip
- Sodic Spot
- Spoil Area
- Stony Spot
- Very Stony Spot
- Wet Spot
- Other
- Special Line Features

**Water Features**
- Streams and Canals

**Transportation**
- Rails
- Interstate Highways
- US Routes
- Major Roads
- Local Roads

**Background**
- Aerial Photography

## MAP INFORMATION

The soil surveys that comprise your AOI were mapped at 1:24,000.

Warning: Soil Map may not be valid at this scale.

Enlargement of maps beyond the scale of mapping can cause misunderstanding of the detail of mapping and accuracy of soil line placement. The maps do not show the small areas of contrasting soils that could have been shown at a more detailed scale.

Please rely on the bar scale on each map sheet for map measurements.

Source of Map: Natural Resources Conservation Service
Web Soil Survey URL: http://websoilsurvey.nrcs.usda.gov
Coordinate System: Web Mercator (EPSG:3857)

Maps from the Web Soil Survey are based on the Web Mercator projection, which preserves direction and shape but distorts distance and area. A projection that preserves area, such as the Albers equal-area conic projection, should be used if more accurate calculations of distance or area are required.

This product is generated from the USDA-NRCS certified data as of the version date(s) listed below.

Soil Survey Area: Eastern Fresno Area, California
Survey Area Data: Version 5, Sep 26, 2008

Soil map units are labeled (as space allows) for map scales 1:50,000 or larger.

Date(s) aerial images were photographed: May 12, 2010—Jul 3, 2011

The orthophoto or other base map on which the soil lines were compiled and digitized probably differs from the background imagery displayed on these maps. As a result, some minor shifting of map unit boundaries may be evident.

# Map Unit Legend

| Eastern Fresno Area, California (CA654) | | | |
|---|---|---|---|
| **Map Unit Symbol** | **Map Unit Name** | **Acres in AOI** | **Percent of AOI** |
| Ep | El Peco loam | 0.3 | 0.1% |
| Fu | Fresno fine sandy loam | 137.5 | 74.4% |
| Fv | Fresno fine sandy loam, shallow | 40.5 | 21.9% |
| Hsd | Hesperia sandy loam | 6.7 | 3.6% |
| **Totals for Area of Interest** | | **184.8** | **100.0%** |

# Physical Soil Properties

This table shows estimates of some physical characteristics and features that affect soil behavior. These estimates are given for the layers of each soil in the survey area. The estimates are based on field observations and on test data for these and similar soils.

*Depth* to the upper and lower boundaries of each layer is indicated.

Particle size is the effective diameter of a soil particle as measured by sedimentation, sieving, or micrometric methods. Particle sizes are expressed as classes with specific effective diameter class limits. The broad classes are sand, silt, and clay, ranging from the larger to the smaller.

*Sand* as a soil separate consists of mineral soil particles that are 0.05 millimeter to 2 millimeters in diameter. In this table, the estimated sand content of each soil layer is given as a percentage, by weight, of the soil material that is less than 2 millimeters in diameter.

*Silt* as a soil separate consists of mineral soil particles that are 0.002 to 0.05 millimeter in diameter. In this table, the estimated silt content of each soil layer is given as a percentage, by weight, of the soil material that is less than 2 millimeters in diameter.

*Clay* as a soil separate consists of mineral soil particles that are less than 0.002 millimeter in diameter. In this table, the estimated clay content of each soil layer is given as a percentage, by weight, of the soil material that is less than 2 millimeters in diameter.

The content of sand, silt, and clay affects the physical behavior of a soil. Particle size is important for engineering and agronomic interpretations, for determination of soil hydrologic qualities, and for soil classification.

The amount and kind of clay affect the fertility and physical condition of the soil and the ability of the soil to adsorb cations and to retain moisture. They influence shrink-swell potential, saturated hydraulic conductivity (Ksat), plasticity, the ease of soil dispersion, and other soil properties. The amount and kind of clay in a soil also affect tillage and earthmoving operations.

*Moist bulk density* is the weight of soil (ovendry) per unit volume. Volume is measured when the soil is at field moisture capacity, that is, the moisture content at 1/3- or 1/10-bar (33kPa or 10kPa) moisture tension. Weight is determined after the soil is dried at 105 degrees C. In the table, the estimated moist bulk density of each soil horizon is expressed in grams per cubic centimeter of soil material that is less than 2 millimeters in diameter. Bulk density data are used to compute linear extensibility, shrink-swell potential, available water capacity, total pore space, and other soil properties. The moist bulk density of a soil indicates the pore space available for water and roots. Depending on soil texture, a bulk density of more than 1.4 can restrict water storage and root penetration. Moist bulk density is influenced by texture, kind of clay, content of organic matter, and soil structure.

*Saturated hydraulic conductivity (Ksat)* refers to the ease with which pores in a saturated soil transmit water. The estimates in the table are expressed in terms of micrometers per second. They are based on soil characteristics observed in the field, particularly structure, porosity, and texture. Saturated hydraulic conductivity (Ksat) is considered in the design of soil drainage systems and septic tank absorption fields.

*Available water capacity* refers to the quantity of water that the soil is capable of storing for use by plants. The capacity for water storage is given in inches of water per inch of soil for each soil layer. The capacity varies, depending on soil properties that affect retention of water. The most important properties are the content of organic matter, soil texture, bulk density, and soil structure. Available water capacity is an important factor in the choice of plants or crops to be grown and in the design and management of irrigation systems. Available water capacity is not an estimate of the quantity of water actually available to plants at any given time.

*Linear extensibility* refers to the change in length of an unconfined clod as moisture content is decreased from a moist to a dry state. It is an expression of the volume change between the water content of the clod at 1/3- or 1/10-bar tension (33kPa or 10kPa tension) and oven dryness. The volume change is reported in the table as percent change for the whole soil. The amount and type of clay minerals in the soil influence volume change.

Linear extensibility is used to determine the shrink-swell potential of soils. The shrink-swell potential is low if the soil has a linear extensibility of less than 3 percent; moderate if 3 to 6 percent; high if 6 to 9 percent; and very high if more than 9 percent. If the linear extensibility is more than 3, shrinking and swelling can cause damage to buildings, roads, and other structures and to plant roots. Special design commonly is needed.

*Organic matter* is the plant and animal residue in the soil at various stages of decomposition. In this table, the estimated content of organic matter is expressed as a percentage, by weight, of the soil material that is less than 2 millimeters in diameter. The content of organic matter in a soil can be maintained by returning crop residue to the soil.

Organic matter has a positive effect on available water capacity, water infiltration, soil organism activity, and tilth. It is a source of nitrogen and other nutrients for crops and soil organisms.

*Erosion factors* are shown in the table as the K factor (Kw and Kf) and the T factor. Erosion factor K indicates the susceptibility of a soil to sheet and rill erosion by water. Factor K is one of six factors used in the Universal Soil Loss Equation (USLE) and the Revised Universal Soil Loss Equation (RUSLE) to predict the average annual rate of soil loss by sheet and rill erosion in tons per acre per year. The estimates are based primarily on percentage of silt, sand, and organic matter and on soil structure and Ksat. Values of K range from 0.02 to 0.69. Other factors being equal, the higher the value, the more susceptible the soil is to sheet and rill erosion by water.

*Erosion factor Kw* indicates the erodibility of the whole soil. The estimates are modified by the presence of rock fragments.

*Erosion factor Kf* indicates the erodibility of the fine-earth fraction, or the material less than 2 millimeters in size.

*Erosion factor T* is an estimate of the maximum average annual rate of soil erosion by wind and/or water that can occur without affecting crop productivity over a sustained period. The rate is in tons per acre per year.

*Wind erodibility groups* are made up of soils that have similar properties affecting their susceptibility to wind erosion in cultivated areas. The soils assigned to group 1 are the most susceptible to wind erosion, and those assigned to group 8 are the least susceptible. The groups are described in the "National Soil Survey Handbook."

*Wind erodibility index* is a numerical value indicating the susceptibility of soil to wind erosion, or the tons per acre per year that can be expected to be lost to wind erosion. There is a close correlation between wind erosion and the texture of the surface layer, the size and durability of surface clods, rock fragments, organic matter, and a calcareous reaction. Soil moisture and frozen soil layers also influence wind erosion.

Reference:
United States Department of Agriculture, Natural Resources Conservation Service. National soil survey handbook, title 430-VI. (http://soils.usda.gov)

# Report—Physical Soil Properties

| Physical Soil Properties–Eastern Fresno Area, California | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Map symbol and soil name | Depth | Sand | Silt | Clay | Moist bulk density | Saturated hydraulic conductivity | Available water capacity | Linear extensibility | Organic matter | Erosion factors | | | Wind erodibility group | Wind erodibility index |
| | | | | | | | | | | Kw | Kf | T | | |
| | *In* | *Pct* | *Pct* | *Pct* | *g/cc* | *micro m/sec* | *In/In* | *Pct* | *Pct* | | | | | |
| Ep—El Peco loam | | | | | | | | | | | | | | |
| El peco | 0-10 | -43- | -43- | 10-14- 18 | 1.35-1.45 | 4.00-14.00 | 0.05-0.12 | 0.0-2.9 | 0.5-1.0 | .43 | .43 | 3 | 4L | 86 |
| | 10-23 | -44- | -44- | 7-13- 18 | 1.40-1.55 | 4.00-14.00 | 0.05-0.10 | 0.0-2.9 | 0.0-0.5 | .43 | .43 | | | |
| | 23-33 | — | — | — | — | 0.01-0.10 | 0.00 | — | — | | | | | |
| | 33-60 | -27- | -53- | 15-20- 25 | 1.35-1.50 | 0.42-1.40 | 0.05-0.10 | 0.0-2.9 | 0.0 | .43 | .43 | | | |
| Fu—Fresno fine sandy loam | | | | | | | | | | | | | | |
| Fresno | 0-6 | -69- | -16- | 10-15- 20 | 1.45-1.55 | 4.00-14.00 | 0.08-0.10 | 0.0-2.9 | 0.5-1.0 | .43 | .43 | 3 | 3 | 86 |
| | 6-21 | -35- | -38- | 20-28- 35 | 1.35-1.50 | 0.01-0.42 | 0.09-0.12 | 3.0-5.9 | 0.0-0.5 | .43 | .43 | | | |
| | 21-28 | — | — | — | — | 0.01-0.10 | 0.00 | — | — | | | | | |
| | 28-39 | -43- | -40- | 10-18- 25 | 1.45-1.65 | 1.40-4.00 | 0.08-0.12 | 0.0-2.9 | 0.0 | .43 | .43 | | | |
| | 39-63 | -68- | -20- | 5-13- 20 | 1.45-1.65 | 1.40-4.00 | 0.08-0.12 | 0.0-2.9 | 0.0 | .43 | .43 | | | |
| Fv—Fresno fine sandy loam, shallow | | | | | | | | | | | | | | |
| Fresno | 0-6 | -69- | -16- | 10-15- 20 | 1.45-1.55 | 4.00-14.00 | 0.08-0.10 | 0.0-2.9 | 0.5-1.0 | .43 | .43 | 2 | 3 | 86 |
| | 6-18 | -35- | -38- | 20-28- 35 | 1.35-1.50 | 0.01-0.42 | 0.09-0.12 | 3.0-5.9 | 0.0-0.5 | .43 | .43 | | | |
| | 18-24 | — | — | — | — | 0.01-0.10 | 0.00 | — | — | | | | | |
| | 24-60 | -43- | -40- | 10-18- 25 | 1.45-1.65 | 1.40-4.00 | 0.08-0.12 | 0.0-2.9 | 0.0 | .43 | .43 | | | |

| Physical Soil Properties–Eastern Fresno Area, California | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Map symbol and soil name | Depth | Sand | Silt | Clay | Moist bulk density | Saturated hydraulic conductivity | Available water capacity | Linear extensibility | Organic matter | Erosion factors | | | Wind erodibility group | Wind erodibility index |
| | | | | | | | | | | Kw | Kf | T | | |
| | *In* | *Pct* | *Pct* | *Pct* | *g/cc* | *micro m/sec* | *In/In* | *Pct* | *Pct* | | | | | |
| Hsd—Hesperia sandy loam | | | | | | | | | | | | | | |
| Hesperia | 0-11 | -68- | -20- | 7-13- 18 | 1.50-1.60 | 14.00-42.00 | 0.10-0.15 | 0.0-2.9 | 0.5-1.0 | .32 | .32 | 5 | 3 | 86 |
| | 11-32 | -68- | -20- | 7-13- 18 | 1.50-1.60 | 14.00-42.00 | 0.10-0.15 | 0.0-2.9 | 0.0-0.5 | .32 | .32 | | | |
| | 32-60 | -68- | -20- | 7-13- 18 | 1.50-1.60 | 14.00-42.00 | 0.10-0.15 | 0.0-2.9 | 0.0-0.5 | .32 | .32 | | | |
| | 60-65 | - 5- | -85- | 5-10- 30 | 1.45-1.60 | 0.42-1.40 | 0.15-0.18 | 0.0-2.9 | 0.0-0.5 | .49 | .49 | | | |

# Data Source Information

Soil Survey Area: Eastern Fresno Area, California
Survey Area Data: Version 5, Sep 26, 2008

# Soil Features

This table gives estimates of various soil features. The estimates are used in land use planning that involves engineering considerations.

A *restrictive layer* is a nearly continuous layer that has one or more physical, chemical, or thermal properties that significantly impede the movement of water and air through the soil or that restrict roots or otherwise provide an unfavorable root environment. Examples are bedrock, cemented layers, dense layers, and frozen layers. The table indicates the hardness and thickness of the restrictive layer, both of which significantly affect the ease of excavation. *Depth to top* is the vertical distance from the soil surface to the upper boundary of the restrictive layer.

*Subsidence* is the settlement of organic soils or of saturated mineral soils of very low density. Subsidence generally results from either desiccation and shrinkage, or oxidation of organic material, or both, following drainage. Subsidence takes place gradually, usually over a period of several years. The table shows the expected initial subsidence, which usually is a result of drainage, and total subsidence, which results from a combination of factors.

*Potential for frost action* is the likelihood of upward or lateral expansion of the soil caused by the formation of segregated ice lenses (frost heave) and the subsequent collapse of the soil and loss of strength on thawing. Frost action occurs when moisture moves into the freezing zone of the soil. Temperature, texture, density, saturated hydraulic conductivity (Ksat), content of organic matter, and depth to the water table are the most important factors considered in evaluating the potential for frost action. It is assumed that the soil is not insulated by vegetation or snow and is not artificially drained. Silty and highly structured, clayey soils that have a high water table in winter are the most susceptible to frost action. Well drained, very gravelly, or very sandy soils are the least susceptible. Frost heave and low soil strength during thawing cause damage to pavements and other rigid structures.

*Risk of corrosion* pertains to potential soil-induced electrochemical or chemical action that corrodes or weakens uncoated steel or concrete. The rate of corrosion of uncoated steel is related to such factors as soil moisture, particle-size distribution, acidity, and electrical conductivity of the soil. The rate of corrosion of concrete is based mainly on the sulfate and sodium content, texture, moisture content, and acidity of the soil. Special site examination and design may be needed if the combination of factors results in a severe hazard of corrosion. The steel or concrete in installations that intersect soil boundaries or soil layers is more susceptible to corrosion than the steel or concrete in installations that are entirely within one kind of soil or within one soil layer.

For uncoated steel, the risk of corrosion, expressed as *low*, *moderate*, or *high*, is based on soil drainage class, total acidity, electrical resistivity near field capacity, and electrical conductivity of the saturation extract.

For concrete, the risk of corrosion also is expressed as *low*, *moderate*, or *high.* It is based on soil texture, acidity, and amount of sulfates in the saturation extract.

# Report—Soil Features

| Soil Features–Eastern Fresno Area, California | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Map symbol and soil name | Restrictive Layer | | | | Subsidence | | Potential for frost action | Risk of corrosion | |
| | Kind | Depth to top | Thickness | Hardness | Initial | Total | | Uncoated steel | Concrete |
| | | *In* | *In* | | *In* | *In* | | | |
| Ep—El Peco loam | | | | | | | | | |
| El peco | Duripan | 20-40 | 0-3 | Indurated | 0 | 0 | None | High | Low |
| Fu—Fresno fine sandy loam | | | | | | | | | |
| Fresno | Duripan | 20-36 | 0-3 | Indurated | 0 | 0 | None | High | Moderate |
| Fv—Fresno fine sandy loam, shallow | | | | | | | | | |
| Fresno | Duripan | 10-20 | 0-3 | Indurated | 0 | 0 | None | High | Moderate |
| Hsd—Hesperia sandy loam | | | | | | | | | |
| Hesperia | | — | — | | 0 | 0 | None | High | Low |

# Data Source Information

Soil Survey Area: Eastern Fresno Area, California
Survey Area Data: Version 5, Sep 26, 2008

# MEMO

To: Charlie Krauter, John Bushoven
From: John Lichter and Tony Mucciardi
Date: October 21, 2013
Re: West Lincoln Avenue Almonds TRU Study

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The following is an introduction to Ground Penetrating Radar (GPR), the TreeRadar™ Unit root inspection protocol and results presentation and a summary of our methods and results concerning our study at the West Lincoln Avenue Almonds Plot.

## An Introduction to Ground-Penetrating Radar (GPR)

Ground-Penetrating Radar (GPR) is an established technique that has been used worldwide for over 30 years to locate objects underground, including pipes, barrels, drums, and other engineering and environmental targets. When an electromagnetic wave emitted from a small surface transmit antenna encounters a boundary between objects with different electromagnetic properties it will reflect, refract, and/or diffract from the boundary in a predictable manner.

Use of GPR instrumentation for internal trunk decay detection and subsurface structural root mapping is a novel and recent application to the arboricultural field that has been developed and patented by TreeRadar™, Inc. under the name TRU™ (Tree Radar Unit).

An air-filled trunk (hollow) or partially air-filled incipient decay zone are excellent reflectors for detection by GPR systems. In addition electromagnetic differences between tree roots and the surrounding soil matrix provide the necessary contrast and reflection properties that are detected by GPR.

GPR measurement as a method of mapping tree roots has several advantages over other methods: (1) it is capable of scanning root systems of large trees under field conditions in a short time, (2) it is completely non-invasive and does not disturb the soils or damage the trees examined and causes no harm to the environment, (3) being non-invasive, it allows repeated measurements that reveal long-term root system development, (4) it allows observation of root distribution beneath hard surfaces (concrete, asphalt, bricks), roads and buildings, (5) its accuracy is sufficient to resolve structural roots with diameters from less than 1 cm (0.4 in) to 3 cm (1.2 in) or more, (6) it can characterize roots at both the individual tree and stand levels, facilitating correlations with tree-and stand-level measurements of physiological processes (e.g., sap flow) in complex ecological studies.

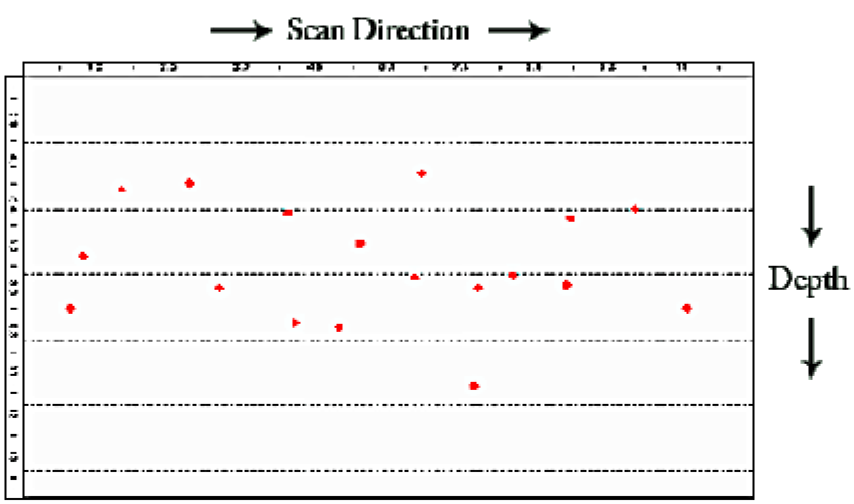
## Roots Inspection Protocol

TreeRadar™, Inc. has developed and patented a system known as TRU™ (Tree Radar Unit) which represents a novel application of ground-penetrating radar (as described in the Introduction section). TRU can be used to inspect both tree trunks for internal decay and subsurface structural roots (roots whose diameter is 1cm (0.4in) and larger), respectively, completely non-invasively.

A TRU roots inspection consists of two independent steps: (1) on-site data collection, and (2) off-site data analysis using TreeRadar's proprietary TreeWin™ software program to analyze the data after the field data collection runs.

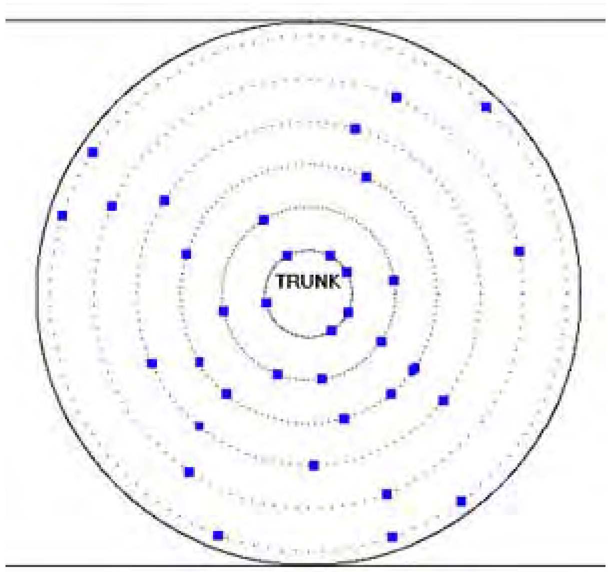
The data analysis results can be presented in two formats.

One is a 2D "Virtual Trench" in which a planar 2D view is generated that shows the predicted root locations and depths as if a backhoe had excavated by digging a trench. This is shown in the figure below. The way to interpret the 2D planar view is to imagine a backhoe digging a trench that was, for example, 6m (20ft) long and 1m (3ft) deep. The backhoe's digging blade would sever all of the roots. After the trench was dug, imagine stepping into and kneeling in the trench and looking at either cut side. You would see the severed root endings. If you painted them a color to make them stand out from the excavated soil, you would be seeing a collection of colored "dots" that would show you where the roots were located along the excavated trench line and their respective depths below the surface. This is the view shown in the Virtual Trench 2D plot, one for each scan line.



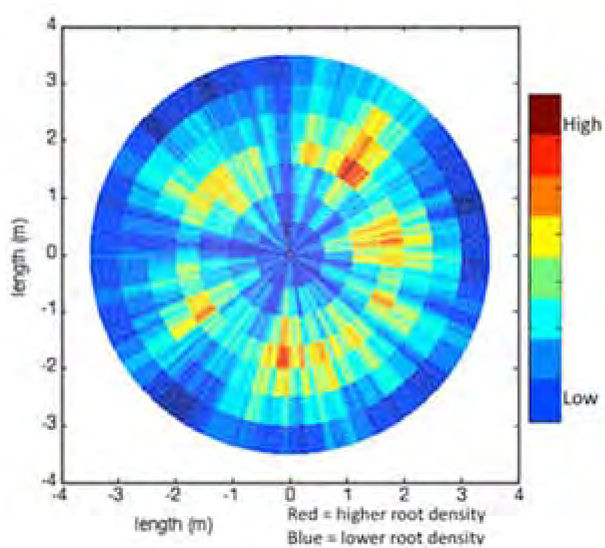

**Virtual Trench** - 2D Planar Depth Image of Root Location (top scale, ft) and Depth (left scale, in) for One Scan Line

The second presentation takes the ensemble of line scans and shows the view looking down from above, i.e., a top-down 3D root map. This top-down view (plan view) is valuable for determining the spatial root layout and density.




**3D Top-Down Image of Root Layout**

A third presentation is the Root Density Map. This depicts all detected roots projected to the surface with different colors representing varying densities of roots found in a given location along the scans. Areas with low root densities are shown with blue colors and areas with high root densities are given red colors as shown below.



## *Methods*

Using both 400 and 900 MHz antennas, I utilized my TreeRadar™ Unit to scan the soil within an almond orchard off West Lincoln Avenue near Fresno, California. You created a plot which was approximately 12 feet (northwest to southeast) by 14 feet (northeast to southwest) with a tree located near the north corner of the plot (see Figure 1). A natural gas line ran diagonally through the plot in a southwest to northeast direction passing to the east of the tree in the plot at approximately 40 inches below grade. The plot was divided into a grid labeled A to F and 1 to 6. Scans were run east to west on the lettered lines and north to south on the numbered lines (see top down results).

Figure 1. View of plot showing gridlines and tree near north corner of plot.

I submitted a sketch of the site and scan lines, information on the approximate location of the pipe and the data files to Dr. Tony Mucciardi with TreeRadar, Inc. for analysis.

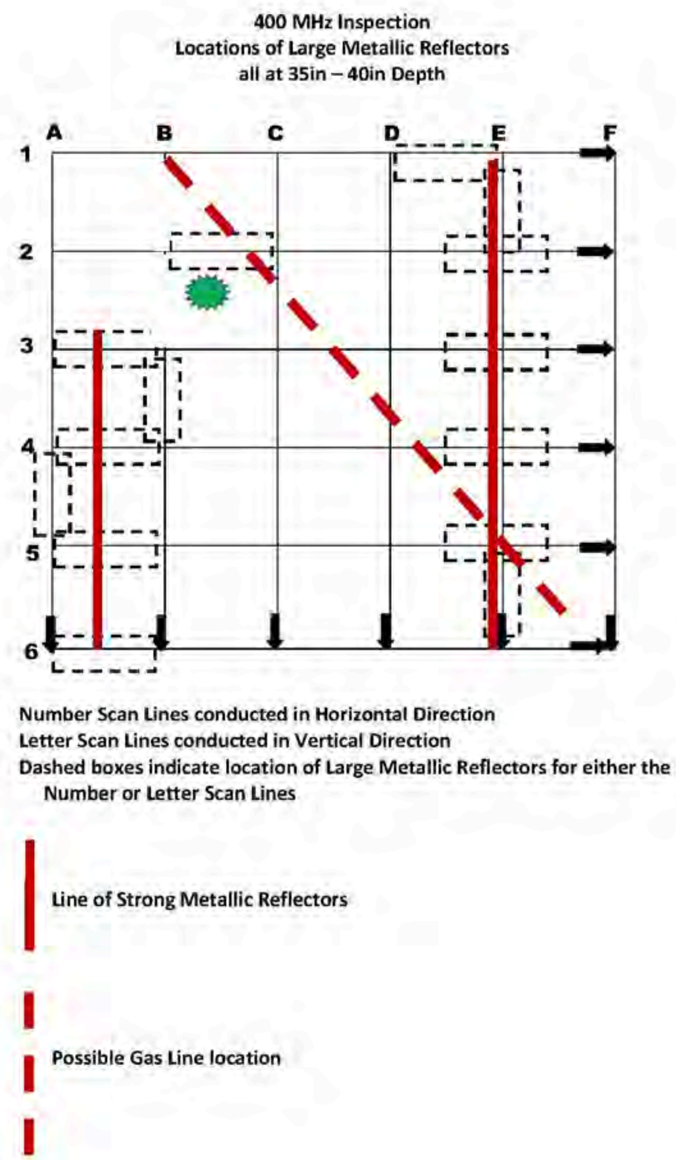
### *400 vs. 900 MHz Scans*

Results are presented from scans with both 400 and 900 MHz antennas. The 400 MHz antenna has the ability to scan to a depth of 9 to 12 feet while the 900 MHz antenna is limited to a depth of 3 feet. The 400 MHz antenna detects roots larger than approximately 0.8 inches diameter while the 900 MHz antenna detects roots larger than 0.4 inches diameter.

### *Results*

*Top Down Views:*

Location of Metallic Reflectors: The location of metallic reflectors and the possible location of the gas pipeline (fitted to two of the reflectors) are depicted on the plot with scan lines indicated as well as scan directions (see below) and the location of the tree trunk. Setting the TRU to a more appropriate deeper depth setting may have modified the predicted location of the metallic reflectors. The deeper depth setting – down to about 70 inches will be used in future inspections.



*2D Cross-sectional Maps/Virtual Trench:*
The 2D cross-sectional maps, known as the Virtual Trench, depict the predicted location of roots with X's and metallic reflectors with boxes within each scan line with the start of the scan line on the left of the plot. The ground surface is shown as a dark line. The distance along the scan line is plotted on the x-axis with the depth on the y-axis. The different color X's represent roots in the three contiguous depth zones as described above. Also included to the left of the plot is an indication of root density (# roots per foot of scan) for the three depth ranges and total depth. Note that scan #B was a truncated scan which started to the southwest of the tree trunk.

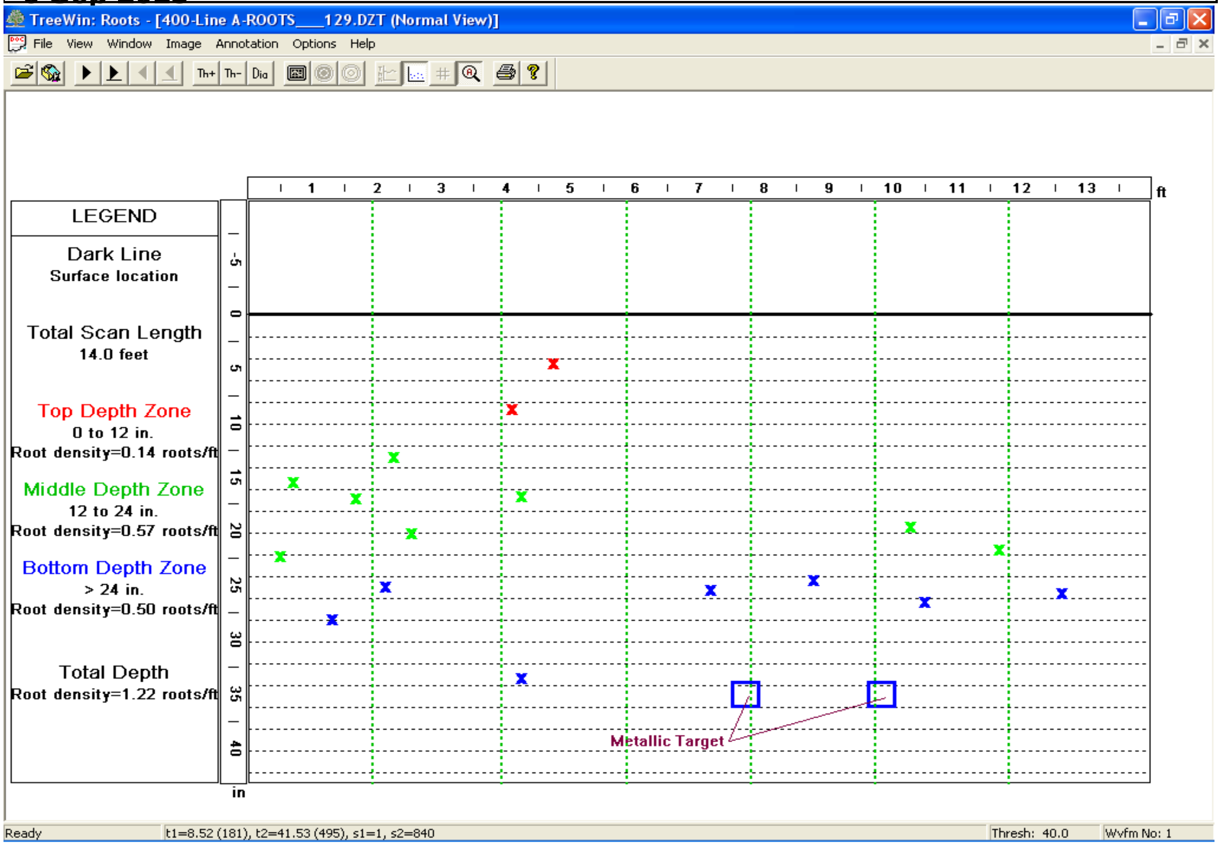
Looking at all the 400 MHz scans, the majority of roots were found between 12 and 35 inches depth. In only one case roots were found to the depth of the metallic reflector (Scan #B). In this same scan, a root was found approximately 6 inches away from the metallic reflector. Roots were 10 or more inches away from the metallic reflectors in other scans (#A,E,2,3,6). The density of roots is least between trees – see density across total depth for scans #C,D and #4,5,6. The 900 MHz scans show a dramatic decrease in root density between scans 3 to 6 (3.22 to 0 roots/ft.).

*3D Top-Down Plan Views/Virtual Excavation:*
The 3D top-down plan views, known as the Virtual Excavation, are attached for both 400 and 900 MHz scans which show the location of scan lines, tree in the plot and markers (pink lines) which I placed at every intersection with a grid line. Square boxes indicate metallic reflectors while X's indicate the location of roots. The top down views include a "total depth range" plot which shows all roots found to the depth of the scan (43.3 inches) while other plots show roots found within three depth slices; 0-12, 12-24 and below 24 inches depth. Roots found in the top foot were colored red, those in the second foot were colored blue and those below 2 feet were colored blue.

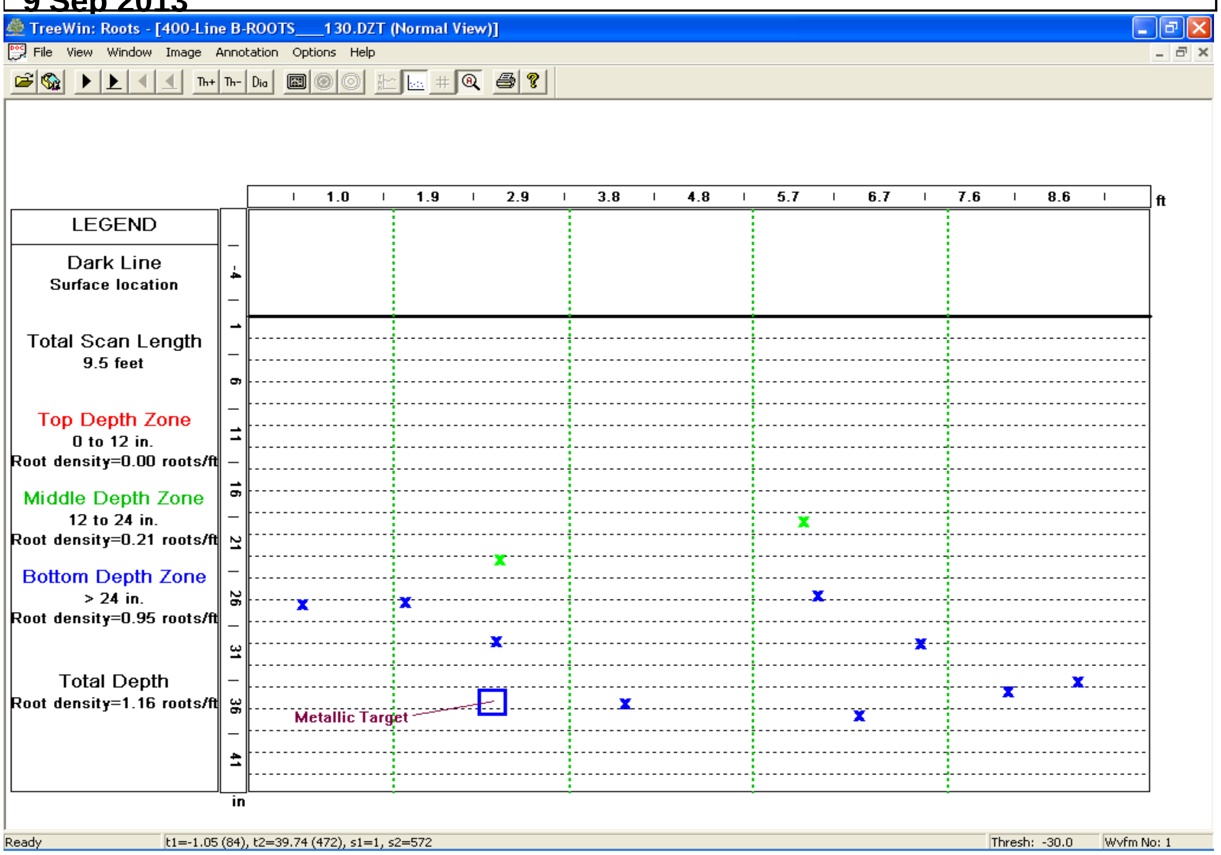
Looking at the top down view for the total depth range for both antennas, one can see that roots were found across the entire plot. However, there were more roots found within scan lines 1 to 4 and between A and F. More roots were detected with the 900 MHz antenna due to its lower minimum root diameter detection capability. Relatively few roots greater than or equal to 0.8 inches were found in the top foot of soil (see 400 MHz, Top 1/3 Depth Range). Roots were found to the lowest depth range of the scans as seen in the 400 MHz, Bottom 1/3 Depth Range plot. Note that for the 900 MHz results, the bottom 1/3 of the depth range was a 4" depth slice due to the maximum depth of 30 inches for the 900 MHz antenna. The metallic reflectors were below this depth range as well so they were not detected in the 900 MHz scans.

*Root Density Map:*
A root density map is also attached which superimposes the density of roots along scan lines for the entire depth range. Note that the overall root density is greater for the 900 MHz scans due to the antenna's lower minimum root diameter detection capability. The root density map for both antennas reveals the greater density of roots closer to the tree on the plot and the tree adjacent to the plot (berm area). Note that the root density on scan line 6 looks high but this is influenced by the presence of metallic reflectors.

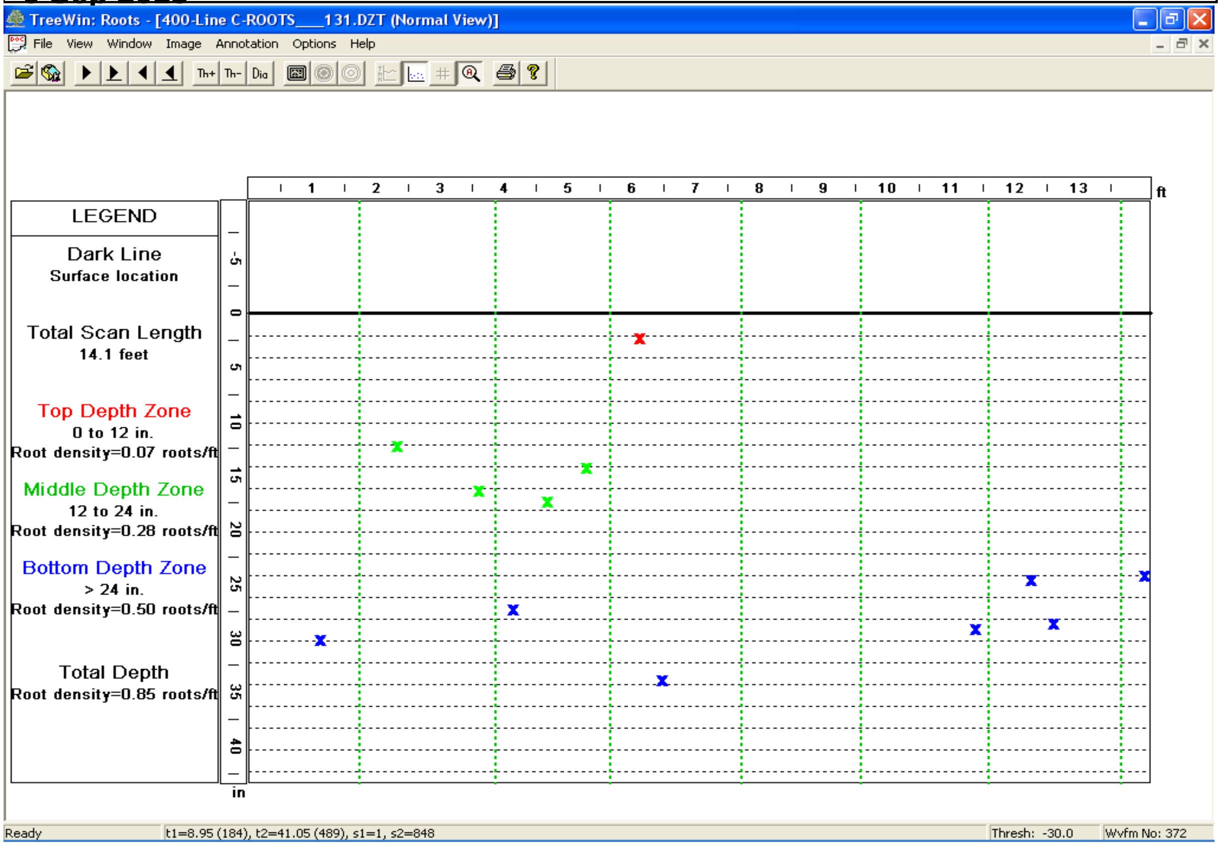
## W Lincoln Ave Almonds-400MHz - Scan # A (129) - Length = 14.0ft - 9 Sep 2013



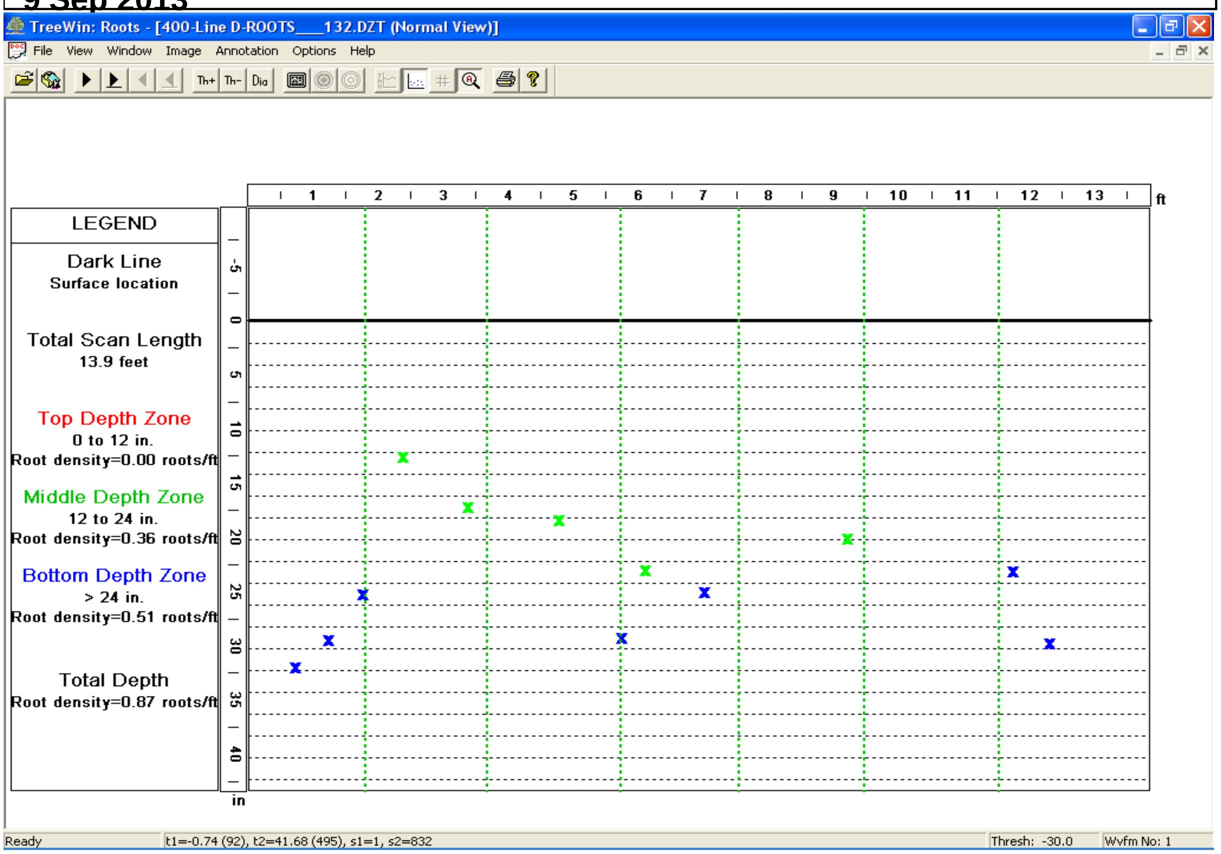

## W Lincoln Ave Almonds-400MHz - Scan # B (130) - Length = 9.5ft - 9 Sep 2013



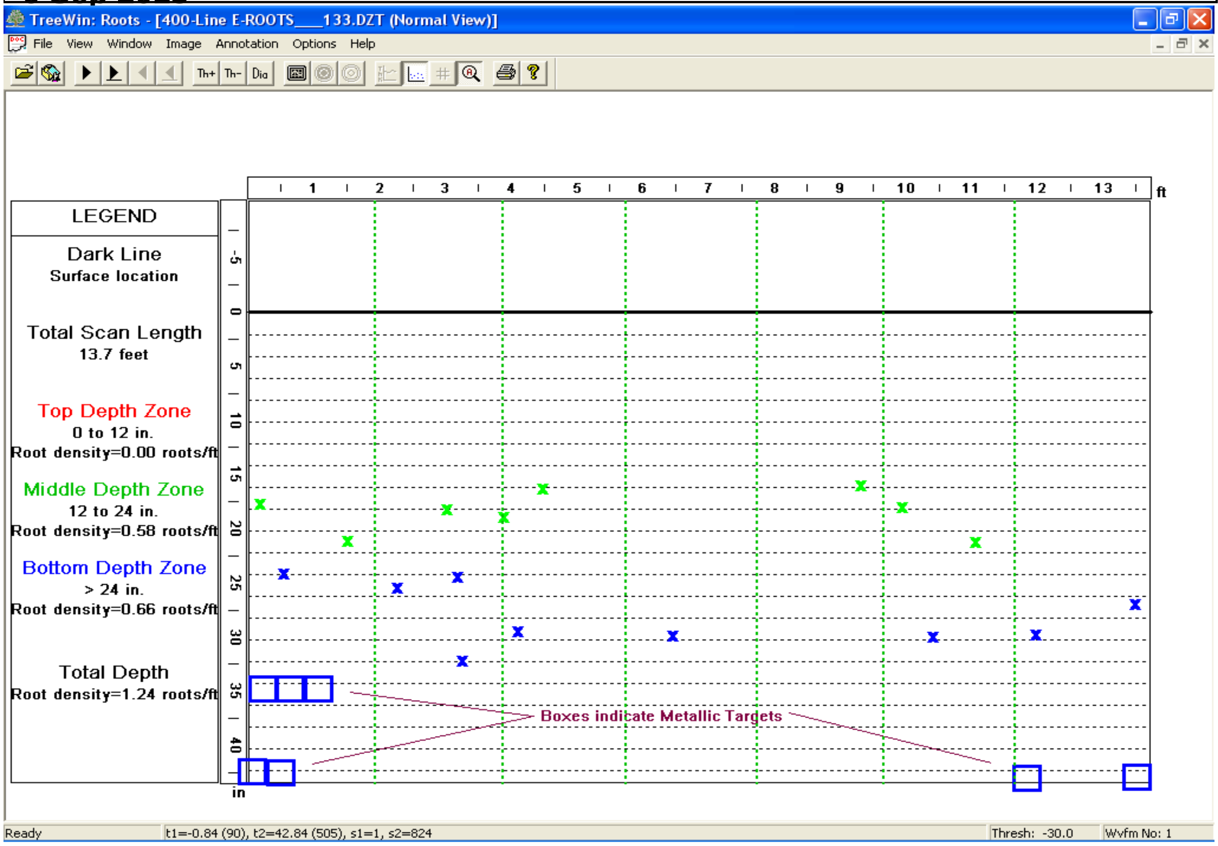
## W Lincoln Ave Almonds-400MHz - Scan # C (131) - Length = 14.0ft - 9 Sep 2013



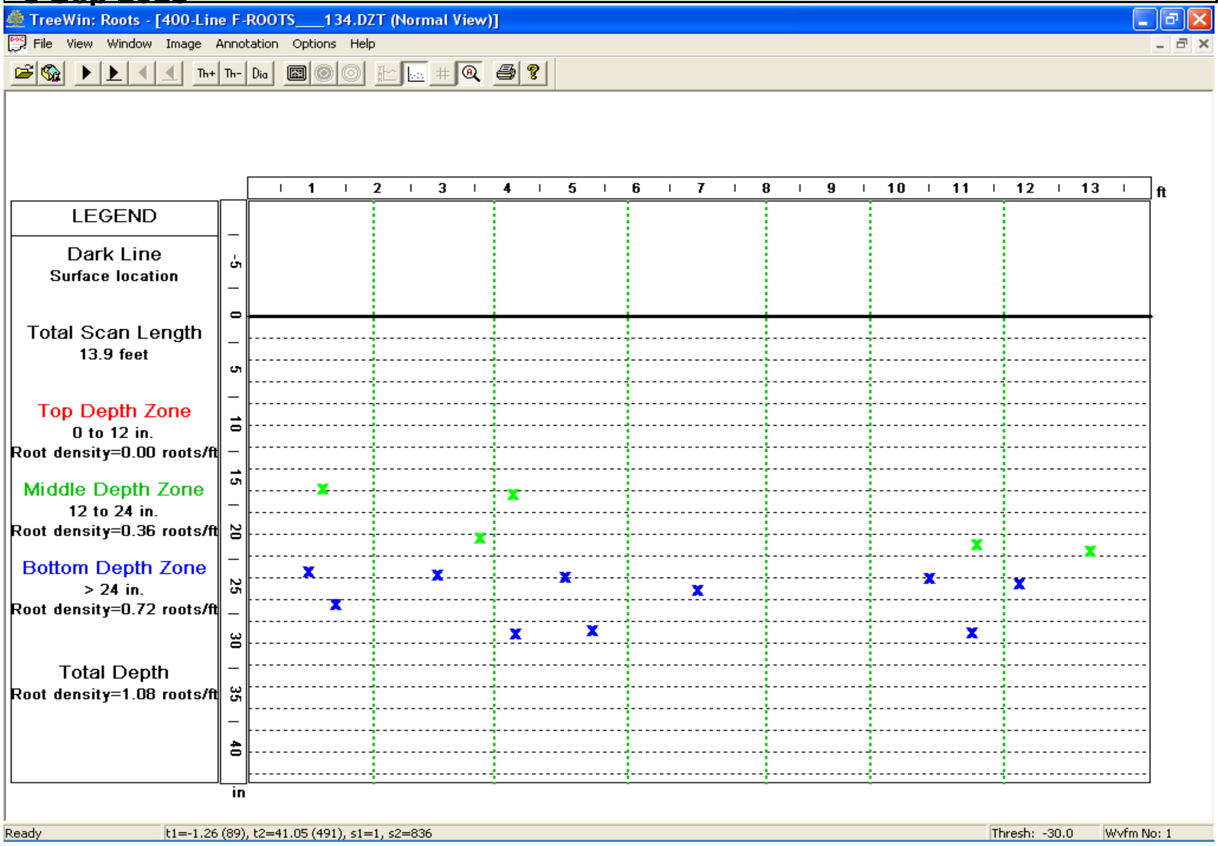

## W Lincoln Ave Almonds-400MHz - Scan # D (132) - Length = 13.9ft - 9 Sep 2013



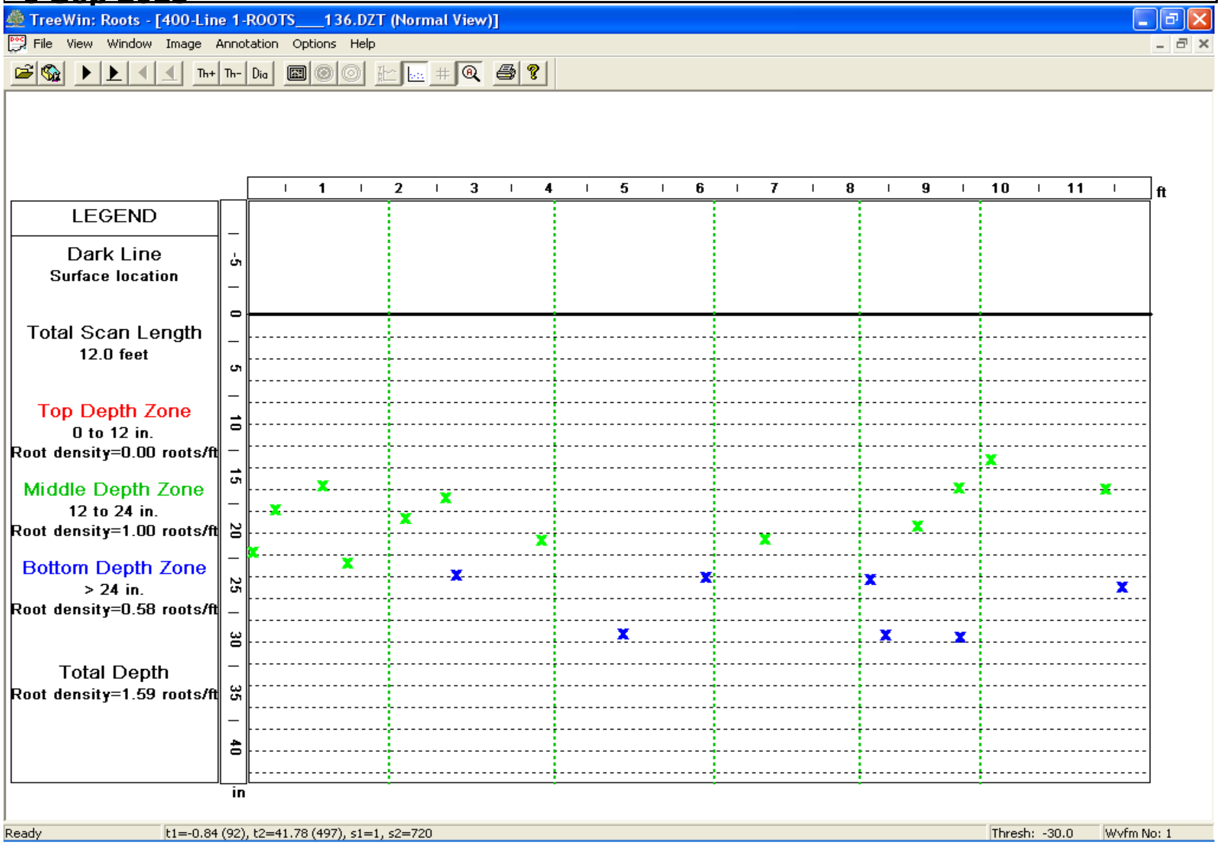
## W Lincoln Ave Almonds-400MHz - Scan # E (133) - Length = 13.7ft - 9 Sep 2013



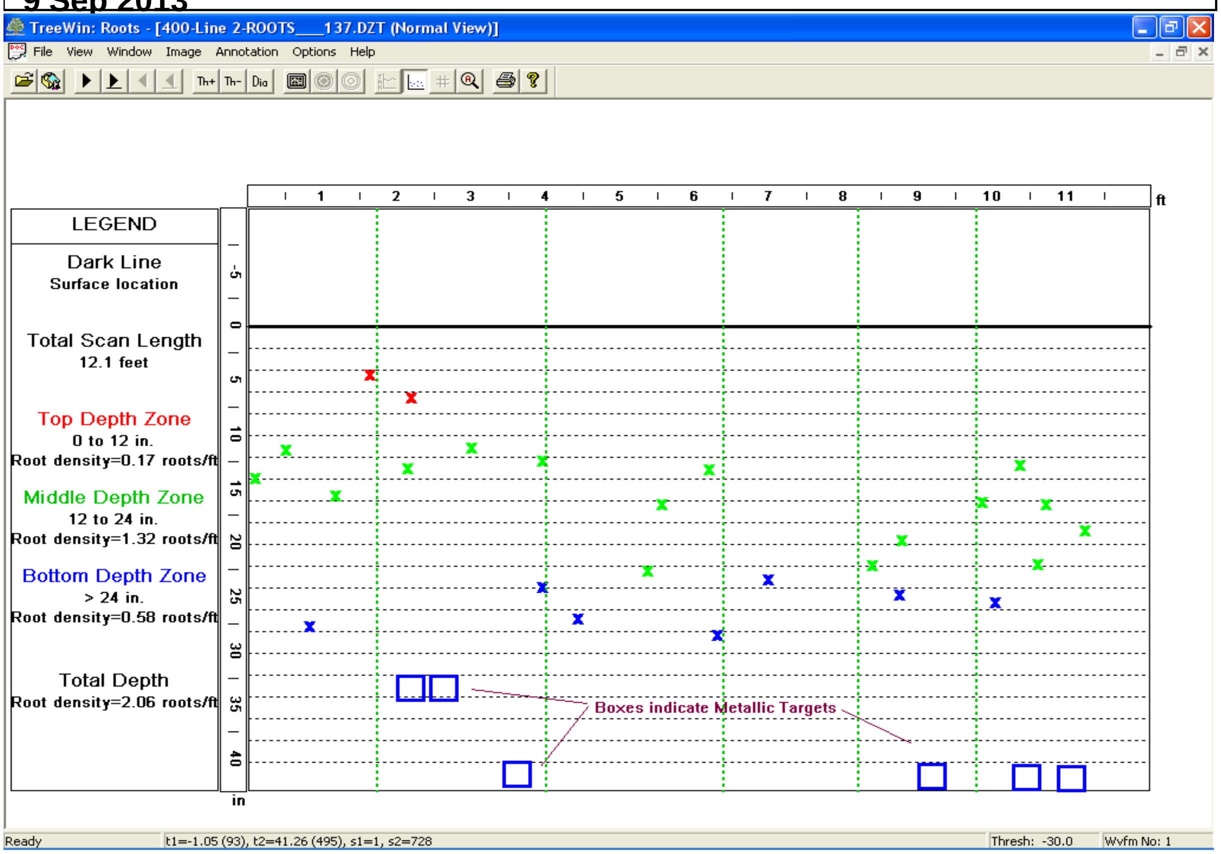

## W Lincoln Ave Almonds-400MHz - Scan # F (134) - Length = 13.9ft - 9 Sep 2013



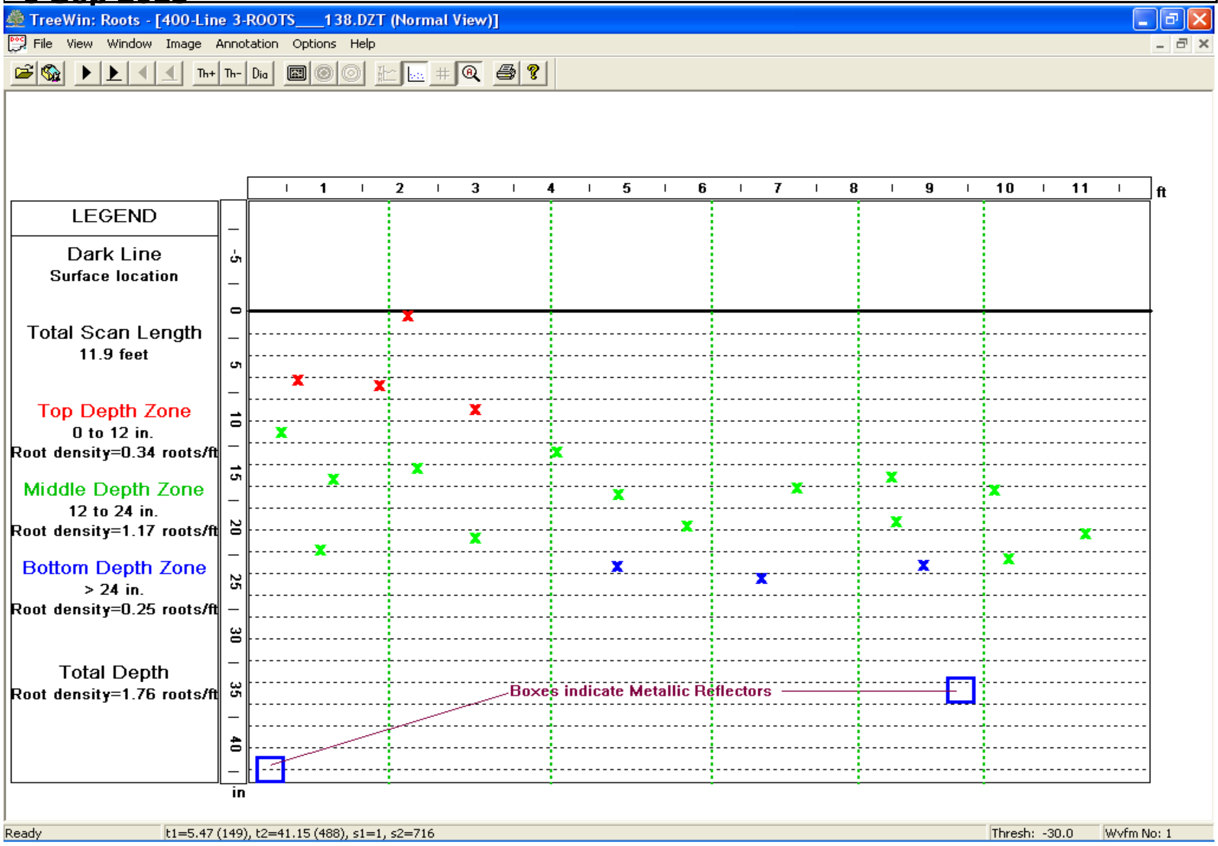
## W Lincoln Ave Almonds-400MHz - Scan # 1 (136) - Length = 12.0ft - 9 Sep 2013



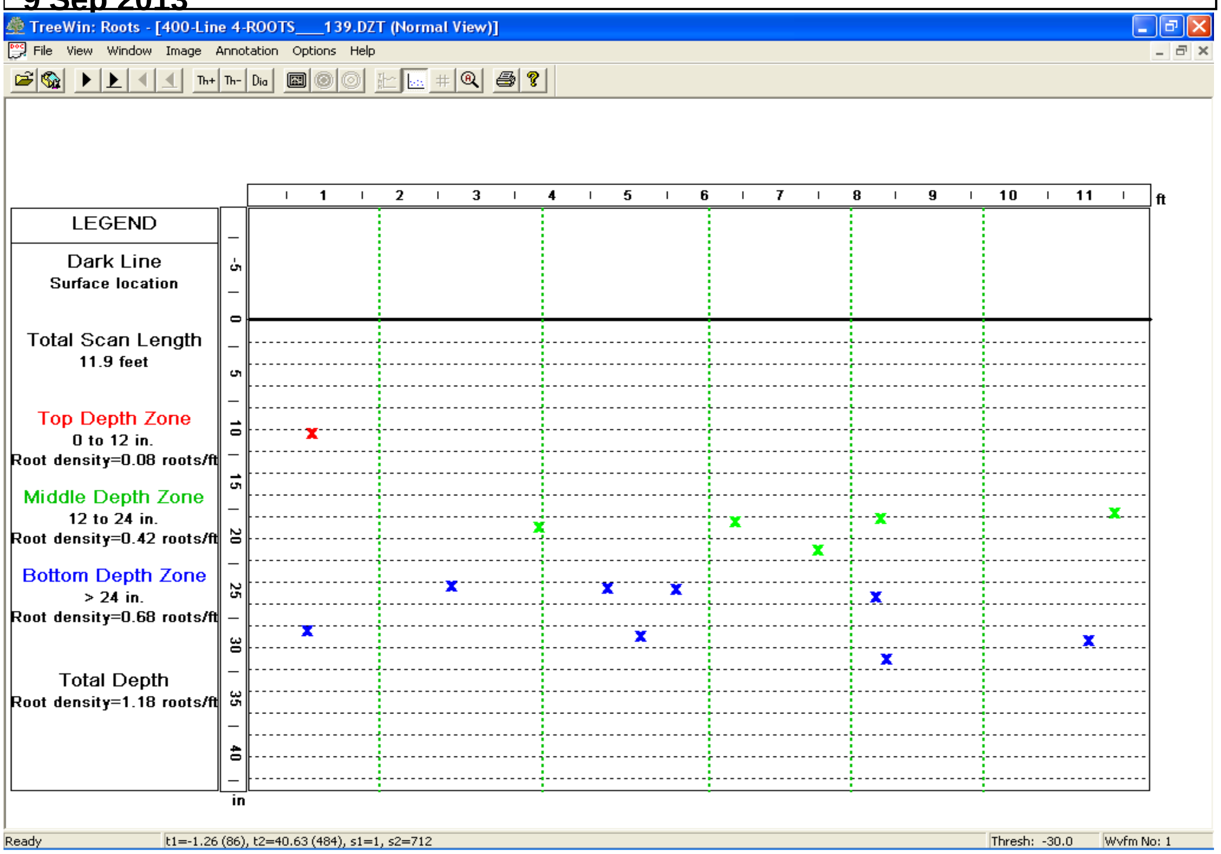

## W Lincoln Ave Almonds-400MHz - Scan # 2 (137) - Length = 12.1ft - 9 Sep 2013



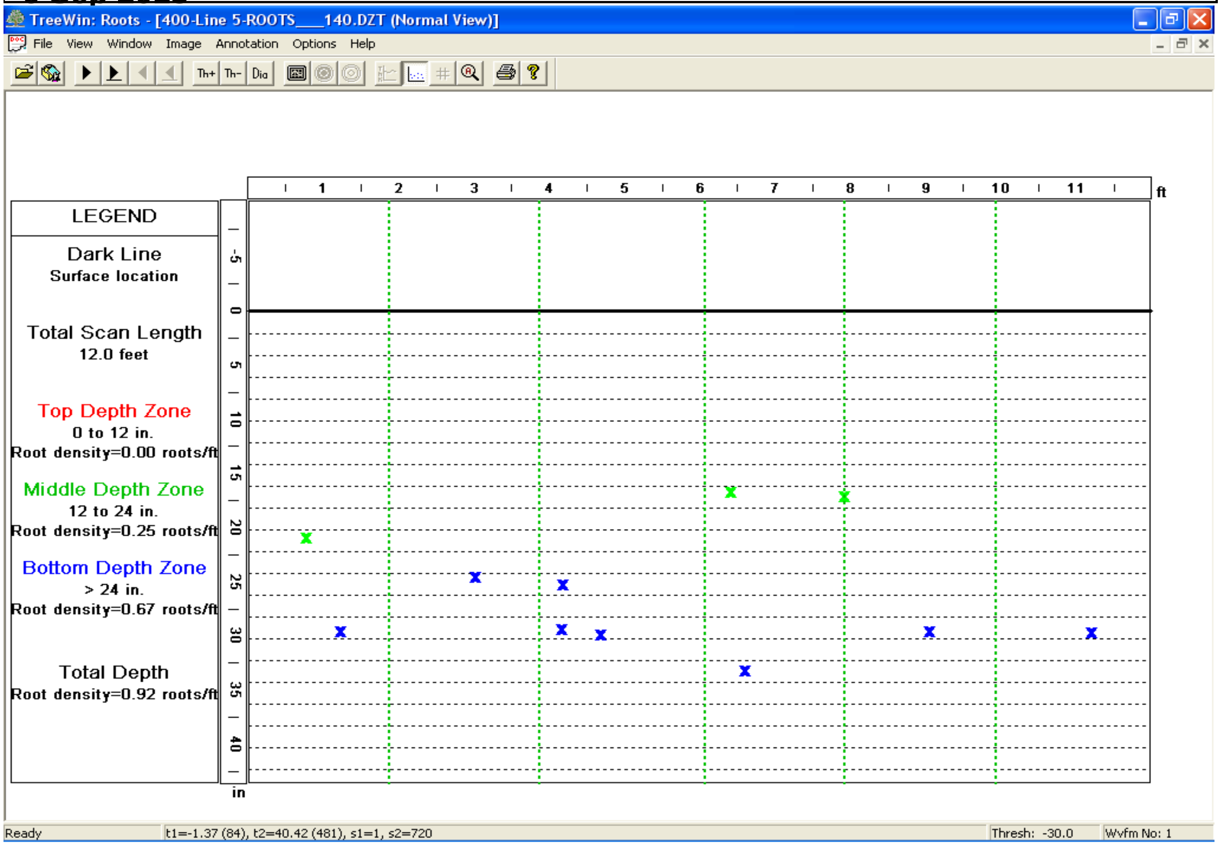
## W Lincoln Ave Almonds-400MHz - Scan # 3 (138) - Length = 11.9ft - 9 Sep 2013



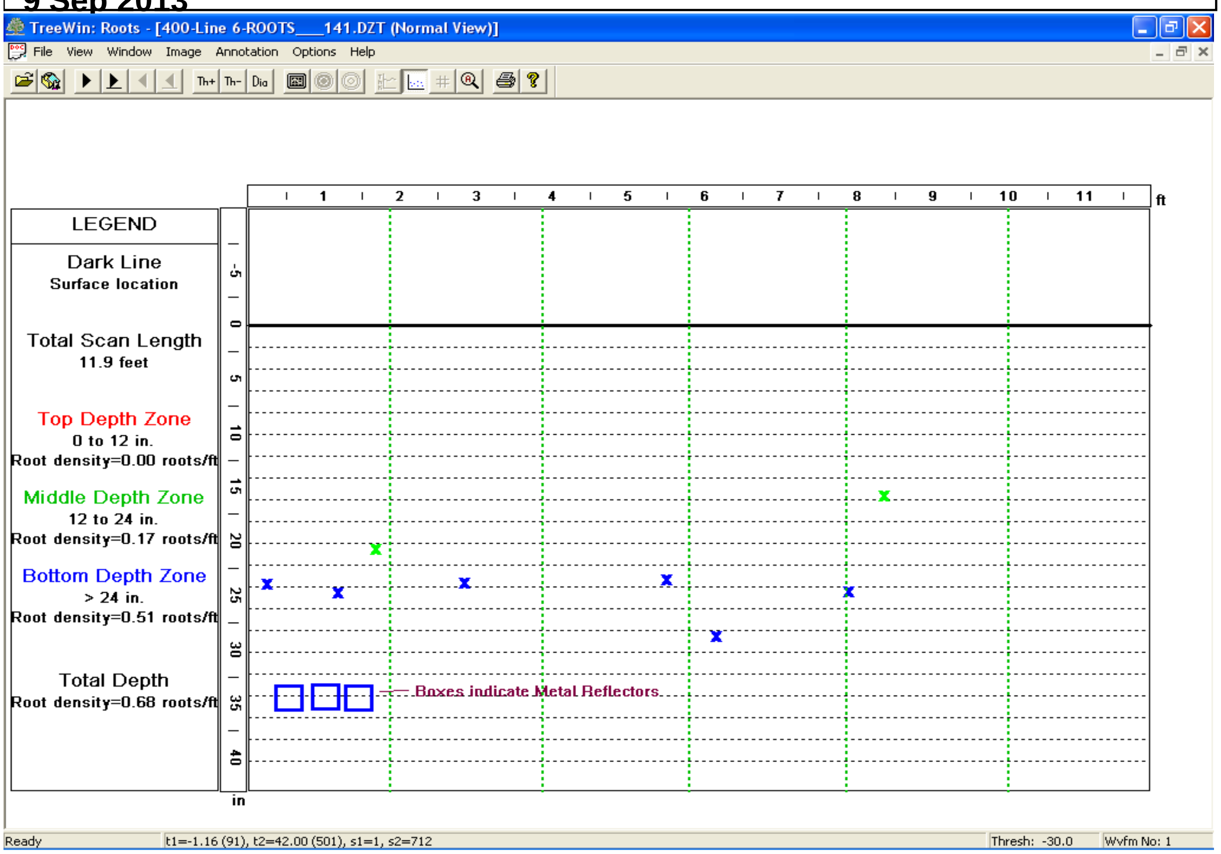

## W Lincoln Ave Almonds-400MHz - Scan # 4 (139) - Length = 11.9ft - 9 Sep 2013



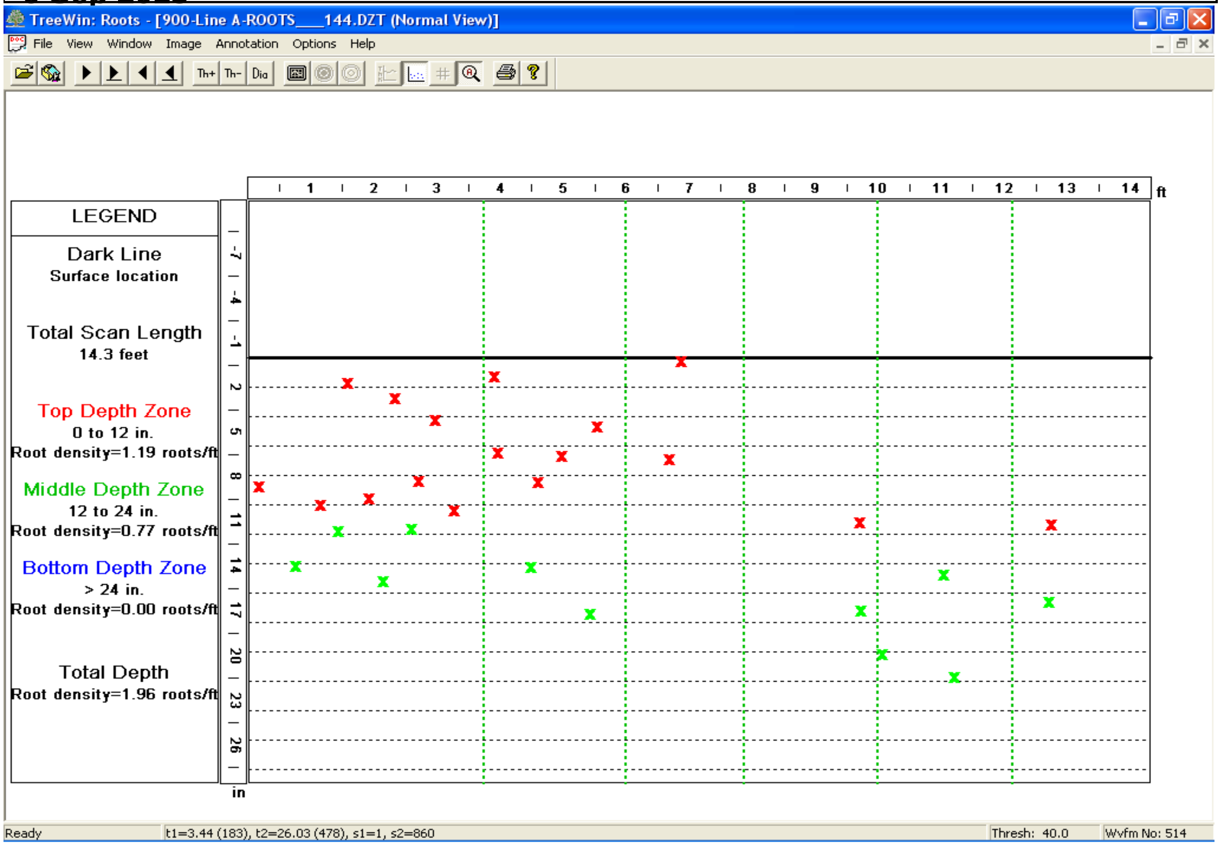
## W Lincoln Ave Almonds-400MHz - Scan # 5 (140) - Length = 12.0ft - 9 Sep 2013



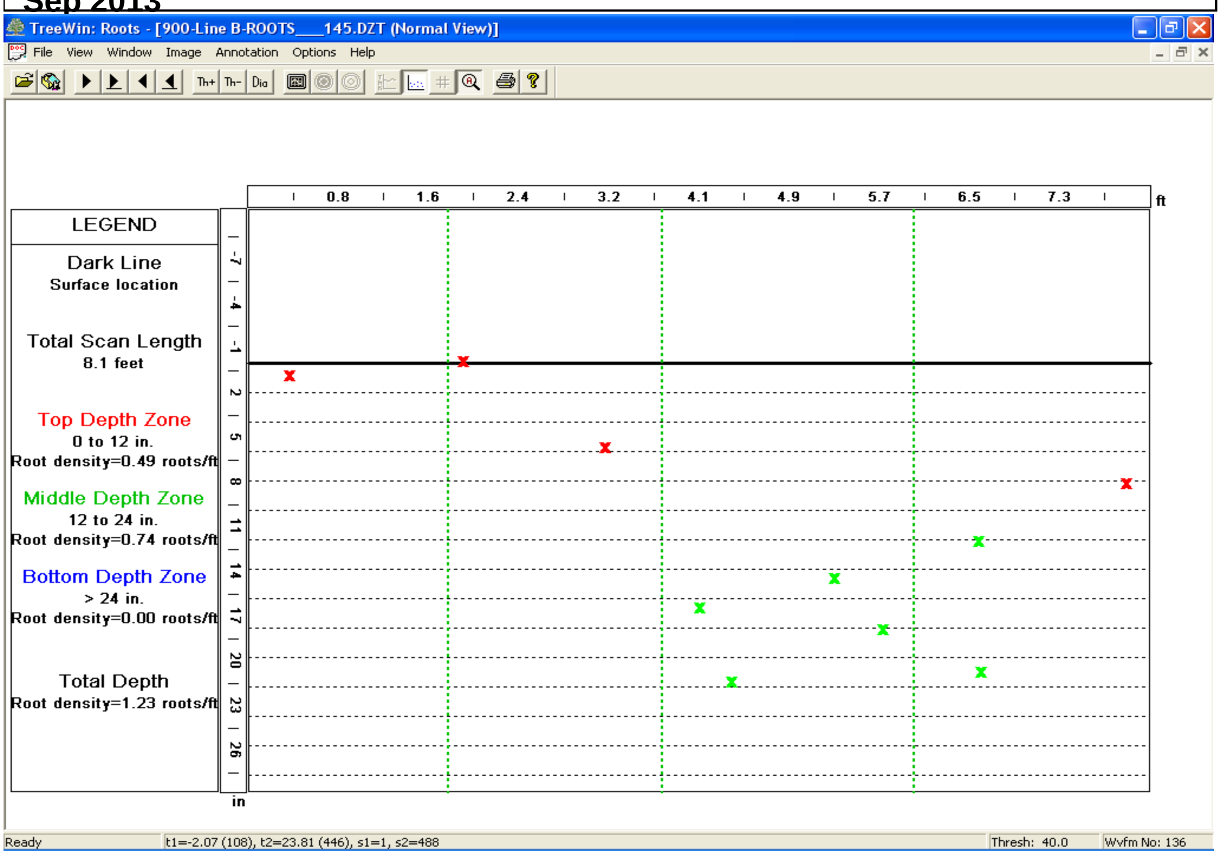

## W Lincoln Ave Almonds-400MHz - Scan # 6 (141) - Length = 11.9ft - 9 Sep 2013



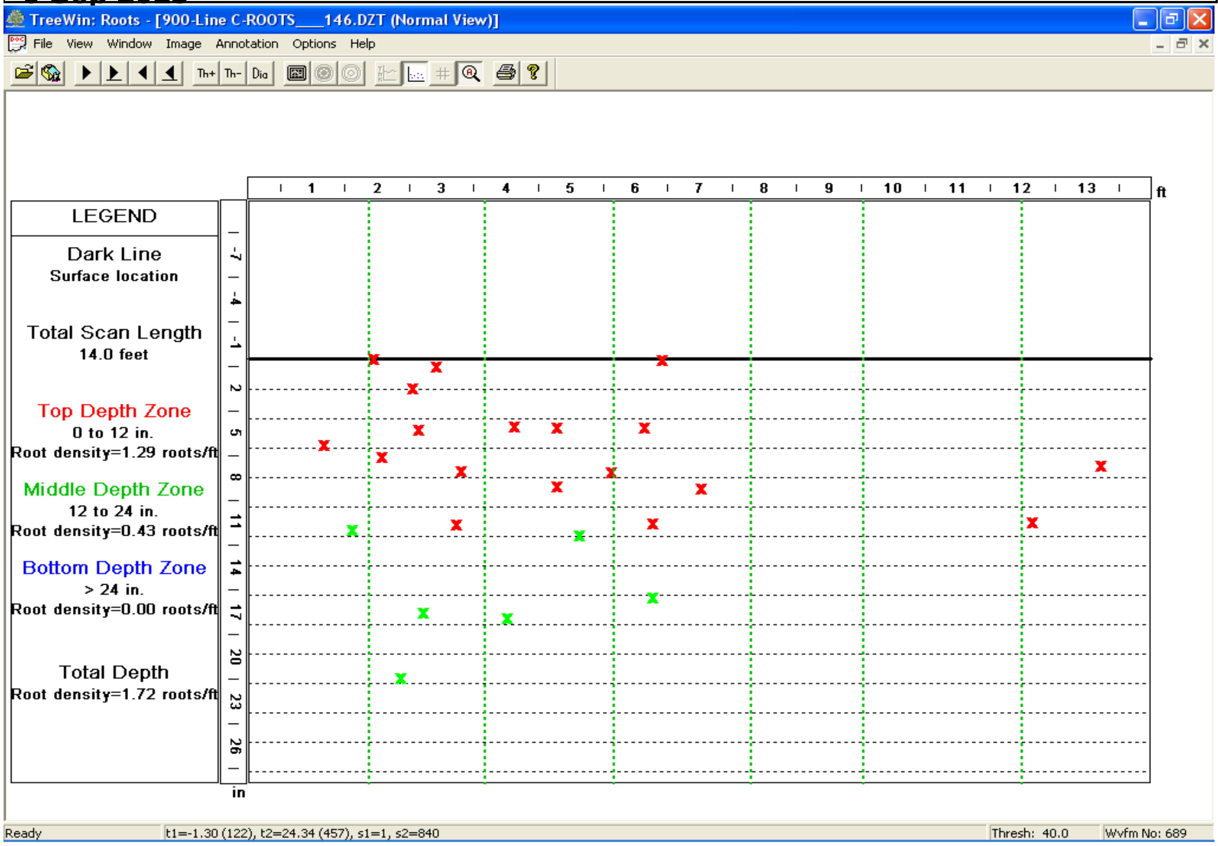
## W Lincoln Ave Almonds-900 MHz - Scan # A (144) - Length = 14.3ft - 9 Sep 2013



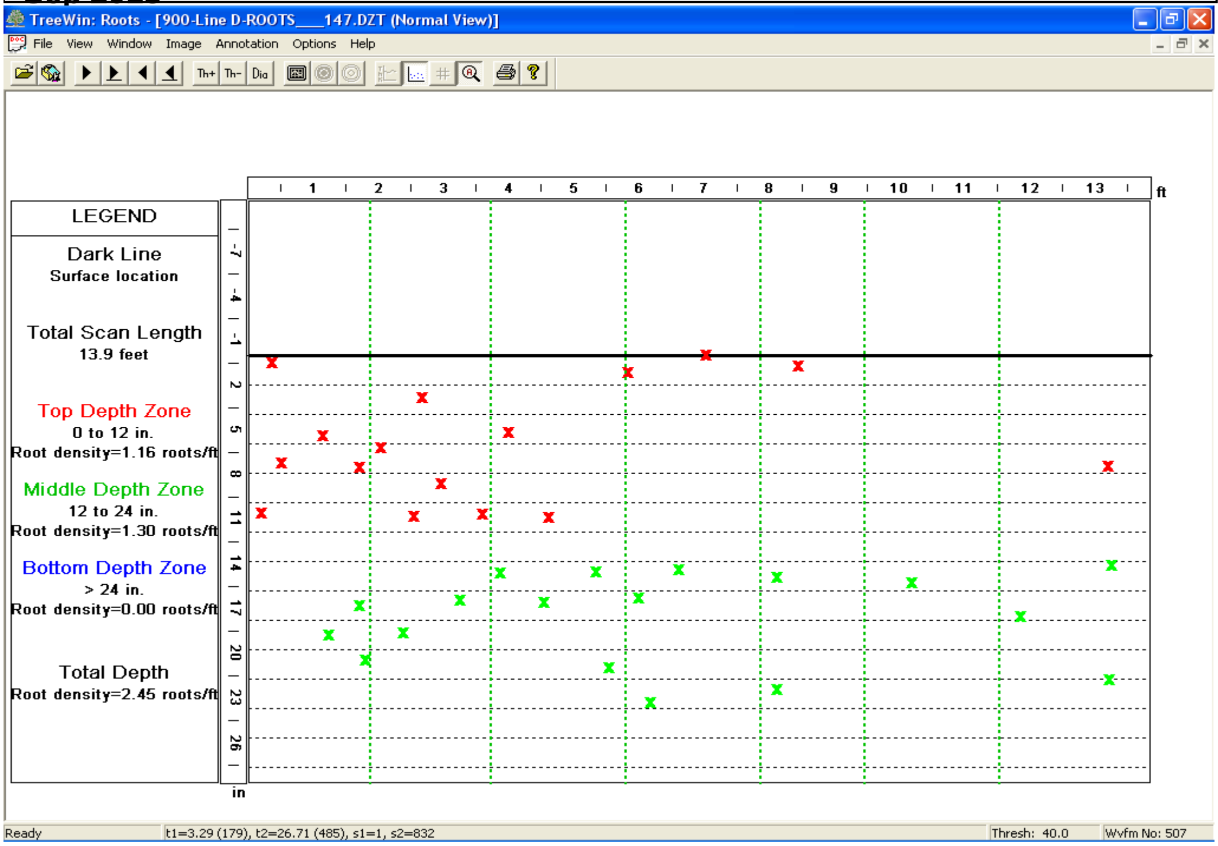

## W Lincoln Ave Almonds-900 MHz - Scan # B (145) - Length = 8.1ft - 9 Sep 2013



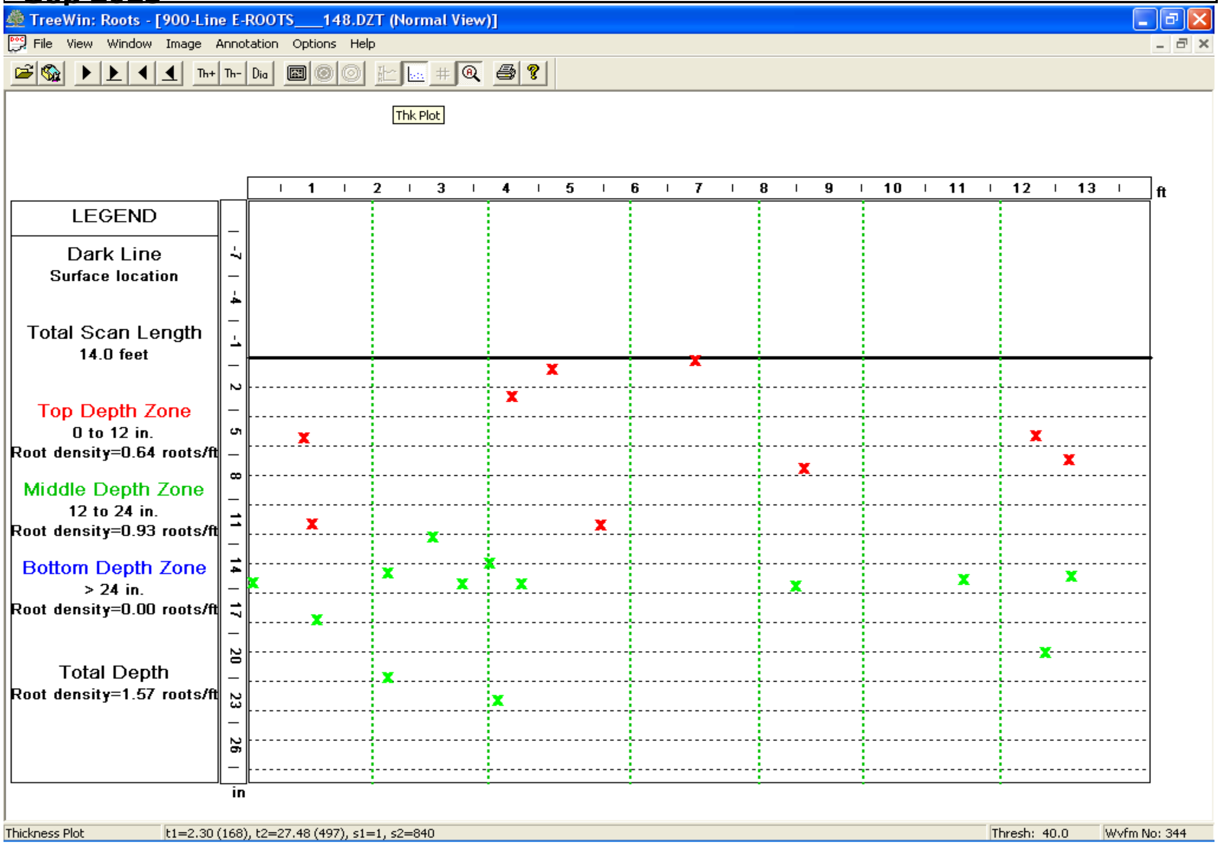
## W Lincoln Ave Almonds-900 MHz - Scan # C (146) - Length = 14.0ft - 9 Sep 2013



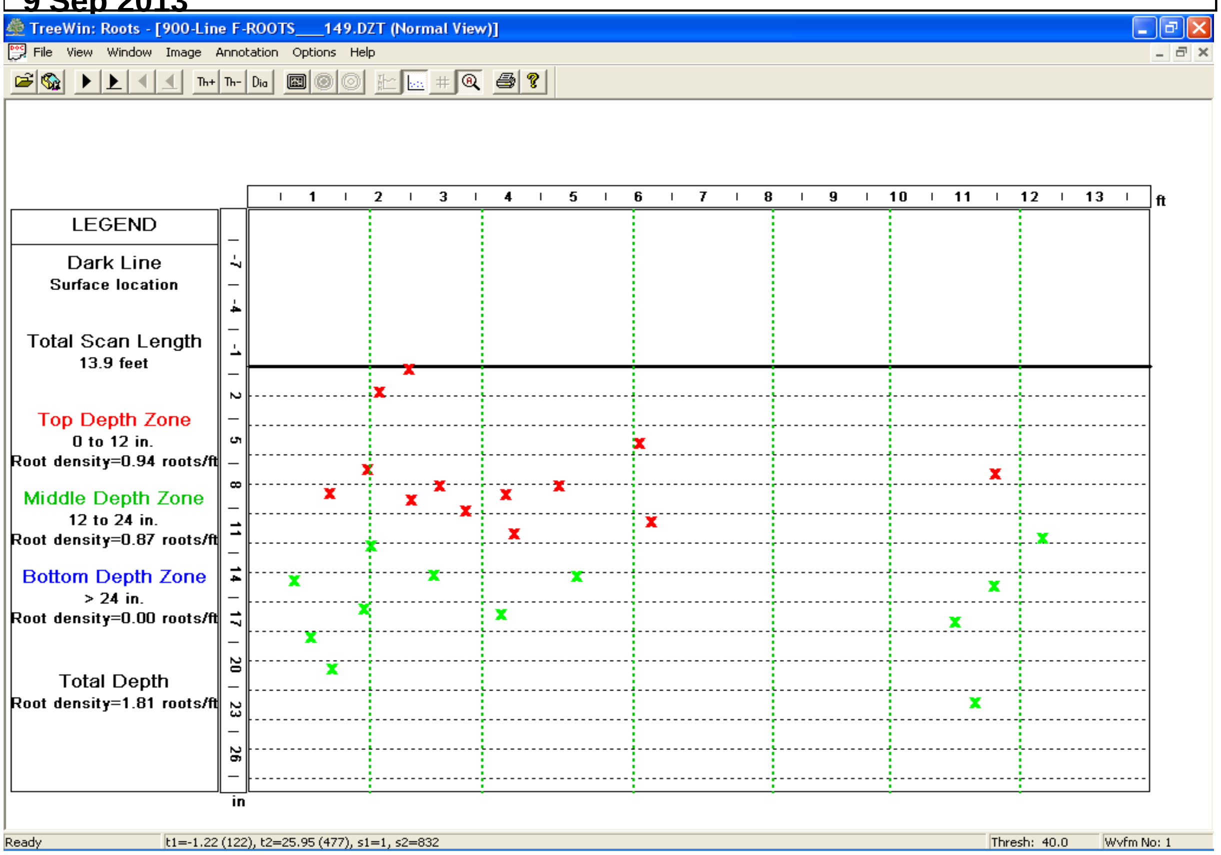

## W Lincoln Ave Almonds-900 MHz - Scan # D (147) - Length = 13.9ft - 9 Sep 2013



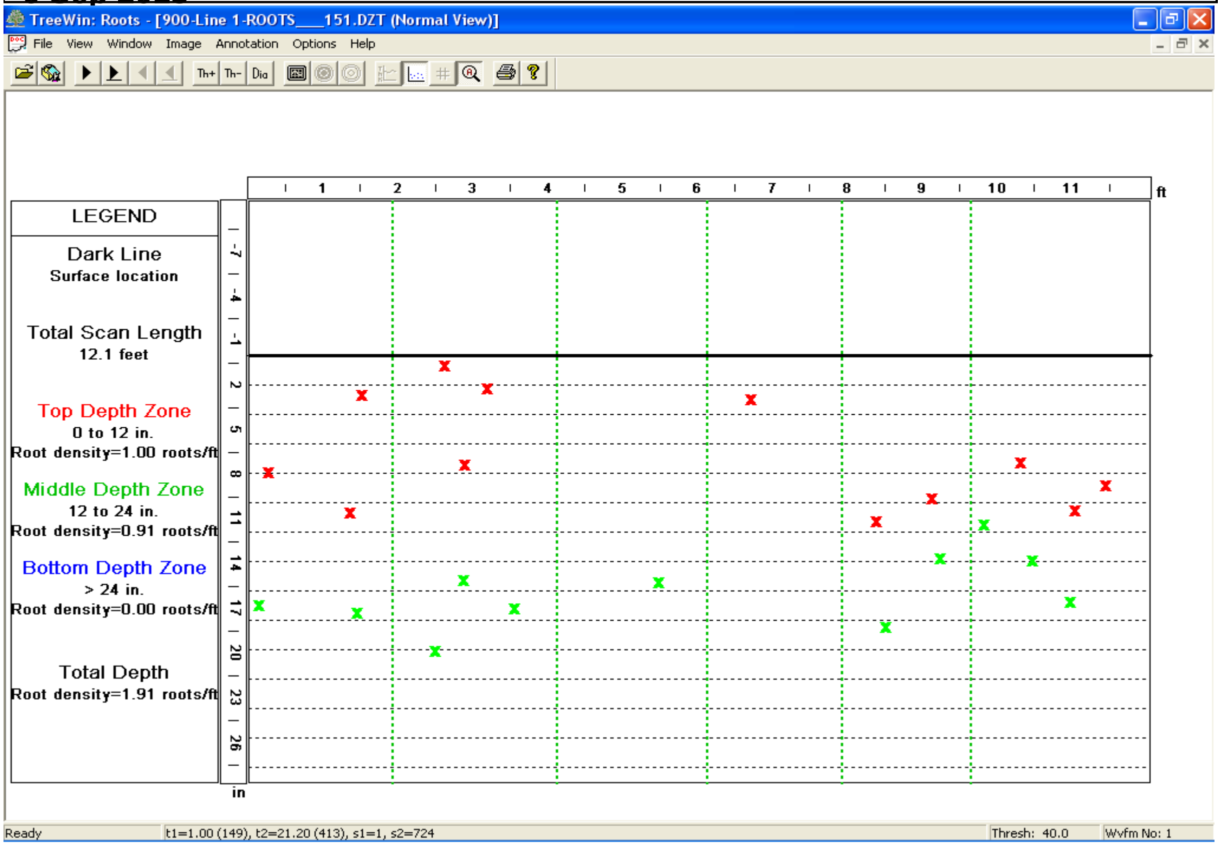
# W Lincoln Ave Almonds-900 MHz - Scan # E (148) - Length = 14.0ft - 9 Sep 2013



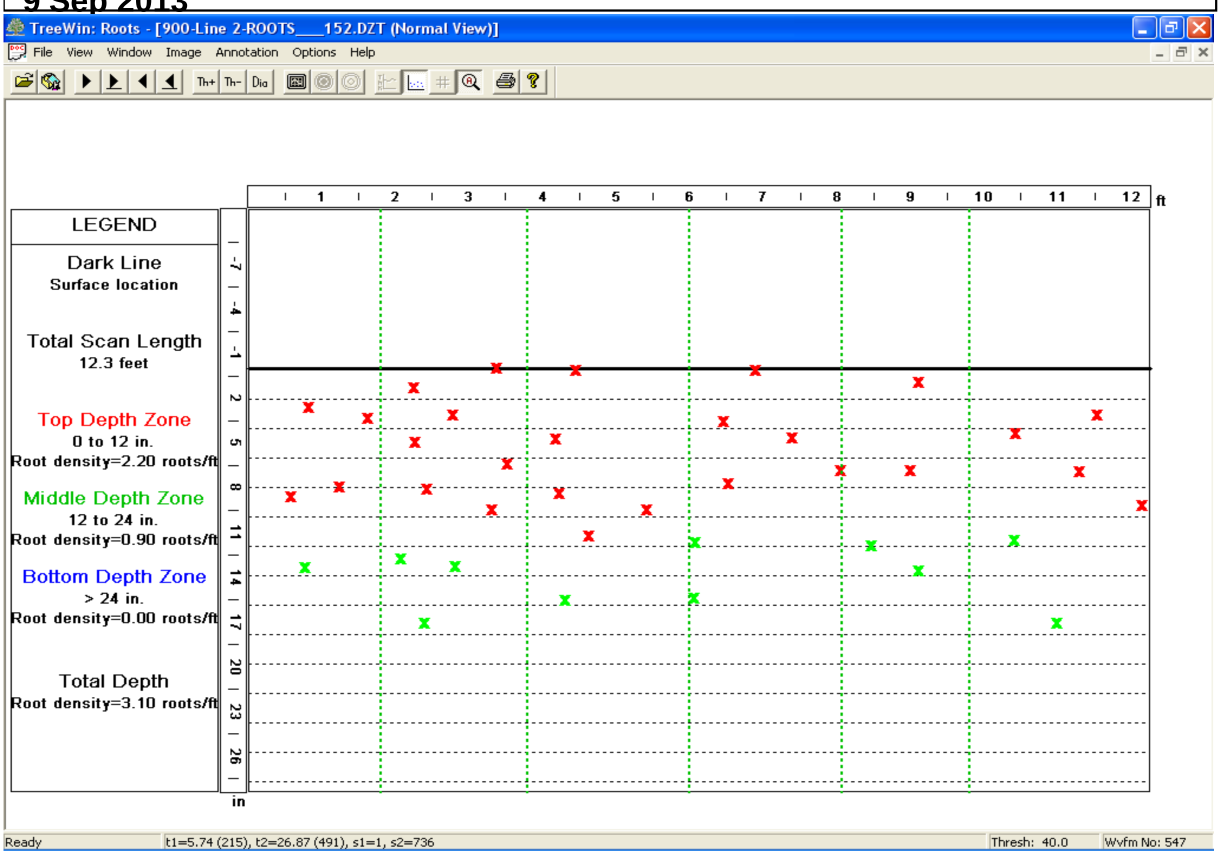

# W Lincoln Ave Almonds-900 MHz - Scan # F (149) - Length = 13.9ft - 9 Sep 2013



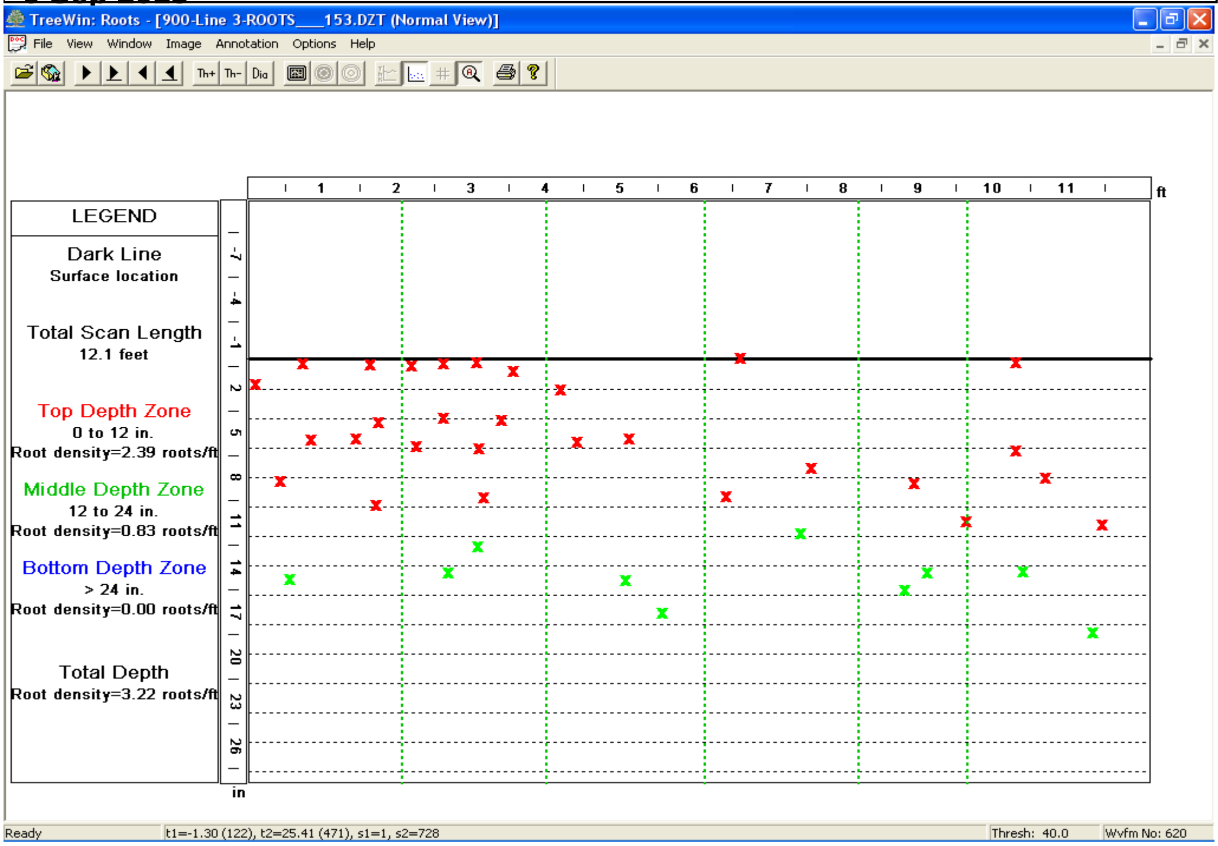
## W Lincoln Ave Almonds-900 MHz - Scan # 1 (151) - Length = 12.1ft - 9 Sep 2013



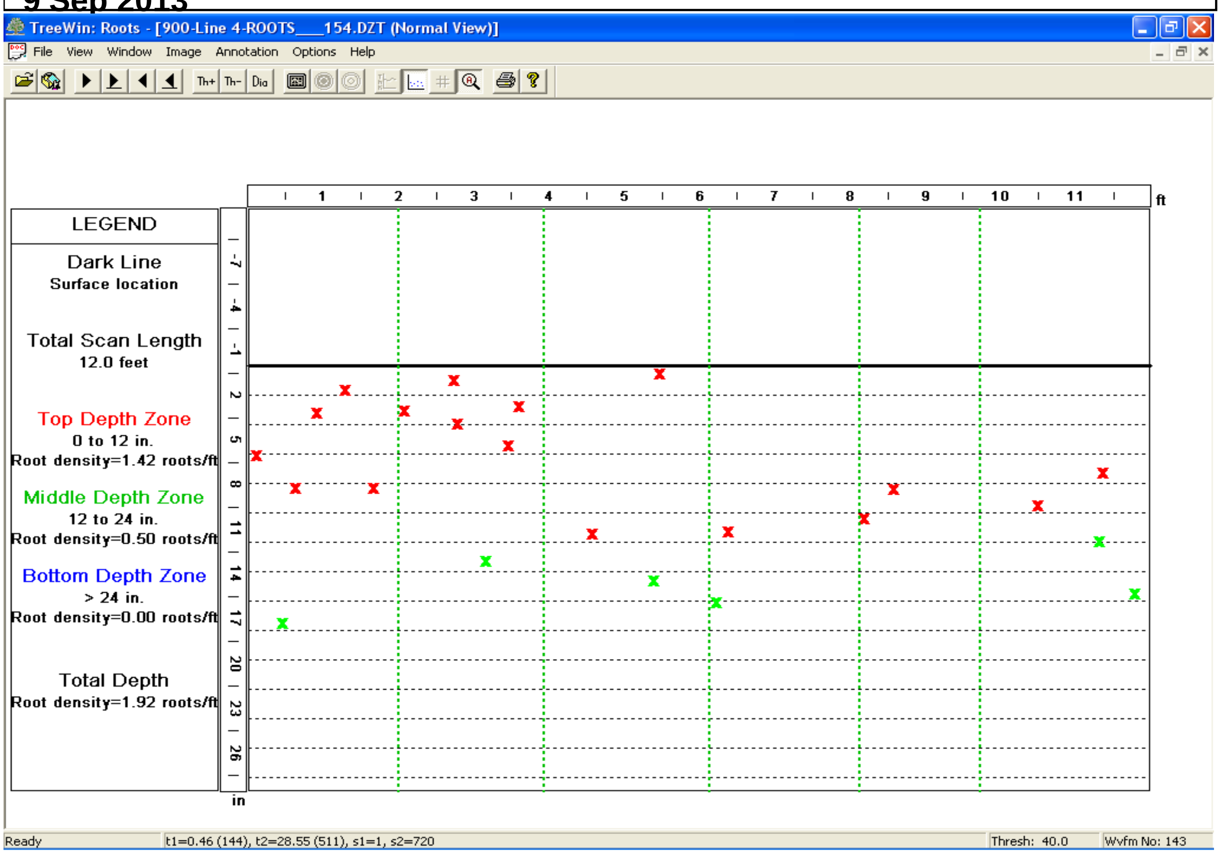

## W Lincoln Ave Almonds-900 MHz - Scan # 2 (152) - Length = 12.3ft - 9 Sep 2013



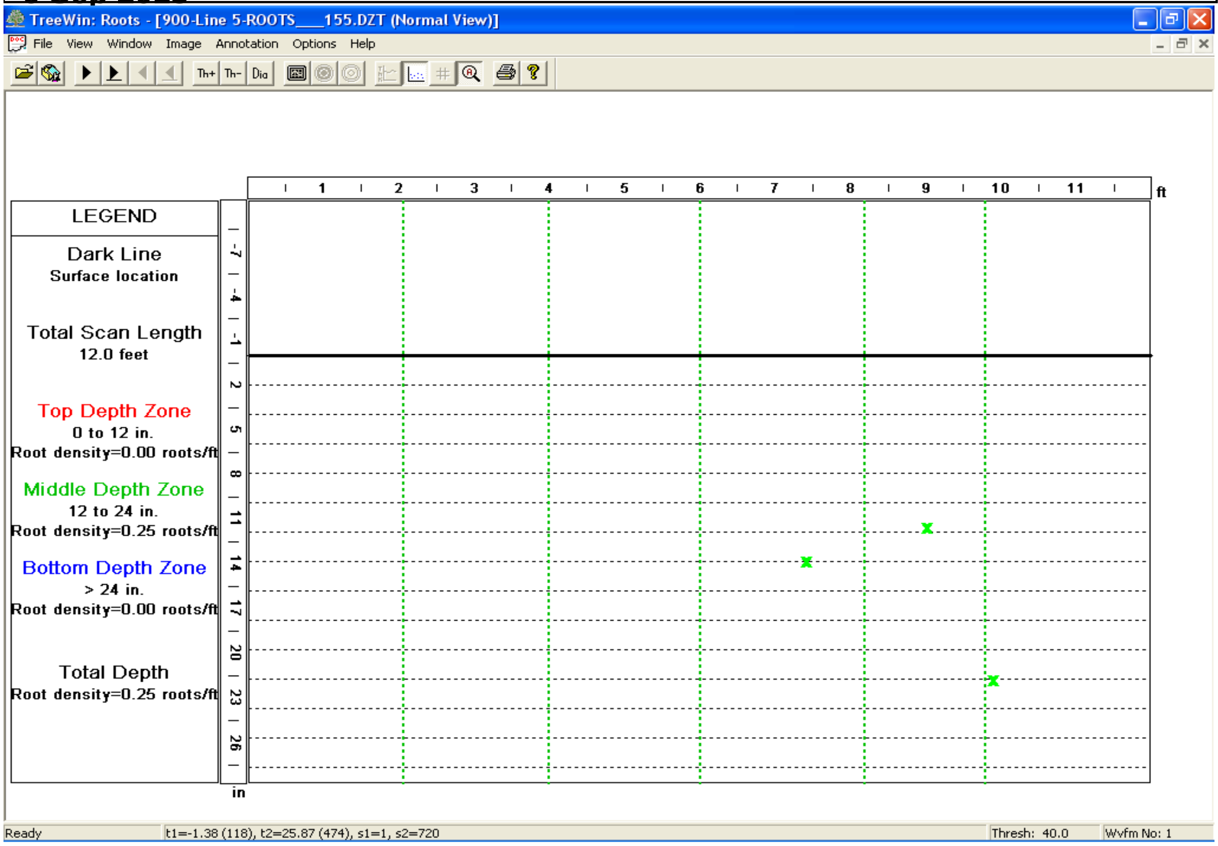
## W Lincoln Ave Almonds-900 MHz - Scan # 3 (153) - Length = 12.1ft - 9 Sep 2013



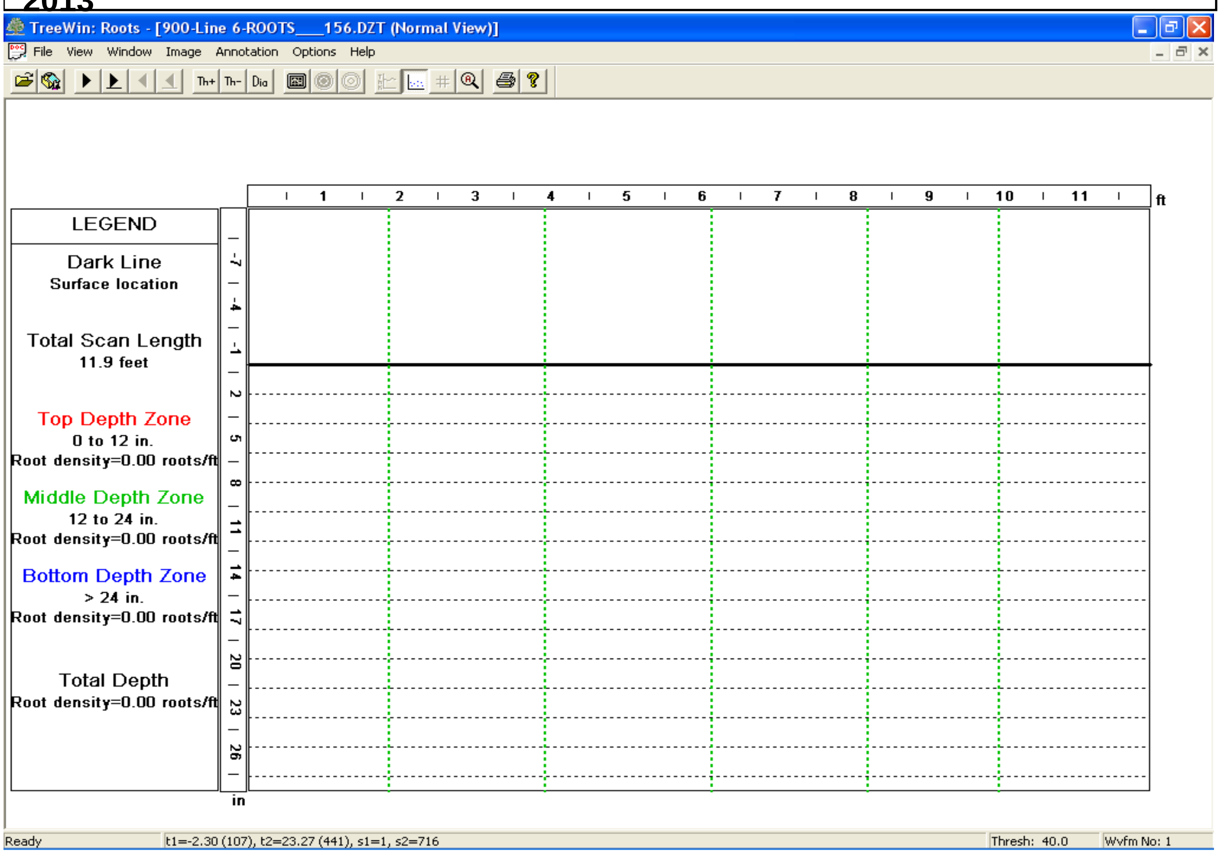

## W Lincoln Ave Almonds-900 MHz - Scan # 4 (154) - Length = 12.0ft - 9 Sep 2013



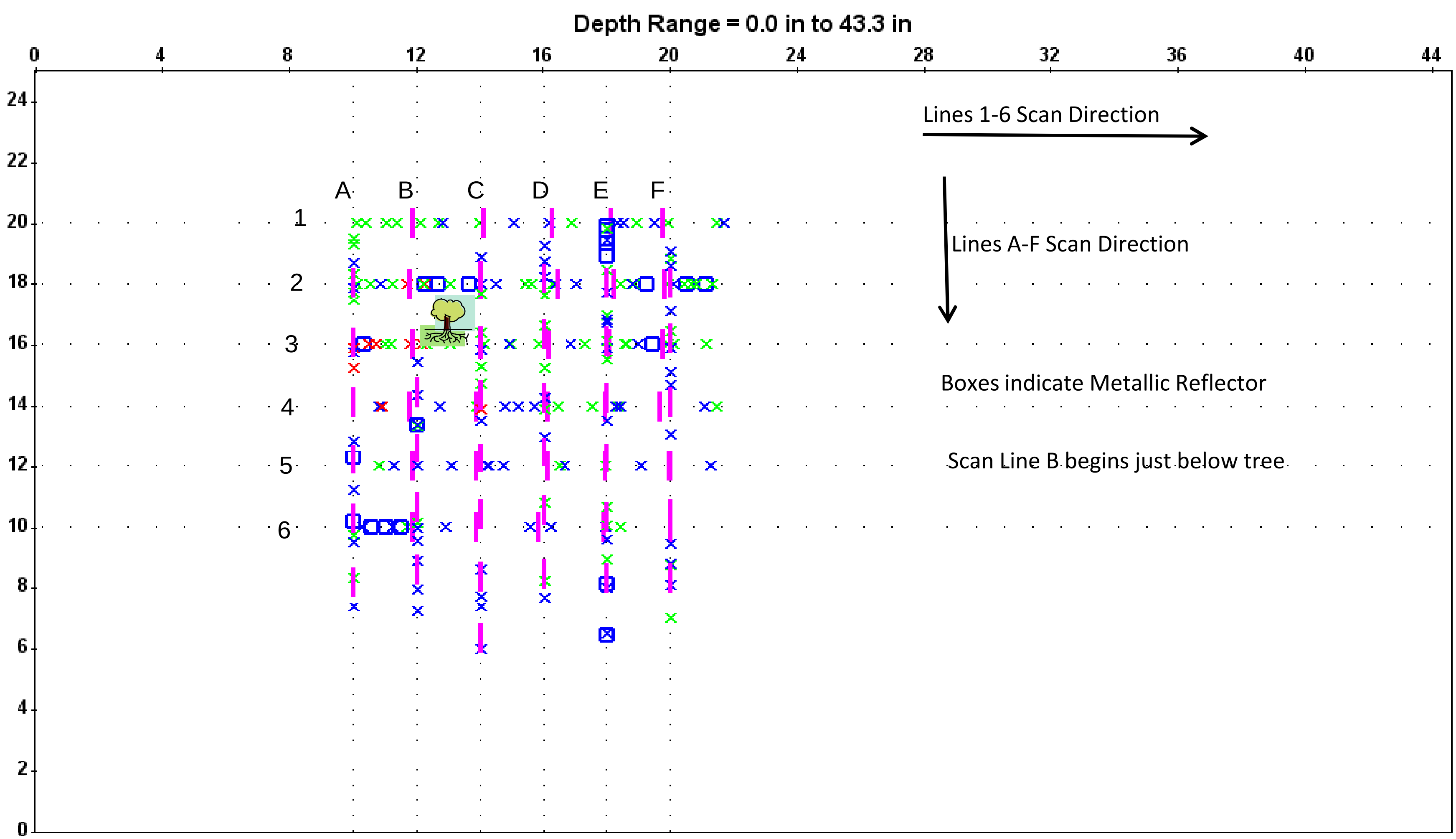
## W Lincoln Ave Almonds-900 MHz - Scan # 5 (155) - Length = 12.0ft - 9 Sep 2013




## W Lincoln Ave Almonds-900 MHz - Scan # 6 (156) - Length = 11.9ft - 9 Sep 2013

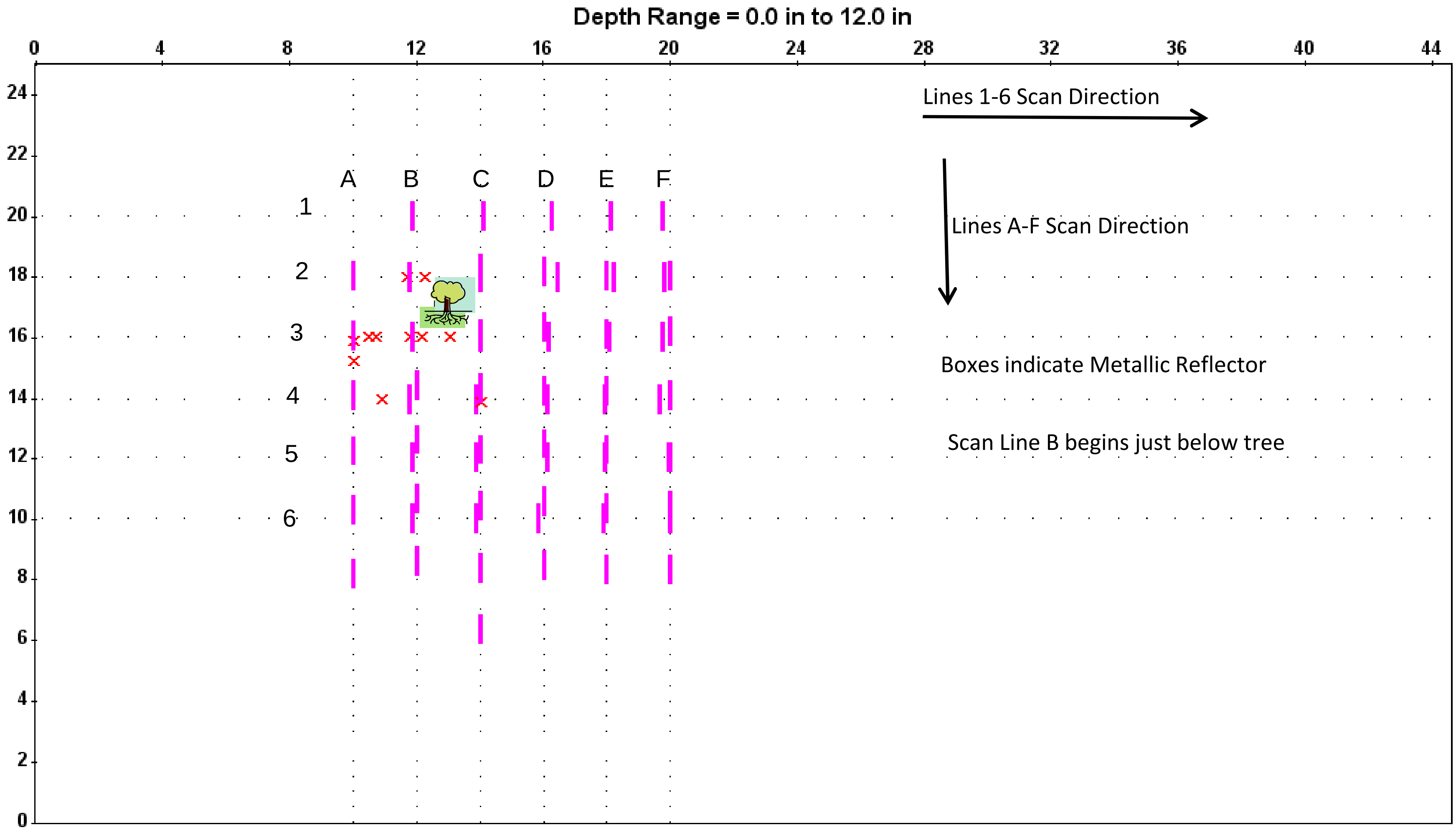


W Lincoln Ave Almonds - 400 MHz
Total Depth Range



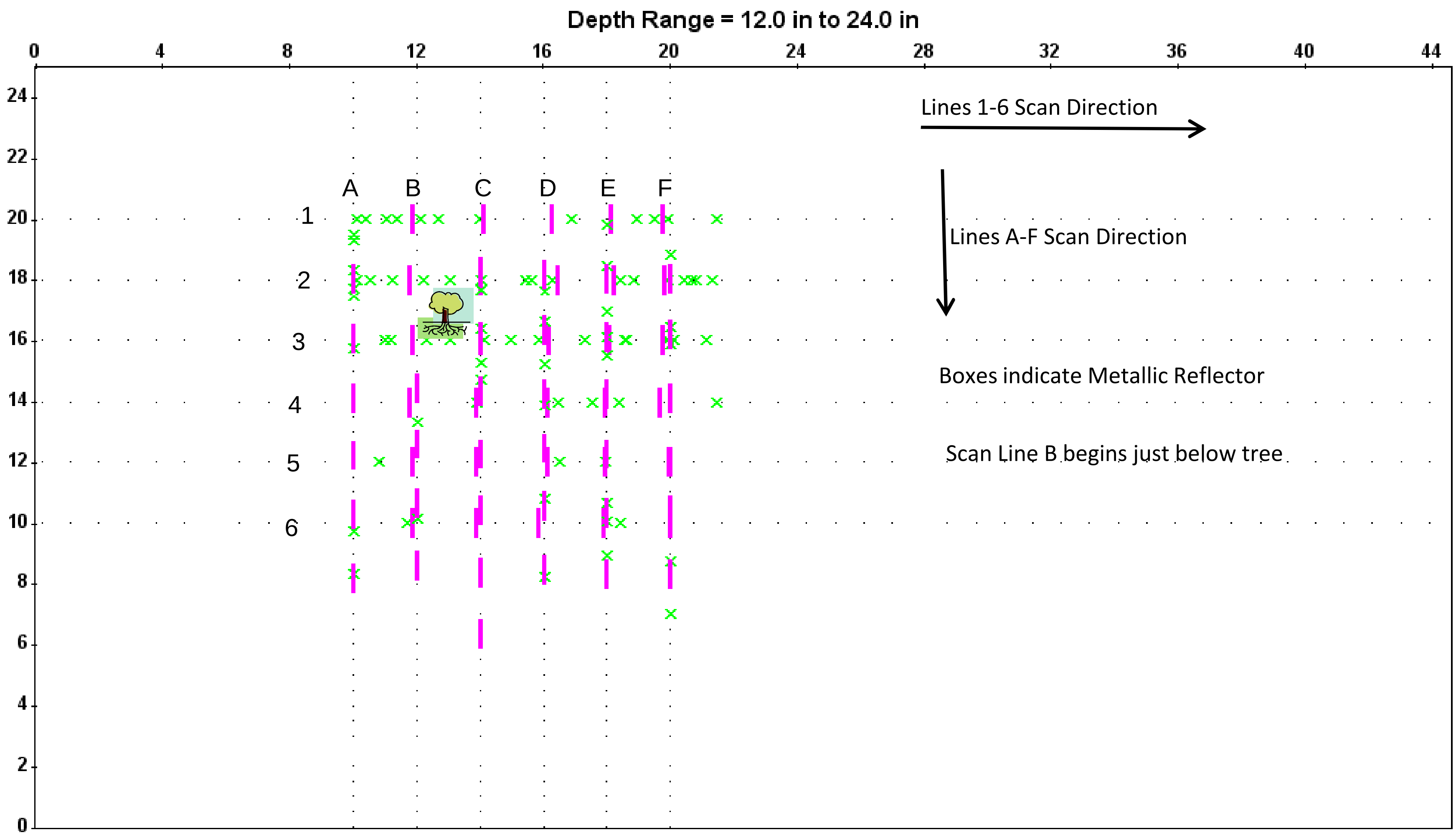

Note: not to scale

**W Lincoln Ave Almonds - 400 MHz**
**Top 1/3 Depth Range**



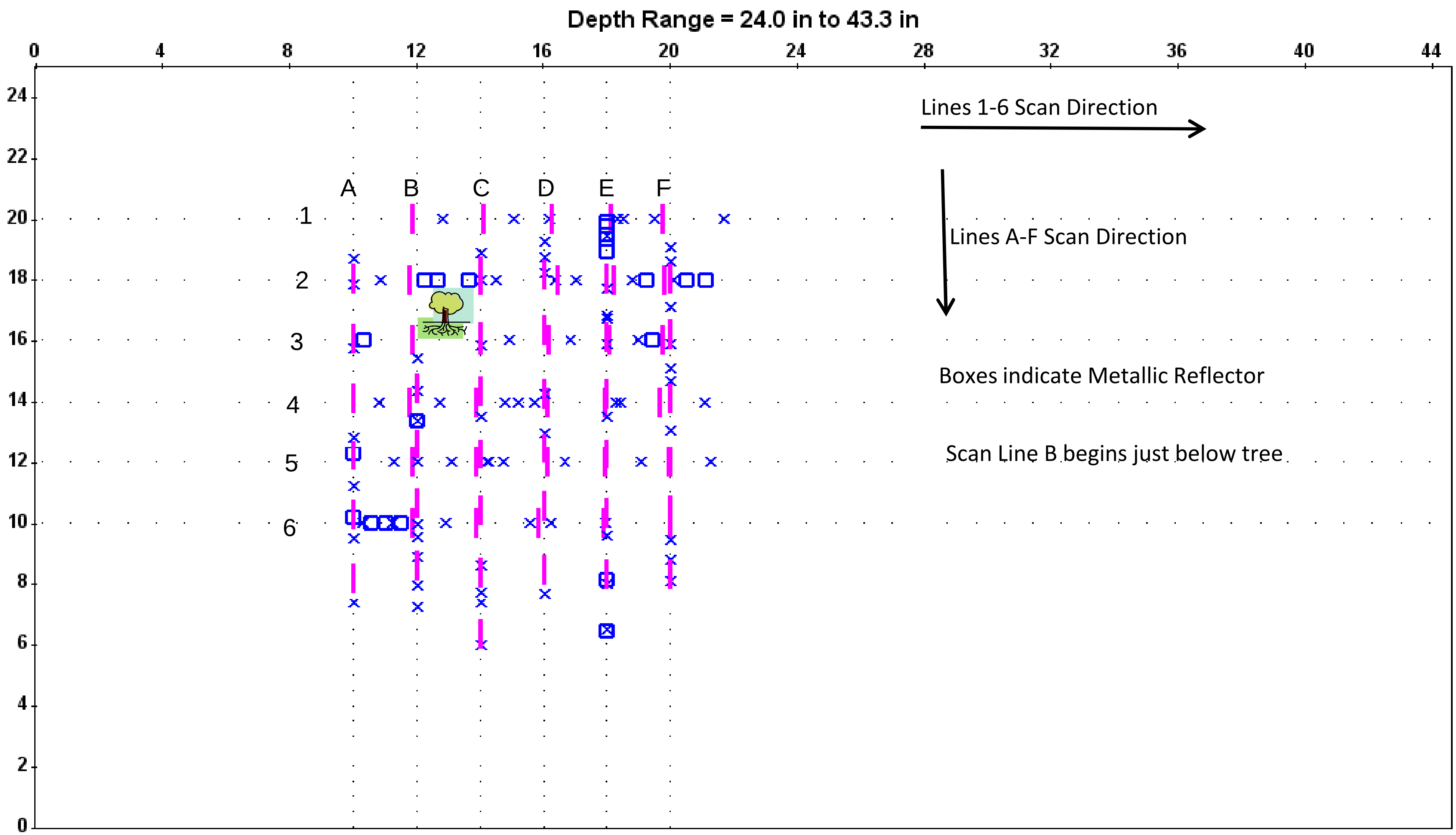

Note: not to scale

# W Lincoln Ave Almonds - 400 MHz
# Middle 1/3 Depth Range

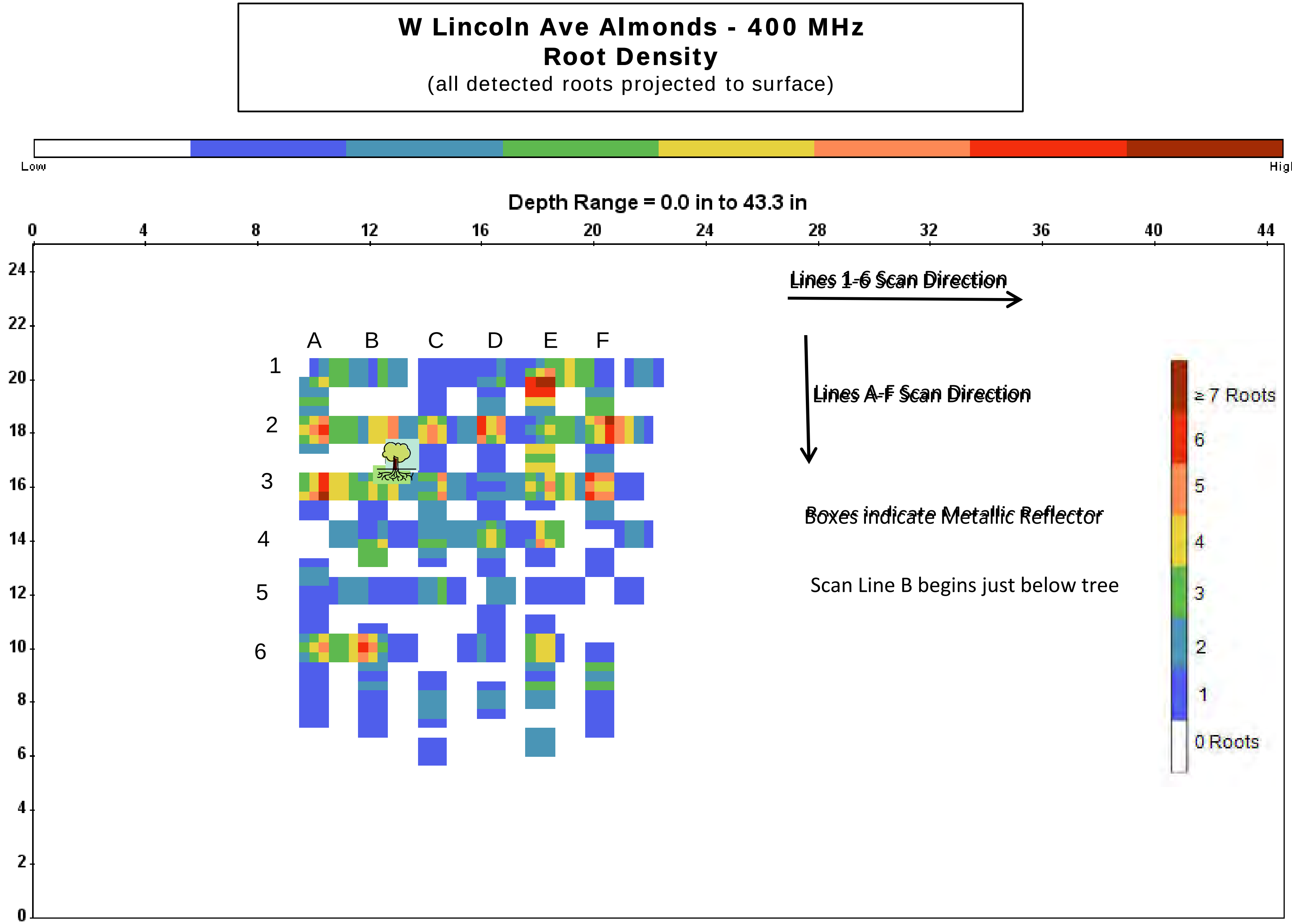



Note: not to scale

# W Lincoln Ave Almonds - 400 MHz
## Bottom 1/3 Depth Range

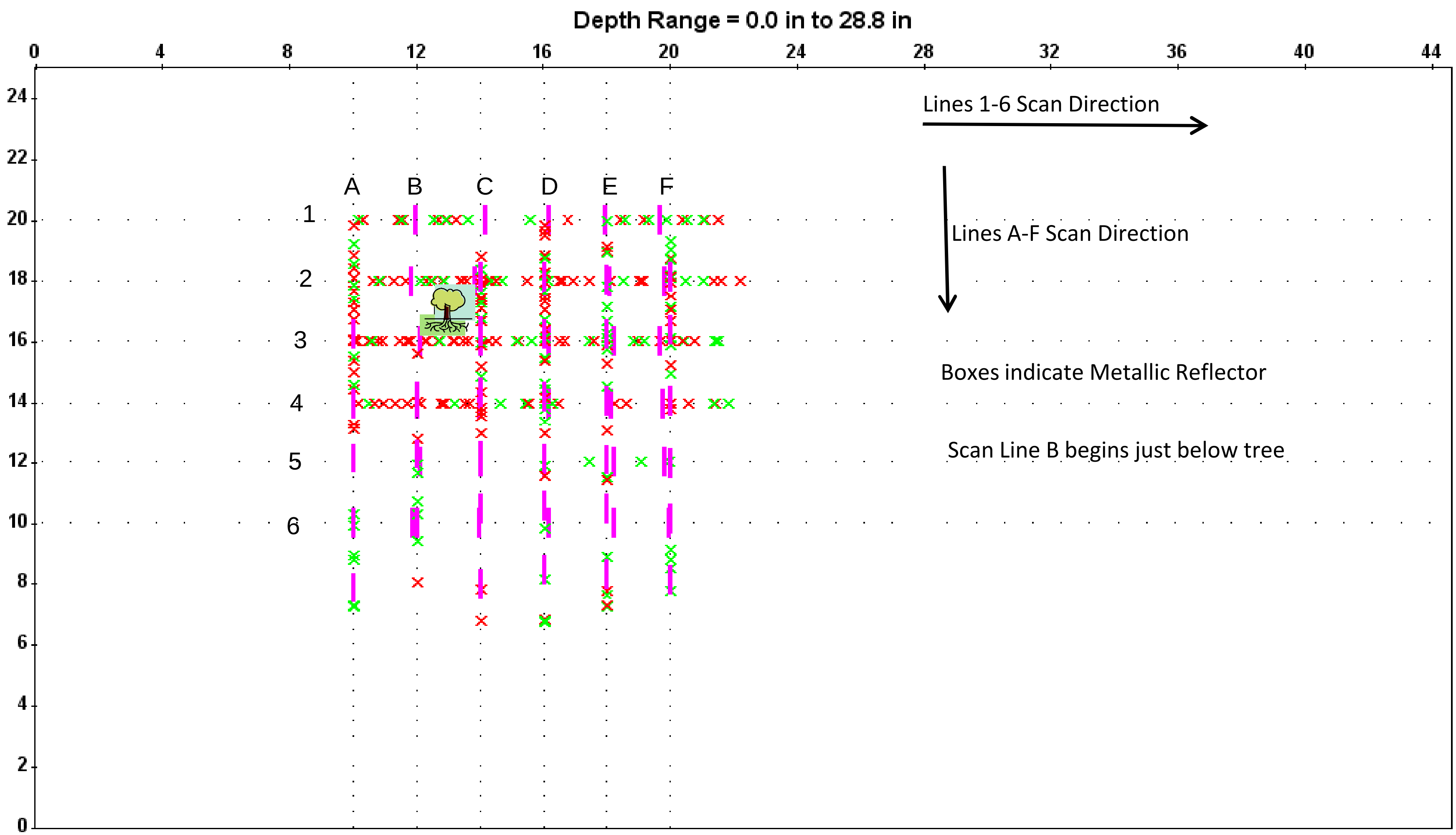



Note: not to scale



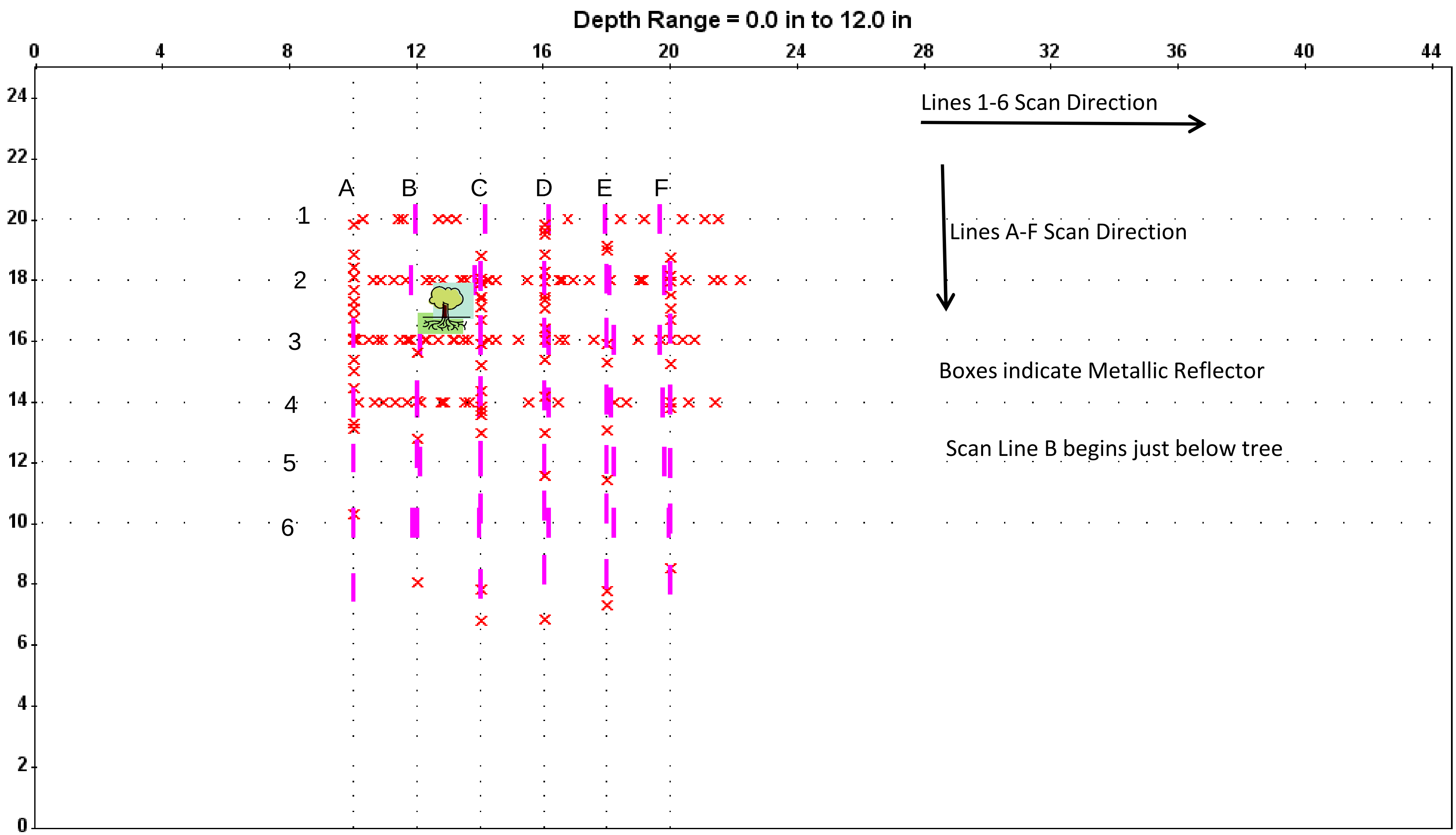

Note: not to scale

**W Lincoln Ave Almonds-900 MHz**
**Total Depth Range**



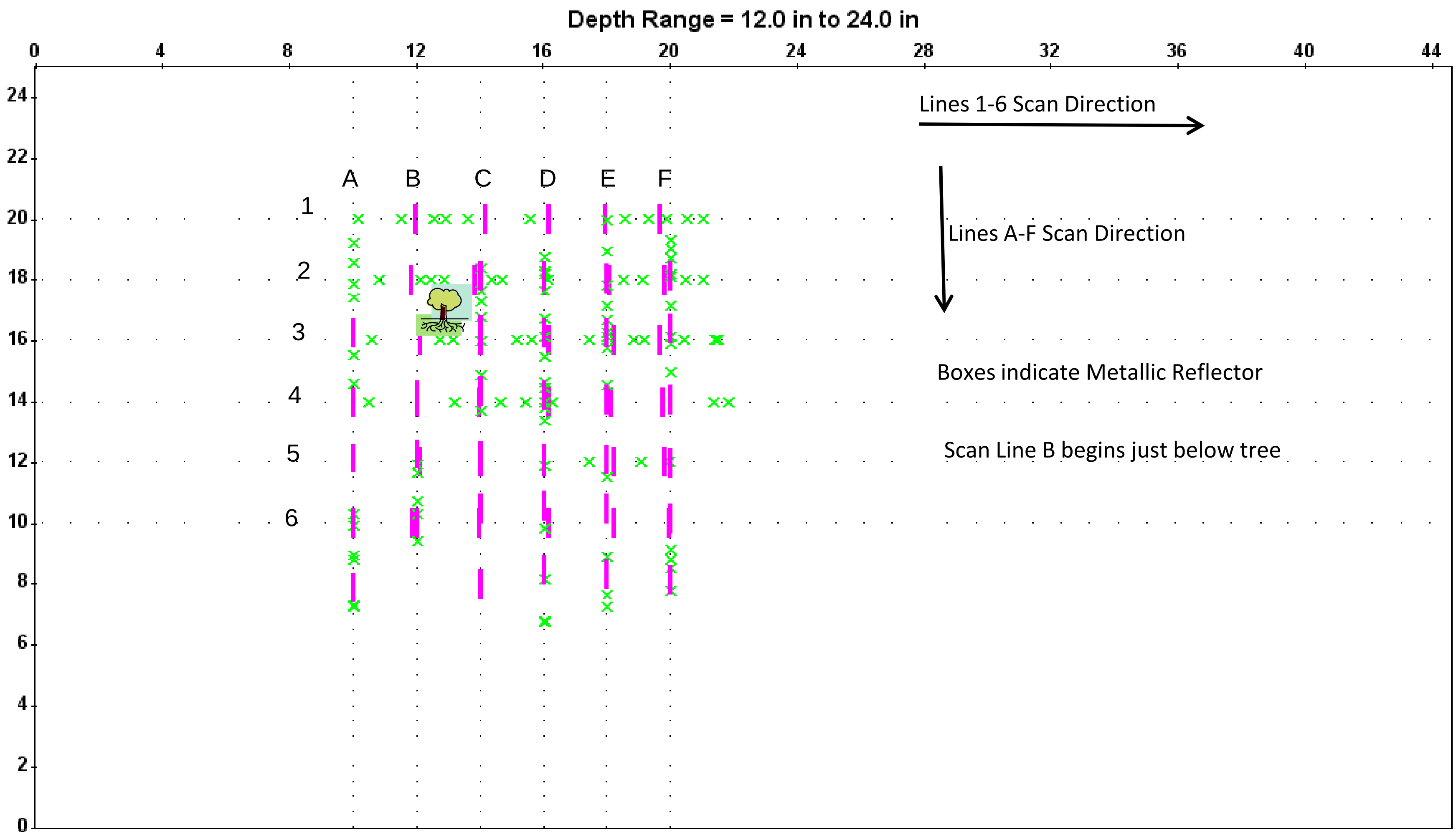

Note: not to scale

**W Lincoln Ave Almonds-900 MHz**
**Top 1/3 Depth Range**



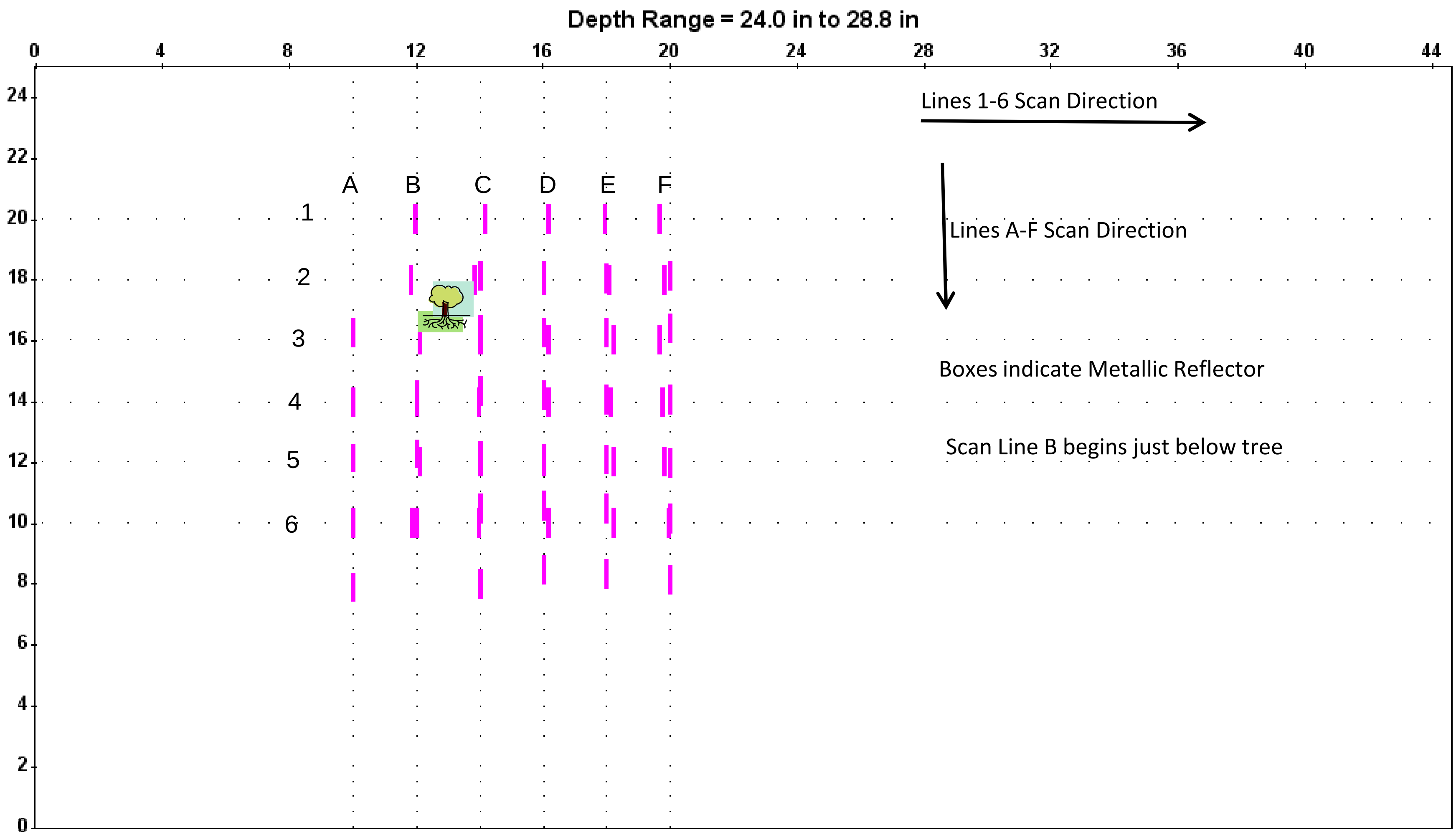

Note: not to scale

# W Lincoln Ave Almonds-900 MHz
# Middle 1/3 Depth Range



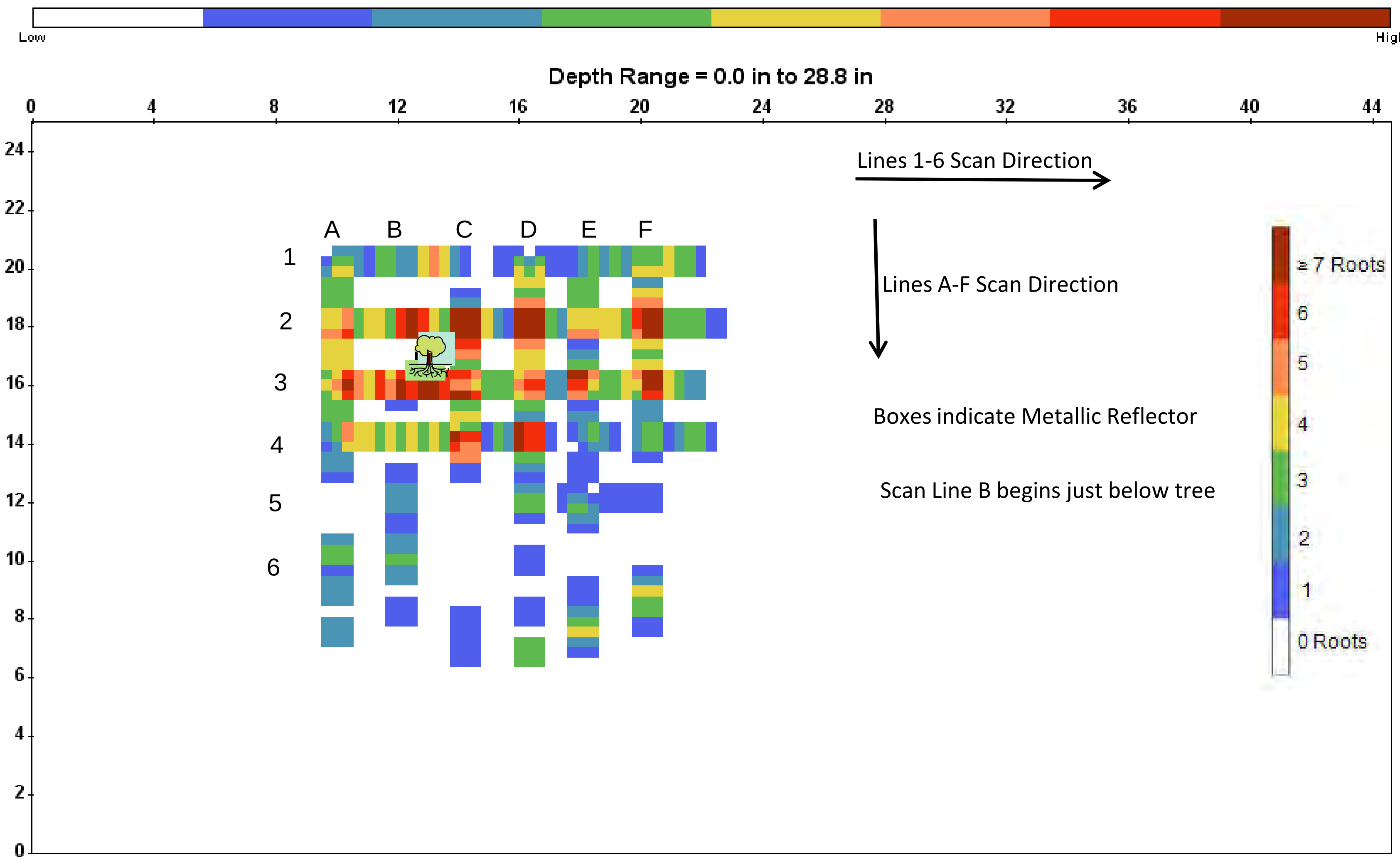

Note: not to scale

# W Lincoln Ave Almonds-900 MHz
## Bottom 1/3 Depth Range




Note: not to scale

**W Lincoln Ave Almonds-900 MHz**
**Root Density**
(all detected roots projected to surface)




Note: not to scale

# Appendix D

## Walnut Orchard near Lockeford in San Joaquin County

A walnut orchard a mile east of Lockeford on CA 12 was identified in the GIS as having a pipeline routed through it as well as an adjacent wine grape vineyard, east of the walnuts. A 55 year old tree was located over the pipeline. The root system of the tree was scanned with a Ground Penetrating Radar system by Tree Associates on October 29 and the scanned tree was excavated on October 30. The soil survey reports from the Natural Resources Conservation Service and the GPR report from Tree Associates are included in the following appendix

Soil Map—San Joaquin County, California
(Walnut/wine grapes - Lockeford, CA)


Map Scale: 1:4,000 if printed on A portrait (8.5" x 11") sheet.

N

Meters: 0, 50, 100, 200, 300

Feet: 0, 150, 300, 600, 900

Map projection: Web Mercator Corner coordinates: WGS84 Edge tics: UTM Zone 10N WGS84

## MAP LEGEND

**Area of Interest (AOI)**

Area of Interest (AOI)

**Soils**

Soil Map Unit Polygons

Soil Map Unit Lines

Soil Map Unit Points

**Special Point Features**

Blowout

Borrow Pit

Clay Spot

Closed Depression

Gravel Pit

Gravelly Spot

Landfill

Lava Flow

Marsh or swamp

Mine or Quarry

Miscellaneous Water

Perennial Water

Rock Outcrop

Saline Spot

Sandy Spot

Severely Eroded Spot

Sinkhole

Slide or Slip

Sodic Spot

Spoil Area

Stony Spot

Very Stony Spot

Wet Spot

Other

Special Line Features

**Water Features**

Streams and Canals

**Transportation**

Rails

Interstate Highways

US Routes

Major Roads

Local Roads

**Background**

Aerial Photography

## MAP INFORMATION

The soil surveys that comprise your AOI were mapped at 1:24,000.

Warning: Soil Map may not be valid at this scale.

Enlargement of maps beyond the scale of mapping can cause misunderstanding of the detail of mapping and accuracy of soil line placement. The maps do not show the small areas of contrasting soils that could have been shown at a more detailed scale.

Please rely on the bar scale on each map sheet for map measurements.

Source of Map: Natural Resources Conservation Service
Web Soil Survey URL: http://websoilsurvey.nrcs.usda.gov
Coordinate System: Web Mercator (EPSG:3857)

Maps from the Web Soil Survey are based on the Web Mercator projection, which preserves direction and shape but distorts distance and area. A projection that preserves area, such as the Albers equal-area conic projection, should be used if more accurate calculations of distance or area are required.

This product is generated from the USDA-NRCS certified data as of the version date(s) listed below.

Soil Survey Area: San Joaquin County, California
Survey Area Data: Version 7, Nov 25, 2013

Soil map units are labeled (as space allows) for map scales 1:50,000 or larger.

Date(s) aerial images were photographed: Nov 3, 2010—Apr 29, 2012

The orthophoto or other base map on which the soil lines were compiled and digitized probably differs from the background imagery displayed on these maps. As a result, some minor shifting of map unit boundaries may be evident.

# Map Unit Legend

| San Joaquin County, California (CA077) | | | |
|---|---|---|---|
| **Map Unit Symbol** | **Map Unit Name** | **Acres in AOI** | **Percent of AOI** |
| 112 | Bruella sandy loam, hard substratum, 0 to 2 percent slopes | 12.0 | 26.4% |
| 256 | Tokay fine sandy loam, 0 to 2 percent slopes | 33.5 | 73.6% |
| **Totals for Area of Interest** | | **45.5** | **100.0%** |

# Physical Soil Properties

This table shows estimates of some physical characteristics and features that affect soil behavior. These estimates are given for the layers of each soil in the survey area. The estimates are based on field observations and on test data for these and similar soils.

*Depth* to the upper and lower boundaries of each layer is indicated.

Particle size is the effective diameter of a soil particle as measured by sedimentation, sieving, or micrometric methods. Particle sizes are expressed as classes with specific effective diameter class limits. The broad classes are sand, silt, and clay, ranging from the larger to the smaller.

*Sand* as a soil separate consists of mineral soil particles that are 0.05 millimeter to 2 millimeters in diameter. In this table, the estimated sand content of each soil layer is given as a percentage, by weight, of the soil material that is less than 2 millimeters in diameter.

*Silt* as a soil separate consists of mineral soil particles that are 0.002 to 0.05 millimeter in diameter. In this table, the estimated silt content of each soil layer is given as a percentage, by weight, of the soil material that is less than 2 millimeters in diameter.

*Clay* as a soil separate consists of mineral soil particles that are less than 0.002 millimeter in diameter. In this table, the estimated clay content of each soil layer is given as a percentage, by weight, of the soil material that is less than 2 millimeters in diameter.

The content of sand, silt, and clay affects the physical behavior of a soil. Particle size is important for engineering and agronomic interpretations, for determination of soil hydrologic qualities, and for soil classification.

The amount and kind of clay affect the fertility and physical condition of the soil and the ability of the soil to adsorb cations and to retain moisture. They influence shrink-swell potential, saturated hydraulic conductivity (Ksat), plasticity, the ease of soil dispersion, and other soil properties. The amount and kind of clay in a soil also affect tillage and earthmoving operations.

*Moist bulk density* is the weight of soil (ovendry) per unit volume. Volume is measured when the soil is at field moisture capacity, that is, the moisture content at 1/3- or 1/10-bar (33kPa or 10kPa) moisture tension. Weight is determined after the soil is dried at 105 degrees C. In the table, the estimated moist bulk density of each soil horizon is expressed in grams per cubic centimeter of soil material that is less than 2 millimeters in diameter. Bulk density data are used to compute linear extensibility, shrink-swell potential, available water capacity, total pore space, and other soil properties. The moist bulk density of a soil indicates the pore space available for water and roots. Depending on soil texture, a bulk density of more than 1.4 can restrict water storage and root penetration. Moist bulk density is influenced by texture, kind of clay, content of organic matter, and soil structure.

*Saturated hydraulic conductivity (Ksat)* refers to the ease with which pores in a saturated soil transmit water. The estimates in the table are expressed in terms of micrometers per second. They are based on soil characteristics observed in the field, particularly structure, porosity, and texture. Saturated hydraulic conductivity (Ksat) is considered in the design of soil drainage systems and septic tank absorption fields.

*Available water capacity* refers to the quantity of water that the soil is capable of storing for use by plants. The capacity for water storage is given in inches of water per inch of soil for each soil layer. The capacity varies, depending on soil properties that affect retention of water. The most important properties are the content of organic matter, soil texture, bulk density, and soil structure. Available water capacity is an important factor in the choice of plants or crops to be grown and in the design and management of irrigation systems. Available water capacity is not an estimate of the quantity of water actually available to plants at any given time.

*Linear extensibility* refers to the change in length of an unconfined clod as moisture content is decreased from a moist to a dry state. It is an expression of the volume change between the water content of the clod at 1/3- or 1/10-bar tension (33kPa or 10kPa tension) and oven dryness. The volume change is reported in the table as percent change for the whole soil. The amount and type of clay minerals in the soil influence volume change.

Linear extensibility is used to determine the shrink-swell potential of soils. The shrink-swell potential is low if the soil has a linear extensibility of less than 3 percent; moderate if 3 to 6 percent; high if 6 to 9 percent; and very high if more than 9 percent. If the linear extensibility is more than 3, shrinking and swelling can cause damage to buildings, roads, and other structures and to plant roots. Special design commonly is needed.

*Organic matter* is the plant and animal residue in the soil at various stages of decomposition. In this table, the estimated content of organic matter is expressed as a percentage, by weight, of the soil material that is less than 2 millimeters in diameter. The content of organic matter in a soil can be maintained by returning crop residue to the soil.

Organic matter has a positive effect on available water capacity, water infiltration, soil organism activity, and tilth. It is a source of nitrogen and other nutrients for crops and soil organisms.

*Erosion factors* are shown in the table as the K factor (Kw and Kf) and the T factor. Erosion factor K indicates the susceptibility of a soil to sheet and rill erosion by water. Factor K is one of six factors used in the Universal Soil Loss Equation (USLE) and the Revised Universal Soil Loss Equation (RUSLE) to predict the average annual rate of soil loss by sheet and rill erosion in tons per acre per year. The estimates are based primarily on percentage of silt, sand, and organic matter and on soil structure and Ksat. Values of K range from 0.02 to 0.69. Other factors being equal, the higher the value, the more susceptible the soil is to sheet and rill erosion by water.

*Erosion factor Kw* indicates the erodibility of the whole soil. The estimates are modified by the presence of rock fragments.

*Erosion factor Kf* indicates the erodibility of the fine-earth fraction, or the material less than 2 millimeters in size.

*Erosion factor T* is an estimate of the maximum average annual rate of soil erosion by wind and/or water that can occur without affecting crop productivity over a sustained period. The rate is in tons per acre per year.

*Wind erodibility groups* are made up of soils that have similar properties affecting their susceptibility to wind erosion in cultivated areas. The soils assigned to group 1 are the most susceptible to wind erosion, and those assigned to group 8 are the least susceptible. The groups are described in the "National Soil Survey Handbook."

*Wind erodibility index* is a numerical value indicating the susceptibility of soil to wind erosion, or the tons per acre per year that can be expected to be lost to wind erosion. There is a close correlation between wind erosion and the texture of the surface layer, the size and durability of surface clods, rock fragments, organic matter, and a calcareous reaction. Soil moisture and frozen soil layers also influence wind erosion.

Reference:

United States Department of Agriculture, Natural Resources Conservation Service. National soil survey handbook, title 430-VI. (http://soils.usda.gov)

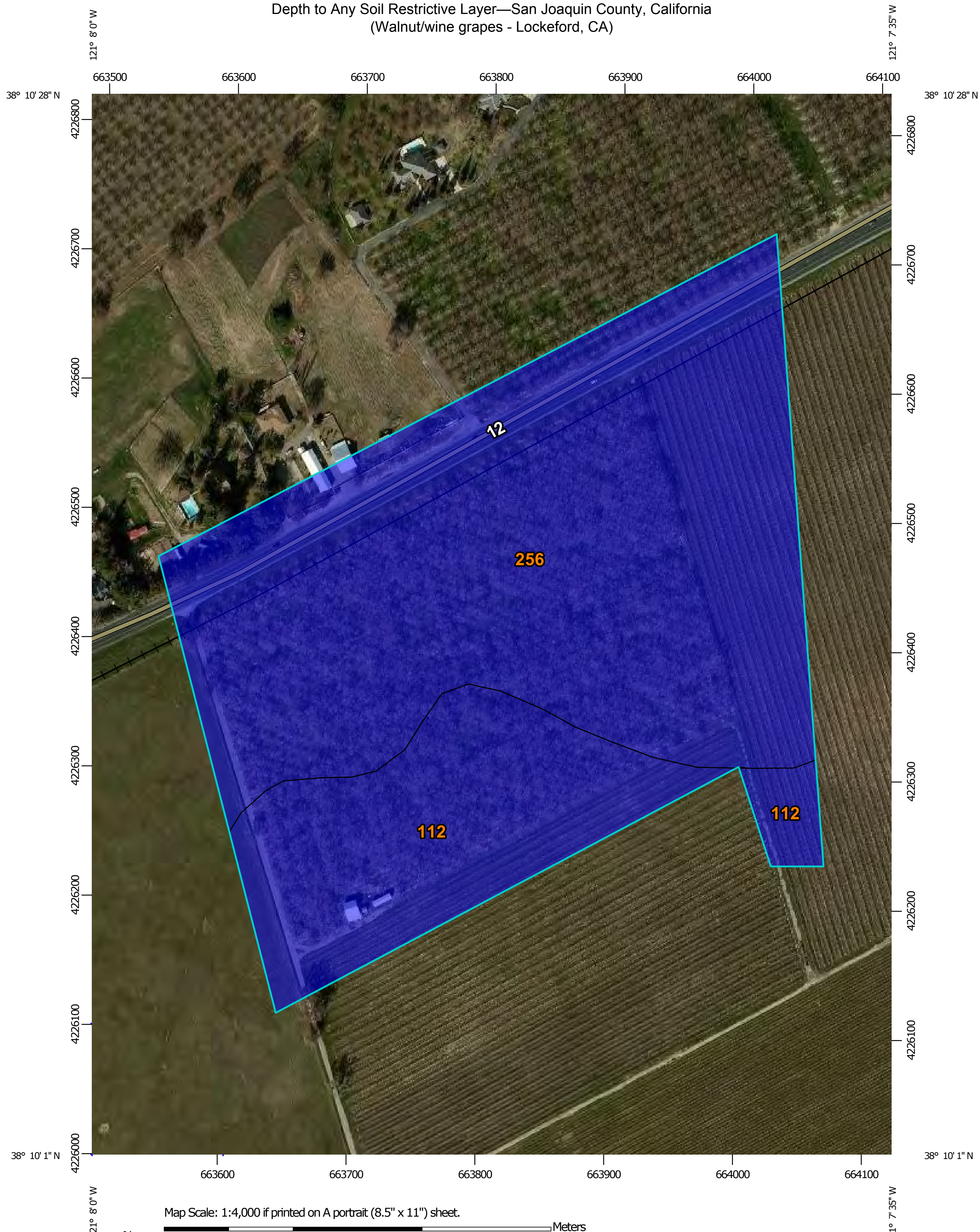
# Report—Physical Soil Properties

| Physical Soil Properties–San Joaquin County, California | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Map symbol and soil name | Depth | Sand | Silt | Clay | Moist bulk density | Saturated hydraulic conductivity | Available water capacity | Linear extensibility | Organic matter | Erosion factors | | | Wind erodibility group | Wind erodibility index |
| | | | | | | | | | | Kw | Kf | T | | |
| | *In* | *Pct* | *Pct* | *Pct* | *g/cc* | *micro m/sec* | *In/In* | *Pct* | *Pct* | | | | | |
| 112—Bruella sandy loam, hard substratum, 0 to 2 percent slopes | | | | | | | | | | | | | | |
| Bruella | 0-8 | -65- | -19- | 12-16- 20 | 1.50-1.65 | 14.00-42.00 | 0.11-0.13 | 0.0-2.9 | 0.5-1.0 | .28 | .28 | 5 | 3 | 86 |
| | 8-42 | -62- | -14- | 18-24- 30 | 1.45-1.60 | 1.40-4.00 | 0.13-0.17 | 3.0-5.9 | 0.0 | .24 | .24 | | | |
| | 42-60 | -51- | -15- | 30-34- 40 | 1.50-1.65 | 0.42-1.40 | 0.07-0.09 | 3.0-5.9 | 0.0 | .24 | .24 | | | |
| 256—Tokay fine sandy loam, 0 to 2 percent slopes | | | | | | | | | | | | | | |
| Tokay | 0-19 | -71- | -17- | 10-13- 15 | 1.50-1.60 | 14.00-42.00 | 0.13-0.15 | 0.0-2.9 | 1.0-3.0 | .24 | .24 | 5 | 3 | 86 |
| | 19-45 | -70- | -16- | 10-14- 18 | 1.50-1.60 | 14.00-42.00 | 0.12-0.14 | 0.0-2.9 | 0.0 | .28 | .28 | | | |
| | 45-60 | -68- | -21- | 8-12- 15 | 1.50-1.65 | 14.00-42.00 | 0.10-0.14 | 0.0-2.9 | 0.0 | .28 | .28 | | | |

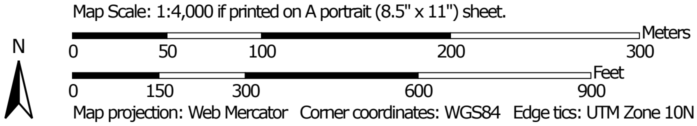
# Data Source Information

Soil Survey Area: San Joaquin County, California
Survey Area Data: Version 7, Nov 25, 2013

Depth to Any Soil Restrictive Layer—San Joaquin County, California
(Walnut/wine grapes - Lockeford, CA)




Map Scale: 1:4,000 if printed on A portrait (8.5" x 11") sheet.




Map projection: Web Mercator Corner coordinates: WGS84 Edge tics: UTM Zone 10N WGS84

## MAP LEGEND

**Area of Interest (AOI)**

Area of Interest (AOI)

**Soils**

**Soil Rating Polygons**

- 0 - 25
- 25 - 50
- 50 - 100
- 100 - 150
- 150 - 200
- > 200
- Not rated or not available

**Soil Rating Lines**

- 0 - 25
- 25 - 50
- 50 - 100
- 100 - 150
- 150 - 200
- > 200
- Not rated or not available

**Soil Rating Points**

- 0 - 25
- 25 - 50
- 50 - 100
- 100 - 150
- 150 - 200
- > 200
- Not rated or not available

**Water Features**

Streams and Canals

**Transportation**

- Rails
- Interstate Highways
- US Routes
- Major Roads
- Local Roads

**Background**

Aerial Photography

## MAP INFORMATION

The soil surveys that comprise your AOI were mapped at 1:24,000.

Warning: Soil Map may not be valid at this scale.

Enlargement of maps beyond the scale of mapping can cause misunderstanding of the detail of mapping and accuracy of soil line placement. The maps do not show the small areas of contrasting soils that could have been shown at a more detailed scale.

Please rely on the bar scale on each map sheet for map measurements.

Source of Map: Natural Resources Conservation Service
Web Soil Survey URL: http://websoilsurvey.nrcs.usda.gov
Coordinate System: Web Mercator (EPSG:3857)

Maps from the Web Soil Survey are based on the Web Mercator projection, which preserves direction and shape but distorts distance and area. A projection that preserves area, such as the Albers equal-area conic projection, should be used if more accurate calculations of distance or area are required.

This product is generated from the USDA-NRCS certified data as of the version date(s) listed below.

Soil Survey Area: San Joaquin County, California
Survey Area Data: Version 7, Nov 25, 2013

Soil map units are labeled (as space allows) for map scales 1:50,000 or larger.

Date(s) aerial images were photographed: Nov 3, 2010—Apr 29, 2012

The orthophoto or other base map on which the soil lines were compiled and digitized probably differs from the background imagery displayed on these maps. As a result, some minor shifting of map unit boundaries may be evident.

# Depth to Any Soil Restrictive Layer

| Depth to Any Soil Restrictive Layer— Summary by Map Unit — San Joaquin County, California (CA077) | | | | |
|---|---|---|---|---|
| **Map unit symbol** | **Map unit name** | **Rating (centimeters)** | **Acres in AOI** | **Percent of AOI** |
| 112 | Bruella sandy loam, hard substratum, 0 to 2 percent slopes | >200 | 12.0 | 26.4% |
| 256 | Tokay fine sandy loam, 0 to 2 percent slopes | >200 | 33.5 | 73.6% |
| **Totals for Area of Interest** | | | **45.5** | **100.0%** |

## Description

A "restrictive layer" is a nearly continuous layer that has one or more physical, chemical, or thermal properties that significantly impede the movement of water and air through the soil or that restrict roots or otherwise provide an unfavorable root environment. Examples are bedrock, cemented layers, dense layers, and frozen layers.

This theme presents the depth to any type of restrictive layer that is described for each map unit. If more than one type of restrictive layer is described for an individual soil type, the depth to the shallowest one is presented. If no restrictive layer is described in a map unit, it is represented by the "> 200" depth class.

This attribute is actually recorded as three separate values in the database. A low value and a high value indicate the range of this attribute for the soil component. A "representative" value indicates the expected value of this attribute for the component. For this soil property, only the representative value is used.

## Rating Options

*Units of Measure:* centimeters

*Aggregation Method:* Dominant Component

*Component Percent Cutoff:* *None Specified*

*Tie-break Rule:* Lower

*Interpret Nulls as Zero:* No

# MEMO

To: Charlie Krauter, John Bushoven
From: John Lichter and Tony Mucciardi
Date: November 6, 2013
Re: Lockeford Walnut Stump TRU Study

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The following is an introduction to Ground Penetrating Radar (GPR), the TreeRadar™ Unit root inspection protocol and results presentation and a summary of our methods and results concerning our study at the Lockeford Walnut Stump Plot.

## An Introduction to Ground-Penetrating Radar (GPR)

Ground-Penetrating Radar (GPR) is an established technique that has been used worldwide for over 30 years to locate objects underground, including pipes, barrels, drums, and other engineering and environmental targets. When an electromagnetic wave emitted from a small surface transmit antenna encounters a boundary between objects with different electromagnetic properties it will reflect, refract, and/or diffract from the boundary in a predictable manner.

Use of GPR instrumentation for internal trunk decay detection and subsurface structural root mapping is a novel and recent application to the arboricultural field that has been developed and patented by TreeRadar™, Inc. under the name TRU™ (Tree Radar Unit).

An air-filled trunk (hollow) or partially air-filled incipient decay zone are excellent reflectors for detection by GPR systems. In addition electromagnetic differences between tree roots and the surrounding soil matrix provide the necessary contrast and reflection properties that are detected by GPR.

GPR measurement as a method of mapping tree roots has several advantages over other methods: (1) it is capable of scanning root systems of large trees under field conditions in a short time, (2) it is completely non-invasive and does not disturb the soils or damage the trees examined and causes no harm to the environment, (3) being non-invasive, it allows repeated measurements that reveal long-term root system development, (4) it allows observation of root distribution beneath hard surfaces (concrete, asphalt, bricks), roads and buildings, (5) its accuracy is sufficient to resolve structural roots with diameters from less than 1 cm (0.4 in) to 3 cm (1.2 in) or more, (6) it can characterize roots at both the individual tree and stand levels, facilitating correlations with tree-and stand-level measurements of physiological processes (e.g., sap flow) in complex ecological studies.

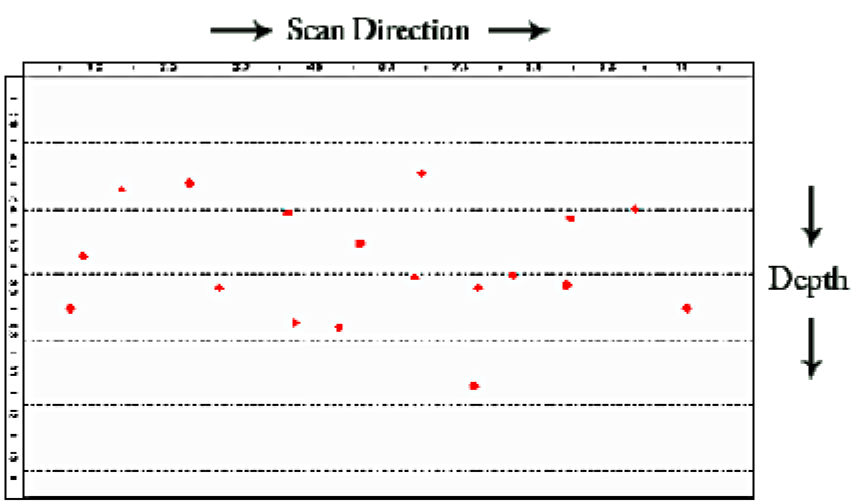
## Roots Inspection Protocol

TreeRadar™, Inc. has developed and patented a system known as TRU™ (Tree Radar Unit) which represents a novel application of ground-penetrating radar (as described in the Introduction section). TRU can be used to inspect both tree trunks for internal decay and subsurface structural roots (roots whose diameter is 1cm (0.4in) and larger), respectively, completely non-invasively.

A TRU roots inspection consists of two independent steps: (1) on-site data collection, and (2) off-site data analysis using TreeRadar's proprietary TreeWin™ software program to analyze the data after the field data collection runs.

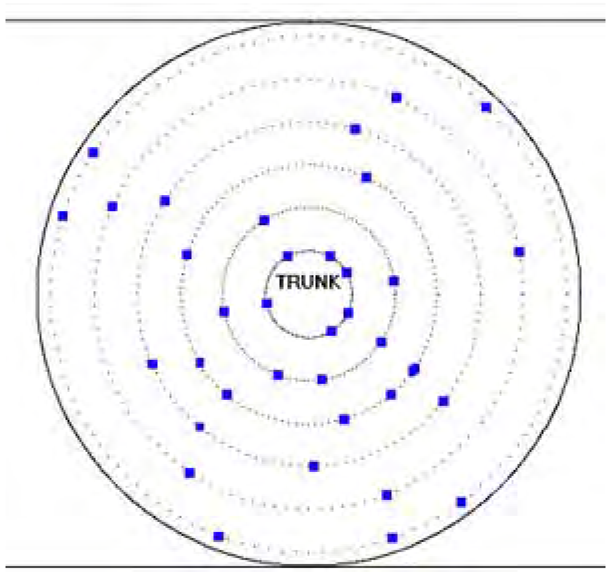
The data analysis results can be presented in two formats.

One is a 2D "Virtual Trench" in which a planar 2D view is generated that shows the predicted root locations and depths as if a backhoe had excavated by digging a trench. This is shown in the figure below. The way to interpret the 2D planar view is to imagine a backhoe digging a trench that was, for example, 6m (20ft) long and 1m (3ft) deep. The backhoe's digging blade would sever all of the roots. After the trench was dug, imagine stepping into and kneeling in the trench and looking at either cut side. You would see the severed root endings. If you painted them a color to make them stand out from the excavated soil, you would be seeing a collection of colored "dots" that would show you where the roots were located along the excavated trench line and their respective depths below the surface. This is the view shown in the Virtual Trench 2D plot, one for each scan line.



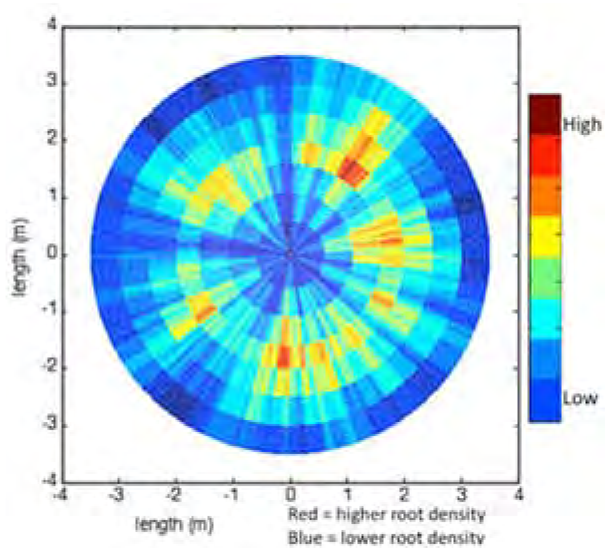

**Virtual Trench** - 2D Planar Depth Image of Root Location (top scale, ft) and Depth (left scale, in) for One Scan Line

The second presentation takes the ensemble of line scans and shows the view looking down from above, i.e., a top-down 3D root map. This top-down view (plan view) is valuable for determining the spatial root layout and density.




**3D Top-Down Image of Root Layout**

A third presentation is the Root Density Map. This depicts all detected roots projected to the surface with different colors representing varying densities of roots found in a given location along the scans. Areas with low root densities are shown with blue colors and areas with high root densities are given red colors as shown below.



## *Methods*

I utilized my TreeRadar™ Unit, equipped with 400 MHz antenna to scan the soil adjacent to a stump within a walnut orchard in Lockeford, California. The stump was from a 54 year old English walnut grafted onto California black walnut rootstock. The stump was 37 inches in diameter. The soil, according to the soil map, was Bruella Sandy Loam, containing 51-65% sand (Figure 1).

**Figure 1. Looking downward and toward the south southwest at walnut stump and plot. Note white line bisecting trunk which was start stop line. Blue lines are scan lines. White box is excavation location and green line is predicted pipe location.**

Scans were complete circles centered at the stump with the following radii: 4, 6, 8, 10 and 12 feet. All scans started to the north of the stump on a line running north to south through the center of the stump. All scans ran in a clockwise direction. All scan lines intersected the excavation pit except the 12 foot scan line which was just outside the pit (Figures 1 and 2).

I submitted a sketch of the site and scan lines, information on the approximate location of the pipe and the data files to Dr. Tony Mucciardi with TreeRadar, Inc. for analysis. The actual depth of pipe was used to calibrate the radar depth axis.

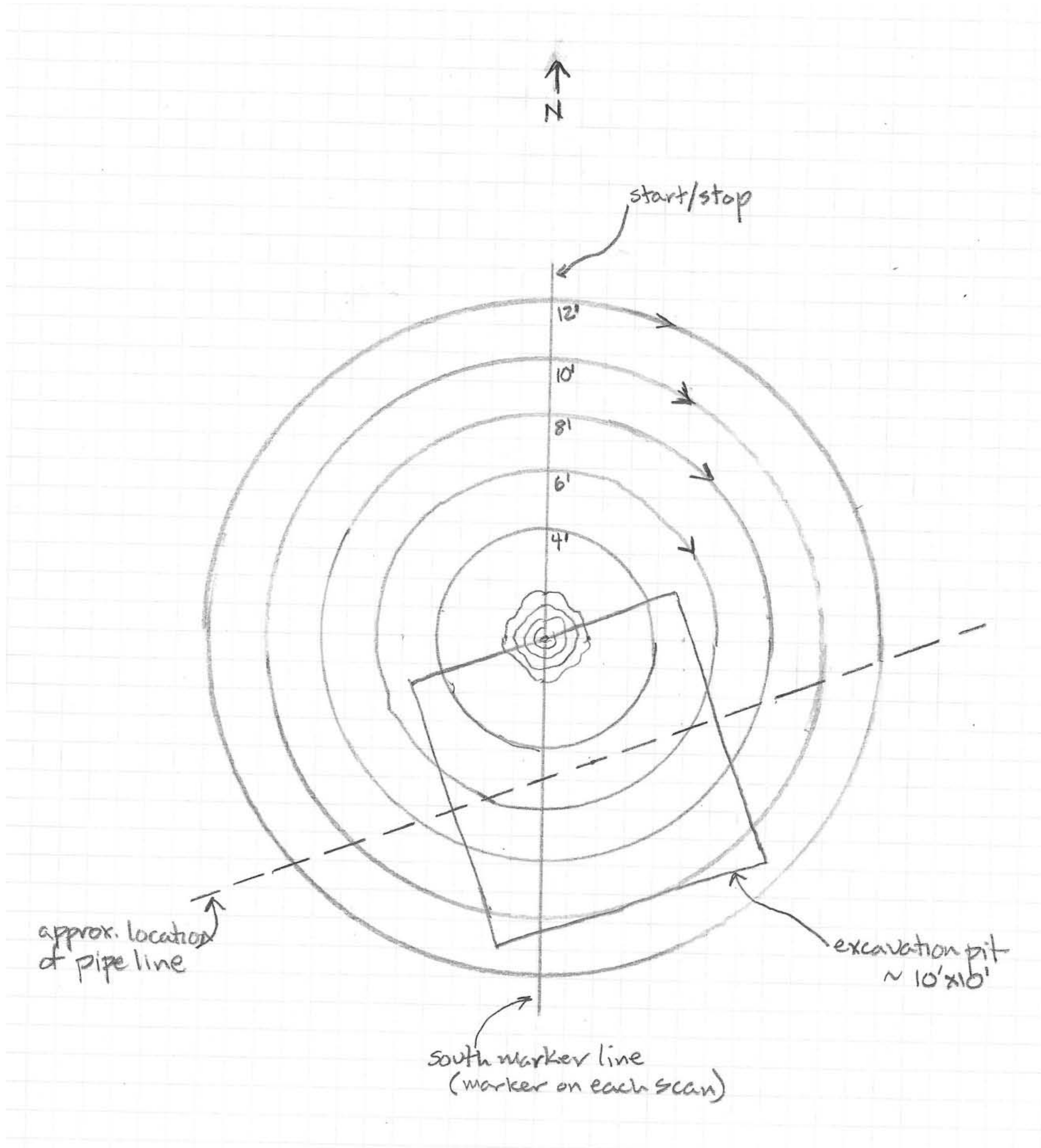



**Figure 2. Sketch of stump, scan lines, excavation pit and approximate pipe location from potholing.**

## *Results*

Results presented in various views described below are attached. Note that the 400 MHz antenna, which has the ability to scan to a depth of 9 to 12 feet detects roots larger than approximately 0.8 inches diameter.

*2D Cross-sectional Maps/Virtual Trench:*

The 2D cross-sectional maps, known as the Virtual Trench, depict the predicted location of roots with X's and metallic reflectors with boxes within each scan line with the start of the scan line on the left of the plot. The ground surface is shown as a dark line. The distance along the scan line is plotted on the x-axis with the depth on the y-axis. The different color

X's represent roots in three contiguous depth zones (0-1.5, 1.5-3 and greater than 3 foot depths). Also included to the left of the plot is the root density (# roots per foot of scan) for the three depth ranges and total depth.

Looking at all the scans, one can see that roots were found from 2 inches to approximately 45 inches below the surface. The root density was greatest within the 18-36 inch depth zone (1.13 to 1.82 roots/foot of scan). The root density was relatively low for both the 0-18 and >36 inch depth zones.

No "pipe reflection" was found on the first (4 ft.) scan as the scan did not run over the pipe as shown in Fig. 2 above. Only one such reflection was found on the second (6 ft.) scan as the scan ran more or less tangential to the pipe. In the remaining scans, two pipe reflections were found as the scan crossed the pipe twice.

Roots were found above and relatively close to the pipe in the 8 and 12 foot scans.

*3D Top-Down Plan Views/Virtual Excavation:*

The 3D top-down plan views, known as the Virtual Excavation, are attached which show the location of scan lines, tree in the plot and markers (pink lines) which I placed where the scan intersected the north/south line south of the trunk and where I noted the pipe and in one case an animal burrow entrance (northwest quadrant). Square boxes indicate metallic reflectors while X's indicate the location of roots. The top down views include a "total depth range" plot which shows all roots found to the depth of the scan (63.4 inches) while other plots show roots found within three depth slices; 0-18, 18-36 and below 36 inches depth. Roots found in the top slice were colored red, those in the second slice were colored blue and those in the bottom slice were colored blue.

Looking at the top down view for the total depth range, one can see that roots were found across the entire plot. However, there was a lower density of roots found in the southwest quadrant and the greatest density appears to be in the northeast quadrant. The majority of roots in the 0-18 inch range were found in the northeast quadrant and there were few roots in this depth range in the southern half of the plot. The vast majority of roots were found in the middle depth range. Looking at the 36 to 63 inch depth range, the majority of roots were found in the southern half of the plot and four roots were found more or less over the pipe.

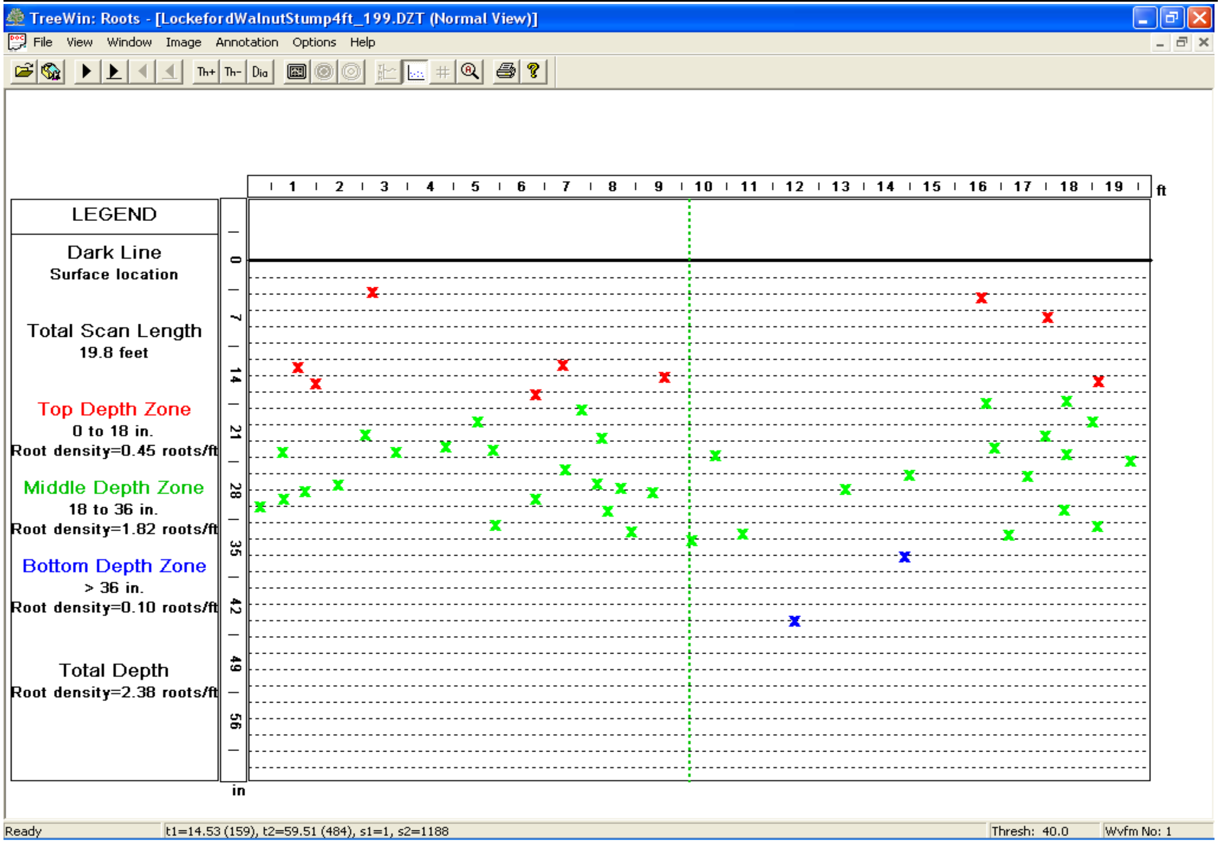
*Root Density Map:*

A root density map is also attached which superimposes the density of roots along scan lines for the entire depth range. The root density map reveals the greatest density of roots in closest to the trunk and in the northeast quadrant.

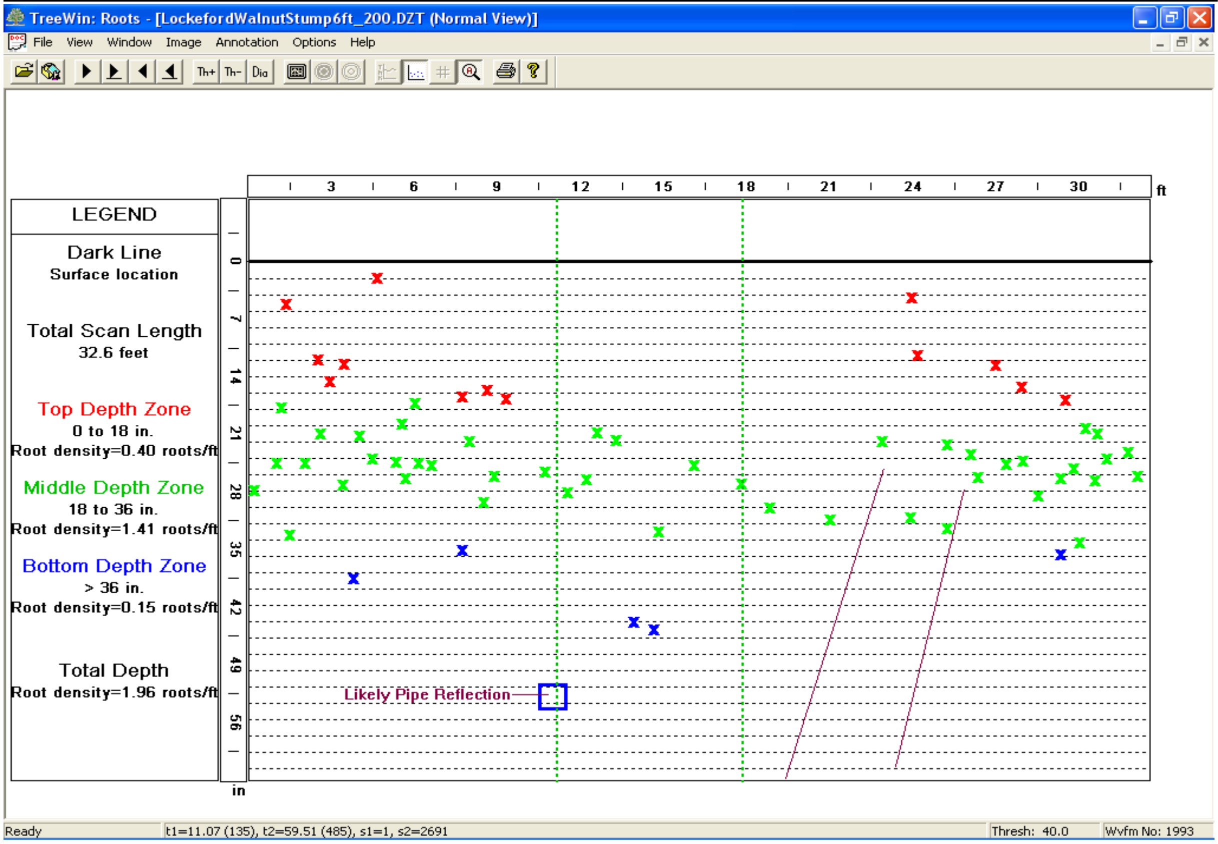
*Root Morphology Map:*

Four root morphology maps are attached. These are maps which are created by connecting the detected roots to approximate what the root system may look like fro a top down or plan view. Two maps are monochrome and the others are color coded according to depth zone of roots. Note the north south line (dotted) on each scan.

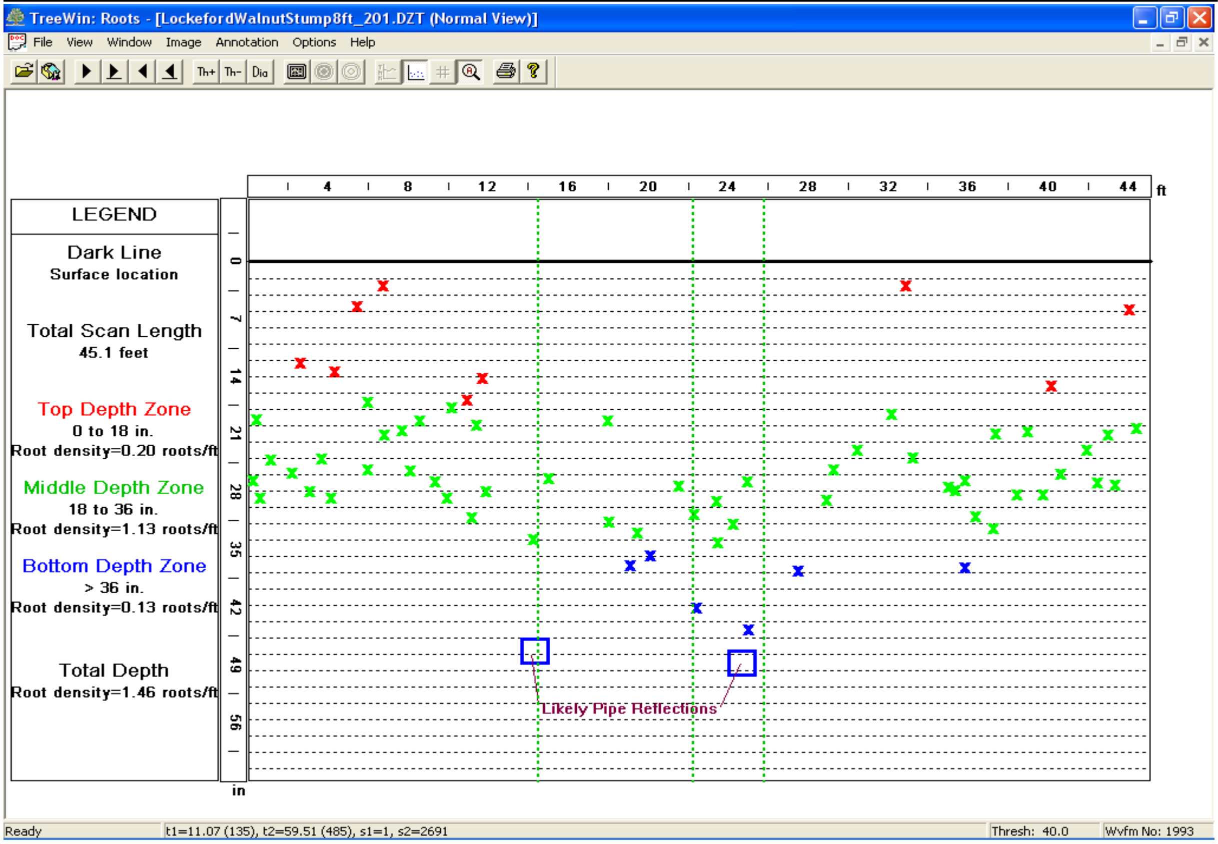
# Walnut Stump - Scan # 4ft (199) - Length = 19.8ft - 29 Oct 2013



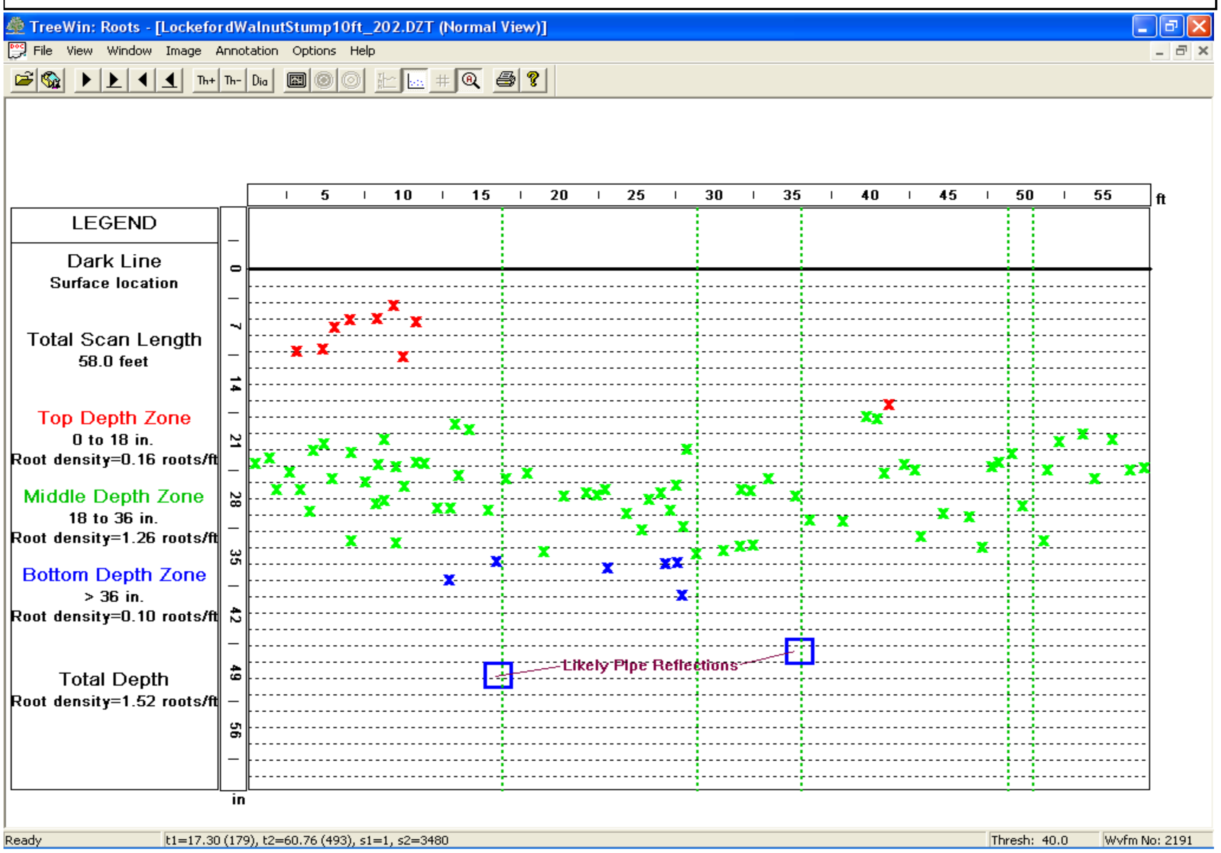

# Walnut Stump - Scan # 6ft (200) - Length = 32.6ft - 29 Oct 2013



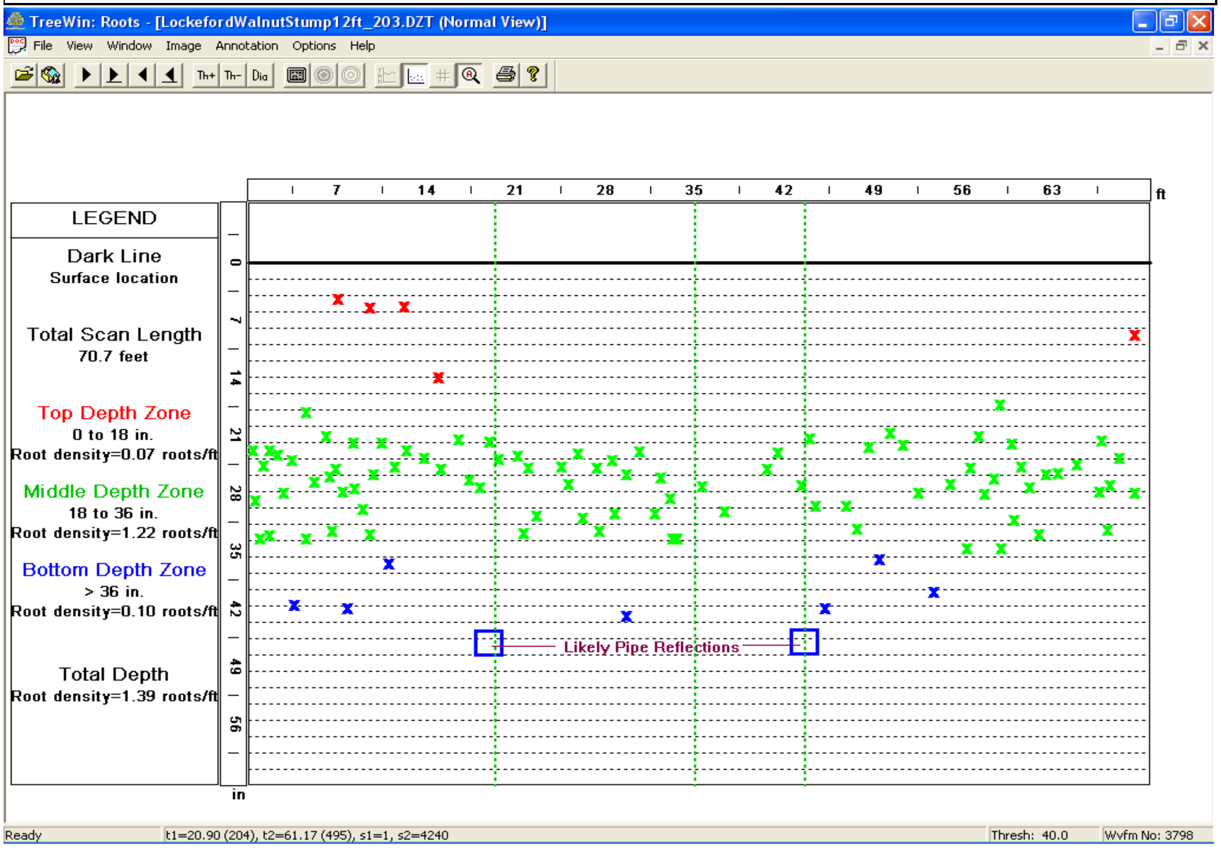
## Walnut Stump - Scan # 8ft (201) - Length = 45.1ft - 29 Oct 2013

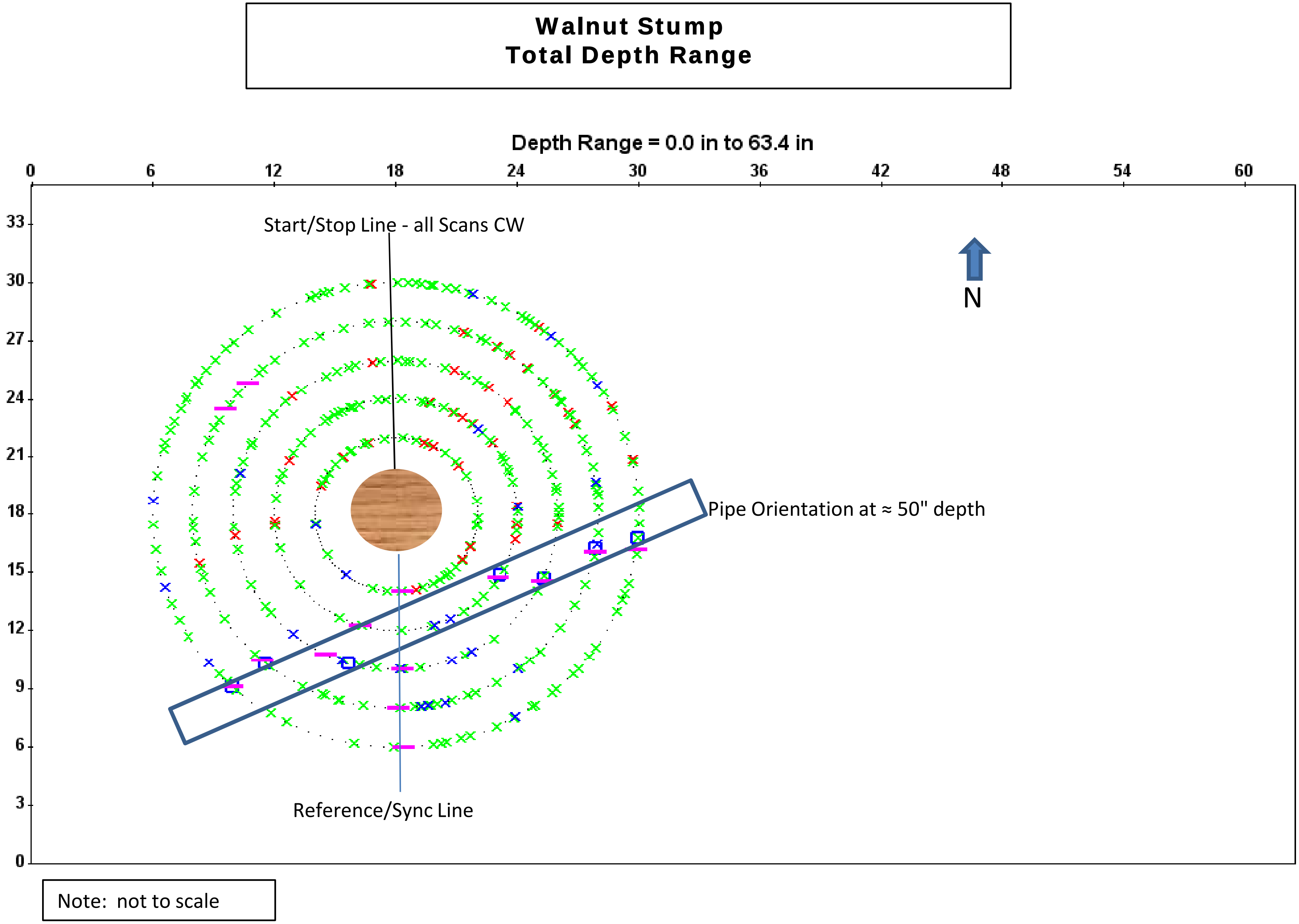



## Walnut Stump - Scan # 10ft (202) - Length = 58.0ft - 29 Oct 2013

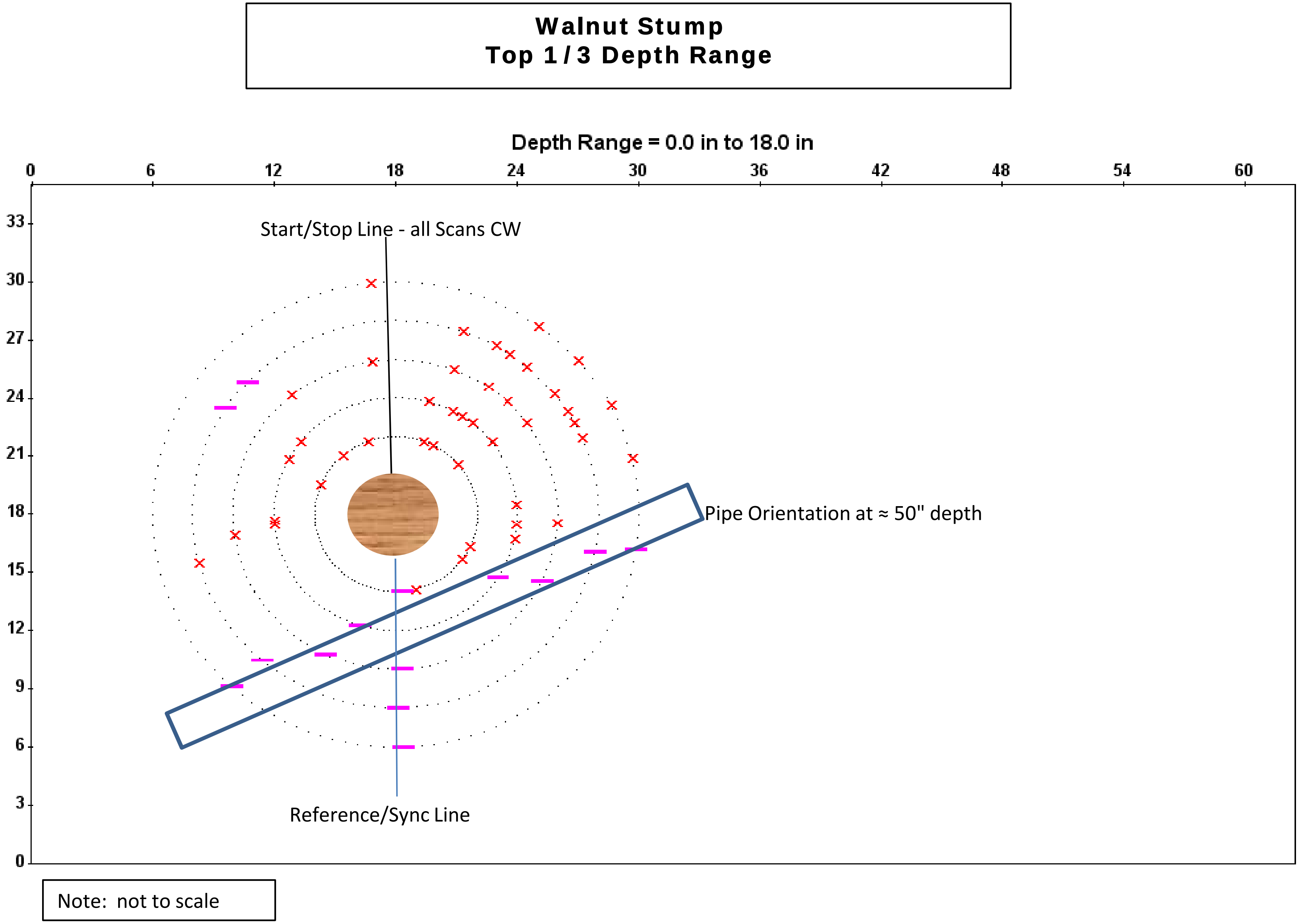


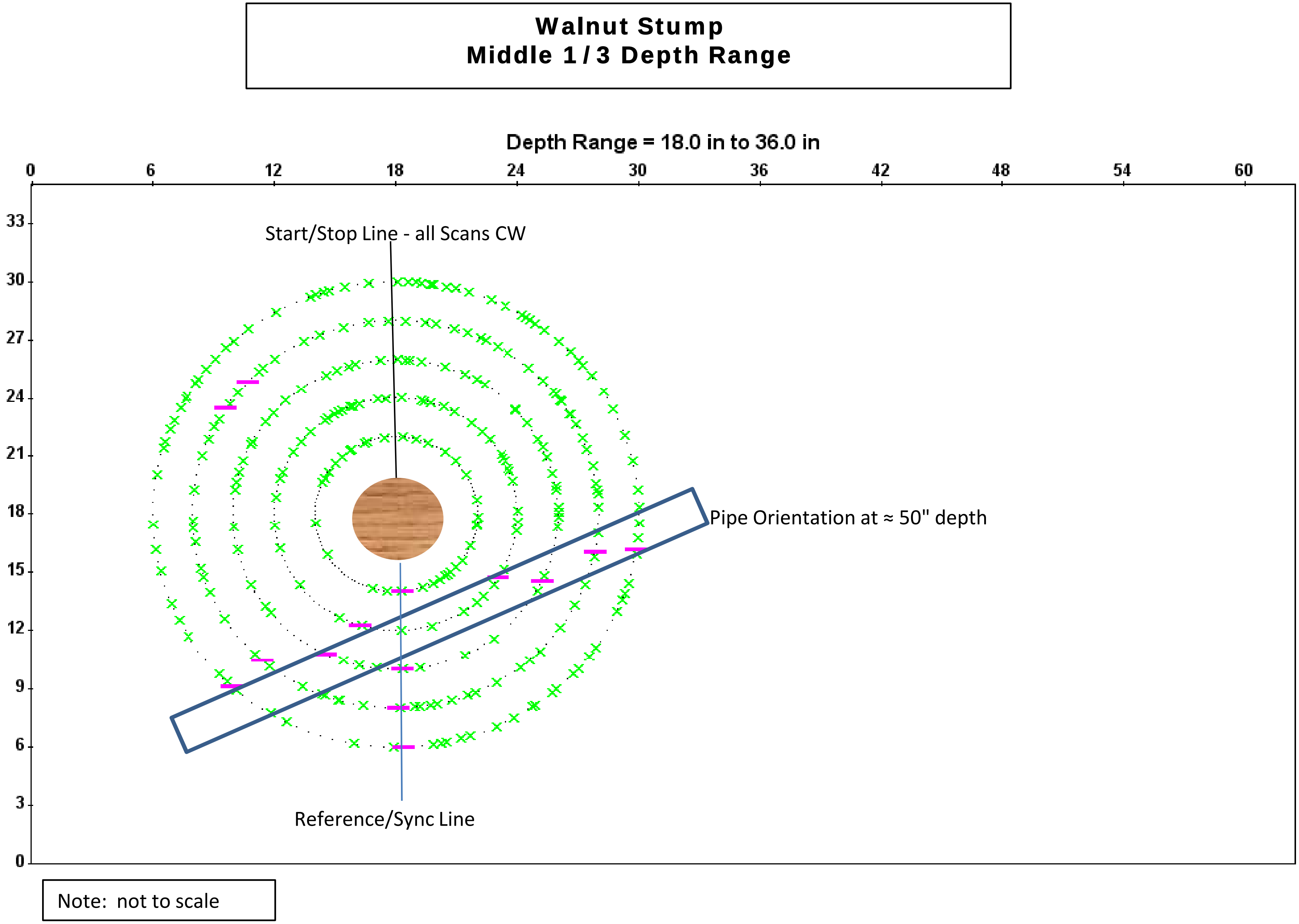
## Walnut Stump - Scan # 12ft (203) - Length = 70.7ft - 29 Oct 2013



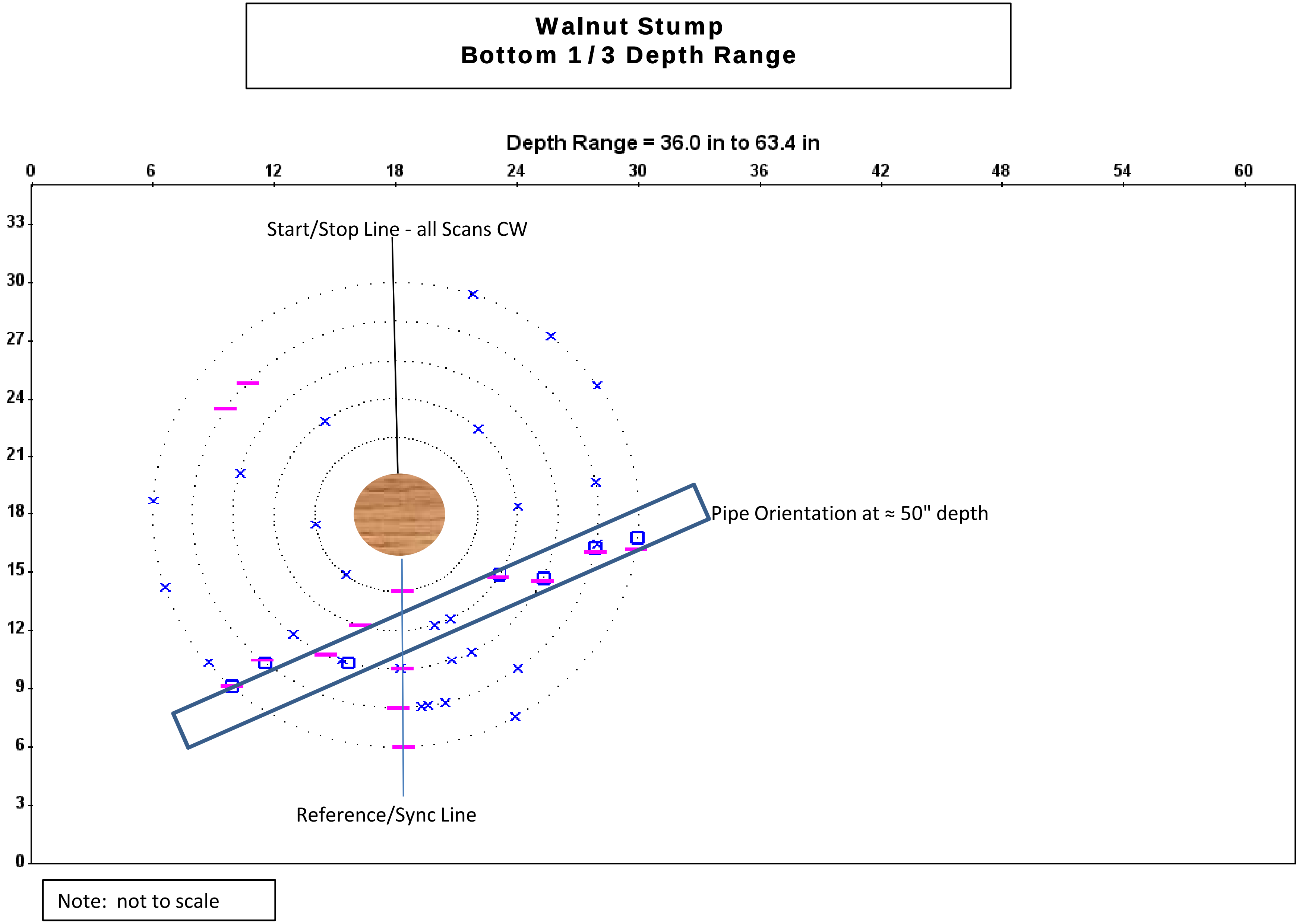


Walnut Stump
Total Depth Range
Depth Range = 0.0 in to 63.4 in
0
6
12
18
24
30
36
42
48
54
60
33
30
27
24
21
18
15
12
9
6
3
0
Start/Stop Line - all Scans CW
N
Pipe Orientation at ≈ 50" depth
Reference/Sync Line
Note: not to scale

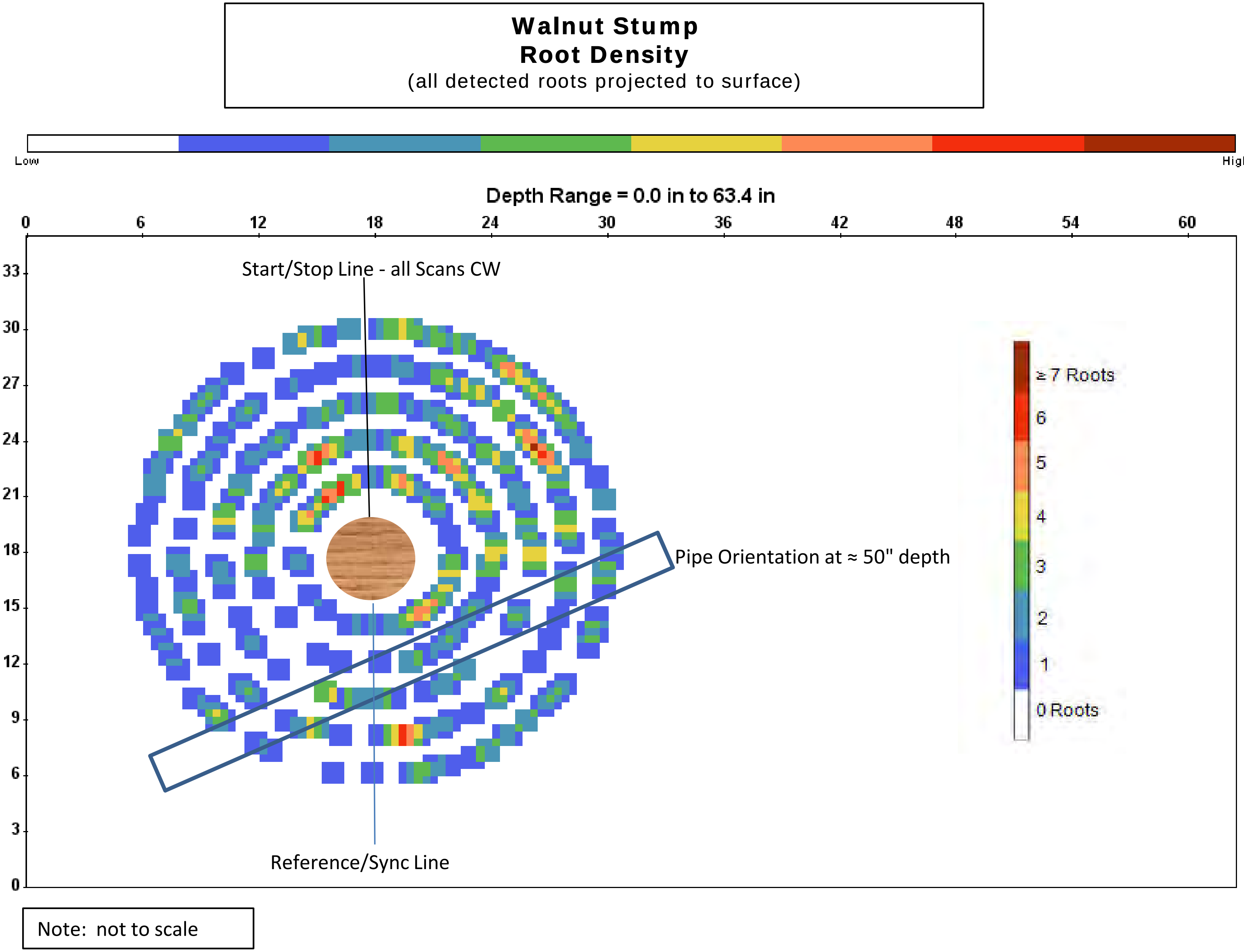

Walnut Stump
Top 1 / 3 Depth Range
Depth Range = 0.0 in to 18.0 in
0
6
12
18
24
30
36
42
48
54
60
33
30
27
24
21
18
15
12
9
6
3
0
Start/Stop Line - all Scans CW
Pipe Orientation at ≈ 50" depth
Reference/Sync Line
Note: not to scale



Walnut Stump
Middle 1 / 3 Depth Range
Depth Range = 18.0 in to 36.0 in
0
6
12
18
24
30
36
42
48
54
60
33
30
27
24
21
18
15
12
9
6
3
0
Start/Stop Line - all Scans CW
Pipe Orientation at ≈ 50" depth
Reference/Sync Line
Note: not to scale

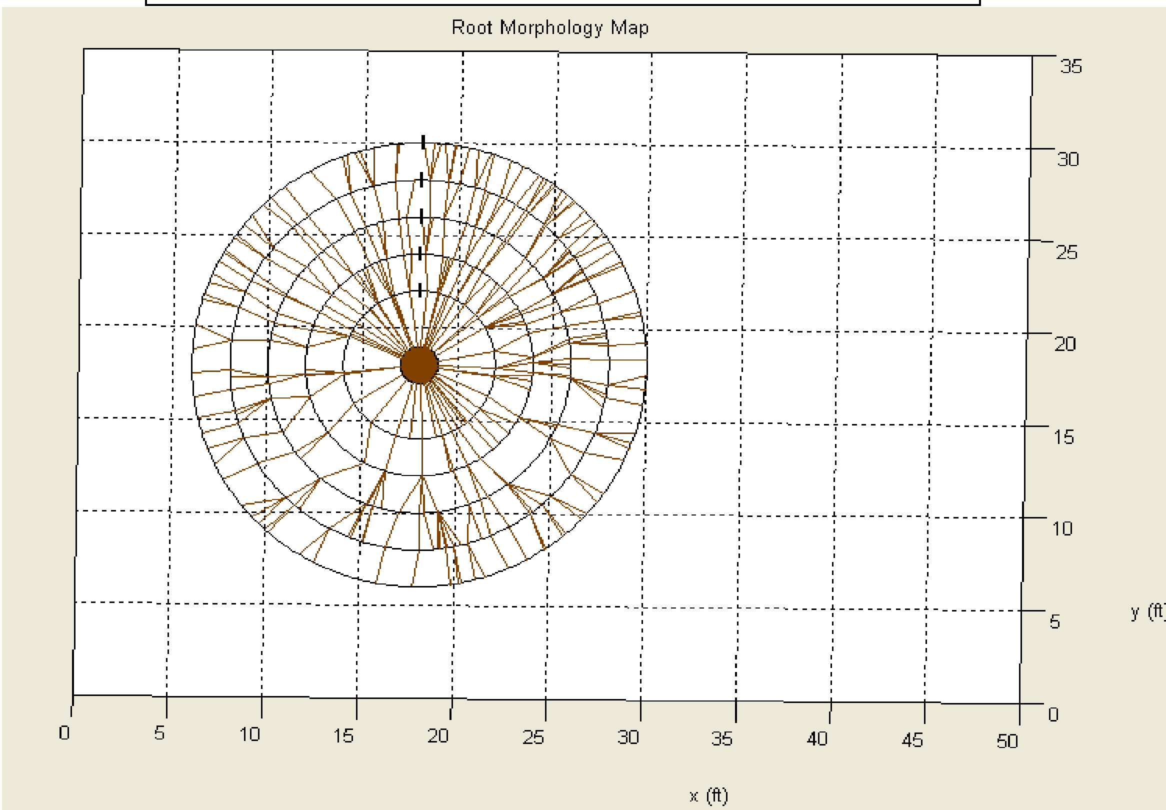


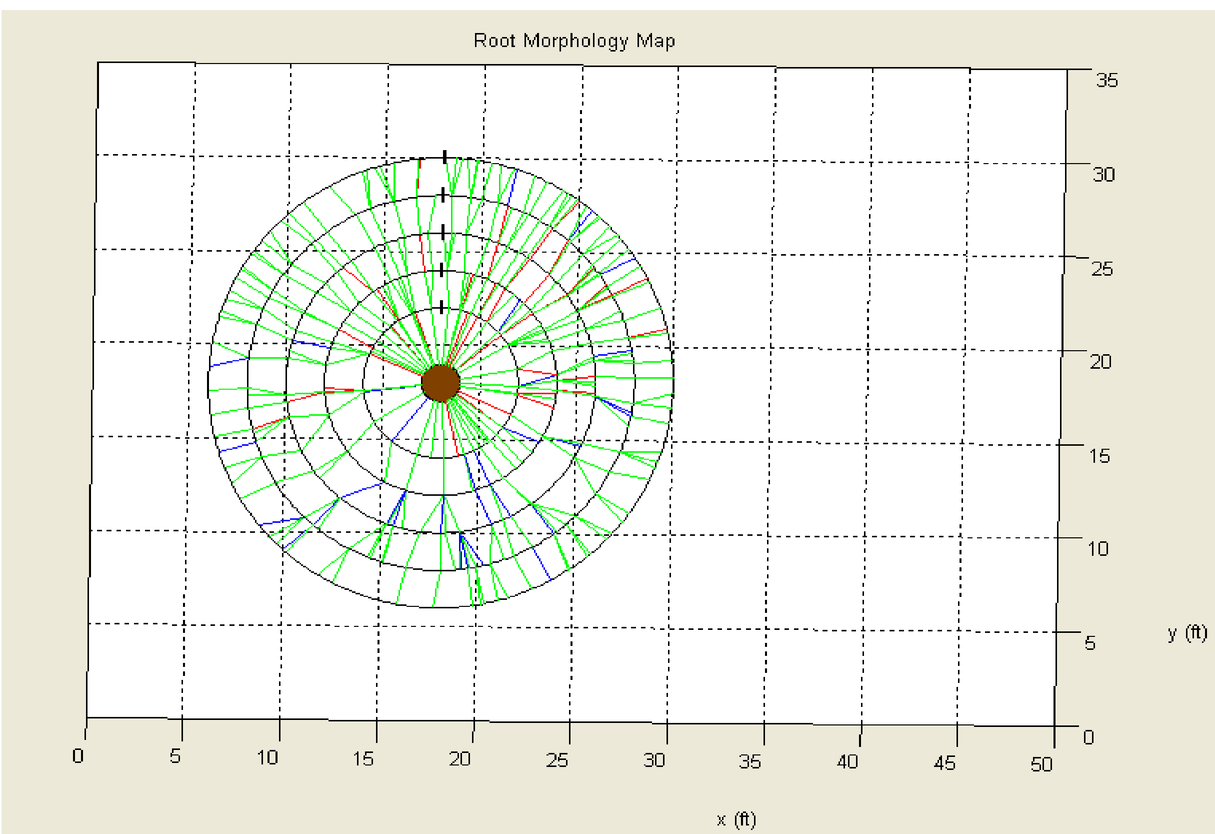
Walnut Stump
Bottom 1/3 Depth Range
Depth Range = 36.0 in to 63.4 in
0
6
12
18
24
30
36
42
48
54
60
33
30
27
24
21
18
15
12
9
6
3
0
Start/Stop Line - all Scans CW
Pipe Orientation at ≈ 50" depth
Reference/Sync Line
Note: not to scale



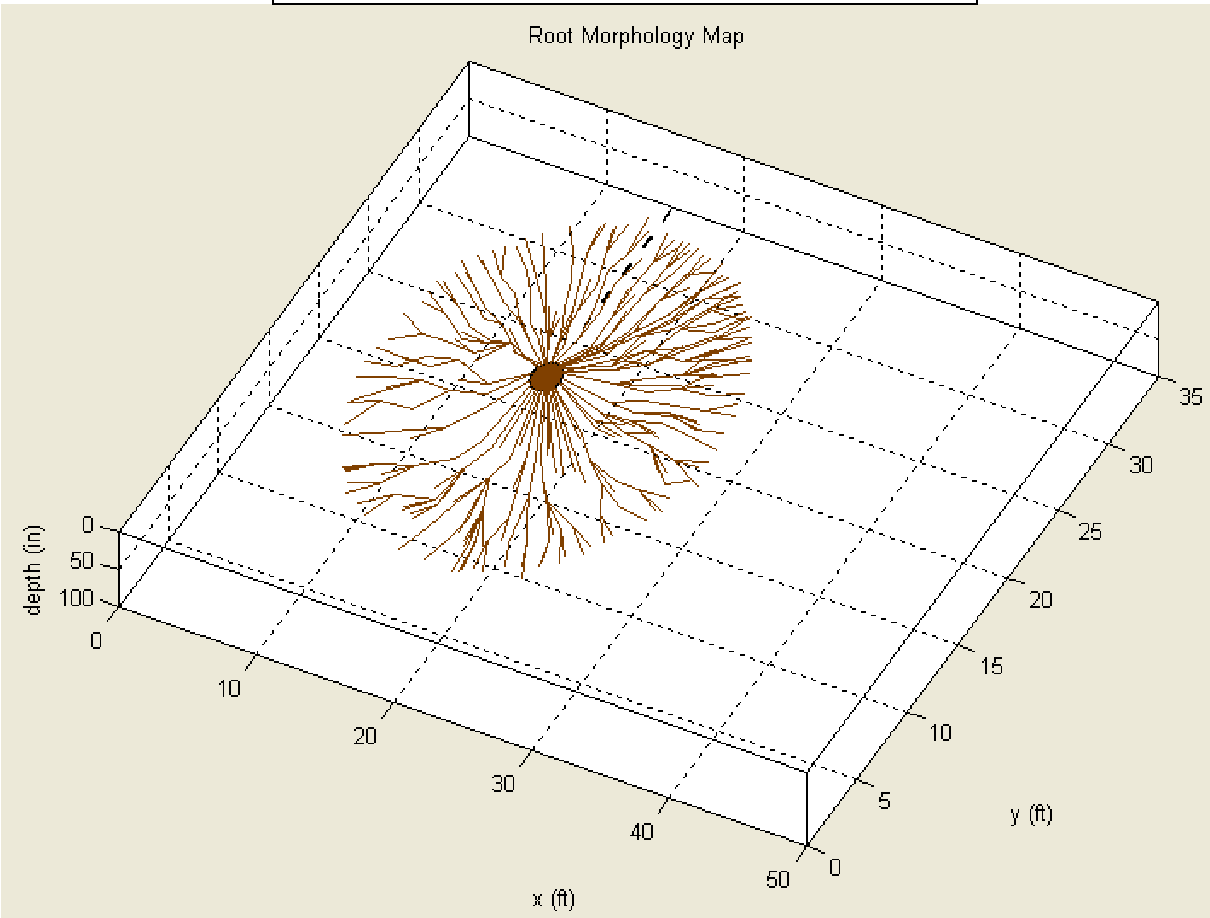
Walnut Stump
Root Density
(all detected roots projected to surface)
Low
High
Depth Range = 0.0 in to 63.4 in
0
6
12
18
24
30
36
42
48
54
60
33
30
27
24
21
18
15
12
9
6
3
0
Start/Stop Line - all Scans CW
Pipe Orientation at ≈ 50" depth
Reference/Sync Line
≥ 7 Roots
6
5
4
3
2
1
0 Roots
Note: not to scale

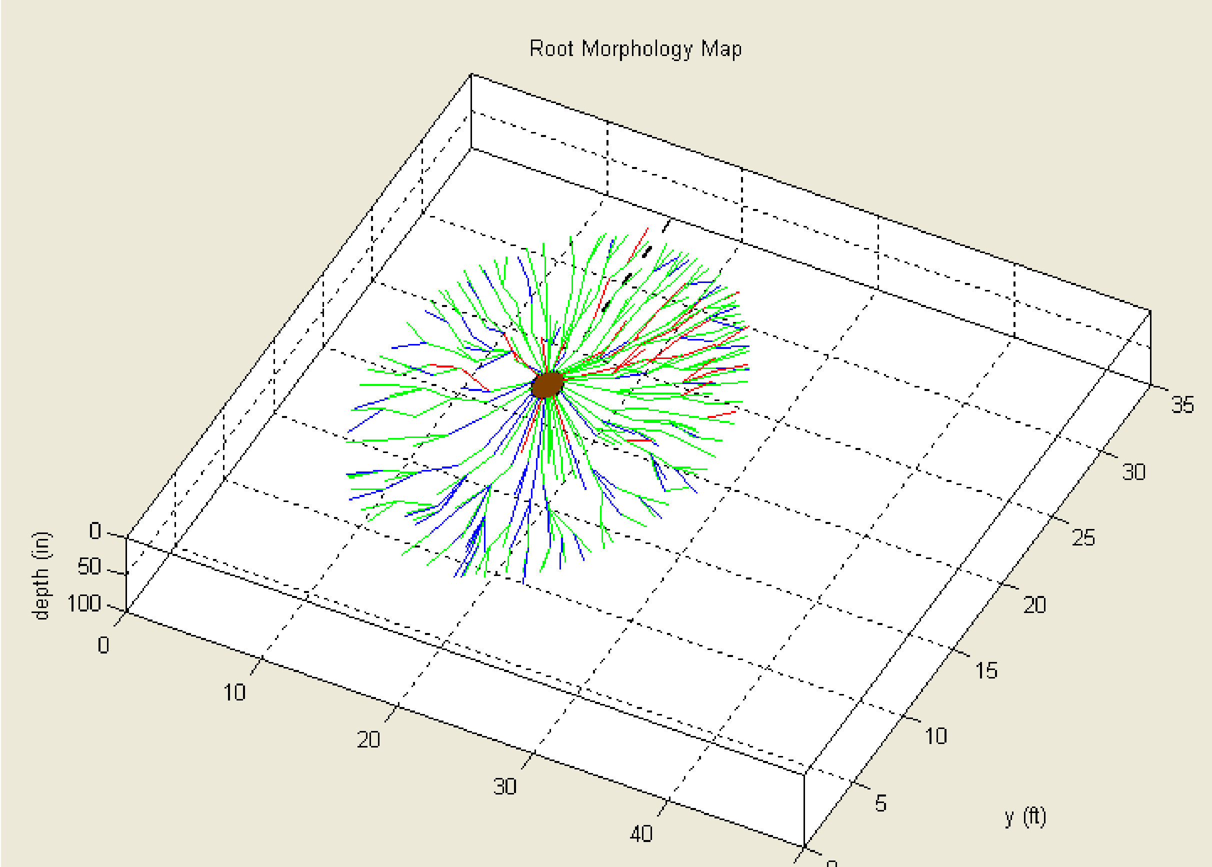
Walnut Stump – Room Morphology Map
Rotated so that Start/Stop Line is at 12:00
Top-Down (Plan) View with Color Coded Depth



Walnut Stump
Root Morphology Map
(note: start/stop line is at 1:30 location)



# Attachment 8:

**Mears Group, Inc and GE Energy DE Technicians. "Completed PG&E External Corrosion Direct Examination Data Sheet, Form H (modified)". Rev. 10. (38 Total)**

**PG&E Sharefile Location:**

Gas Transmission Right of Way (ROW) > Shared Documents > Vegetation_Management > Root Study Documentation > Dynamic Risk Docs > Complete Modified H-Forms and A-Forms

# Appendix 9:

**Mears Group, Inc. "PGE 2013 Tree Root Inv DE Summary (2) xlsx". December 17, 2013.**

| Dig Number | Dig Location | Coating Type | Coating Condition At Tree Root | Coating Condition At Adjacent Pipe | Coating Insp Results | MICKit5 Test Performed | Pipe Wall-Loss | Survey Results |
|---|---|---|---|---|---|---|---|---|
| 111A MP 15.14 RWVIM 142/143-13 | Tree line / Edge of Road South Dickenson Ave in Fresno, CA | CTE | Poor | Poor | Extensive damage to coating caused where tree roots were in contact with coating. Large areas of missing coating from 3:00 - 9:00 position. | No | Split casing surface corroded. Corrosion mapping on casing was not performed per PG&E. | No correllating DCVG/ACVG indicatioins, minor CIS indications |
| 111A MP 11.96 RWVIM 140-13 | Almond Orchard West Lincoln Ave in Fresno, CA | CTE | Fair | Fair | One area of coating damage in area of tree root, seven areas outside of affected area. | No | External corrosion present with a maximum 10.9% wall loss. | Yes, correllates to ACVG/DCVG indications |
| 111A MP 12.27 RWVIM 141-13 | Almond Orchard West Lincoln Ave in Fresno, CA | CTE | Poor | Poor | Extensive degredation and disbondment of coating in and adjacent to tree root affected area. | No | External corrosion and mechanical damage present with a maximum 14.6% wall loss. | Yes, correllates to ACVG/DCVG indications |
| 167-30 MP 0.61 RWVIM 138-13 | Tree line / Edge of Road County Road Y in Afton, CA | Plastic Tape | Good | Good | No coating damage found within inspection area. | No | Coating was not removed, a pipe inspection was not performed. | No correllating DCVG, ACVG, or CIS indicatons |
| 167-30 MP 0.61 RWVIM 139-13 | Tree line / Edge of Road County Road Y in Afton, CA | Plastic Tape | Good | Good | No coating damage found within inspection area. | No | Coating was not removed, a pipe inspection was not performed. | No correllating DCVG, ACVG, or CIS indicatons |
| 167-30 MP 0.61 RWVIM 144-13 | Tree line / Edge of Road County Road Y in Afton, CA | Plastic Tape | Good | Good | No coating damage found within inspection area. | No | Coating was not removed, a pipe inspection was not performed. | No correllating DCVG, ACVG, or CIS indicatons |
| 197C MP 16.4 RWVIM 133-13 | Tree line / Edge of Road Highway 124 in Ione, CA | CTE | Good | Good | No coating damage found within inspection area. | Yes | None | No correllating DCVG, ACVG, or CIS indicatons |
| 197C MP 16.4 RWVIM 137-13 | Tree line / Edge of Road Highway 124 in Ione, CA | CTE | Good | Good | No coating damage found within inspection area. | No | None | No correllating DCVG, ACVG, or CIS indicatons |
| 7210-01 MP 1.9 RWVIM 165-13 | Orchard Sunset Ave in Los Banos, CA | CTE | Fair | Good | 3 areas with coating damage in area of tree root. No coating defects outside of root affected area. | Yes | None | Yes, correllates to ACVG/DCVG indications |
| 1615-01 MP 7.22 RWVIM 247-13 | Tree line / Edge of Road Hall Road in Modesto, CA. | CTE | Poor | Good | Significant coating damage at root affected area. Coating was in good condition at adjacent pipe. Coating was inspected after pipe cut out and root removal. | Yes | None | Yes, correllates to ACVG/DCVG indications, and to CIS indications |
| 167 MP 24.80 RWVIM 160-13 | Walnut Orchard Pennington Road in Live Oak, CA | CTE | Fair | Good | 3 areas with coating damage in area of tree root. No coating defects outside of root affected area. | No | None. 17 indications found during Magnetic Particle Exam. | IIT surveys performed as specified by PG&E, however did not align spatially with dig location. |
| 167 MP 24.88 RWVIM 159-13 | Walnut Orchard Pennington Road in Live Oak, CA | CTE | Fair | Good | 2 areas of coating damage in area of tree root. No coating defects outside of root affected area. | Yes | None | Yes, correllates to ACVG/DCVG indications, however no real correllation to CIS data. |
| 172A MP 6.0 RWVIM 158-13 | Walnut Orchard Dodge Rd/Hwy 45 in Princeton, CA | CTE | Good | Good | No root interaction with coating was found within inspection area. No coating defects were present. | Yes | Mechanical damage present with a maximum 1.1% wall loss. | IIT surveys performed as specified by PG&E, however did not align spatially with dig location. |
| 197A MP 14.0 RWVIM 259-13 | Walnut Orchard Highway 12/88 in Lockeford, CA | CTE | Fair | Good | 2 areas of coating damage in area of tree root. No coating defects outside of root affected area. | No | None | IIT surveys performed in an area not spatially aligning with dig location. |
| 197A MP 14.3 RWVIM 155-13 | Walnut Orchard Highway 12/88 in Lockeford, CA | CTE | Fair | Good | 2 areas of coating damage in area of tree root. No coating defects outside of root affected area. | Yes | None | IIT surveys performed in an area not spatially aligning with dig location. |
| 197A MP 4.09 RWVIM 77-13 | Golf Course Woodbridge Rd in Woodbridge, CA | CTE | Fair | Good | 7 areas of coating damage in area of tree root. No coating defects outside of root affected area. | Yes | None | No correllating DCVG, ACVG, or CIS indicatons |
| 197A MP 4.10 RWVIM 78-13 | Golf Course Woodbridge Rd in Woodbridge, CA | CTE | Fair | Good | 4 areas of coating damage in area of tree root. No coating defects outside of root affected area. | Yes | None | Yes, correllates to ACVG/DCVG indications, however no real correllation to CIS data. |
| 197A MP 4.20 RWVIM 76-13 | Golf Course Woodbridge Rd in Woodbridge, CA | CTE | Fair | Good | 6 areas of coating damage in area of tree root. No coating defects outside of root affected area. | Yes | None | IIT surveys performed as specified by PG&E, however did not align spatially with dig location. |

# Appendix 10:

**Tulsa and Canus - NACE Certified Inspectors. "Completed Leak Repair, Inspection, and Gas Quarterly Incident Report (A-Form)". (Rev 03/11). (47 Total)**

**PG&E Sharefile Location:**

Gas Transmission Right of Way (ROW) > Shared Documents > Vegetation_Management > Root Study Documentation > Dynamic Risk Docs > Complete Modified H-Forms and A-Forms

# Appendix 11:

**Dynamic Risk, Inc. "PG&E Tree Root Matrix Spreadsheet". December 20, 2013.**

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| Site Location Information | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Dig Identification | 2013 digs | Project Status | Project Type | Address | City | LAT | LON | Northing | Easting | Line | Dig Completion | Year Pipe Constructed |
| RWVIM-155-13 | 2013 | 26-Oct | Grape | Hwy 12 | Lockeford | 38.169777 | -121.128646 | | | 197A | 11/2/2013 | 1957 |
| RWVIM-130-13 | | Complete | Full Root | 7633N. Weber Lane, Tree #9 | Fresno | 36.844460 | -119.928225 | | | 118A | 8/12/2013 | 1931 |
| RWVIM-140-13 | 2013 | Complete | Orchard | West Lincoln Ave | Fresno | 36.644747 | -120.016020 | | | 111A | 10/21/2013 | 1942 |
| RWVIM-141-13 | 2013 | Complete | Orchard | West Lincoln Ave | Fresno | 36.647458 | -120.011694 | | | 111A | 10/21/2013 | 1942 |
| RWVIM-158-13 | 2013 | 4-Nov | Orchard | Hwy 45 South of Dodge Rd | Princeton | 39.370797 | -122.031701 | | | 172A | 11/11/2013 | 1957 |
| RWVC 41-13B (RWVIM-99-13) | | Complete | Full Root | 15803 Via Hornitos | San Lorenzo | N/A | N/A | 4169812.1400 | 574775.7230 | L153 | 11/10/2012 | 1949 |
| RWVIM-159-13 | 2013 | Complete | Orchard | Pennington & Schroeder Rd | Live Oak | 39.269497 | -121.696247 | | | 167 | 10/26/2013 | 1954 |
| RWVIM-129-13 | | Complete | Full Root | 7633N. Weber Lane, Tree #8 | Fresno | 36.844460 | -119.928225 | | | 118A | 8/12/2013 | 1931 |
| RWVIM-127-13 | | Complete | Full Root | 7633N. Weber Lane, Tree #6 | Fresno | 36.844460 | -119.928225 | | | 118A | 8/12/2013 | 1931 |
| RWVIM-132-13 | | Complete | Full Root | Hwy 88 | Lockford | 38.169530 | -121.136651 | | | 197A | 8/22/2013 | 1957 |
| RWVIM-138-13 | 2013 | Complete | Full Root | Road Y | Afton | 39.405564 | -121.966495 | | | 167-30 | 9/21/2013 | 1987 |
| 132-8 | pre 2013 | Complete | Full Root | 734 Manzanita Ave. | Sunnyvale | 37.395001 | -122.024128 | | | L132 | 9/20/2012 | 1944 |
| RWVIM-131-13 | | Complete | Full Root | Hwy 88 | Ione | 38.318847 | -120.938815 | | | 197C | 8/24/2013 | 1965 |
| RWVIM-73-13 | | Complete | Full Root | 8055 San Gregorio #1 | Atascadero | 35.513700 | -120.721196 | | | 306 | 6/18/2013 | 1962 |
| 153-12 | pre 2013 | Complete | Full Root | 2193 Corte Hornitos | San Lorenzo | N/A | N/A | 4169677.4720 | 574876.8880 | L153 | 4/1/2013 | 1949 |
| RWVIM-76-13 | 2013 | Complete | Full Root | Wood Bridge Country Club | Stockton | 38.163535 | -121.312811 | | | 197A | 9/28/2013 | 1957 |
| RWVIM-88-13 | | Complete | Full Root | 2432 N State Hwy 59 | Merced | 37.308943 | -120.504920 | | | 118A | 7/12/2013 | 1939 |
| RWVIM-106-13 | | Complete | Full Root | 7633N. Weber Lane, Tree #3 | Fresno | 36.844460 | -119.928225 | | | 118A | 7/19/2013 | 1931 |
| RWVIM-107-13 | | Complete | Full Root | 7633N. Weber Lane, Tree #4 | Fresno | 36.844460 | -119.928225 | | | 118A | 7/19/2013 | 1931 |
| RWVIM-128-13 | | Complete | Full Root | 7633N. Weber Lane, Tree #7 | Fresno | 36.844460 | -119.928225 | | | 118A | 8/12/2013 | 1931 |
| RWVIM-103-13 | | Complete | Full Root | 811 San Lucas Court | Mountain View | 37.403068 | -122.071449 | | | L132 | 2/20/2013 | 1944 |
| RWVIM-81-13 | | Complete | Full Root | 1963 Rock St., Unit 17 | Mountain View | 37.246870 | -122.053970 | | | L109 | 5/28/2013 | 1973 |
| RWVC-41-13A (RWVIM-99-13) | pre 2013 | Complete | Stump | 15803 Via Hornitos | San Lorenzo | N/A | N/A | 4169812.1400 | 574775.7230 | L153 | 11/10/2012 | 1949 |
| RWVIM-92-13 | | Complete | Full Root | 7633N. Weber Lane, Tree #2 | Fresno | 36.844460 | -119.928225 | | | 118A | 7/19/2013 | 1931 |
| RWVIM-82-13 | | Complete | Full Root | 1963 Rock Street, Unit 19 | Mountain View | 37.246920 | -122.054140 | | | L109 | 5/28/2013 | 1973 |
| RWVIM-96-13 | | Complete | Full Root | 785 San Lucas Ave. | Mountain View | 37.403756 | -122.072851 | | | L132 | 2/20/2013 | 1944 |
| RWVIM-90-13 | 2013 | Complete | Full Root | 5725 Hall Road | Modesto | 37.722722 | -121.129503 | | | 108 | 9/16/2013 | 1955 |
| 153-4 | pre 2013 | Complete | Full Root | 15685 Wicks Blvd. | San Leandro | N/A | N/A | 4170179.6100 | 574499.0200 | L153 | 1/1/2013 | 1949 |
| RWVIM-133-13 | 2013 | 18-Nov | Full Root | Hwy 124 Charles Hwd Park | Ione | 38.343921 | -120.933846 | | | 197C-1 | 12/4/2013 | 1966 |
| RWVIM-101-13 | | Complete | Full Root | 741 Santa Christina Court | Sunnyvale | 37.39508676 | -122.022912 | | | L132 | 4/18/2013 | 1944 |

| Site Location Information | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Dig Identification** | **2013 digs** | **Project Status** | **Project Type** | **Address** | **City** | **LAT** | **LON** | **Northing** | **Easting** | **Line** | **Dig Completion** | **Year Pipe Constructed** |
| RWVIM-144-13 | 2013 | Complete | Stump | Road Y | Afton | N/A | N/A | | | 167-30 | 9/21/2013 | 1987 |
| RWVIM-78-13 | 2013 | Complete | Full Root | Wood Bridge Country Club | Stockton | 38.167392 | -121.308506 | | | 197A | 10/5/2013 | 1957 |
| RWVIM-98-13 | | Complete | Full Root | 749 Santa Christina Court | Sunnyvale | 37.395109 | -122.022649 | | | L132 | 4/17/2013 | 1944 |
| RWVC-38-13 (L109) | | Complete | Full Root | 1963 Rock Street | Mountain View | 37.411480 | -122.090139 | | | L109 | 3/24/2013 | 1973 |
| RWVC-38-13 (L132) | | Complete | Full Root | 1963 Rock Street | Mountain View | 37.411480 | -122.090139 | | | L132 | 3/24/2013 | 1947 |
| RWVIM-137-13 | 2013 | 18-Nov | Full Root | Hwy 124 Charles Hwd Park | Ione | 38.343921 | -120.933846 | | | 197C-1 | 12/4/2013 | 1966 |
| 153-1 | pre 2013 | Complete | Full Root | 15633 Wicks Blvd. | San Leandro | N/A | N/A | 4170283.6610 | 574421.0560 | L153 | 1/1/2013 | 1949 |
| RWVIM-102-13 | | Complete | Full Root | 735 Madrone Ave | Sunnyvale | 37.395265 | -122.025526 | | | L132 | 4/26/2013 | 1944 |
| RWVIM-139-13 | 2013 | Complete | Full Root | Road Y | Afton | 39.405564 | -121.966495 | | | 167-30 | 9/21/2013 | 1987 |
| RWVIM-100-13 | | Complete | Full Root | 15747 Via Sorrento | San Lorenzo | 37.673902 | -122.153557 | | | L153 | 3/2/2013 | 1949 |
| 153-3a | pre 2013 | Complete | Full Root | 15667 Wicks Blvd. | San Leandro | 37.676091 | -122.154340 | | | L153 | 10/15/2012 | 1949 |
| RWVC-55-13 (RWVIM-105-13) | | Complete | Full Root | 2194 Corte Hornitos | San Lorenzo | 37.671056 | -122.150934 | | | L153 | 2/28/2013 | 1949 |
| RWVIM-77-13 | 2013 | Complete | Full Root | Wood Bridge Country Club | Stockton | 38.155717 | -121.300470 | | | 197B | 9/30/2013 | 1957 |
| RWVIM-104-13 | | Complete | Full Root | 810 San Lucas Court | Mountain View | 37.403288 | -122.071889 | | | L132 | 2/20/2013 | 1944 |
| RWVIM-126-13 | | Complete | Full Root | 7633N. Weber Lane, Tree #5 | Fresno | 36.844460 | -119.928225 | | | 118A | 8/12/2013 | 1931 |
| RWVIM-136-13 | | Complete | Full Root | Hwy 88 | Lockford | 38.169530 | -121.136651 | | | 197A | 8/22/2013 | 1957 |
| RWVIM-160-13 | 2013 | Complete | Orchard | Pennington & Schroeder Rd | Live Oak | 39.272560 | -121.701181 | | | 167 | 10/26/2013 | 1954 |
| RWVIM-165-13 | 2013 | 8-Nov | Orchard | 2254 Sunset Ave | Los Banos | 37.022700 | -120.900130 | | | 7210-01 | 11/10/2013 | 1958 |
| RWVIM-259-13 | 2013 | 26-Oct | Orchard | Hwy 12 (PDVG-5) Walnut Tree | Lockeford | | | | | 111A | 11/2/2013 | 1957 |
| RWVIM-74-13 | | Complete | Full Root | 7905 San Gregorio | Atascadero | 35.514434 | -120.718952 | | | 306 | 6/13/2011 | 1962 |
| RWVIM-75-13 | | Complete | Full Root | 8055 San Gregorio #3 | Atascadero | 35.513700 | -120.721196 | | | 306 | 6/18/2013 | 1962 |
| RWVIM-87-13 | | Complete | Full Root | 2103 Bandoni Ave | San Lorenzo | 37.666102 | -122.146175 | | | 153 | 7/12/2013 | 1949 |
| RWVIM-89-13 | | Complete | Full Root | 7633 N Weber Lane, Tree #1 | Fresno | 36.844350 | -119.928195 | | | 118A | 7/19/2013 | 1931 |

| Pipe Details and Proximity to Tree | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Nominal Pipe Diameter, inches | Pipe Coating | Horizontal offset distance (x), inches | Depth of Cover (y), inches | z-factor, inches | Depth of Cover, (ft) | Distance to Tree, Hypotenuse leg Feet | Tree Species | DBH, inches | Tree Height, feet |
| 10 | HAA | 12 | 58 | 59.2 | 4.83 | 4.93 | Grape | 2 | 6 |
| 8 | CTE | 20 | 35 | 40.3 | 2.92 | 3.36 | Ailanthus | 7 | 28 |
| 12 | HAA | 4 | 41 | 41.2 | 3.42 | 3.43 | Almond | 7 | 15 |
| 16 | HAA | 4 | 44 | 44.2 | 3.67 | 3.68 | Almond | 7 | 16 |
| 18 | HAA | 66 | 48 | 81.6 | 4.00 | 6.80 | Black walnut | 9 | 25 |
| 30 | HAA | 0 | 58 | 58 | 4.83 | 4.83 | Avocado | 12 | 39 |
| 16 | HAA | 0 | 38 | 38 | 3.17 | 3.17 | Walnut | 12 | 26 |
| 8 | CTE | 35 | 33 | 48.1 | 2.75 | 4.01 | Silk | 15 | na |
| 8 | CTE | 30 | 38 | 48.4 | 3.17 | 4.03 | Deodar cedar | 17 | na |
| 10 | HAA | 11 | 52 | 53.2 | 4.33 | 4.43 | Black walnut | 19 | 36 |
| 6 | Tape | 84 | 72 | 111 | 6.00 | 9.22 | Black walnut | 19 | na |
| 24 | HAA | 84 | 72 | 110.6 | 6.00 | 9.22 | Incense cedar | 20 | 54 |
| 10 | CTE | 10 | 52 | 53 | 4.33 | 4.42 | Interior live oak | 21 | 22 |
| 20 | HAA | 20 | 60 | 63.2 | 5.00 | 5.27 | Afghan pine | 21 | 42 |
| 30 | HAA | 49.8 | 48 | 69.2 | 4.00 | 5.77 | Mulberry | 22.9 | 29 |
| 10 | CTE | 0 | 48 | 48 | 4.00 | 4.00 | Coast redwood | 23 | 53 |
| 8 | HAA | 104 | 55 | 117.6 | 4.58 | 9.80 | Elm | 23 | na |
| 8 | HAA | 29 | 33 | 43.9 | 2.75 | 3.66 | Silk | 25 | 37 |
| 8 | CTE | 35 | 36 | 50.2 | 3.00 | 4.18 | Hackberry | 25 | 43 |
| 8 | CTE | 34 | 36 | 49.5 | 3.00 | 4.13 | Deodar cedar | 28 | na |
| 24 | HAA | 96 | 54 | 110.1 | 4.50 | 9.18 | Cottonwood | 28.6 | 76 |
| 34 | Tape | 114 | 60 | 128.8 | 5.00 | 10.73 | Monterey pine | 30.5 | 60 |
| 30 | HAA | 10 | 60 | 60.8 | 5.00 | 5.07 | Willow | 31 | na |
| 8 | CTE | 40 | 30 | 50 | 2.50 | 4.17 | Deodar cedar | 31 | 48 |
| 34 | Tape | 84 | 60 | 103.2 | 5.00 | 8.60 | Monterey pine | 31.5 | 60 |
| 24 | HAA | 48 | 48 | 67.9 | 4.00 | 5.66 | Avocado | 32.5 | 41 |
| 10 | HAA | 0 | 48 | 48 | 4.00 | 4.00 | Valley oak | 33 | 52 |
| 30 | HAA | 0 | 48 | 48 | 4.00 | 4.00 | Italian stone pine | 35 | 48 |
| 6 | HAA | 42 | 63 | 75.7 | 5.25 | 6.31 | Interior live oak | 35.5 | 37 |
| 24 | HAA | 98 | 48 | 109.1 | 4.00 | 9.09 | Black walnut | 36 | 44 |

| Pipe Details and Proximity to Tree | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| **Nominal Pipe Diameter, inches** | **Pipe Coating** | **Horizontal offset distance (x), inches** | **Depth of Cover (y), inches** | **z-factor, inches** | **Depth of Cover, (ft)** | **Distance to Tree, Hypotenuse leg Feet** | **Tree Species** | **DBH, inches** | **Tree Height, feet** |
| 6 | Tape | 116 | 96 | 150.6 | 8.00 | 12.55 | Valley Oak | 36 | na |
| 10 | CTE | 58 | 48 | 75.3 | 4.00 | 6.28 | Deodar cedar | 36 | 71 |
| 24 | HAA | 37 | 36 | 51.6 | 3.00 | 4.30 | Elm | 36 | 45 |
| 34 | Tape | 75 | 48 | 89 | 4.00 | 7.42 | Coast redwood | 39.1 | 81 |
| 24 | HAA | 131 | 36 | 135.9 | 3.00 | 11.33 | Coast redwood | 39.1 | 81 |
| 6 | HAA | 36 | 61 | 70.8 | 5.08 | 5.90 | Interior live oak | 40 | 40 |
| 30 | HAA | 54 | 48 | 72.2 | 4.00 | 6.02 | Monterey pine | 47 | 41 |
| 24 | HAA | 36 | 50 | 61.6 | 4.17 | 5.13 | Privet | 47.8 | 52 |
| 6 | Tape | 88 | 96 | 130.2 | 8.00 | 10.85 | Valley Oak | 48 | na |
| 30 | CTE | 36 | 48 | 66 | 4.00 | 5.50 | Date Palm | 60 | 51 |
| 30 | HAA | 20.5 | 48 | 52.2 | 4.00 | 4.35 | Monterey cypress | 62.5 | 51 |
| 30 | HAA | 54 | 48 | 72.2 | 4.00 | 6.02 | Myoporum | 65 | 34 |
| 10 | CTE | 50 | 48 | 69.3 | 4.00 | 5.78 | Silver maple | 74 | 75 |
| 24 | HAA | 126 | 48 | 134.8 | 4.00 | 11.23 | Cottonwood | 98.5 | 74 |
| 8 | CTE | 41 | 36 | 54.6 | 3.00 | 4.55 | Eucalyptus | 49 | na |
| 10 | HAA | 35 | 40 | 53.2 | 3.33 | 4.43 | Black walnut | 14 | na |
| 16 | HAA | 0 | 42 | 42 | 3.50 | 3.50 | Plum | 11 | 15 |
| 6 | CTE | 24 | 54 | 59.1 | 4.50 | 4.93 | Apricot | 9 | 11 |
| 10 | HAA | 64 | 50 | 81.2 | 4.17 | 6.77 | Walnut | 29 | na |
| 20 | HAA | 0 | 60 | 60 | 5.00 | 5.00 | Eucalyptus | 24 | na |
| 20 | HAA | 37 | 48 | 60.6 | 4.00 | 5.05 | Afghan pine | 18.6 | na |
| 30 | HAA | 9 | 84 | 84.5 | 7.00 | 7.04 | Firethorn | 15 | 20 |
| 8 | HAA | 11 | 39 | 40.5 | 3.25 | 3.38 | Eucalyptus | 24 | na |

| Tree and Soil Information | | | | | | Direct Examinatic | | | |
|---|---|---|---|---|---|---|---|---|---|
| **Spread, feet** | **Tree Age, years** | **Condition** | **Soil Type** | **Irrigatied** | **Presence of Water** | **EC Damage** | **Do roots Contact Coating** | **Number of Linear Indications found** | **Stress Corrosion Cracking (SCC)** |
| 6 | 110 | Good | Sandy Loam | Y | n | n | y | 0 | NA |
| na | 22 | Fair | Sandy loam | n | na | na | y | 0 | NA |
| 17 | 11 | Fair | Sandy loam | y | n | Y | y | 0 | NA |
| 15 | 11 | Good | Sandy Loam | y | n | y | y | 0 | NA |
| 28 | 20 | Good | Silty clay loam | y | n | n | n | 0 | NA |
| 26 | 23 | Good | Sandy Clay Loam | n | n | na | n | 0 | NA |
| 32 | 33 | Fair | Sandy Loam | y | n | n | y | 0 | NA |
| na | na | Poor | Sandy Loam | n | n | na | y | 0 | NA |
| na | 50 | Fair | Sandy loam | n | n | y | y | 15 | N |
| 34 | 37 | Good | Sandy Loam | n | n | n | y | 0 | NA |
| na | 28 | Dead | Silty clay loam | n | y | n | n | 0 | NA |
| 11 | 44 | Good | Clay/ Heavy clay | y | y | n | n | 0 | NA |
| 30 | 29 | Good | Sandy clay loam | n | n | y | y | 0 | NA |
| 18 | 33 | Good | Clay Loam | n | n | na | y | 0 | NA |
| 30 | 39 | Fair | Silty clay loam | n | y | n | y | 13 | N |
| 23 | 21 | Good | Sandy Loam | y | n | n | y | 0 | NA |
| na | 45 | Poor | Clay Loam | n | n | na | n | 0 | NA |
| 28 | 30 | Good | Sandy Loam | n | n | na | y | 0 | NA |
| 43 | 45 | Fair | Sandy loam | n | n | y | y | 27 | N |
| na | 47 | Good | Sandy loam | n | n | y | y | 3 | N |
| 48 | 34 | Good | Clay | y | n | y | y | 16 | N |
| 50 | 54 | Good | Clay Loam/Sandy Loam | y | n | na | n | 0 | NA |
| na | na | Dead | Silty clay loam | n | n | n | y | 0 | NA |
| 24 | 47 | Fair | Sandy Loam | n | n | na | y | 0 | NA |
| 50 | 54 | Good | Heavy Clay/Sand | y | y | na | n | 0 | NA |
| 39 | 27 | Good | Silty clay loam | y | n | y | y | 14 | N |
| 65 | 40 | Good | Sandy loam | y | n | n | y | 0 | NA |
| 52 | 38 | Good | Silty clay loam | n | n | n | y | 0 | NA |
| 40 | 60 | Poor | Sandy Loam | n | n | n | n | 0 | NA |
| 32 | 58 | Good | Heavy clay | y | y | y | y | 8 | N |

| Tree and Soil Information | | | | | | Direct Examinatic | | | |
|---|---|---|---|---|---|---|---|---|---|
| **Spread, feet** | **Tree Age, years** | **Condition** | **Soil Type** | **Irrigatied** | **Presence of Water** | **EC Damage** | **Do roots Contact Coating** | **Number of Linear Indications found** | **Stress Corrosion Cracking (SCC)** |
| na | 60 | Good | Silty, Clay, Loam | n | n | n | n | 0 | NA |
| 50 | 47 | Good | Sandy loam | y | n | n | y | 0 | NA |
| 31 | 36 | Fair | Heavy clay | y | y | y | y | 16 | N |
| 28 | 44 | Good | Clay/ Sandy Loam | y | y | na | n | 0 | NA |
| 28 | 43 | Good | Heavy clay | y | n | y | y | 16 | N |
| 39 | 60 | Poor | Sandy Loam | n | n | n | y | 0 | NA |
| 40 | 47 | Good | Silty clay loam | y | n | n | y | 0 | NA |
| 48 | 27 | Good | Heavy clay | y | y | y | y | 6 | N |
| na | 60 | Good | Silty clay loam | n | n | n | n | 0 | NA |
| 29 | na | Good | Clay loam | y | n | na | n | 0 | NA |
| 44 | 23 | Good | Clay loam | n | n | n | n | 0 | NA |
| 40 | na | Poor | Silty clay loam | n | n | na | y | 0 | NA |
| 87 | 56 | Good | Sandy loam | y | n | n | y | 0 | NA |
| 70 | 65 | Good | Silty clay loam | y | n | y | y | 0 | NA |
| na | 44 | Good | Sandy loam | n | n | y | y | 15 | N |
| na | 35 | Good | Sandy Loam | n | n | n | y | 0 | NA |
| 19 | na | Good | Clay Loam, Loam, Clay, Sandy Loam | Y | n | n | y | 17 | N |
| 18 | 19 | Fair | Sandy Loam | y | n | n | y | 0 | NA |
| na | 50 | Poor | Loam | Y | n | n | y | 0 | NA |
| na | na | na | Clay Loam | n | n | na | y | 0 | NA |
| na | na | Good | Sandy clay loam | n | na | na | y | 0 | NA |
| na | na | Fair | Clay Loam | n | y | na | y | 0 | NA |
| na | na | Good | Sandy loam | n | n | y | y | 15 | N |

| on Results | | | | | Document Tracking | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Pictures of Linear Indications | Who performed H-Form | Presence of Coating Damage | UT Test | MPT Test | H-Form Complete/ Received | A-Form Complete/ Received | Frizzell Report complete/ Received | Mears Above Ground Survey Reports Completed/ Received | GPR with Fresno State University/ Findings Review | MicKit Performed/ Report received |
| NA | Mears | y | y | y | Y | Y | Y | Y | | Y |
| NA | NA | y | na | y | Not Performed | Y | y | NOT PERFORMED | | NOT PERFORMED |
| NA | Mears | y | y | y | Y | Y | Y | Y | Y | NOT PERFORMED |
| NA | Mears | y | y | y | Y | Y | Y | Y | | NOT PERFORMED |
| NA | Mears | n | y | y | Y | Y | Y | Y | | Y |
| NA | NA | n | na | na | Not Performed | Y | Y | NOT PERFORMED | | NOT PERFORMED |
| NA | Mears | y | y | y | Y | Y | Y | Y | Y | Y |
| NA | NA | y | na | na | Not Performed | Y | Y | NOT PERFORMED | | NOT PERFORMED |
| YES | GE | y | y | y | Y | Y | Y | NOT PERFORMED | | NOT PERFORMED |
| NA | GE | y | y | y | Y | Y | Y | Y | | NOT PERFORMED |
| NA | Mears | n | n | n | Y | Y | Y | Y | | NOT PERFORMED |
| NA | Mears | n | y | y | Y | Unobtainable | Y | NOT PERFORMED | | NOT PERFORMED |
| NA | GE | y | y | y | Y | Y | y | NOT PERFORMED | | NOT PERFORMED |
| NA | NA | y | na | na | Not Performed | Y | Y | NOT PERFORMED | | NOT PERFORMED |
| YES | Mears | y | y | y | Y | Unobtainable | Y | NOT PERFORMED | | NOT PERFORMED |
| NA | Mears | y | y | y | Y | Y | y | Y | | Y |
| NA | NA | n | na | na | Not Performed | Y | Y | NOT PERFORMED | | NOT PERFORMED |
| NA | NA | y | na | na | Not Performed | Y | Y | NOT PERFORMED | | NOT PERFORMED |
| YES | GE | y | y | y | Y | Y | Y | NOT PERFORMED | | NOT PERFORMED |
| YES | GE | y | y | y | Y | Y | Y | NOT PERFORMED | | NOT PERFORMED |
| YES | GE | y | y | y | Y | Y | Y | NOT PERFORMED | | NOT PERFORMED |
| NA | NA | n | na | na | Not Performed | Y | Y | NOT PERFORMED | | NOT PERFORMED |
| NA | Mears | y | y | y | Y | Not Performed | Y | NOT PERFORMED | | NOT PERFORMED |
| NA | NA | y | na | na | Not Performed | Y | Y | NOT PERFORMED | | NOT PERFORMED |
| NA | NA | n | na | na | Not Performed | Y | Y | NOT PERFORMED | | NOT PERFORMED |
| YES | GE | y | y | y | Y | Y | Y | NOT PERFORMED | | NOT PERFORMED |
| NA | Mears | y | y | y | Y | Y | Y | Y | | Y (2) |
| NA | Mears | y | y | y | Y | Unobtainable | Y | NOT PERFORMED | | NOT PERFORMED |
| NA | Mears | n | n | y | Y | Y | y | Y | | Y |
| YES | GE | y | n | y | Y | Y | Y | NOT PERFORMED | | NOT PERFORMED |

| on Results | | | | | Document Tracking | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Pictures of Linear Indications** | **Who performed H-Form** | **Presence of Coating Damage** | **UT Test** | **MPT Test** | **H-Form Complete/ Received** | **A-Form Complete/ Received** | **Frizzell Report complete/ Received** | **Mears Above Ground Survey Reports Completed/ Received** | **GPR with Fresno State University/ Findings Review** | **MicKit Performed/ Report received** |
| NA | Mears | n | n | n | Y | Y | y | Y | | NOT PERFORMED |
| NA | Mears | y | y | y | Y | Y | y | Y | | Y |
| YES | GE | y | y | y | Y | Y | Y | NOT PERFORMED | | NOT PERFORMED |
| NA | NA | n | na | na | Not Performed | Y | Y | NOT PERFORMED | | NOT PERFORMED |
| YES | GE | y | y | y | Y | Y | Y | NOT PERFORMED | | NOT PERFORMED |
| NA | Mears | y | n | y | Y | Y | y | Y | | NOT PERFORMED |
| NA | Mears | y | y | y | Y | Unobtainable | Y | NOT PERFORMED | | NOT PERFORMED |
| YES | GE | y | n | y | Y | Y | Y | NOT PERFORMED | | NOT PERFORMED |
| NA | Mears | n | n | n | Y | Y | y | Y | | NOT PERFORMED |
| NA | NA | n | na | na | Not Performed | Y | Y | NOT PERFORMED | | NOT PERFORMED |
| NA | Mears | n | y | y | Y | Unobtainable | Y | NOT PERFORMED | | NOT PERFORMED |
| NA | NA | y | na | na | Not Performed | Y | Y | NOT PERFORMED | | NOT PERFORMED |
| NA | Mears | y | y | y | Y | Y | y | Y | | Y |
| NA | GE | y | y | y | Y | Y | Y | NOT PERFORMED | | NOT PERFORMED |
| YES | GE | y | y | y | Y | Y | Y | NOT PERFORMED | | NOT PERFORMED |
| NA | GE | y | y | y | Y | Y | Y | Y | | NOT PERFORMED |
| YES | Mears | y | y | y | Y | Y | Y | Y | | NOT PERFORMED |
| NA | Mears | y | y | y | Y | Y | Y | Y | | Y |
| NA | Mears | y | y | y | Y | Y | Y | Y | Y | NOT PERFORMED |
| NA | NA | y | na | na | Not Performed | Y | Y | NOT PERFORMED | | NOT PERFORMED |
| NA | NA | y | na | na | Not Performed | Y | y | NOT PERFORMED | | NOT PERFORMED |
| NA | NA | y | na | na | Not Performed | Y | Y | NOT PERFORMED | | NOT PERFORMED |
| YES | GE | y | y | y | Y | Y | Y | NOT PERFORMED | | NOT PERFORMED |